GEOLOGICAL SURVEY OF CANADA
DEPARTMENT OF ENERGY, MINES AND RESOURCES, OTTAWA

PAPER 75-31

BOREHOLE GEOPHYSICS APPLIED TO METALLIC MINERAL PROSPECTING: A REVIEW

GEOLOGICAL SURVEY OF CANADA
A.V. DYCK; EDITOR
P.J. HOOD
J.A. HUNTER
P.G. KILLEEN
A. OVERTON

EARTH PHYSICS BRANCH
A.M. JESSOP
A.S. JUDGE

1975

Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

GEOLOGICAL SURVEY
PAPER 75-31

BOREHOLE GEOPHYSICS APPLIED TO METALLIC MINERAL PROSPECTING: A REVIEW

GEOLOGICAL SURVEY OF CANADA
A.V. DYCK; EDITOR
P.J. HOOD
J.A. HUNTER
P.G. KILLEEN
A. OVERTON

EARTH PHYSICS BRANCH
A.M. JESSOP
A.S. JUDGE

1975

Available by mail from *Information Canada*, Ottawa, K1A 0S9

from the Geological Survey of Canada
601 Booth St., Ottawa, K1A 0E8

and

Information Canada bookshops in

HALIFAX — 1683 Barrington Street
MONTREAL — 640 St. Catherine Street W.
OTTAWA — 171 Slater Street
TORONTO — 221 Yonge Street
WINNIPEG — 393 Portage Avenue
VANCOUVER — 800 Granville Street

or through your bookseller

A deposit copy of this publication is also available
for reference in public libraries across Canada

Price - Canada: $2.50
Other Countries: $3.00

Catalogue No. M44-75-31

Price subject to change without notice

Information Canada
Ottawa
1975

CONTENTS

Page

1. INTRODUCTION
A.V. Dyck

2. BOREHOLE SEISMIC METHODS
A. Overton

3. ELECTRICAL BOREHOLE METHODS APPLIED TO MINERAL PROSPECTING
A.V. Dyck

4. BOREHOLE GRAVIMETRY
A. Overton

5. MAGNETIC DRILLHOLE MEASUREMENTS IN MINERAL EXPLORATION
P.J. Hood and A.V. Dyck

6. NUCLEAR TECHNIQUES FOR BOREHOLE LOGGING IN MINERAL EXPLORATION
P.G. Killeen

7. DIRECTIONAL SURVEYING OF BOREHOLES

A.V. Dyck

8. TEMPERATURE MEASUREMENT IN BOREHOLES FOR THE MINING INDUSTRY

A.M. Jessop and A.S. Judge

9. BOREHOLE GEOPHYSICAL METHODS IN PERMAFROST

J.A. Hunter

List of Illustrations

BOREHOLE GEOPHYSICS APPLIED TO METALLIC MINERAL PROSPECTING: A REVIEW

ABSTRACT

This report presents a review of the literature on borehole geophysical methods and applications most relevant to prospecting for and evaluation of metalliferous mineral deposits. Seismic, electrical, gravimetric, magnetic, nuclear, temperature measurement and directional surveying techniques are discussed; a brief review of borehole geophysical methods in permafrost concludes the review.

It is apparent from the literature that the electrical and magnetic methods have been used in boreholes for the past twenty-five years for the purpose of directly detecting deposits missed by the borehole; many successful applications are evident. Other techniques have seen more limited use; in these cases various possibilities exist. Those methods with inherently shallow depth of penetration fill the complementary role of *in situ* determination of rock properties and metal content.

RESUME

Ce rapport présente une recension de publications sur des méthodes géophysiques pratiquées sur les sondages et leurs applications à la prospection et à l'évaluation des gîtes métallifères. On apporte des considérations sur les différentes méthodes utilisées: sismique, électrique, gravimétrique, magnétique, nucléaire ainsi que sur les mesures de température et de déviation des sondages. En conclusion, ce rapport donne un bref aperçu de ces méthodes pratiquées spécifiquement dans le pergélisol.

