12. BOREHOLE LOGGING TECHNIQUES APPLIED TO BASE METAL ORE DEPOSITS

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Glenn, W.E. and Nelson, P.H., Borehole logging techniques applied to base metal ore deposits; in Geophysics and Geochemistry in the Search for Metallic Ores; Peter J. Hood, editor, Geological Survey of Canada, Economic Geology Report 31, p. 273-294, 1979.

Abstract

Interest in the application of borehole logging to metallic mineral exploration and deposit evaluation has grown substantially in recent years. However, borehole logging tools and techniques were developed primarily by the petroleum industry and neither the tools nor their application are directly suited to the needs of the metallic mineral industry. Lack of generally available commercial logging services for small diameter holes and for the measurement of quantities such as magnetic susceptibility, induced polarization, and ore grade has inhibited the growth of borehole logging in metallic mineral mining.

The need to study new mining technology and to search at greater depths for new ore deposits has created a demand for a slim-hole logging capability. The requirements range from elemental and mineralogical analyses, through properties used in geophysical exploration to bulk rock properties for either conventional or novel mining techniques. This paper reviews the presently available capabilities for downhole analyses for geological information, for geophysical properties and for fluid flow. Much of the review is based upon direct experience with a facility operated in-house by a major metals mining company.

Résumé

Il y a eu au cours des dernières années un intérêt croissant pour l'application de la diagraphie par trou de sonde à l'exploration des minéraux métalliques et à l'évaluation des gisements. Toutefois, les outils et les techniques de diagraphie par trou de sonde ont été mis au point principalement par l'industrie pétrolière; ni les outils ni leur utilisation n'étaient directement adaptés aux besoins de l'industrie des minéraux métalliques. Le manque de services commerciaux de diagraphie accessibles en ce qui concerne les trous de petit diamètre et la mesure de quantités comme la susceptibilité magnétique, la polarisation provoquée et la teneur en minerai a empêché le développement de la diagraphie par trou de sonde dans le secteur des minéraux métalliques.

Le besoin d'étudier de nouvelles techniques d'exploitation et de creuser à des profondeurs plus grandes afin de trouver de nouveaux gisements de minerai a fait naître une demande pour la diagraphie en diamètre réduit. Les besoins vont des analyses élémentaires et minéralogiques jusqu'aux propriétés utilisées en exploration géophysique et aux propriétés de la roche prise dans son ensemble, en ce qui a trait aux techniques d'exploitation classiques ou nouvelles. Le présent document étudie les méthodes actuelles d'analyse, au fond du trou, de l'information géologique, des propriétés géophysiques et de l'écoulement des fluides. La majeure partie de l'étude est basée sur des expériences pratiques à l'aide d'une installation exploitée par une importante société d'exploitation de minéraux métalliques.

INTRODUCTION

Research on the application of well logs to porphyry copper exploration and development began at Kennecott Copper Corp. in 1971. Logging research was justified for many reasons, among which was the need to develop additional techniques for locating and evaluating deeper mineral deposits. Due to a lack of a logging service oriented to metallic mineral applications both in terms of tools and data analyses, Kennecott decided to develop its own logging system in addition to carrying out research on well log applications. This approach allowed a great deal of flexibility for studying what tool specifications were needed, what field techniques were best and what kinds of data were important.

In general, the use of logging in the base minerals industry lags behind that of almost all other sectors of the exploration and geotechnical disciplines. We will not attempt to diagnose reasons for this deficiency, but it means that if the mining industry finds the incentives to apply borehole measurements on a widespread basis tomorrow, it faces reduced start-up costs in terms of tool development. This is not to say that the development and deployment still required will be inexpensive, but with the exception of techniques for mineralogical and elemental analysis, many useful tools have already been developed and are available to base metal explorationists on an "off-the-shelf" basis. Moreover the development of small diameter tools has been accelerating at a rapid pace in the last few years. The stimulation comes not from the base metal mining industry but from other sectors, including,

- production logging for oil and gas,
- uranium and coal exploration and exploitation,
- geothermal exploration and exploitation,
- geological engineering studies, such as power plant siting, tunnelling, etc.

We hope we have made it clear that the true "state-of-the-art" in mineral logging comes not so much from the mineral industry as from the whole spectrum of users of downhole measurements. Since a true overview of all sources and users of slimhole borehole technology is not possible, and would quickly become out-dated, we will simply list some recent and on-going developments in logging technology applicable to the mining industry and devote the remainder of

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the paper to our own experience in applying different techniques to the exploration and engineering problems encountered within the base metal mining industry.

Recent Developments

1. The development of a borehole assaying tool for nickel, with very encouraging indications of its applicability to copper (Seigel and Nargolwalla, 1975).
2. Recent improvements in the stability of a magnetic susceptibility logging instrument: less than 10 μcgs maximum drift in an operating environmental temperature of 70°C, by the U.S. Geological Survey (J. Scott, pers. comm.).
3. The availability of "high resolution" focussed density tools in slim-hole versions, applicable to the logging of thin seams, veins, and fractures (Fishel, 1976).
4. The continued efforts at quantifying the electrical resistivity and induced polarization response in terms of the sulphide and clay content of the rock (Clavier, et al., 1976; Snyder et al., 1977; Patchett, 1975) and the current on-going development of several commercial and industrial groups of tools for the measurements of polarization and dielectric properties in boreholes.
5. Continuing refinement of precision temperature logging and the analysis of continuous logs (for example, Conaway, 1977) to correlate rock type using thermal conductivity.
6. A calibration facility oriented to base mineral environments under development at the U.S. Bureau of Mines.

The above listing is almost a random sampling of recent developments which might easily be adapted for specific purposes in base mineral exploration and engineering. Another approach is to consider physical and chemical properties which might be measured in situ and applications for which the data will be most useful. Table 12.1 represents one such compilation; it intentionally includes engineering applications as well as exploration. This extension emphasizes our belief that downhole logging will eventually have as much importance for the mining engineer as for the explorationist.

Application of Techniques

In the remainder of this paper we describe an in-house downhole logging facility used for a variety of research and developmental purposes and describe some specific applications and results. Our discussion is keyed to the ten properties listed in Table 12.1; the underlined entries indicate the categories for which examples are given in this paper.

It should be stated that in order to limit the paper we have excluded exploration techniques which combine surface and borehole methods (see Hohmann et al., 1977, for electromagnetic prospecting examples) and cross-hole techniques for investigating large volumes of rock between boreholes (see Lytle et al., 1976, for electromagnetic probing example; R.L. Aamodt, 1976, for examples using acoustic energy; and Daniels, 1977, for IP examples). That is, we confine our presentation to probes in a single borehole with a radius of investigation determined by the rock/fluid properties and the probe geometry.

Keys and MacCary (1971) reviewed the application of borehole geophysics to water resources investigations and much of the material they covered is appropriate to metallic mineral mining applications. From the geotechnical vantage point Van Schalkwyk (1976) reviewed a wide range of equipment which is useful for rock mechanics and engineering studies. Other authors have reviewed the use of borehole instrumentation for various slim-hole applications. For example, Dyck et al. (1975) gave an excellent overview of borehole geophysics applied to metallic mineral prospecting. Each of these three review articles is interesting in terms of its scope and perspective and each contains a useful list of references.

Table 12.1

Physical and chemical in-situ properties obtained by borehole logging with regard to mining applications

	Exploration	Porphyry Copper Characterization	Dump Leaching	Mine Development
Elemental and mineralogical analysis	X̲	X	X	X
Rock type identification and correlation	X̲	X	X	X
Rock quality and fractures	X	X̲		X
Density	X			X
Porosity		X̲	X	
Electrical and magnetic properties	X̲	X̲		
Temperature and thermal properties		X	X	X̲
Fuid flow		X	X̲	X
Water sampling	X	X	X	X

Underlined entries indicate the categories for which examples are given in this paper.

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KENNECOTT COPPER CORPORATION BOREHOLE LOGGING SYSTEM

Kennecott Copper Corp. currently (1977) has three logging trucks, of which only one is designed to measure a broad range of rock properties. The other two are devoted to hydrologic and environmental logging. A brief description of the Kennecott Copper Corp. logging truck (Fig. 12.1 and 12.2) is given here. It is a four-wheel drive Ford F600 truck chassis with a 14 feet (4.3 m) long, 6 feet (1.8 m) wide, 6 feet (1.8 m) high custom-built van on the bed. The van portion is divided into a forward operator/recorder cubicle and a rear mechanical/storage area. A boom is located over the rear centre of the vehicle. The truck is equipped with 1830 m of four-conductor 4.8 mm, steel armour cable with a Gearhart-Owen four-conductor cable head and an extensive set of electronic and mechanical equipment. The electrical power unit is a 6.5 kW gasoline generator. The truck typically carries fourteen different logging tools. The various tools and their primary function(s) are shown in Table 12.2. All tools are 2.25 inches (5.7 cm) or less in diameter.

Many of the tools require only one conductor and the armour for operation, but others such as the IP tool require all four plus the armour. Except for the resistivity and single-point resistance tools, all tools accomplish some electronic signal processing and enhancement downhole before the signal is transmitted to the surface. Uphole modules are mounted in removable nuclear instrumentation modules and do various amounts of signal processing and output the analog signals to one or more channels of a four-channel Texas Instruments chart recorder. A plug-in patch panel (Fig. 12.2) and programmed patch boards (Fig. 12.3) allow the operator to connect tool functions, module functions and auxiliary electronic equipment such as an oscilloscope in any fashion desired or to operate the system in some predetermined fashion by simply plugging in a board. The flexibility of the patch panel is essential for a research and development logging system in that the electronic equipment can be quickly interconnected in a modified or new configuration and a new tool can quickly become operational. A block diagram of the system just described is given in Figure 12.4.

ELEMENTAL AND MINERALOGICAL ANALYSES IN BOREHOLES

One of the most exciting and promising frontiers in mineral logging is the development of tools to analyze for specific elements in the borehole. In the specific case the logging would be a borehole assay for particular ore minerals. In the general case the type of logging would provide an in situ geochemical description of the mineral deposit.

Czubeck (1979) describes the current activity in borehole assaying, most of which is based upon radioactive and fluorescent techniques. A neutron activation method for the borehole assay of copper and nickel has been described by Nargolwalla et al. (1974) and Seigel and Nargolwalla (1975). Their system, called Metalog, available as a routine service, was tested in Anaconda's porphyry copper mine near Yerington, Nevada (Staff, Scintrex Limited, 1976). The test results are very envouraging and are presented in Figure 12.5. Because of limited experience with this technology we will not attempt to describe progress in the field of nuclear analysis, but will discuss a few examples obtained with more conventional methods. It is likely that the results from these other methods will supplement and constrain the nuclear analytical methods when they become available.

The most readily available analytical technique in boreholes is the measurement of the natural gamma radiation. In the mining environment the total count can often be directly correlated with the potassium content from the laboratory analysis of core material as shown in Figure 12.6. In fact, based upon this kind of direct correlation, our logs are routinely scaled in K_2O content in most environments. Where the uranium or thorium content is significant this straightforward procedure does not apply, and spectral information is required to distinguish the three elements. Indeed, spectral logging is applied to uranium exploration and is discussed elsewhere in these proceedings (Killeen, 1979).

Figure 12.1. *Kennecott Copper Company's logging truck.*

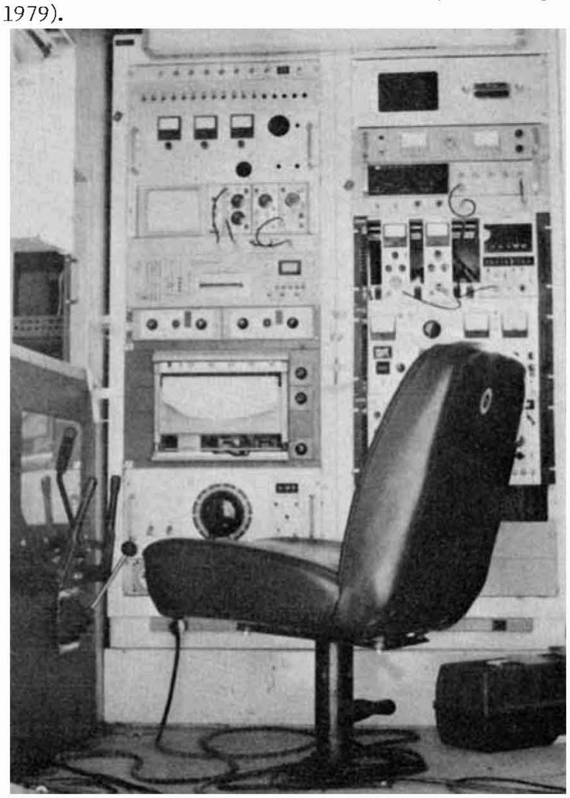

Figure 12.2. *Interior view of operator section of Kennecott Copper Company's logging truck.*

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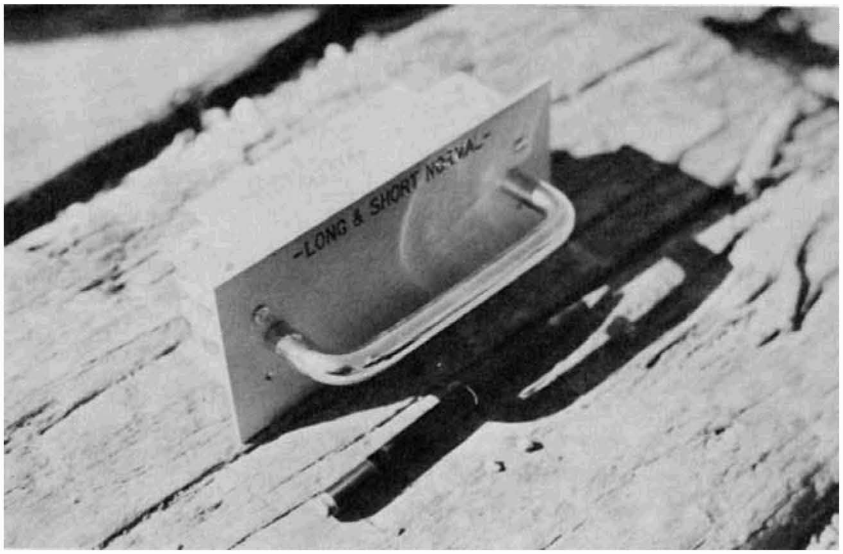