Il ressort à la lecture de cette recension que les méthodes électriques et magnétiques ont été utilisées avec succès depuis 25 ans dans le but d'un repérage direct des gîtes, repérage qui n'est pas atteint par le trou de forage seul. L'application des autres méthodes s'est avérée plus restreinte bien qu'il existe, toutefois, de multiples possibilités d'utilisation pour celles-ci; par exemple, elles peuvent dans le cas de forages peu profonds jouer un rôle complémentaire dans la détermination *in situ* des propriétés des roches et de leur teneur en métaux.

1. INTRODUCTION

A.V. Dyck

Borehole geophysical methods have, for many years, been used extensively for well logging in the exploration for petroleum. The methods are usually applied with a view to making *in situ* measurements of the physical properties of the rocks surrounding the hole. It can be readily appreciated that a significantly greater sampling volume can be obtained through such measurements than through examination of the drill core alone. In many instances the existence of these methods has made it possible to dispense with the necessity of obtaining core. Subsurface geological mapping has been a main goal of well-logging measurements. Several papers have been published dealing with the development of the well-logging industry (*see*, for example: Johnson, 1962; Evans, 1970).

More recently the mining industry has become interested in borehole geophysical methods. In exploration for ferrous and non-ferrous deposits borehole measurements are usually a 'third-dimension' prospecting method in which the aim is to detect ore directly. The increased sampling volume is possibly an even greater advantage in metalliferous exploration than in other applications because of the irregular and complex nature of such deposits. Several general papers have been published on the uses of borehole methods in mining geophysics including papers by Zablocki (1966), Baltosser and Lawrence (1970) and Anderson (1974), the latter dealing mainly with nonmetallic minerals.

Table 1.1

HOLE AND CORE SIZES

SPECIFICATIONS

BIT SIZE		COREBARREL SIZE	O.D. OF SET BIT		I.D. OF SET BIT	
			in.	mm	in.	mm
XRP		XRP	1.275	32.39	.885	22.48
XRT	*‡	XRT	1.160	29.46	.735	18.67
EX	†‡	EX, EWX	1.470	37.34	.845	21.46
EXT	*	EXT, EWT	1.470	37.34	.905	22.99
AX	†‡	AX, AWX	1.875	47.63	1.185	30.09
AXT	*	AXT, AWT	1.875	47.63	1.281	32.54
BX	*†‡	BX, BWX	2.345	59.56	1.655	42.04
NX	*†‡	NX, NWX	2.965	75.31	2.155	54.74
HWX	*‡	HWX	3.890	98.81	3.000	76.20
H	*	H	3.890	98.81	2.875	73.04
EXK	*	EXK, EWK	1.470	37.34	.905	22.99
AXK	*	AXK, AWK	1.875	47.63	1.281	32.54

* Conforms to Canadian Diamond Drilling Association Standards (C.D.D.A.)
† Conforms to U.S.A. Standards (D.C.D.M.A.)
‡ Conforms to British Standards Institute (B.S.I.)

All sizes shown are Mean Dimensions with a tolerance of ± 0.005 inch

(J.K. Smit & Sons, Toronto, Ontario)

The information return can be greatly increased with very modest additional cost once a hole has been drilled. For example Levanto (1959) has estimated that 200 borehole magnetic measurements can be made for the price of one metre of drilling. The most obvious advantage of borehole measurements over surface profiling is the possibility of bringing the measuring equipment much closer to the deposit, particularly in the case of deeply buried ones. It should be mentioned that methods with inherently shallow limits of penetration must fill the complementary role of *in situ* determination of rock properties and metal content.

This report comprises a review of the literature on the borehole geophysical methods and applications that are most relevant to prospecting for and evaluation of metallic mineral deposits. Mr. L. S. Collett has coordinated this initial phase of a cooperative program involving the Geological Survey of Canada and several members of the Canadian mining industry. It is hoped that this survey of the literature will help indicate the direction that a development program must take in order to provide the mining industry with a range of borehole geophysical techniques which can be applied with confidence.

The report is organized in sections by method, each section having been contributed by a member of the Geological Survey of Canada as well as a contribution from the Earth Physics Branch of the Department of Energy, Mines and Resources. A useful glossary of well-logging terminology may be found in a paper by Sheriff (1970). A compilation of hole and core sizes may be found in Table 1. 1.

REFERENCES

Anderson, W. B.
1974: Potential uses for borehole logs in mineral exploration; Can. Min. Metall., Bull., v. 67, no. 743, p. 164-168.

Baltosser, R. W. and Lawrence, H. W.
1970: Application of well logging techniques in metallic mineral mining; Geophysics, v. 35, no. 1, p. 143-152.

Evans, H. B.
1970: Status and trends in logging; Geophysics, v. 35, no. 1, p. 93-112.

Johnson, H. M.
1962: A history of well logging; Geophysics, v. 27, p. 507-527.

Levanto, A. E.
1959: A 3-component magnetometer for small drill-holes and its use in ore prospecting; Geophys. Prospect., v. 7, p. 183-195.

Sheriff, R. E.
1970: Glossary of terms used in well logging; Geophysics, v. 35, p. 1116-1139.

Zablocki, G. J.
1966: Some applications of geophysical logging methods in mineral exploration drill holes; Trans. 7th Int. Well Logging of SPWLA, May 8-11, 1966.

2. BOREHOLE SEISMIC METHODS

A. Overton

INTRODUCTION

Seismic, elastic-wave, acoustic or sonic methods, have found wide application in borehole investigations. Determinations of seismic velocity for both compressional and shear waves, porosity, density, elastic parameters, cave size and shape, effectiveness of cement bond to casing, fracture condition of borehole wall, fracture condition between boreholes, and borehole wall condition by visual display of reflected sound waves, are all developments of acoustic methods. The names of the various probes used to conduct specific investigations and the company whose tradename they bear are listed below, along with their definition and descriptions.

Acoustic log: or sonic, or acoustilog. A generic term for well logs which display any of several aspects of acoustic-wave propagation. In some acoustic logs (sonic or continuous velocity logs), the travel time of the compressional wave between two points is measured. In others (amplitude log), the amplitude of part of the wave train is measured. Other acoustic logs (character log, three-D log, variable density log (VDL), microseismogram log, signature log) display part of the wave train in wiggle or variable-density form. Still others (cement-bond log, fracture log) are characterized by the measurements rather than their form. Borehole televiewer is also an acoustic log. Acoustic log is a Lane-Wells trademark. Acoustilog is a Pan Geo Atlas Corporation trademark.

Amplitude log: A borehole log of the amplitude of a portion of the acoustic wave used in acoustic logging. Two types are Cement-bond log and Fracture log.

1. Cement-bond log (CBL): A well log of the amplitude of the acoustic wave which indicates the degree of bonding of the cement to the casing and formations. If the casing is poorly cemented, energy which travels through the casing at the high velocity of acoustic waves in steel, is strong and little energy travels in the formation; if the casing is well cemented, the casing signal nearly disappears and the formation signal is strong. The cement bond log may consist of an amplitude log which represents the amplitude of a portion of the longitudinal acoustic wave train, or a display of the acoustic wave train such as the character log, three-D, microseismogram, VDL, or acoustic signature log.
2. Fracture log: A well log of the cumulative amplitude of the wave arrivals from a sonic logging probe during a certain gate time. A fracture zone attenuates the acoustic energy.

Borehole televiewer or Seisviewer: A well log wherein a pulsed, narrow acoustic (sonar) beam scans the borehole wall in a tight helix as the probe moves up the borehole. A display of the amplitude of the reflected wave on a cathode ray tube (television screen) is photographed yielding a picture of the borehole wall which reveals fractures, vugs, etc.; BHTV is a Mobil Oil trademark.

Character log: A display of the acoustic wave train in wiggle form, as opposed to the similar sort of display in variable density form in the three-D log, microseismogram, or VDL log.

Continuous velocity log: CVL; a Birdwell trademark, or sonic log, is a log of formation seismic velocity against depth. The quantity recorded and graphed is usually the reciprocal of velocity, i. e. the travel time over a short interval, often expressed in microseconds per foot.

Microseismogram log: Similar to the variable-density log or three-D log, a WELEX trademark.