Figure 12.3. *Program patch board.*

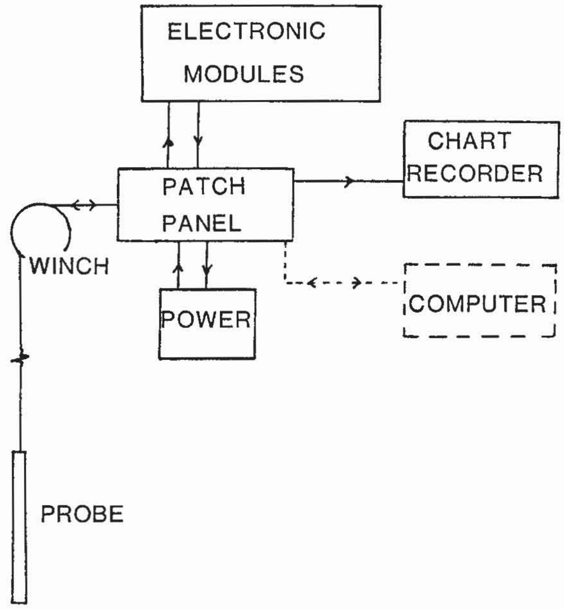

Figure 12.4. *Block diagram of logging system*

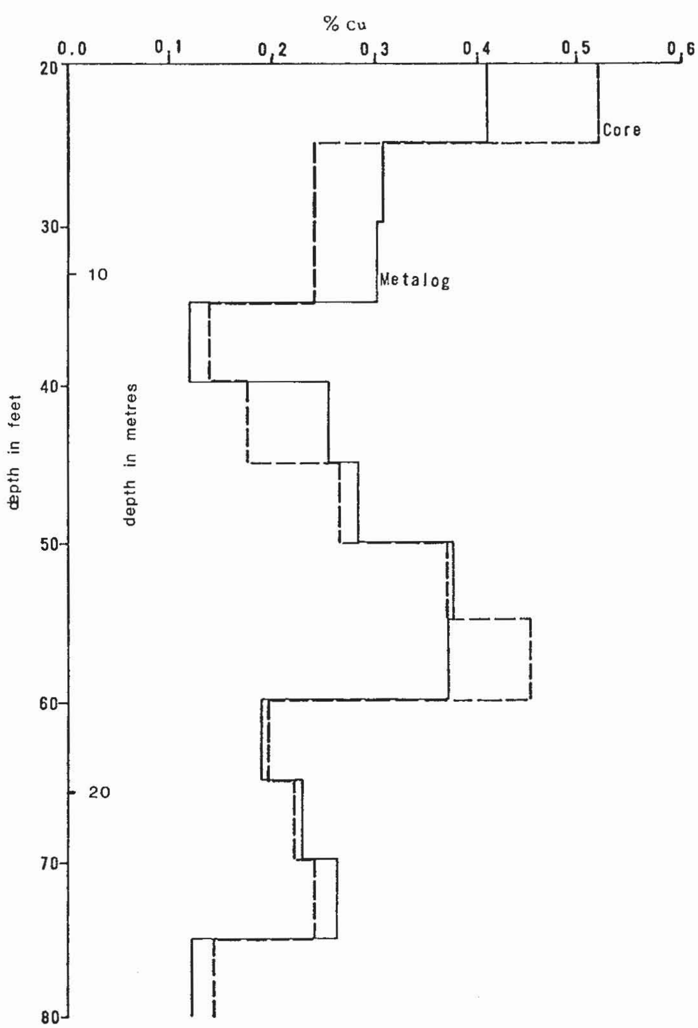

Figure 12.5. *Borehole assaying.*

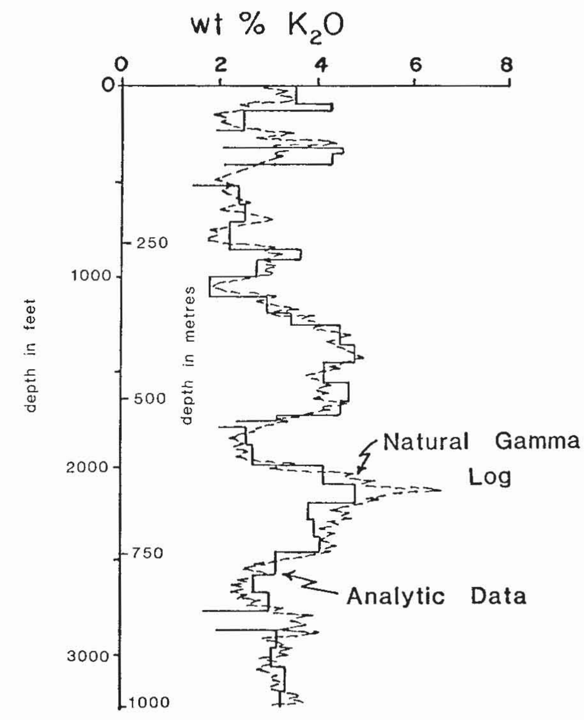

Figure 12.6. *Comparison of analytic and well log analysis of* K_2O.

Examples of the dependence of the neutron log on both pore water and water bound in hydrous minerals have been presented before (Savre and Burke, 1971; Snyder, 1973; Nelson and Glenn, 1975) and the example of Nelson and Glenn is reproduced in Figure 12.7. The chemically bound water can be so high that it can be directly measured by the neutron tool and hence mask the pore water contributions to the neutron log. We will show in the section on porosity that when the two contributions are mixed, it is still possible to remove the bound water contribution. In any case the bound water can be quantitatively assessed, giving a measure of the hydrated mineral content of the rock, usually translatable as the altered, clay mineral fraction.

Table 12.2

Response of drillhole logging tools to rock properties

LOGGING TOOLS	Temperature	Hole Diameter	Porosity	Bound Water	Fluid Loss	Potassium	Density	Fracturing,RQD	Sulphides	Magnetite
Temperature	1				4					
Caliper		1			4			4		
Neutron			2	2	3			4		
Natural Gamma						2		4		
Gamma-Gamma(density)			2	4	3		1		2	
Velocity (Δ T)			2		3			2		
Resistivity			3	4	4			3	2	
IP				4					2	
Magnetic Susceptibility										1
Fluid Flow					1					

PHYSICAL PROPERTIES

1 Quantitative measure – high success
2 Quantitative measure – moderate success
3 Always responds qualitatively
4 Often responds qualitatively

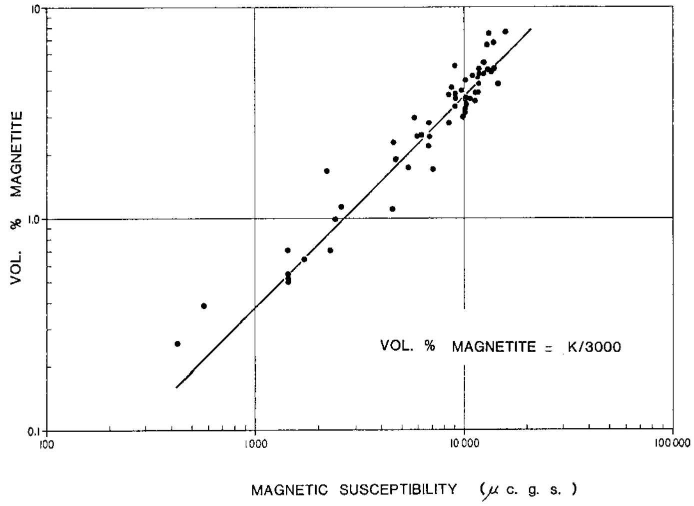

Figure 12.8. *Plot of magnetic susceptibility from logs versus volume per cent magnetite.*

A third fairly direct measurement is the magnetite content estimated from the magnetic susceptibility tool. Figure 12.8, taken from Snyder (1973), demonstrates the correlation. Here again, as in the case of potassium, is one of the rare cases where a single element or mineral type possesses a distinctive physical property which can be readily measured and is unique to that mineral type in many cases of interest.

An obvious need in mining applications is a direct measure of the sulphide content. Our attempts at this measurement are detailed in subsequent sections on density and electrical properties.

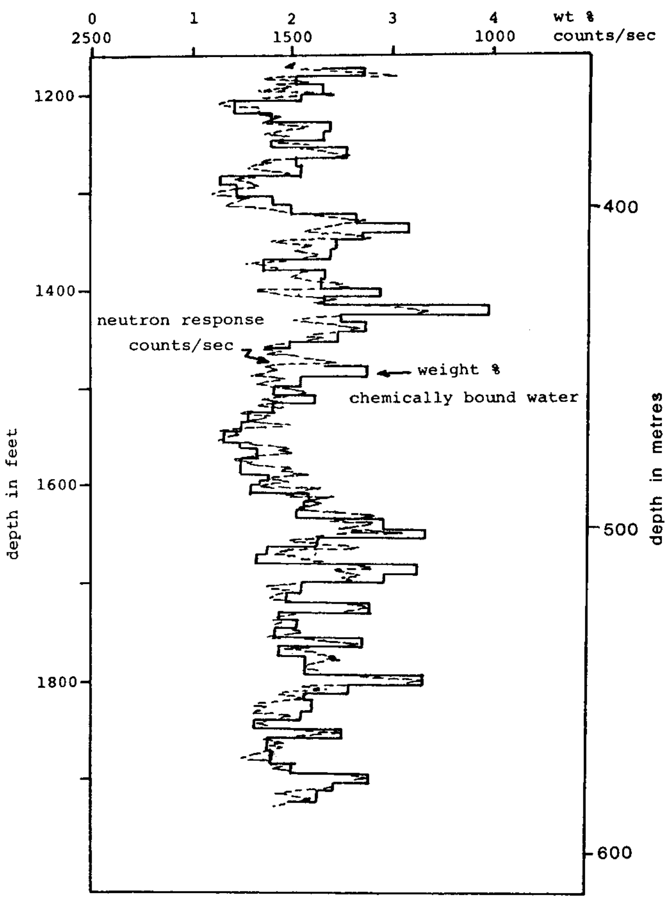

Figure 12.7. *Comparison of the neutron log with bound water analysis on pulps.*

ROCK TYPE IDENTIFICATION AND CORRELATION

Identification of rock types is facilitated where there is a direct correlation between an easily identified mineral species, such as magnetite, and the rock unit. A good example of this is evident at one of Kennecott's porphyry deposits. The copper mineralization is in an andesite pile crosscut by numerous latite dykes. The dykes and andesites show contrasting expressions on both the natural gamma (potassium) and magnetic susceptibility (magnetite) logs. Figure 12.9 illustrates this contrast. The latite between 163 and 186 m shows a high natural gamma response and a near-zero magnetic susceptibility, whereas the andesite exhibits a lower natural gamma response and magnetic susceptibility averaging around 3000 μcgs. Note that the density of the latite is also lower than the density of the andesite. A short interval between 151 and 159 m has a very similar response on all logs as does the latite except that the magnetic susceptibility is not zero. We interpret this interval to be a near miss of the same dyke intersected at 163 m. The result suggests that the drillhole is parallel to a dyke over this interval.

We have noted a striking correlation between resistivity variation and sulphide zoning at one of Kennecott's porphyry copper deposits. The highly variable, low to high, resistivity pattern evident in the upper part of the long and short normal log* for each hole shown on a cross-section in Figure 12.10 is coincident with the pyrite halo in this deposit. The lower cut-off of this variable resistivity is closely correlated with a particular copper grade. Some detailed features of the resistivity logs can be correlated among the drillholes. These correlated features have been associated with both a variation in sulphide veining and the degree of sulphide

* Industry standard: 40 and 16 inches (1.22 and 0.488 m) respectively.

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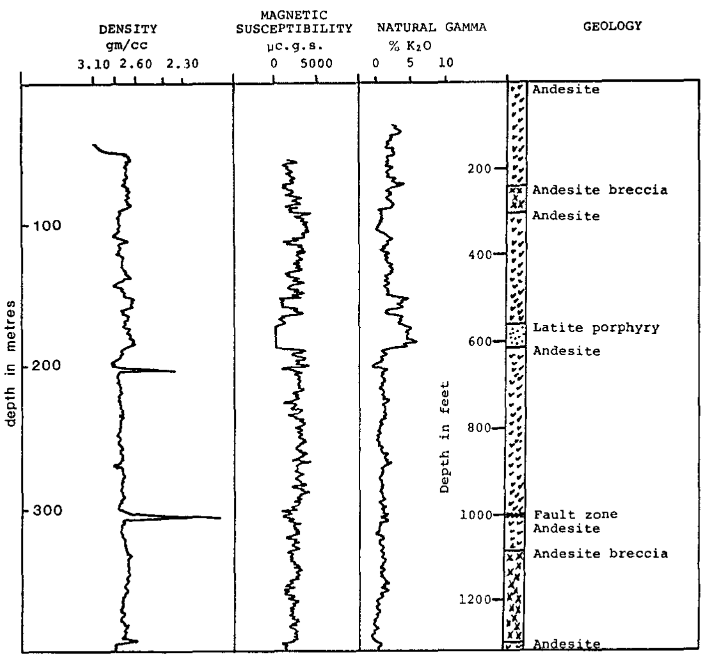

Figure 12.9. *Latite dyke correlation on natural gamma and magnetic susceptibility logs.*