Sonar Caliper log: The sonar caliper is used to measure the profiles of storage caverns and large-diameter boreholes. Sound pulses are sent out from a transmitter and the time for the sound to travel to the cavern or borehole wall and back to the transmitter is recorded. The principle is similar to that of radar but uses sound instead of radio waves. The subsurface equipment consists of a probe which contains the sound transmitter and receivers, and a device for measuring the velocity of sound in the medium surrounding the tool.

The surface equipment includes a panel which incorporates an oscillograph and a special Polaroid camera for automatic direct production of cross-sectional profiles of the hole.

Final results are presented in three forms: vertical profiles in four different planes; calculated volumes; or a plastic model (Dawson-Grove, 1969).

Sonic log: A Schlumberger trademark. A well log of the travel time (transit time) for acoustic waves over a unit distance, hence the reciprocal of the longitudinal wave (P-wave) velocity. The sonic log which is also called acoustic-velocity log or continuous-velocity log is especially used for porosity determinations by the Wyllie relationship (Wyllie *et al.*, 1956, 1958). The interval transit time is integrated down the borehole to give the total travel time. For the compensated sonic log (BHC), two transmitters are pulsed alternately. Averaging the measurements tends to cancel errors due to probe tilt or changes in hole size.

Three-D log: A Birdwell tradename. Three-dimensional velocity log; a display of the seismic or acoustic wavetrain received a short distance (3 to 12 ft.) from a sonic wave transmitter. (Also called microseimogram log and variable density log.)

Variable density log: A microseismogram log using a variable-density display in which the photographic density is proportional to signal amplitude.

VDL log: A three-D log. Schlumberger trademark.

Wiggle trace display: A waveform display which is a graph of amplitude against time.

DEVELOPMENT OF BOREHOLE SEISMIC METHODS

The following text deals with references in a chronological order to illustrate developments in their proper historical context.

Summers and Broding (1952) and Vogel (1952) described the development of early continuous velocity logging equipment. The early objective of these devices was to define the velocity-depth function for use in seismic interpretation. Prior to the continuous velocity logging methods time-depth functions were commonly obtained by lowering a borehole seismometer to various depths in the borehole and recording dynamite blasts from the surface. These were called well velocity surveys, or geophone velocity surveys (Hobson and Findlay, 1967); detailed surveys took considerable time and often gave poor estimates of formation interval velocities due to limitations in timing resolution over small formation intervals.

The two types of early continuous velocity logging probes had a single acoustic source and either a single receiver, or two receivers. Compressional waves, and occasionally shear waves, were recorded. Signal characters and amplitudes could be used to identify some of the rock types traversed (Vogel, 1952).

Sonic travel times, being inversely proportional to the speed of sound, depend upon the elastic properties of the rock matrix, the porosity of the formation and their fluid content and pressure (Tixier *et al.*, 1959). Compressional wave velocities in rocks range from about 1. 8 km/s in shallow shales to about 7. 6 km/s in dolomites. For igneous rocks, velocities are intermediate to these extremes. In hard formations (well cemented and/or compacted), the sonic log characterizes the amount of fluid in the formations; hence, it correlates well with formation porosity. The sonic log has been found an almost ideal means of obtaining continuous porosity measurements in the borehole (Tixier *et al.*, 1960). Used in conjunction with resistivity logs it gives an estimate of formation connate fluid type and saturation ratio (Pirson, 1963).

Schlumberger (1966), described an improved continuous borehole interval velocity probe using two acoustic sources, one above and the other below a pair of spaced receivers. It gives more precise interval velocities by correcting for borehole irregularities and misalignment of the probe in the borehole; it is called the Bore Hole Compensated logger (BHC).

Another concept described by White (1967) utilizes different wave types due to radially, axially, and torsionally excited oscillations in the borehole wall to gain more complete knowledge about borehole conditions such as drilling fluid invasion, layering, fractures, and also elastic constants for the materials logged.

Runge and Powell (1967) described the application of a high speed digital computer toward filtered enhancement of data from a digital field log.

Evans and Cotterell (1967) described full wave recordings of acoustic signals in borehole logging to give both the velocity for compressional waves and for shear waves (shear waves appear to be recorded only under special circumstances). If density is also known as, for example, from scattered-gamma or gamma-gamma density logs, parameters M and μ may be obtained. These parameters are called the plane wave modulus and the shear modulus respectively. Conversely, if M and μ are known from statistical records for a given rock type, then density may be found from either shear or compressional velocity. The conversion technique is based on empirical expressions relating velocities to elastic moduli for various rock types. Hence, when sufficient data are accumulated for rock types of interest, elastic parameters may be derived from the acoustic velocities. Computer analysis of digitized logs carries out the conversions most efficiently. Evans and Cotterell (1967) call these synthesized logs "modulus" or "elastic parameter" logs so that they represent another means of identifying lithologic units. Comparison of derived parameters with the corresponding logged parameters, e. g. densities derived compared with densities logged, reveals deviations for portions of the lithology which violate the empirical relationships and require further investigation.

Well logging in the U. S. S. R. is described by Caldwell (1967) who concludes that practically every type of logging which is used in the United States is found in the U. S. S. R. Acoustic log recording of the complete wave form similar to the microseismograms in the United States is in use. Acoustic velocity logs appear to be not so widely used.

Fons (1969) described geological applications of well logs. This paper presents a compilation of methods for relating log data to the geology and the evaluation of petroleum and mineral deposits. It is basic and broad in scope. Included is information about log analysis for the correlation of lithologic units by the identification of formation components and the environment at the time of formation deposition. Log study of formation alteration subsequent to deposition is also considered. A trend is suggested toward multiple logging techniques with interrelationships between logged parameters narrowing the uncertainty limits on identification of lithology or physical parameters such as porosity and density, rate of deposition, sediment sources, subsidence rate, water depth at time of deposition, transgressive sea environments, nonmarine or clastic deposits, valley fill deposits, marine deposits, barrier bar sands, beach sands, delta complexes, shallow lagoons, marine deep deposits, turbidity current sands, coral reefs, evaporites, faults and fractures, mapping of structure, lithofacies or isopach, structural or regional dip, stratigraphic traps, rock texture, permeability, fluid content and formation age. It is stated that under certain conditions even the colour of the rock or the existence of fossils may be identified by logging. In this system of logging with each particular log contributing to the formation identification, the elastic wave logs used are unit travel time, velocity, acoustic attenuation, shear wave amplitude, acoustic wave persistence, compressional wave amplitude, and borehole televiewer. The logging of every measurable parameter with the correlation of results against core sample evaluations greatly assists in finding ways to substitute logging techniques for the more expensive core analyses.

In their description of log evaluation of nonmetallic minerals deposits, Tixier and Alger (1967, 1970), explain that: well logs can be used to locate and evaluate deposits of various commercially important minerals. It is only necessary that the mineral of interest represent a significant fraction of the formation bulk volume, and that it exhibit characterizing properties measurable by logs. Because modern logging methods measure electrical, density, acoustic, radioactivity and certain nuclear characteristics of formations, they may be used to identify many types of minerals. For evaluation of sulphur deposits, either density or sonic logs provide good resolution when compared with porosity computed from neutron or resistivity logs. Trona beds (impure sodium carbonate) are identified by a sonic reading of approximately 65 microsec/ft., neutron porosity index of about 40 per cent, low natural radioactivity, and pronounced hole enlargement. Gamma-ray logs provide important information for the location, identification, and evaluation of potash mineral deposits. Neutron, sonic, and density logs, in various combinations, augment the gamma-ray data in such studies. Coal beds are characterized by high resistivities, and by high apparent porosities on sonic, neutron, and density logs. Density logs are particularly suited for evaluation of yield from oil shales. In all such explorations for nonmetallic mineral deposits, well-logging methods provide a fast, detailed, and economical reconnaissance of the entire length of drilled hole. Results compare well with core assays.