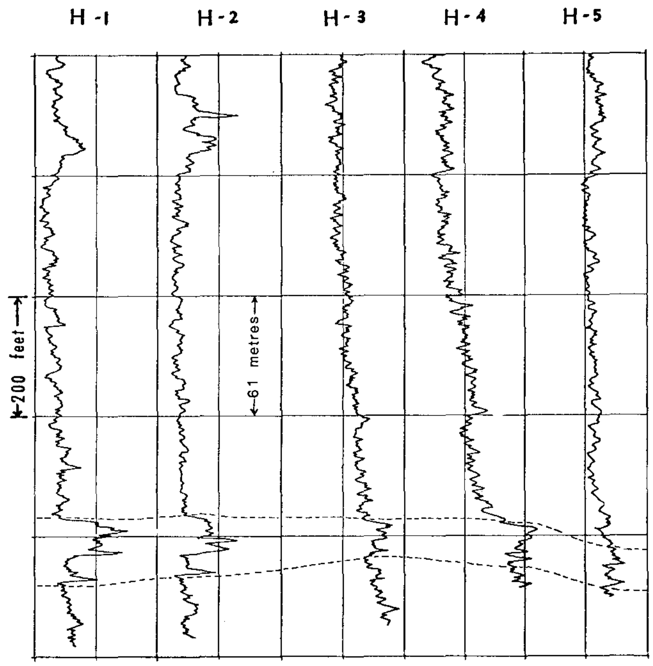

Figure 12.11. *Natural gamma logs.*

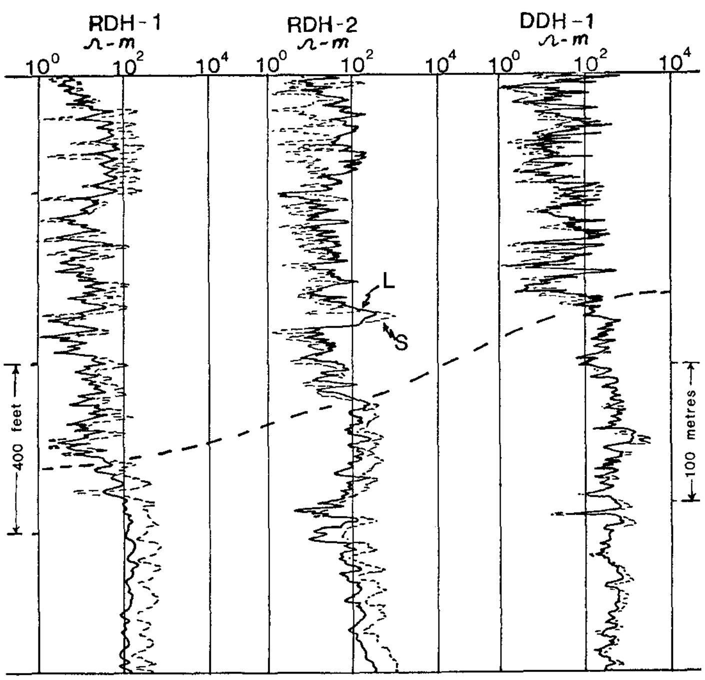

Figure 12.10. *Long and short normal resistivity logs.*

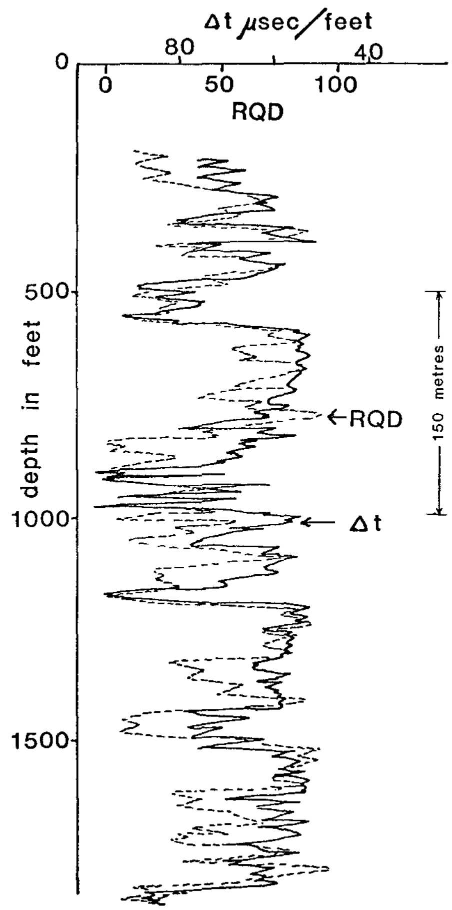

Figure 12.12. *Rock quality designation (RQD) from core versus compressional wave transit time measured in a drillhole.*

oxidation. Also, at the same deposit, the natural gamma log shows a substantial increase in potassium as the causative intrusive is approached. This feature is depicted in Figure 12.11 where logs from five different drillholes are shown. An interval of high potassium can be correlated on all logs as indicated by the dashed lines in Figure 12.11. The increased potassium is seen in the core as an increase in sericite and orthoclase mineralization.

We have numerous examples of rock-type identification and correlation that we have accomplished at several of Kennecott's porphyry copper deposits and prospects. However, we feel the ones given here are sufficient to illustrate the ability to use well logs both to differentiate rock types and to correlate rock units across a deposit. This information is useful for structural geology studies and for the understanding of the porphyry system geometry.

ROCK QUALITY AND FRACTURE LOCATION

With logging techniques it is possible to determine the mechanical properties of rocks and to study the structural geology. In this section logging relevant to both topics will be described.

Rock Quality Designation (RQD) as used by mine geologists is the measure obtained by summing the length of core pieces greater than 10 cm and dividing the total length of sample, typically 1.5 m to 3 m of core. If all the pieces of core in a 1.5 m section, for example, were greater than 10 cm, the RQD would be 100%, if all pieces were smaller than 10 cm the RQD would be 0%. RQD is an empirical measure of rock competence. We have found that the velocity (reciprocal of the compressional wave transit time) log gives a fairly good measure of RQD where the rock is moderately to well fractured and one example is shown in Figure 12.12. In this case, the velocity log responds primarily to the cracks or fractures in the rock.

Fractures or fractured intervals of rock commonly give a characteristic response on several logs: caliper, velocity, neutron and density. An example is shown in Figure 12.13. For illustration note the response of each log at 308 m where the geologist has noted a fault zone in the core. The caliper shows an increased hole diameter which indicates that material has fallen from the fracture or was plucked out by the bit during drilling. The velocity log shows a low velocity, the neutron shows a high porosity and the density log shows a low density at this depth. Several fractures have been picked from these logs and are indicated by an f beside the caliper log at the appropriate places.

The preceding analysis gives a location only for fractures which appear open in the hole and does not provide strike or dip information.

We have used the seisviewer log offered as a service by Birdwell to determine fracture orientation in drillholes. This tool was first described by Zamanek et al. (1970). An example of this log along with the caliper and velocity logs is shown in Figure 12.14. The interpreted fractures and their orientation are noted beside the seisviewer log. The seisviewer tool sends acoustic pulses toward the borehole wall. The tool rotates and sends a signal to the surface when it passes through magnetic north. The acoustic energy reflected from the borehole wall is monitored and sent to the surface where it is presented on an oscilloscope and photographed. The oscilloscope triggers on the north signal. A smooth borehole wall will generate a strong reflection, the bright areas on the log, and a rough, caved borehole wall will generate a weak reflection, the dark areas on the log. Hence fractures are indicated by dark traces on the log. However, if the tool is not centred in the hole or the hole deviates very much from a cylindrical cross-section, the log will exhibit a

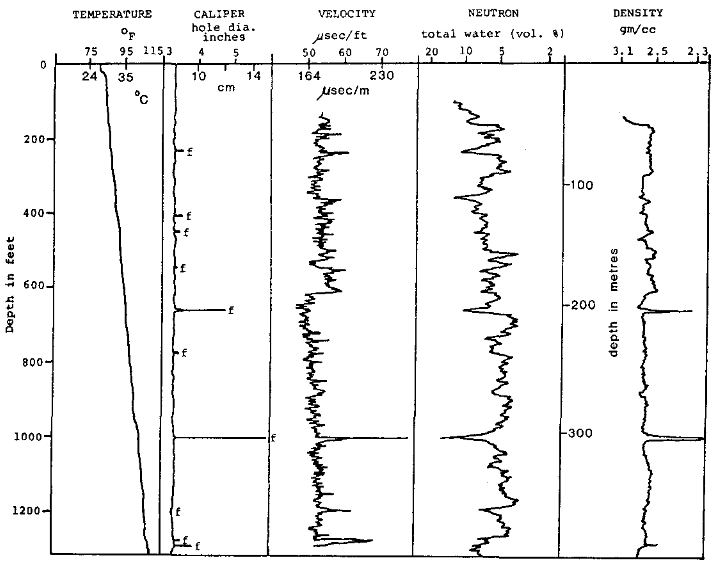

Figure 12.13. *Suite of logs showing rock fracture signature on several well logs.*

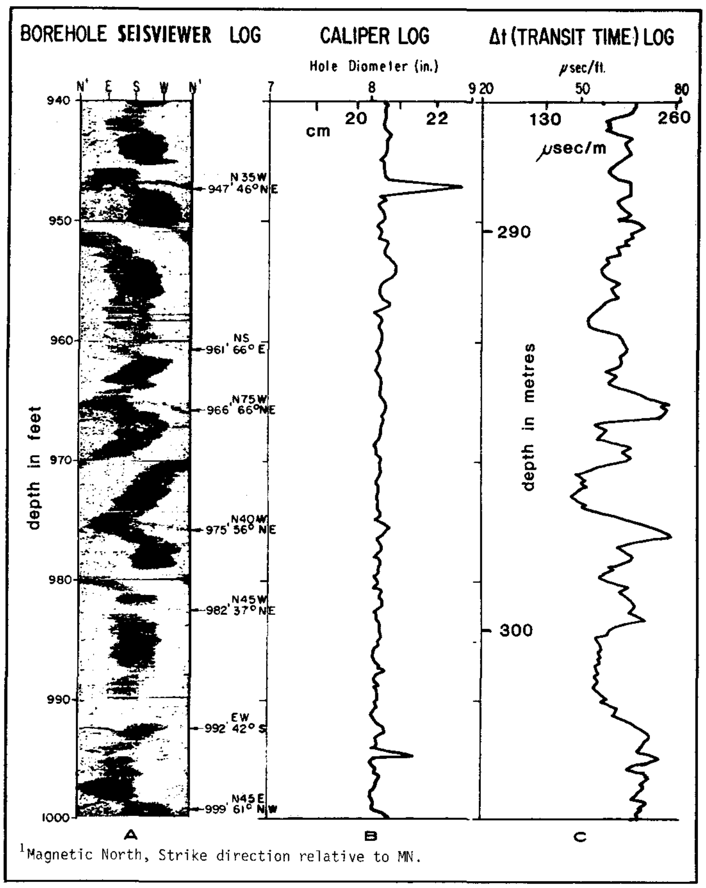

Figure 12.14. *Fracture location and orientation obtained from an acoustic seisviewer log.*

vertical zebra pattern as seen in Figure 12.14. Often this pattern will obscure the fractures. The tool is also continuously pulled vertically and the resultant log is a planar representation of a cylindrical borehole with north at the left and right of the record and depth along the side. A plane intersecting the drillhole will apear as a sinusoid on the flat surface. The dip magnitude and direction are obtained from the excursion and location of the maximum and the minimum of the sinusoid. The data from the seisviewer log can be studied in a conventional way as illustrated in Figure 12.15. This figure shows a contoured equal-area plot of poles to the fractures and Rose diagrams of strike and dip directions. A plot (not shown) was also made for fractures measured on the surface around the drill site and the data agree extremely well with one exception; understandably, the surface study showed very few near-horizontal fractures.

We believe logging for structure can benefit both the exploration and the mine geologist. Both could use the information to develop a better understanding of the three-dimensional structure of a mineral deposit.

DENSITY LOGGING

Routine Density Estimates

We routinely employ a single-detector, gamma-gamma density probe in NX-size boreholes. The maximum tool diameter is 5.5 cm. In operation the entire tool is held against the borehole wall by a decentralizing arm which extends from the tool. Because only a single detector is used, the measurement is uncompensated, that is, no correction is made for borehole rugosity. In cored holes in hard rock this does not present as great a problem as in soft rock because zones of severe rugosity are relatively infrequent and not much data is lost, although recently it has become possible to apply compensation algorithms to slim-hole density logs (Scott, 1977). We have found that it is a relatively straightforward process to acquire reliable density data in NX boreholes, using core to establish the calibration and referencing the tools with calibration blocks during routine logging operations. Merkel and Snyder (1977) discuss some of the problems of calibrating a slim-hole density tool.

Sulphide Estimates from Density Logs

Because the sulphide minerals are almost twice as dense as the silicates, it should be possible to estimate the sulphide content using the density log, provided that the silicate grain density is constant and the porosity can be determined from another log.

The bulk density of a rock containing three components – sulphides, water-filled pore space, and nonsulphide matrix – is given by

$$\rho_b = S\rho_s + \Phi\rho_f + (1 - \Phi - S)\rho_g \qquad \text{(D-1)}$$

where ρ_s, ρ_f, ρ_g are the sulphide, fluid and nonsulphide grain densities, and S, Φ are the sulphide content and pore space as volume fractions.

Rewriting and setting the fluid density $\rho_f = 1$ gives

$$\rho_b = \rho_g + S(\rho_s - \rho_g) + \Phi(1 - \rho_g) \qquad \text{(D-2)}$$

Expressing the sulphides as weight per cent (S') and the porosity as a volume per cent gives

$$\rho_b = \rho_g + 0.01\frac{\rho_b}{\rho_s}S'(\rho_s - \rho_g) - 0.01\Phi(\rho_g - 1) \qquad \text{(D-3)}$$

Solving for S' we get

$$S' = 100\frac{\rho_b - \rho_g + 0.01\Phi(\rho_g - 1)}{\rho_b(1 - \rho_g/\rho_s)} \qquad \text{(D-4)}$$

Equation (D-4) is used to compute the sulphide logs and is presented graphically in Figure 12.16. Figure 12.16 allows quantitative inspection of the dependence of S' on Φ, ρ_b and ρ_g. In addition, a sensitivity analysis for S' on the four variables ρ_b, ρ_g, ρ_s and Φ was carried out by evaluating the derivatives with respect to each of the four variables. Selecting base values of $\rho_b = 2.70$, $\rho_g = 2.65$, $\rho_s = 5.0$ and Φ =4% (equivalent to S' = 9.1 wt. %), the following errors in the sulphide estimate result:

Perturbations:	$\Delta\rho_b$=0.01	$\Delta\rho_g$=0.01	$\Delta\rho_s$=0.01	$\Delta\Phi$=1%
Error in S' (wt.%)	+0.75	-0.81	-0.02	+1.30

Or, equivalently, the following perturbations are required to produce an error in S' of 1.0 weight per cent:

$$\Delta\rho_b = 0.013 \quad \Delta\rho_g = -0.012 \quad \Delta\rho_s = -0.50 \quad \Delta\Phi = 0.77\%$$

Of the four unknowns, changes in the nonsulphide grain density will probably produce the largest errors because there is at present no way to assess grain density in the borehole. The bulk density measurement itself also can be a problem if the count rate is insufficient.

The third variable, the sulphide grain density, is less critical because the sulphide estimate is less sensitive to its fluctuations. The influence can be further reduced if an estimate of the pyrite-to-chalcopyrite ratio is available and no other sulphides are present. Since the pyrite grain density is 5.02 g/cc and chalcopyrite about 4.2 g/cc, we have

$$\rho_s = 4.2c + 5.02p \qquad \text{(D-5)}$$

where c and p denote the chalcopyrite and pyrite fractions and c + p = 1.

Calling p/c = R gives

$$c = 1/(1 + R)$$

$$p = 1 - c = R/(1 + R)$$

and

$$\rho_s = \frac{1}{(1 + R)}(4.2 + 5.02R) \qquad \text{(D-6)}$$

Figure 12.17 is a graph of this function.

Finally, the porosity variations are most easily assessed by using the neutron log to compute a neutron porosity for use in the expression which defines the sulphide estimate. Since the neutron porosity incorporates bound water, the porosity estimate will usually be somewhat high and consequently the sulphide estimate will be high unless bound water is taken into account.

Field Examples of Sulphide Estimation from Density Logging

Figure 12.18 presents an empirical test of the method of sulphide estimation. The data were obtained in a sedimentary sequence penetrated by a quartz latite porphyry. The hole is unusually high in pyrite as shown by the heavy liquids analyses as well as by a visual estimate which checked reasonably well with the laboratory analysis. Magnetite occurs only between 381 to 401 m. The density data were reduced using reasonable values in equation D-4, but unfortunately the new density tool utilized had not been properly calibrated at the time the log was obtained so no

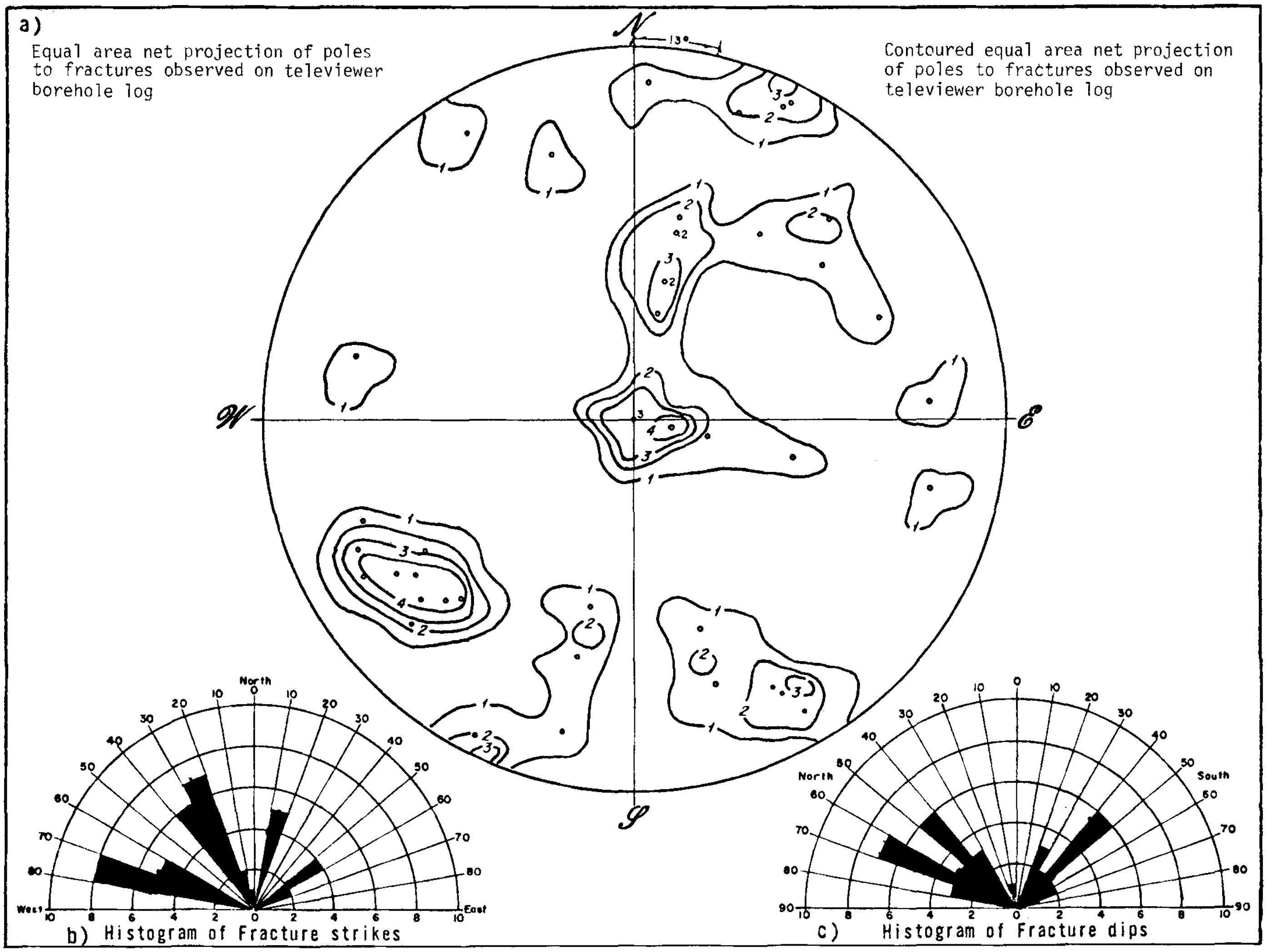

Figure 12.15. *Example of structure analyses from seisviewer log.*

scale could be attached to the resulting sulphide estimate. The density-derived sulphide estimate tracks the laboratory values well, and it is reasonable to expect that the agreement can be improved with a proper calibration and judicious use of equation D-4. At least for high sulphide contents (3 to 8 weight per cent), useful estimates of sulphide content should result and the combination of electrically-derived (see next section) and density-derived estimates should be useful.

Figure 12.19 is a second field example which qualitatively illustrates both the sulphides and porosity effects on the density log. The caliper log shows fractures in several intervals but the reader should examine just two, one between 348 to 360 m and the other between 245 to 280 m. The neutron log shows a high porosity for both intervals. The density log shows a lower density for the upper interval which reflects the increased porosity whereas only a part of the lower interval has a lower density. In fact, between 259 m and 265 m the density is relatively high despite the higher porosity indicated by the neutron log. The higher density reflects the galena and sphalerite veining over this interval. A second interval of sulphide veining where no high porosity exists is evident in the density log between 101 m and 131 m. We found that this mode of qualitative log inspection and interpretation is enhanced greatly when several log types are available. Given the present state-of-the-art, we recommend that the suite of logging tools employed in a given hole be as complete as possible.

Other applications of the density tool include 1) control data for the interpretation of gravity surveys, 2) to establish the bulk modulus in combination with acoustic velocity data, and 3) to obtain bulk tonnage estimates.

POROSITY LOGGING

Porosity is commonly estimated from one or more of the following four logs: neutron, gamma-gamma, resistivity and velocity logs. The methods used are well documented in the literature (e.g. Pirson, 1963; Pickett, 1960; Savre and Burke, 1971). However, each log responds to several rock characteristics including porosity. There is an extensive literature describing the response of these logs in various sedimentary rock sequences but little information exists on the response of these tools in igneous or metamorphic rocks (c.f. Ritch, 1975; Nelson and Glenn, 1975; Merkel and Snyder, 1977; Snyder, 1973). One problem is the calibration of tools. No standard facility such as that available for sedimentary rock environments with the API pits at the University of Houston is available for the igneous and metamorphic rock

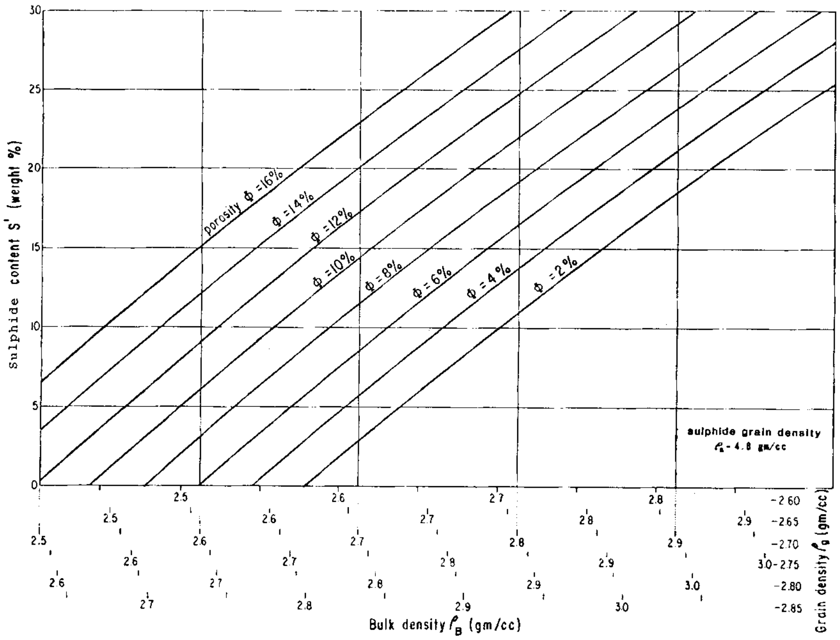

Figure 12.16. *Sulphide content versus bulk density, with porosity and grain density varying parameters. Graph is accurate for* $\rho_g = 2.70$*, most accurate for other* ρ_g *at* $\Phi = 8\%$*. Worst S' error is 1.3% for* $\rho_g = 2.85$*,* $\Phi = 16\%$*.*

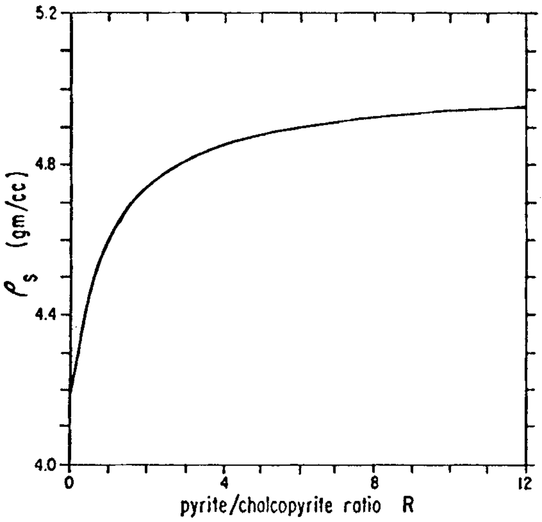

Figure 12.17. *Sulphide grain density dependence on pyrite/chalcopyrite ratio R.*

environment with its typically very low porosity. The API calibration pits are still used to calibrate tools for the mining industry but it becomes necessary to further calibrate the tools with core analyses. We will discuss tool calibration in more detail in a later section. A second problem is that the response of certain logging tools is significantly influenced by rock properties usually ignored in nonmineral applications.

To be specific, we have found for the low porosity of igneous rocks, typically less than 8 per cent, the water in hydrated minerals accounts for a substantial part and sometimes the total response of the neutron tool (refer to Fig. 12.7). The gamma-gamma density and resistivity log determination of porosity in mineralized rock is significantly affected by the variation in base mineral concentration (Fig. 12.17, 12.18 and 12.19). A porosity determined from either log would be in substantial error. The velocity log is strongly affected by fractures and in low porosity igneous rocks the fractures are as important as "pore" porosity on velocity response (Fig. 12.12). Each of these effects on the four logs has been discussed in previous sections and reference has been made to the appropriate figures in those sections.

Figure 12.20 shows a porosity determination from the velocity and neutron logs. The porosity estimate from the velocity tool is based upon the time-average equation (Wylie et al., 1956). On the basis of substantial laboratory analyses of core for bound water at this mining property we have confidence in uniformly subtracting a 1.35 per cent bound water contribution to the neutron log. The only significant deviation of the two logs occurs over the top 30 m of hole which suggests that the bound water contribution here is less than the 1.35 per cent used to correct the log. The open spike in the porosity determination from the velocity log at 72 m is due to a fractured interval of rock between 70 m and 73 m.

Generally it is difficult to anticipate rock conditions well enough to know which of the four tools will be best suited to estimating porosity and which will be so dominated by another effect that it will be useless. If a porosity estimate is desired, the recommended approach is to utilize all four of the basic tools.

ELECTRICAL PROPERTY LOGGING

Induced polarization (IP) measurements are the most widely applied geophysical exploration technique used in the search for disseminated sulphide mineralization. For this reason alone it is useful to continue the measurement to the subsurface as drilling progresses in order to check the testing of a surface anomaly. Other purposes include the use of electrical properties as a correlation tool (see previous example in Fig. 12.10) and as a direct indicator of the total sulphide content in the borehole. In spite of the obvious benefits, IP logging has not yet been widely applied in exploration programs, partly because of the relative difficulty in carrying out the measurement. Snyder et al. (1977) presented an overview of the IP method in boreholes and also address the difficulties of implementing a reliable system.

The Continuous Resistivity and Induced Polarization Logging Tool of Kennecott Copper Corporation

Kennecott has developed a resistivity-IP logging tool which operates over 1500 m of armoured four-conductor cable and is compatible in every respect with the overall system outlined in Figure 12.4. To overcome the problem of transmitting phase information over long lengths of cable, the signal and reference measurements are made in the downhole sonde, frequency modulated in the sonde, transmitted through the cable, and then demodulated and detected by the surface electronics equipment.