Pickett (1970) described applications for borehole geophysics in geophysical exploration. Items relevant to mineral exploration described are: techniques and possibilities for applying borehole measurements in metallic deposits and presentations describing borehole measurement systems currently under development (a borehole gravimeter and the borehole "televiewer"). He draws attention to the empirical relationships between acoustic velocity, bulk compressibility, fluid compressibility, bulk density, shear modulus, and grain material compressibility and porosity. Some of the acoustic borehole measurements mentioned are interval transit time, amplitude, waveform displays, variable intensity, cement bond logs, borehole scanner, and shear wave and compressional wave velocity. He proposed that present capabilities should be sufficient to suggest that a better marriage of borehole geophysics to exploration geophysics should be rewarding.

Two papers by Evans (1970) and Baltosser and Lawrence (1970) are particularly relevant to this review. Their abstracts are therefore reproduced verbatim:

Evans (1970), in "Status and trends in logging" says: "Logging service companies are attempting to provide a fairly good selection of devices which have proven to be popular with the oil industry. However, the introduction of new devices or new services is being limited because oil companies are standardizing the logging suites run in their various geographic operating areas. Some of these new techniques appear to have significant applications. Recently, standard logging suites and evaluation techniques have evolved; these can be evaluated in terms of open hole and cased hole applications and the physical parameters of interest. Generally, these standard procedures depend on the differences in responses of multiple electrical and porosity devices. The multiple measurements are input to response equations which yield the parameters of interest. Although mining companies have been slow to adopt logging techniques, the use of logging devices and interpretation methods in nonpetroleum mineral (groundwater, nonmetals, metallic sulfides, etc.) exploration and evaluation, and in providing geophysical survey parameters is increasing. Nuclear, electrical, acoustic, and other methods are utilized, and newer applications of these to exploration, particularly in lithology determination, suggest themselves. Log digitizing and computer processing of log data have become routine in most major oil companies, but techniques, programs, and equipment vary significantly. Currently, commercial digitizing services are too expensive to be used extensively; the per-log costs, however, are declining as more digitizing companies offer competitive services. Two basic commercial systems for transmission and computation of log data are functioning. To date, these systems yield "quick-look" or reconnaissance parameter computations. Current research and development emphasis is on pulsed neutron-spectroscopy and acoustic parameter measurements and on digital processing techniques."

Baltosser and Lawrence (1970), in "Application of well logging techniques in metallic mineral mining": "Nearly all of the well logging devices currently used in the petroleum industry have found some limited application in metallic mineral exploration and mining. However, due to differing problems, the emphasis in the mineral industries has been on those devices regarded as "exotic" or "specialty" by the petroleum industry. These include devices to measure or determine induced polarization, magnetic susceptibility, and hopefully, nuclear activation and the use of spectral analysis. Problems which the mining industry believes are solvable with well logging methods include bulk assay and recognition of minerals adjacent to and retired from a borehole, delineation of joint and fracture systems, leaching problems which involve porosity, permeability and groundwater movement, bank stability in open pit mines, roof and pillar loading in shaft mines, grindability, and penetration rates in drilling. Devices currently offered by the well logging industry which may be useful for these problems include those capable of measuring electrical properties, natural and induced nuclear radiation, seismic velocities of both compressional and shear modes, temperature, mechanical features of a borehole such as diameter and rugosity, and borehole photography either direct or by television."

Guy *et al.* (1971), in their description of a side-wall acoustic neutron log, pointed to the advantages of using multilogging probes simultaneously for economy of logging time.

Another paper whose relevance deserves an abstract reproduction is due to Myung and Helander (1972): "Correlation of elastic moduli dynamically measured by *in-situ* and laboratory techniques." The abstract follows: "Elastic moduli of 15 cores were determined in the laboratory under simulated formation pressure and compared to the elastic moduli as determined from the 3-D log run in the field. The laboratory system used enabled the compressional and shear velocities of the rock samples to be measured sequentially under triaxial pressure. The core samples were from 11 wells from different areas of the country representing a number of differing competent rock types. The ratio of compressional wave velocities measured in the field and the laboratory varied from 0.94 to 1.13 and the ratio of shear wave velocities measured *in-situ* and in the laboratory varied from 0.92 to 1.16. The elastic moduli computed from theoretical relations developed for homogeneous, isotropic and elastic materials also indicated good agreement between the two sources of measurement indicating that the 3-D velocity system can provide *in-situ* measurements with sufficient accuracy to be of practical field use. Young's modulus and shear modulus were related to both the compressional and shear wave velocities. The correlations developed allow both moduli to be predicted from knowledge of either the compressional or shear wave velocity. Finally, a proposed rock classification method is prepared relating Young's modulus and rock density. Using measurements from 3-D velocity and density logs, sufficient information can be obtained to apply the rock classification system."