The system provides continuous amplitude and phase information at a nominal logging speed of 9 m per minute. Although the system design does not constrain the operating frequency, continuous sinusoidal transmission and detection at a 10 Hz frequency are used. The phase measurement is

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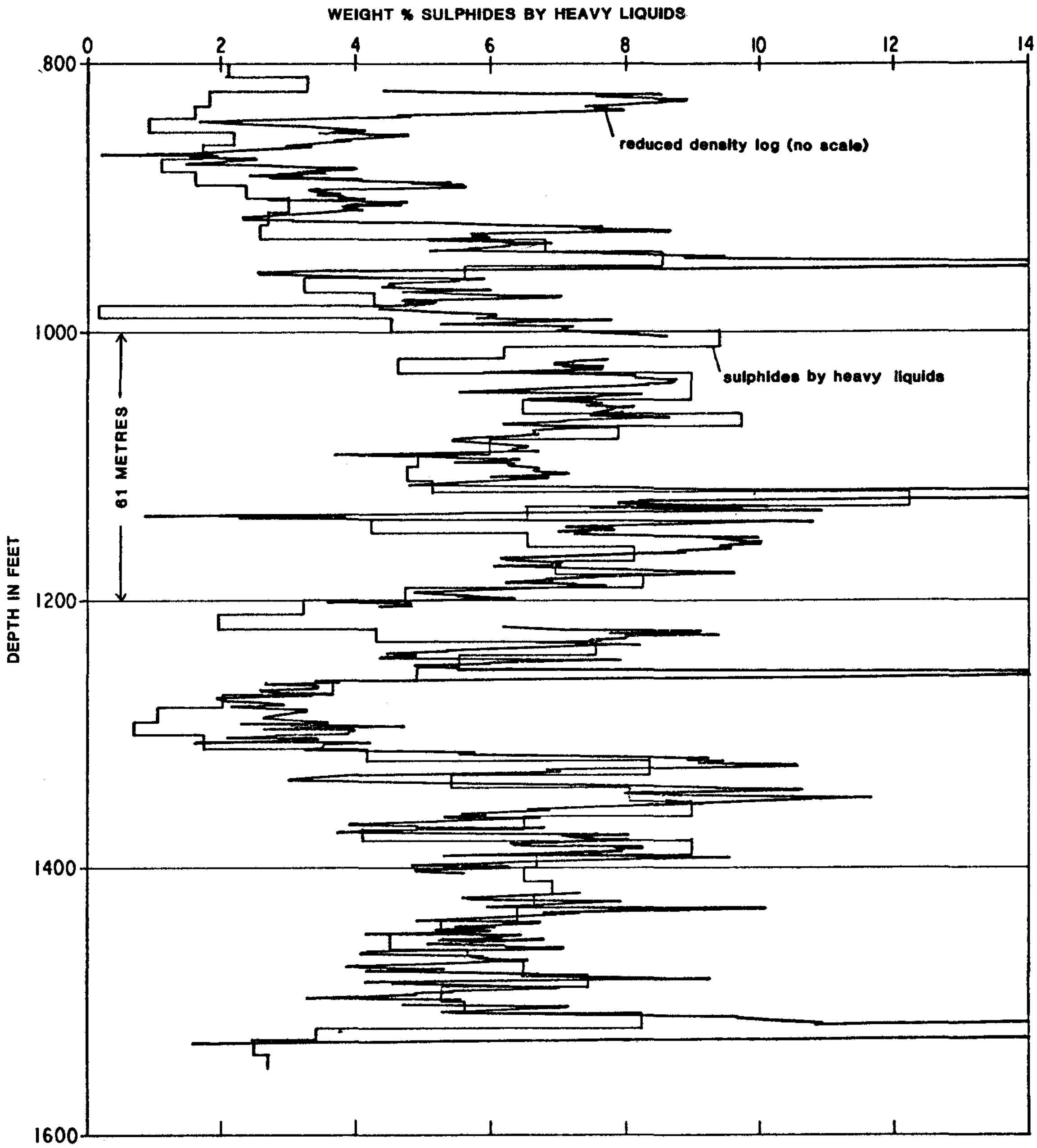

Figure 12.18. *Comparison between sulphide estimates from reduced density log (unscaled due to lack of calibration) and total sulphide.*

accurate to ±0.1 degree, or about ±2 milliradians, at temperatures up to 77°C. Resistivity is recorded on a logarithmic scale. A unique feature is the ability of the operator to change the downhole amplifier gain from the surface. This is necessary because the phase accuracy is limited to an amplitude range of 35 decibels. Operationally this becomes a nuisance only if the resistivity varies by more than two orders of magnitude within a short vertical distance. With the gain change capability, the dynamic range of the system is 100 decibels at a fixed transmitted current. The ability to control the current level gives another 30 decibels of flexibility. We have made continuous logs in various rock types with resistivities ranging from one ohm-metre to greater than 10 000 ohm-metre (40db). The system can accommodate any electrode array which uses one current electrode on the surface, one current electrode downhole, and two potential electrodes downhole. Most of Kennecott's measurements are made with a one-metre pole-pole (normal) array.

Correction Curves for Borehole IP Measurements

Electrical data from boreholes must be corrected to eliminate the contribution of the borehole fluid. Such borehole correction charts (often called departure curves) for a variety of electrode arrays were computed years ago for resistivity logging (e.g. Schlumberger, 1955). The corresponding chart for induced polarization corrections, which amounts to a derivative of the resistivity chart, was published by Brant et al. (1966). We have recomputed the resistivity

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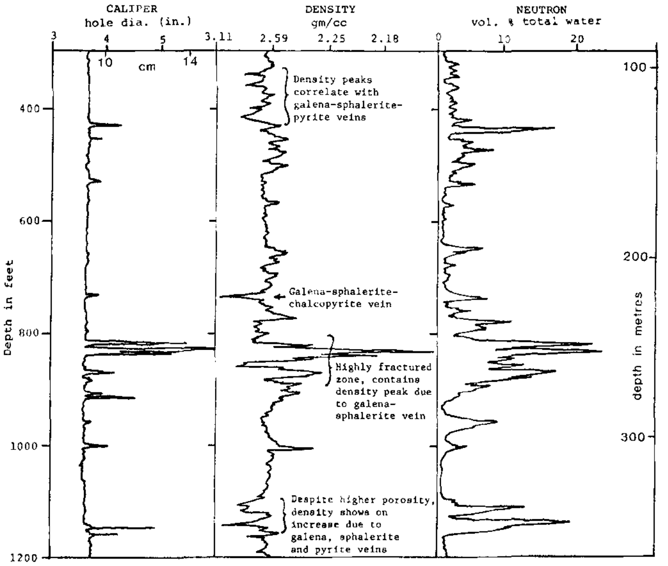

Figure 12.19. *Correlation of density log with sulphide veining.*

and IP departure curves for the pole-pole array in a borehole of resistivity R_m surrounded by an infinite medium of resistivity R_t (Fig. 12.21 and 12.22). The method of computing the resistivity was taken from Gianzero and Rau (1977). The factor B_2 on Figure 12.21 is

$$B_2 = \frac{R_t}{R_a} \quad \frac{\partial R_a}{\partial R_t}$$

similarly,

$$B_1 = \frac{R_m}{R_a} \quad \frac{\partial R_a}{\partial R_m}$$

where R_a is the apparent resistivity.

A check for numerical accuracy found that $B_1 + B_2$ summed to unity to within three decimal places. The resulting resistivity departure curves checked relatively well with the Schlumberger curves. The IP departure curves checked fairly well with the results of Brant et al. (1966) except for small values of the ratio of electrode spacing to hole diameter, where we believe the curves of Brant et al. to be in error.

Borehole Corrections for Resistivity Measurements

The IP logs can be corrected to give the true or formation value of resistivity if the curves of Figures 12.21 and 12.22 are converted to functions R_t/R_m for the pertinent ratio of electrode spacing to hole diameter, AM/d. One such construction is shown in Figure 12.23 for the case of a one-metre array in an NX borehole. NX boreholes range from 7.6 to 8.3 cm in diameter; we used AM/d = 12.6 for this case.

Conceptually, Figure 12.23 would be used by entering on the right-hand ordinate with the value of log (R_a/R_m), moving horizontally to the R_a/R_m curve, then downwards to get the value of log (R_t/R_m). From this point move vertically to intersect the B_2 curve then horizontally to the left to obtain B_2. The phase shift of the rock is then

$$\Phi_t = \Phi_a/B_2$$

In practice, a fifth-order polynomial was fitted to the curves and the logs were corrected to R_t and Φ_t on a digital computer. Note that the correction to the measured phase can be anywhere in the range of 0 to 30 per cent depending upon the resistivity contrast between the rock and the borehole fluid.

This correction procedure requires that the borehole fluid resistivity, R_m, be known. We obtained water samples from the borehole with a water sampler and measured R_m with a fluid conductivity apparatus.

Induced Polarization Logs

Figures 12.24 and 12.25 display IP and resistivity data from two holes containing sulphide mineralization in the southwestern United States. Both logs were obtained in 8.3 cm diameter, water-filled boreholes using the one-metre normal electrode array. DDH-SF1 penetrates andesite and andesite breccia. Sulphide mineralization is pyrite and chalcopyrite, with the pyrite to chalcopyrite ratio ranging from less than one to as high as ten. The borehole fluid resistivity was 14 ohm-metres. Sulphides occur predominantly along veins and also as disseminations.

In Figure 12.24, the erratic nature of the resistivity and phase logs is attributed to the veined character of the sulphides. Estimates of the sulphides content is based upon laboratory analysis (heavy liquid separation) on 3 m composites of the cored samples. These analyses are plotted in the left-hand column on Figure 12.24 and also used to establish the abscissa in Figure 12.26. The data points in Figure 12.26 are 3 m averages of amplitude and phase over the corresponding intervals. The phase values do not display any particular trend as the sulphide content increases. As a result the ratio ϕ/R (also in Fig. 12.26) increases with the sulphide content, roughly following the trendline indicated by the square root of 10 Φ/R. This correspondence is emphasized by overlaying the computed log of $\sqrt{10\Phi/R}$ onto the sulphide content in the left-hand column of Figure 12.24, establishing a rough but adequate estimator of the sulphide content based upon the electrical measurements.

The estimator $\sqrt{10\Phi/R}$ was first suggested by G.D. Van Voorhis following an exhaustive in-house study at Kennecott Exploration, Inc. of data obtained from measurements on samples from several porphyry copper deposits. The estimator normalizes the polarizability, ϕ, with respect to the resistivity which in turn can vary tremendously depending upon the pore structure of the rock and the nature of the mineralization. The idea is not new, having been previously introduced as the so-called metal factor in frequency-domain IP terminology (see Madden and Cantwell, 1967). What is suggested here, however is that the measure or some variation of it, may be quantitatively useful, providing that the statistical variations can be established and that the exceptions to the rule can be understood. The next example is one such exception.

Figures 12.25 and 12.27 display the results of phase and amplitude measurements in a lithic tuff in drillhole SF2. The sulphides are mostly pyrite occurring as fine disseminations and as blebs, with occasional veins. Magnetite is present only in trace amounts. The borehole fluid is water with a resistivity of 7.1 ohm-metres.

The electrical properties in DDH-SF2 are quite different from those of DDH-SF1. The resistivity is high, ranging between 550 and 1050 ohm-metres and as a result the $\sqrt{10\Phi/R}$ estimator is much too low, greatly underestimating the actual sulphide content (see both Fig. 12.25 and 12.27). However the phase in Figure 12.25 is plotted to demonstrate the good correlation between phase and sulphide

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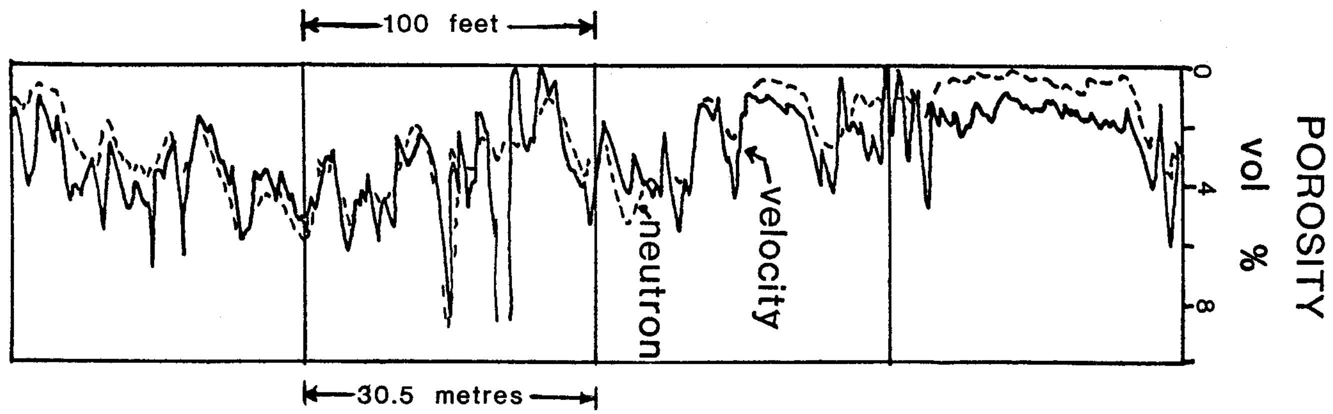

Figure 12.20. Porosity estimates from the neutron and velocity logs.

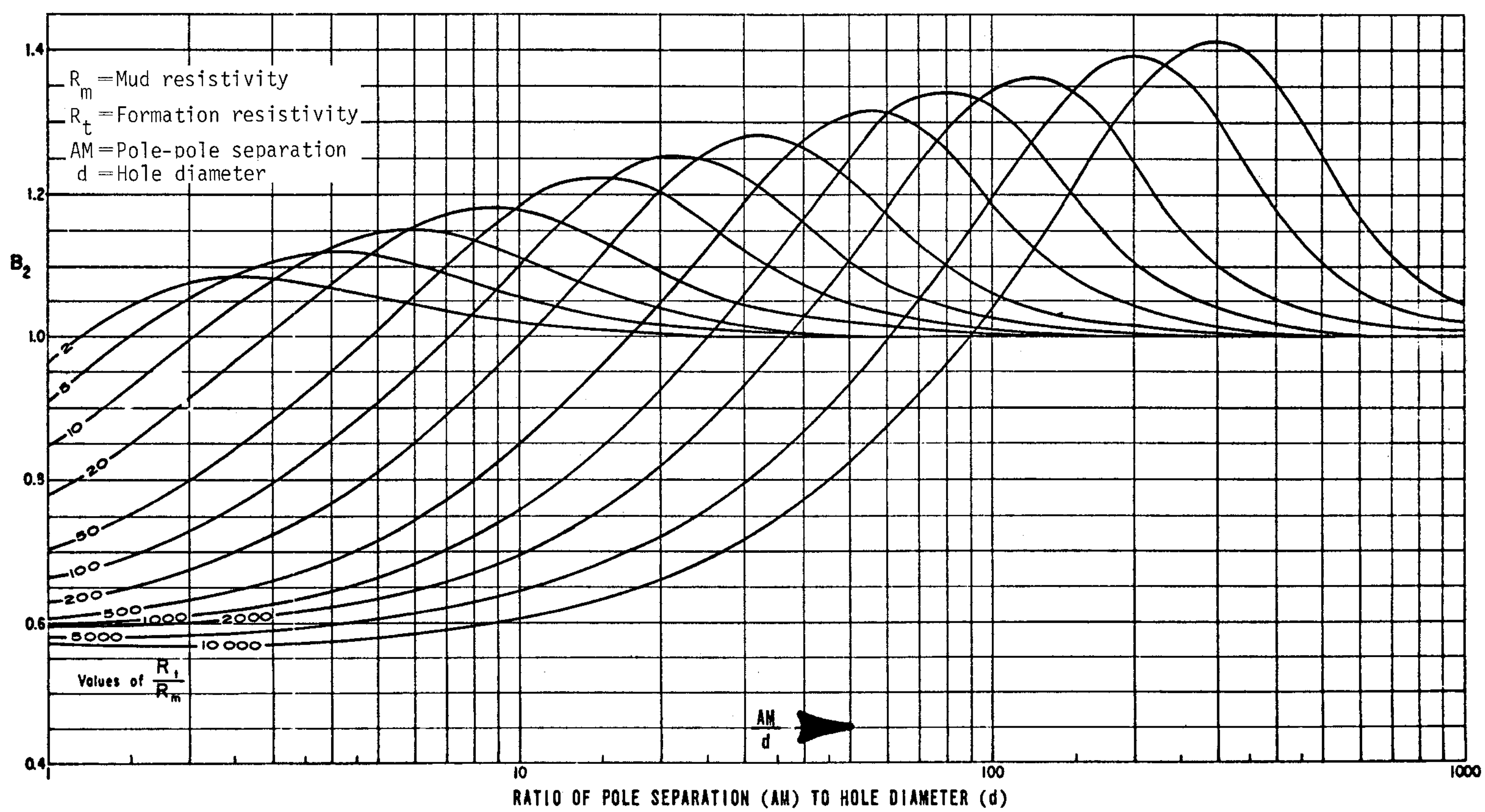

Figure 12.21. IP departure curves. (Beds of infinite thickness.) Centred pole-pole array.