Myung and Baltosser (1972) discuss techniques using the seisviewer, three-D velocity log, and the three-D signature log for fracture evaluation in boreholes. A hole to hole technique is described whereby fractures between boreholes may be studied. They quote a minimum hole size of three inches for the probes.

King *et al.* (1973) described the construction and use of an acoustic borehole logging probe for use in AX size boreholes. This experimental prototype is especially relevant to the mining geophysics requirement for small diameter logging probes. Commercially available acoustic logging probes of small diameter are rare. One of them is the sonic logging probe of one and eleven-sixteenth inch diameter offered by Schlumberger (1974).

Finally a recent "state-of-the-art" philosophy may be represented by the following abstract from the paper by Norquay (1972):

"There has been progressive development in services and procedures. These services are mutually complementary and form a system. The Synergetic Log System (Schlumberger trademark) is such an interrelated sequence of components. A basic concept of the system is that the greater the amount of useable data — the greater the potential for uniqueness in the answer. The definable components are: Measurement, digital recording, digital transmission, analysis and computation, answer log presentation. The latter component, answer log, offers a new base for the development of innovative interpretation uses." Parkhomenko (1971) described theoretical and experimental studies relating to piezoelectric and seismoelectric effects in rocks. The piezoelectric method utilizes a mechanical stress (seismic impulse) to generate an electrical signal (voltage). It is proposed as a possible means of exploring for quartz-rich and nepheline rocks. The seismoelectric method utilizes the electrical potential produced by a seismic wave passing through water-bearing rocks.

CONCLUSIONS

In mining geophysics acoustic exploration methods may be applied in four different ways:

1. Surface-to-surface techniques.
2. Hole-to-surface (or surface-to-hole) techniques;
3. In-hole techniques;
4. Hole-to-hole techniques.

Acoustic exploration methods can be divided into three categories:

A. The direct path method: the travel times for different recording paths are measured. Anomalous values may represent a change in mineral content, or a change in porosity or fracture conditions along the recording path. The method may be applied in the surface-to-surface technique for outlining orebodies which are partially covered by overburden, the acoustic sources and receivers being placed on outcrops, and also in techniques 2, 3 and 4 for defining mineralized zones as a function of seismic ray path; it may therefore be useful in defining the position and size of an orebody by methods 2 and 4. The method is highly susceptible to change in porosity, fracture conditions and variations in rock weathering at the sources and receivers. Sensitivity in indicating mineral content requires a very good velocity contrast between the mineralized zones and the host rock. For example with velocity contrasts as great as 4.6 km/s and 6.1 km/s the detection sensitivity is 53 microsec/m. Effects of weathering, variations in porosity and fracture conditions must be taken into consideration before this detection sensitivity can be realized, or the method may be used to study the latter effects for their own value.

B. The Refraction method; the distances from the sources and/or the receivers to an interface over which the seismic velocity increases are interpreted from associated delay times. Under favourable conditions this method may be applied in any of the four ways involving boreholes and surface to define the size, shape and location of orebodies. Each prospect must be tested for feasibility as mineralized zones may exhibit a higher, lower, or the same seismic velocity compared with that of the host rocks. Effects of weathered zones at the sources and receivers must be considered. The most useful application of the refraction method may be in measuring depths to bedrock or definition of the areal extent of a mineralized zone under overburden. The method is most definitive for large velocity contrasts involving massive orebodies.