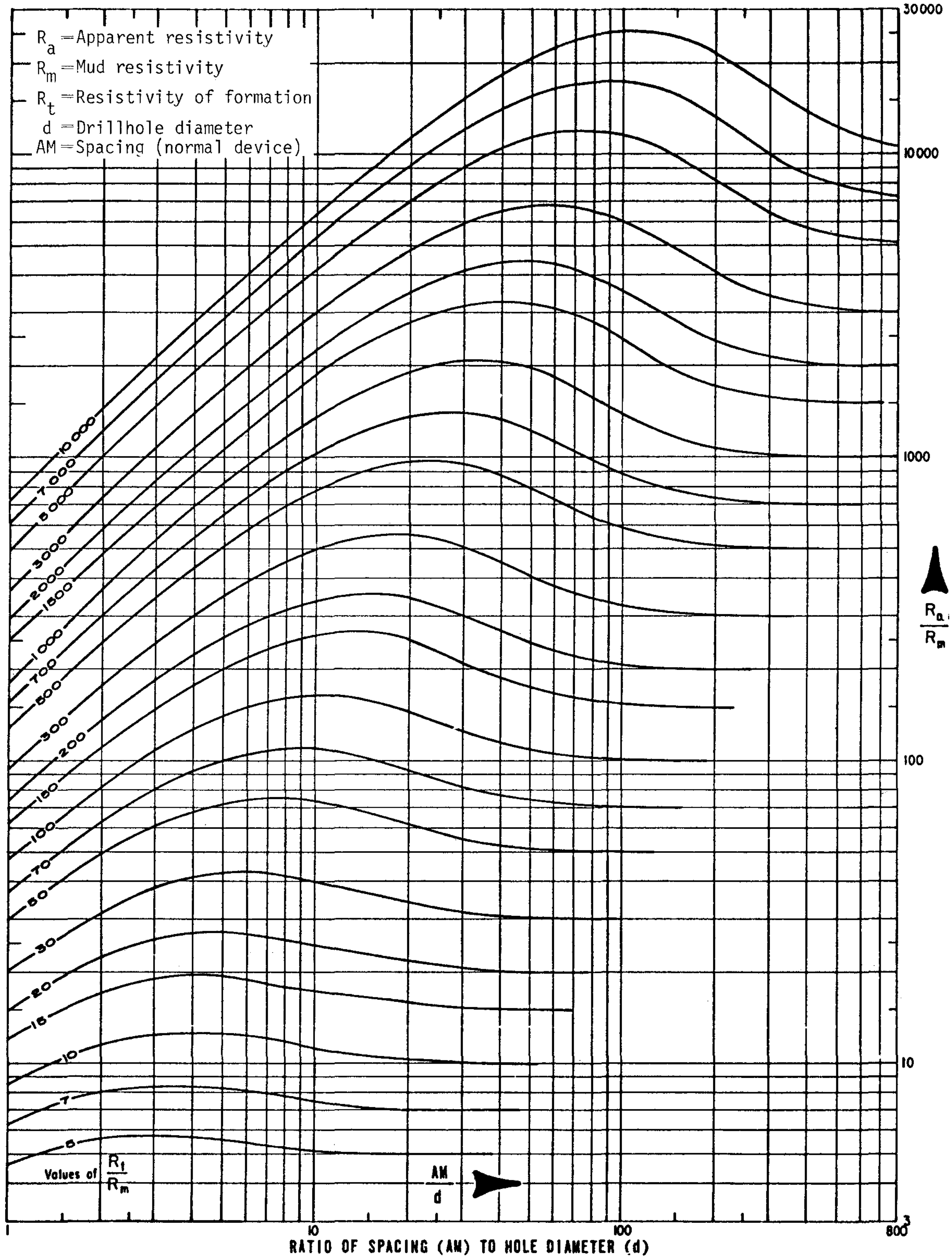

Figure 12.22. *Resistivity departure curves. (Beds of infinite thickness.)*

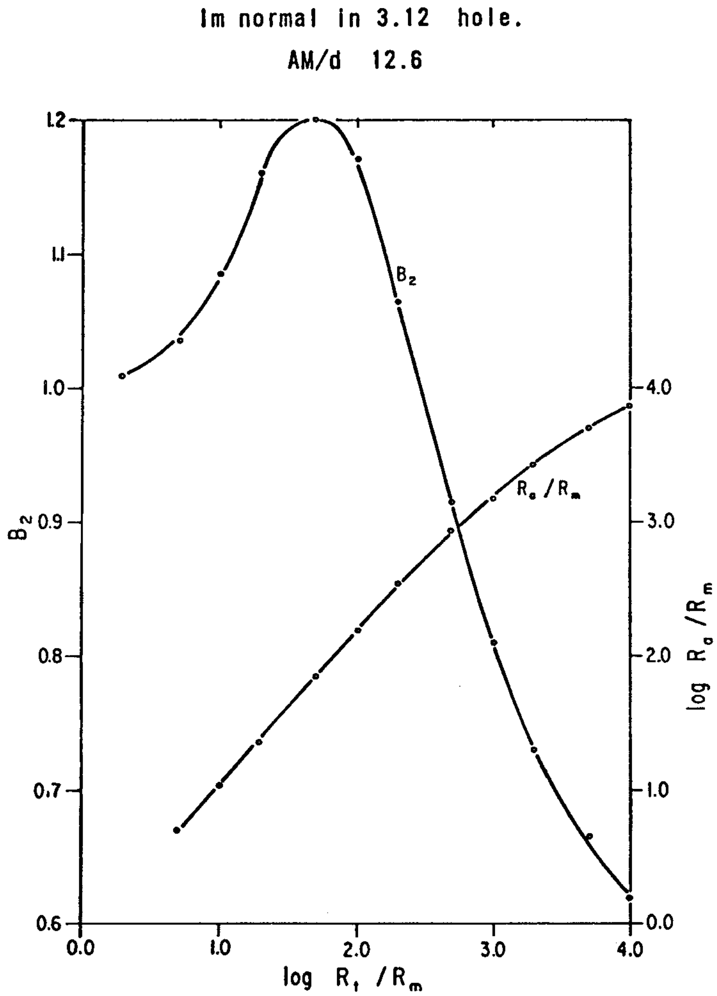

Figure 12.23. *Borehole correction factors for the pole-pole array in a borehole penetrating a uniform medium.*

content, a correlation which did not occur in DDH-SF1. The same data, replotted on a linear graph show a fairly linear correlation between the phase and sulphide content (Fig. 12.28) with about 15 milliradians of phase shift produced by 1.0 weight per cent sulphides. To emphasize the independence of resistivity from sulphide content, Figure 12.29 displays the porosity computations based upon the neutron log, Φ_N, and upon the resistivity log, Φ_r. The Φ_R trace is based upon Archie's Law using a "cementation exponent" of 2.0 and a pore fluid resistivity of 1.75 ohm-metres. The 2.0 value of the cementation exponent is in accord with the values found by Brace and Orange (1968) for laboratory samples of igneous rocks. The 1.75 value is one-fourth the 7.1 ohm-metres value of the borehole fluid, a fact which can be attributed at least in part to the effects of surface conduction in the rock, as also observed by Brace and Orange. The main point, however, is that the resistivity-determined porosity values are reasonably close to the neutron-porosity, which is not the case when conduction is controlled by the sulphide content.

Dependence of IP Parameters upon Sulphide Content

Although the data base is limited (only three other rock types were examined in the same detail as the two cases discussed above), we propose that the functional dependence of IP parameters upon sulphide content divides into two classes governed by the geometrical distribution of sulphides in rock:

A. Mineralization Predominantly Disseminated

Electrical conduction is controlled by the pore fluids so the resistivity is independent of the sulphide content. Hence the resistivity obeys Archie's Law after the fluid resistivity is modified to account for surface conduction. The phase shift is proportional to the sulphide surface area exposed to the pore fluid, usually manifested by a linear dependence of phase upon sulphide content. Such a dependence of phase upon sulphide content is substantiated by our experience with laboratory measurements on artificial samples and also by prediction from simple mathematical models.

B. Mineralization Predominantly Along Veinlets

In this case, the sulphide mineralization is distributed along intersecting planar features and is sufficiently continuous that electrical conduction is controlled by the sulphide content. Empirically, the resistivity decreases inversely with the square of the sulphide content. The phase is relatively independent of sulphide content, because the abundance of sulphide-electrolyte interfaces does not change much as the sulphide content increases. Empirically, the factor $\sqrt{10\Phi/R}$ or some modification of it provides an estimate of the sulphide content.

These two categories are rather general and are probably not distinct; that is, there will be many instances where the mineralization is equally disseminated and controlled by veining. In fact, using a prototype version of the equipment described herein, Snyder (1973) observed a cube root dependence of the Φ/R factor upon sulphide content, but suggested that the dependence will be a function of rock type and sulphide distribution. The eventual form of a quantitative relation and the determination of its usefulness must await further collection and correlation of empirical data. Because of sampling problems this must be done in the field rather than in the laboratory. Although it is possible to perform surface studies in mines, we believe that borehole methods provide the most expedient means of pursuing this goal.

MAGNETIC SUSCEPTIBILITY LOGGING

The magnetic susceptibility tool, like the induced polarization tool, is more useful in mining applications than in other geotechnical applications. A qualitative use, for rock type identification and correlation, has been demonstrated above (Fig. 12.9). The system used by Kennecott for logging is similar to that described by Broding et al. (1952) and Zablocki (1966).

The magnetic susceptibility tool is also used for quantitative studies in exploration. Figure 12.30 is one example where the magnetic susceptibility measurement in several drillholes yielded the thickness and magnetic susceptibility of the Gila conglomerate (southwestern United States). The volume susceptibility is relatively uniform around 1000 μcgs. These data enabled the exploration geophysicist to improve his aeromagnetic interpretation for this prospect.

A second quantitative use, the direct measurement of the magnetite content has been demonstrated by Snyder (1973) and also in Figure 12.8, but we have not pursued this application any further.

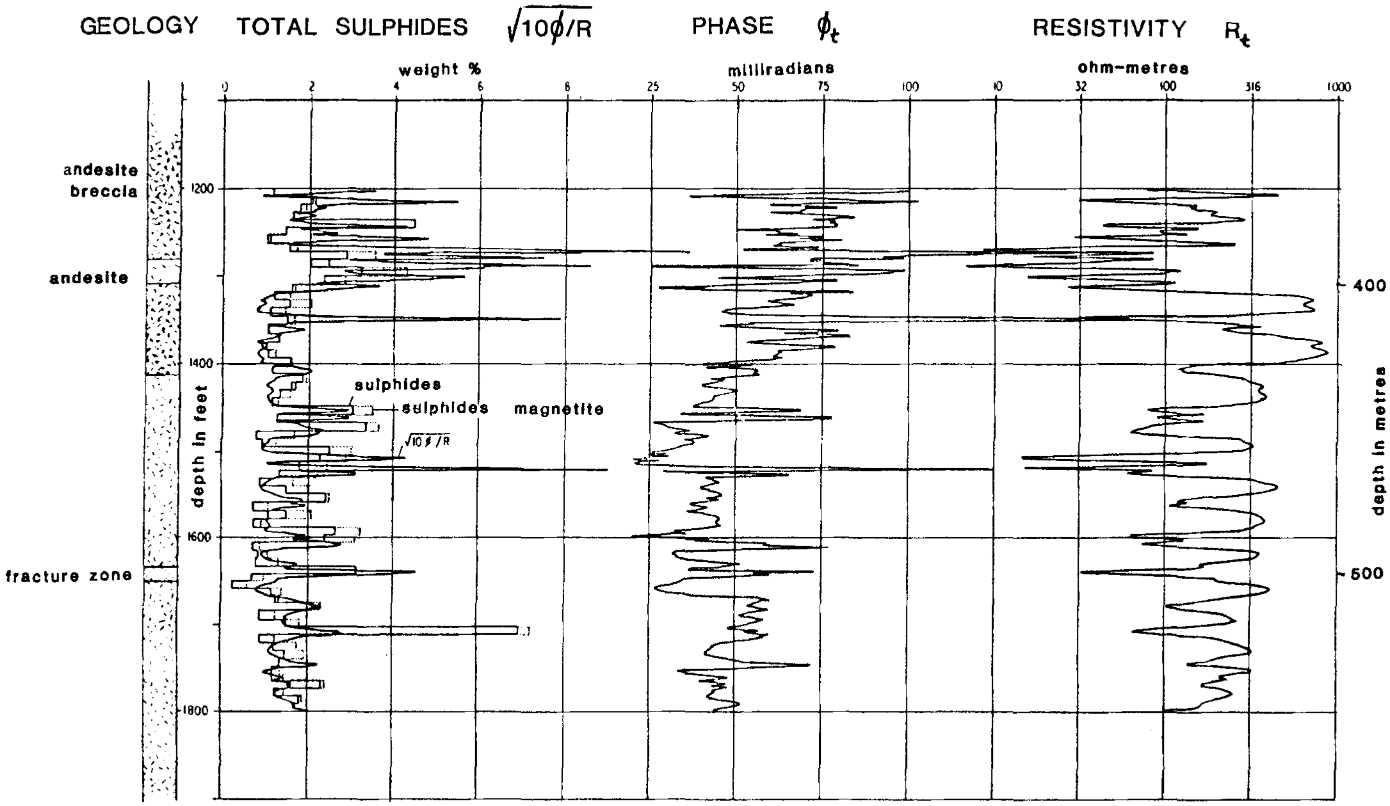

Figure 12.24. Sulphide data and IP log results corrected for borehole effects in DDH-SF1.

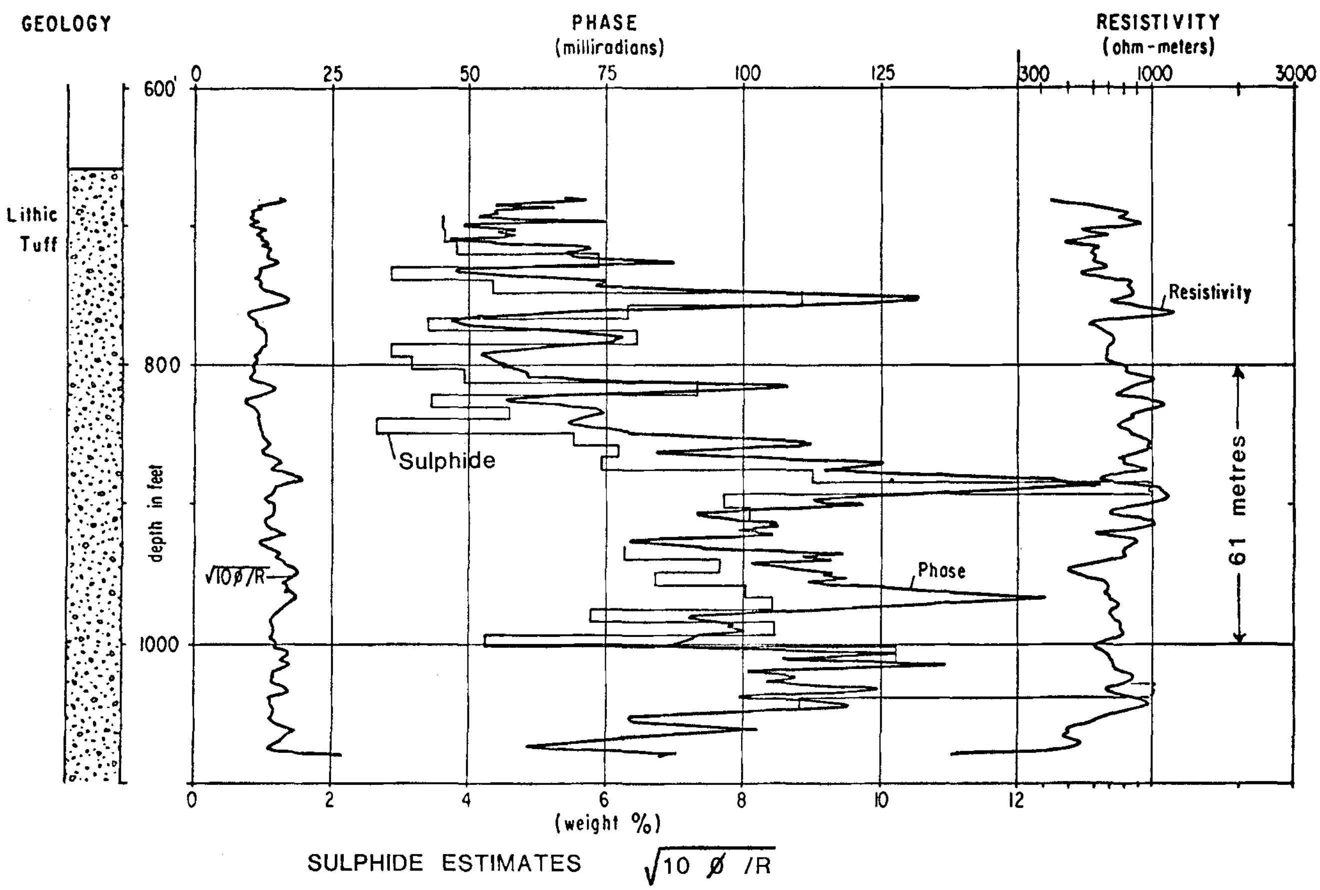

Figure 12.25. IP logs and sulphide estimates in DDH-SF2.

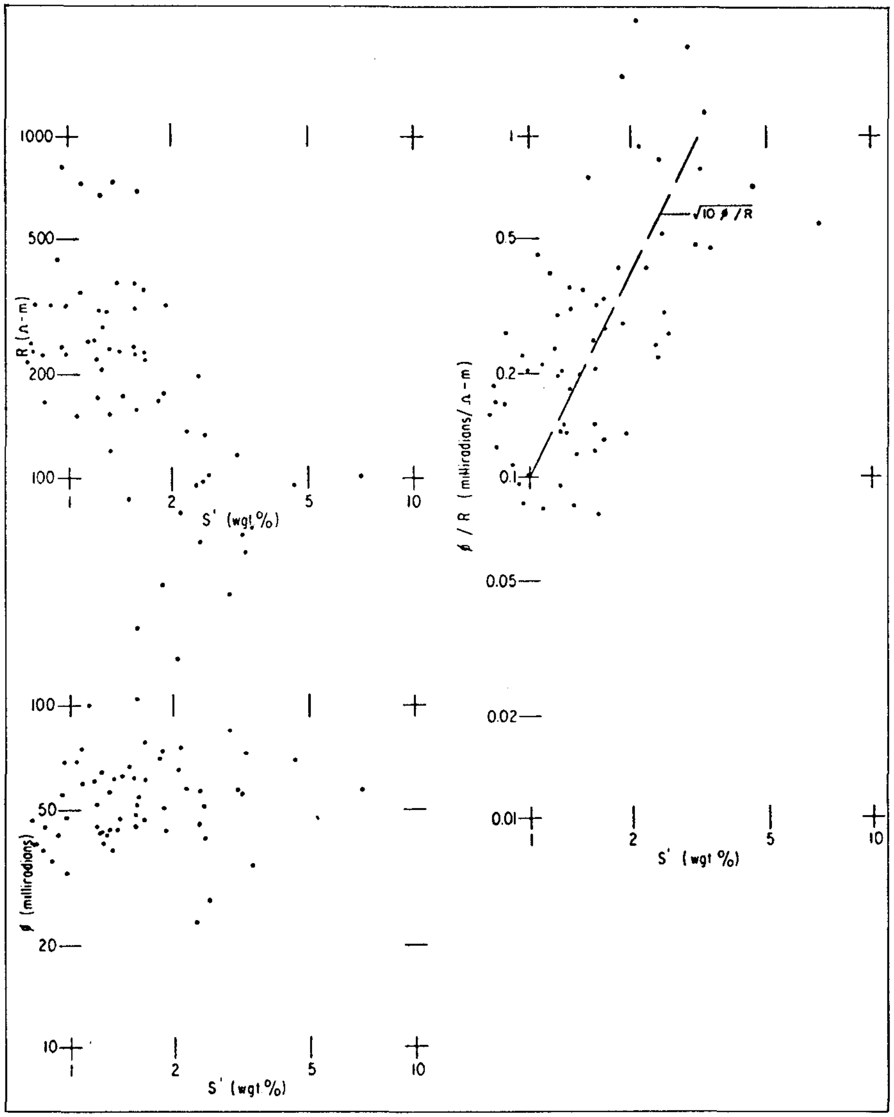

Figure 12.26. *IP parameters and sulphide content, DDH-SF1.*

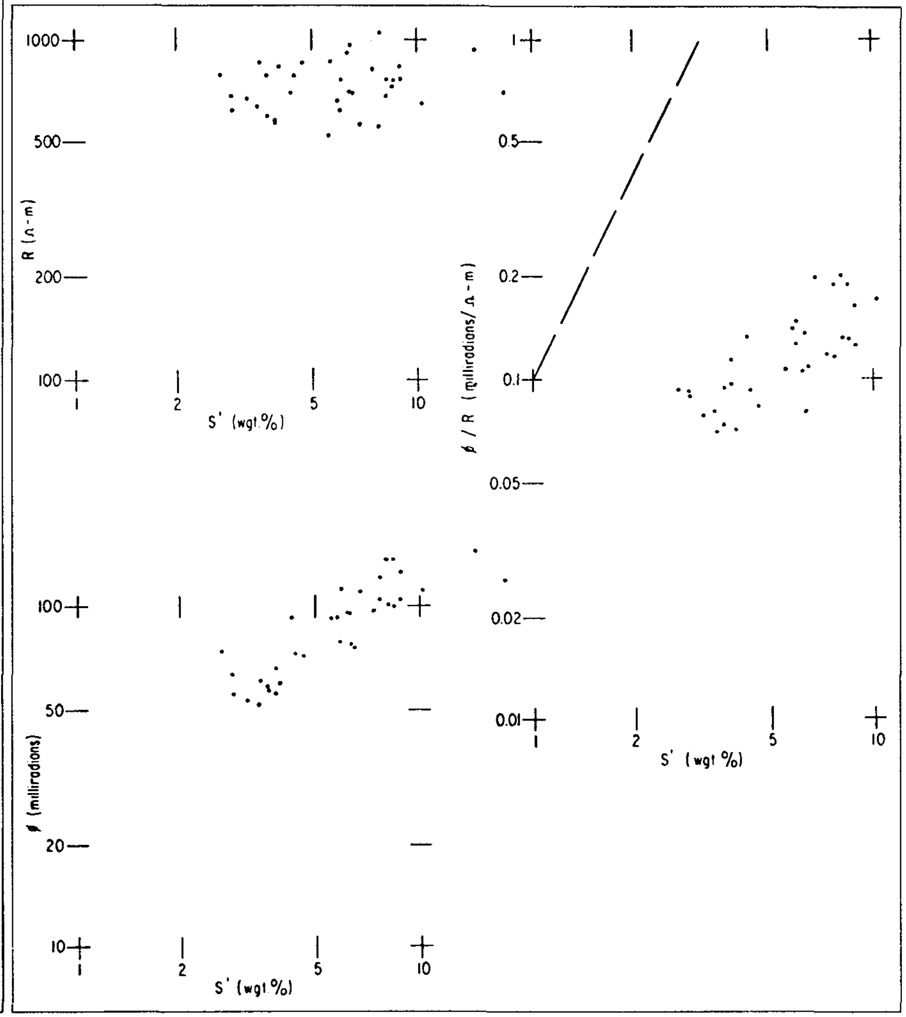

Figure 12.27. *IP parameters and sulphide content, DDH-SF2.*

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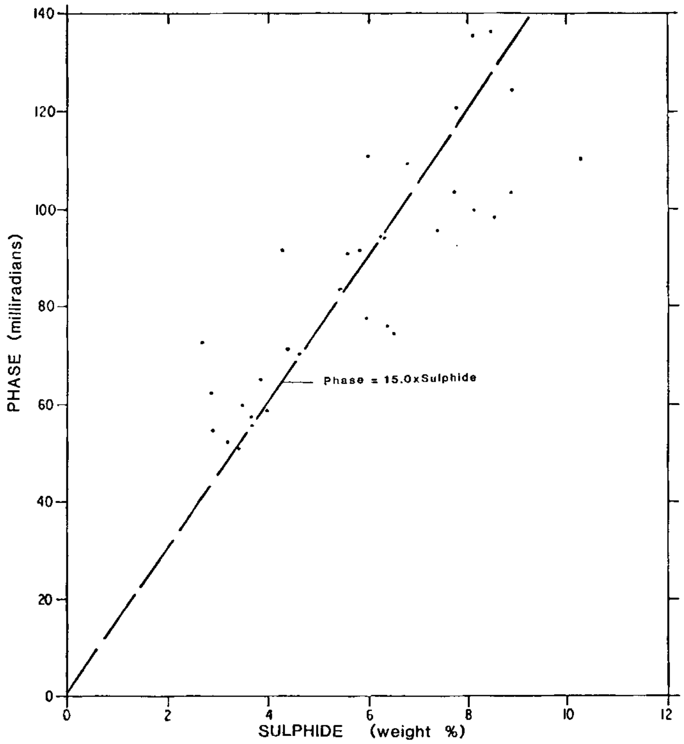

Figure 12.28. *Phase values averaged over 10 foot interval versus sulphide content, DDH-SF2.*

The tool has been calibrated using magnetic susceptibility measurements on core samples and the calibration is routinely checked with spot core measurements. Figure 12.31 shows an example of this ckeck in an exploration hole in southern Arizona.

TEMPERATURE LOGGING

A temperature log is a continuous record of borehole fluid temperature with depth which will be the geothermal gradient only if the fluid is in equilibrium with the adjacent rocks and if there is no vertical circulation of fluid in the drillhole.

Temperature logs are necessary for the correct interpretation of resistivity logs because of temperature effect on electrical resistance (Alger, 1966; Schlumberger, 1972). The fluid resistivity needs to be corrected for temperature before it is used for porosity analyses or for an estimate of total dissolved solids.

Temperature logs can also be used to examine fluid flow in drillholes (Keys and MacCary, 1971; Wilterholt and Tixier, 1972). One method is to inject cooler surface water into a drillhole for some period of time and obtain temperature logs during injection and at periodic intervals postinjection. These logs are then compared to the preinjection log. The injected fluid will cool the borehole fluid and the zones of fluid exit from the hole. The temperature in the drillhole will recover toward the preinjection temperature profile with zones of fluid exit recovering most slowly. Figure 12.32 illustrates this logging method.

A preinjection and two postinjection temperature profiles are shown in Figure 12.32a and the difference between the post- and pre-injection logs are shown in Figure 12.32b. Also shown are fracture locations picked from the caliper log. The rocks are volcanics intruded by dacite and a number of the contacts show the greatest cooling effects on the temperature logs. The direction of any groundwater flow in these rocks should be strongly influenced by intrusive and volcanic rock contacts.

FLUID FLOW DETERMINATION

In the previous section on temperature logging we noted how the temperature log could indicate points of fluid flow or fluid exit in a drillhole. Some attempt can be made to quantify this flow from the temperature anomalies but the method is very imprecise. The rocks will often show temperature variation beyond the zone of flow and mathematical modelling is not simple (Smith and Steffenson, 1970).

A more direct quantitative measure can be made with a spinner log (c.f. Schlumberger Production Log Interpretation, 1974). However, a spinner tool at best measures flow accurately only above 0.75 m/min. Figure 12.33 shows two flow profiles made in holes used for dump leaching at one of Kennecott's operating properties. The logs show that fluid exit is nonuniform and is exiting primarily out the top portion of the completed hole interval.

CALIBRATION OF LOGGING EQUIPMENT

The American Petroleum Institute has established certain recommended standards for calibration and format of borehole logs; for example, nuclear logs (API, 1974) and electrical logs (API, 1967). API has also established a calibration facility on the University of Houston campus, available to anyone for a set fee. The calibration facility is designed for oil field environments and for nuclear logs. The United States Bureau of Mines has established a calibration facility for the mining and engineering logging applications. This facility provides standards for density, magnetic susceptibility, sonic velocity, resistivity and caliper logs (Snodgrass, 1976) and the facility is available to industry.

Kennecott has calibrated nuclear tools at the API pits and the rest of their tools with core analyses. An example of core calibration of the magnetic susceptibility tool was given in Figure 12.31. Since it is neither practical to calibrate the various tools frequently at the calibration facilities in either Houston or Denver nor to continuously check the calibration with core analyses, Kennecott spot check with core analyses and also verify the tool calibration before and after each log with some fixed reference. For example, the density tool calibration is checked with two blocks of material of known densities before and after each log is made. A geometric array of ferrite rods is used to check the calibration of the magnetic susceptibility tool. The calibration of slim hole tools is not an easy matter and Merkel and Snyder (1977) have discussed this problem in some detail. Waller et al. (1975) examined some basic errors inherent in tool calibration.

CONCLUSIONS

1. Borehole logging methods will gradually become more common in the base metals mining industry for exploration, property assessment and engineering studies. The demand will be a direct function of the ability to obtain in-situ data which is not readily available from core, and the ability to reduce the need for core recovery. In other words, the ability to quantify the elements and minerals which have prime importance to the mining geologist is the key factor in the widespread use of borehole techniques.

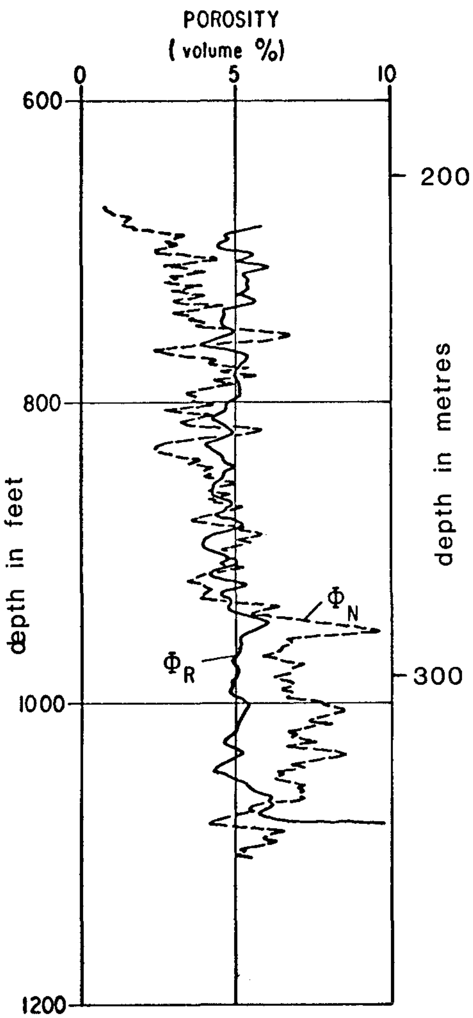

Figure 12.29. Porosity logs in DDH-SF2. Calculated from resistivity using Archie's Law with a 2.0 cementation exponent and a 1.75 ohm-metre mud resistivity. The Φ_N log is computed from the neutron log.

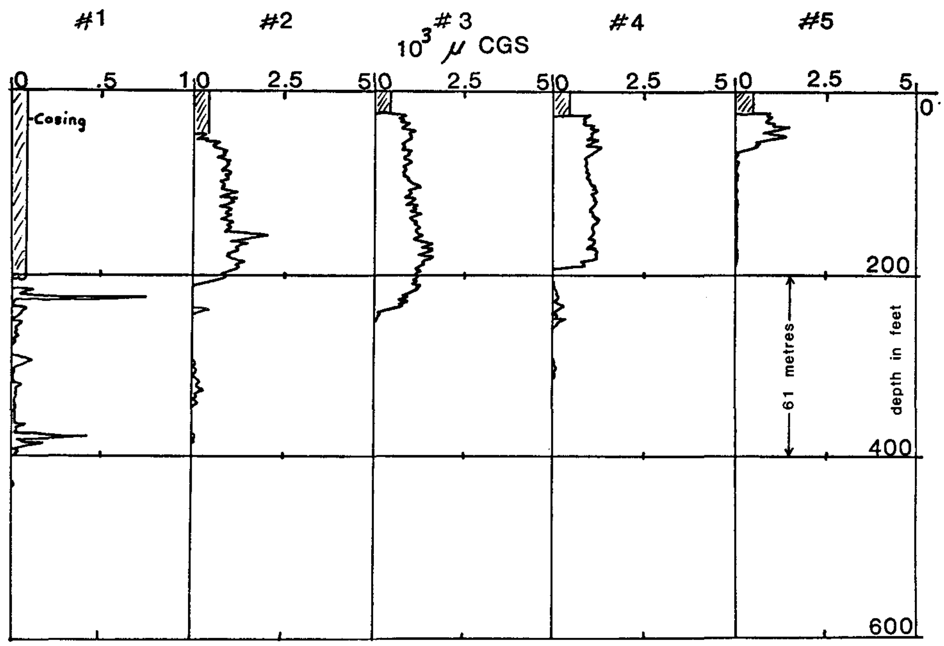

Figure 12.30. Magnetic susceptibility logs in several exploration holes.

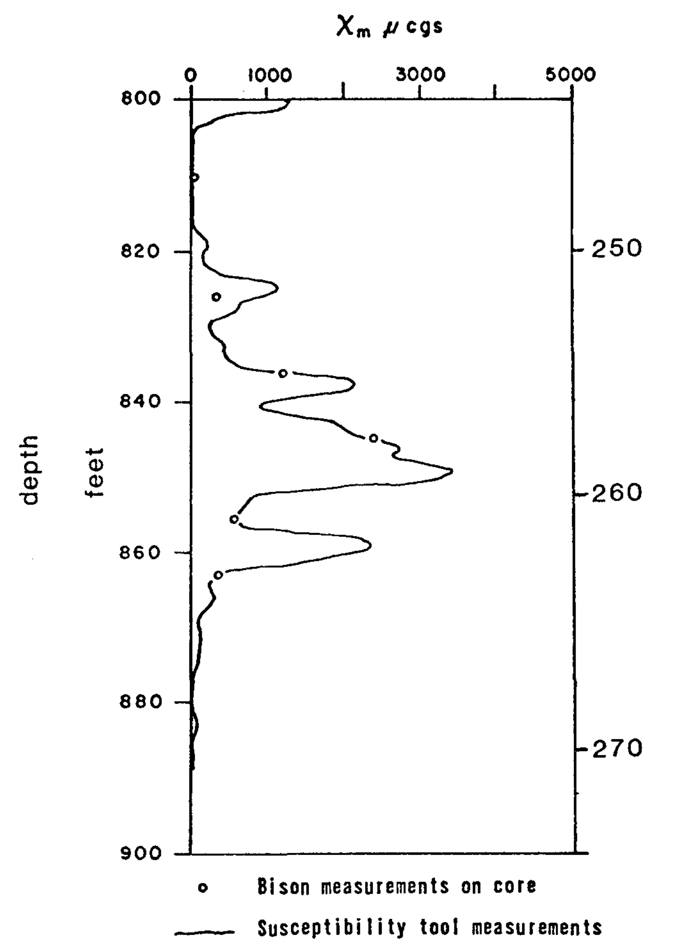

Figure 12.31. Comparison of magnetic susceptibility measurements made in drillhole BB-1 and on BB-1 core samples from southern Arizona.

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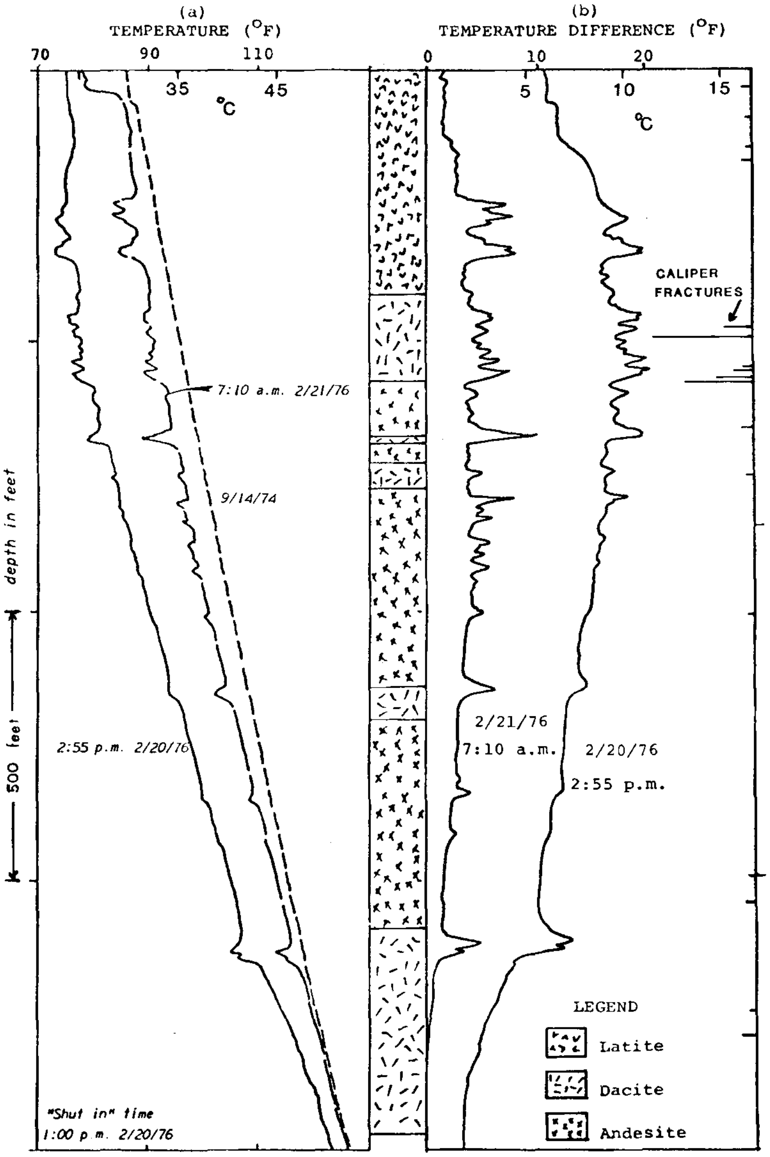

Figure 12.32. *Temperature injection profiles.*

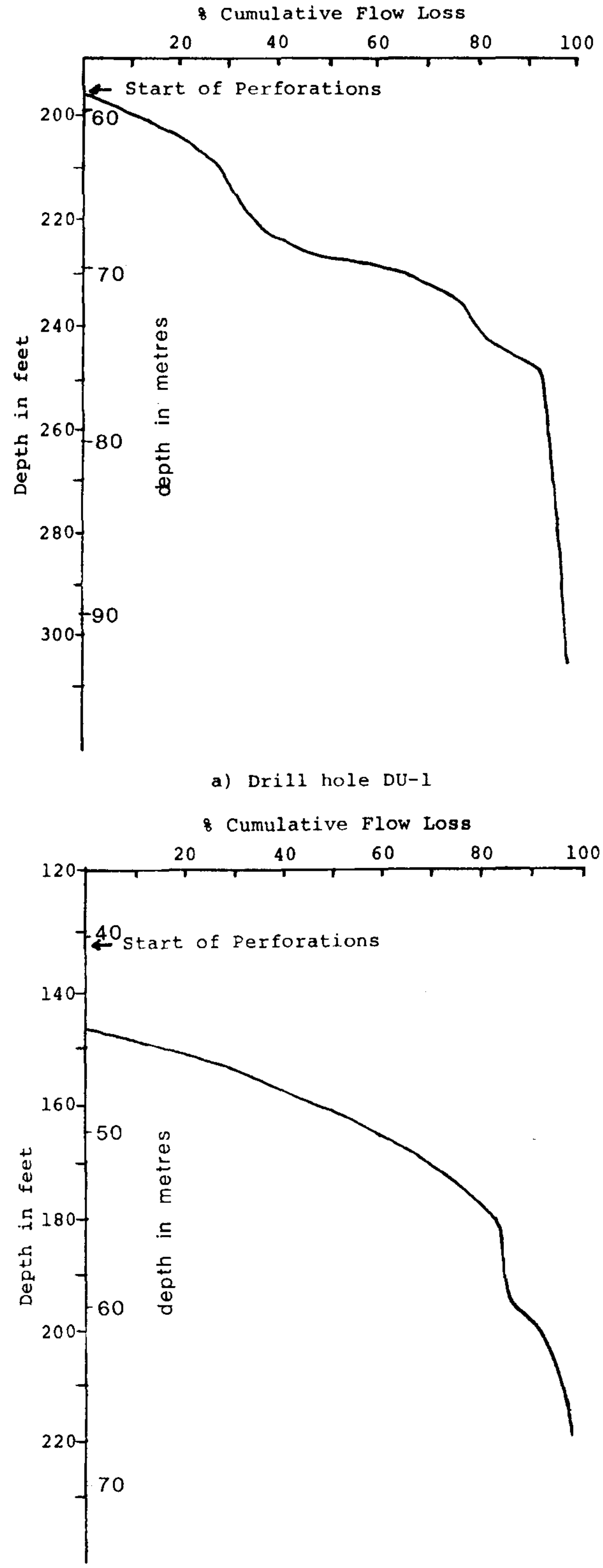

Figure 12.33. *Cumulative per cent fluid loss with depth in two mine dump holes.*

2. In general, the added information which can be gleaned from a combination of logs instead of just one or two is well worth the added cost of acquisition. This is true whether the application is a qualitative one such as rock type and correlation, or a quantitative goal such as estimation of sulphide content.

3. With present technology, it is now possible in the base metal environment to make quantitative estimates of porosity, fracture intensity, bulk density, magnetite content, potassium content, and mineralogically bound water. We feel that with some additional effort and care it will soon be possible to add sulphide content to this list.

4. As pointed out by Snyder (1973) these measurements have particular application in the porphyry copper environment where drillholes are often deep and costly. We emphasize that the logs have enhanced value when they are applied on a deposit-wide basis and are integrated into geological and geochemical studies.

5. We agree with an observation made by Dyck et al. (1975) that there is a need for more case history documentation and published empirical relationships for the mining environment such as exists for a wide range of logging applications in the oil and gas industry.

ACKNOWLEDGMENTS

D.D. Snyder initiated the Kennecott logging program in 1972 and formulated many of the practices and designs, including the initial design of the continuous IP logger. D. Purvance performed the numerical computations for the IP departure curves. E.P. Baumgartner acquired and interpreted several of the logs presented in this paper. Dale Green, Roy Lenk, Jim Simmons and Dave Ewing contributed significantly to the development and maintenance of the logging systems. Jonathan Jackson assisted in the recording and analysis of the spinner logs. We thank Kennecott Copper Corporation for permission to publish the material in this paper.

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