C. The Reflection method: the distances from points of measurements (sources and receivers) to an interface over which there is a change in acoustic impedance (acoustic impedance of a material is the product of its seismic velocity and density) are interpreted from the travel times of reflected sound waves. In many practical cases, for example that of a metallic sulphide in metasedimentary or volcanic host rocks, the density contrast between the mineral and host rocks contributes to a large acoustic impedance contrast even though seismic velocities may not differ greatly for the two materials. Hence the reflection method may be used in any of the borehole-surface configurations for detecting orebodies displaced from the borehole (or surface). Fault zones, fractures and veins may also be located by the method. The frequency content of the sound source markedly affects detection sensitivity and resolution. Field procedures must determine the optimum working frequency.

Seismic methods are not well established for mineral exploration. A great deal of investigation is required to determine appropriate procedures and apparatus. Much can be done in this regard from the ground surface before large expenditures are considered for sophisticated borehole equipment. Efforts should be intensified to explore the capabilities of both the purely seismic methods and the hybrid piezoelectric and seismoelectric methods. In any of the seismic methods signal amplitude variations may also prove to be of diagnostic value in determining changes in mineralization.

Acknowledgments

The author wishes to thank Dr. P.G. Killeen for suggestions and critically reading the manuscript.

BIBLIOGRAPHY

Anderson, W.L. and Riddle, G.A.
1961: Acoustic amplitude ratio logging; J. Pet. Tech., v. 13, p. 1243-1248.

*Baltosser, R.W. and Lawrence, H.W.
1970: Application of well logging techniques in metallic mineral mining; Geophysics, v. 35, p. 143-152.

Berry, J.E.
1959: Acoustic velocity in porous media; J. Pet. Tech., v. 216, p. 262.

Berzon, I.S.
1964: Some results of a study of seismic waves from well shooting; Bull. (Izv.) Acad. Sci. U.S.S.R. Geophys. Series (English translation), p. 793-806.

Biggs, W.P.
1958: Formation evaluation by sonic logging; The Petroleum Engineer, July, p. 376.

Biot, M.A.
1956: Theory of propagation of elastic waves in a fluid-saturated porous solid; J. Acoustic Soc. Am., v. 28, no. 2, p. 168-191.

Birch, F. and Bancroft, D.
1938: The effect of pressure on the rigidity of rocks; J. Geol., v. 46, no. 1, p. 59-87.

Birch, F.
1960: Velocity of compressional waves in rocks to 10 kilobars; J. Geophys. Res., v. 65, no. 4, p. 1083-1102.

Boss, F.E.
1970: How the sonic log is used to enhance the seismic reference service velocity survey; J. Can. well log. Soc., v. 3, no. 1, Dec., p. 17-31.

Breck, H.R., Schoellhorn, S.W., and Baum, R.B.
1957: Velocity logging and its geological and geophysical application; Bull. Am. Assoc. Pet. Geol., v. 41, no. 8, p. 1667.

Broding, R.A. and Poole, U.L.
1960: Collection and processing of digitized acoustic log data; Geophysics, v. 25, p. 939-947.

Brown, H.D., Grijalva, V.E., and Raymer, L.L.
1970: New developments in sonic wave train display and analysis in cased holes; Trans. SPWLA 11th ann. well log. symp., May 3-6, Los Angeles, Calif.

*Caldwell, R.L.
1967: Well logging in the U.S.S.R.; Trans., SPWLA 8th ann. well log. symp., Denver, Colo., June 12-14.

Carroll, R.D.
1966: Rock properties interpreted from sonic velocity logs; J. Soil Mech. Found. Div., A.S.C.E., v. 92, SM2, p. 43-51.

---

* References cited in report 2.

* References cited in report 2.

Carroll, R. D. (cont.)
1969: The determination of the acoustic parameters of volcanic rocks from compressional velocity measurements; Int. J. Rock Mech. Min. Sci., v. 5, p. 557-579.

Christensen, D. M.
1964: A theoretical analysis of wave propagation in fluid filled drill holes for the interpretation of the 3 Dimensional velocity log; Trans. 5th Ann. well log. symp., Midland, Texas, May 13-15.

Coon, R. F. and Merritt, A. H.
1970: Predicting *in situ* modulus of deformation using rock quality indexes; *in* Determination of the *In Situ* Modulus of Deformation of Rock. A. S. T. M. S. T. P. 477, p. 154-173.

Crawford, G. E., Hoyer, W. A., and Spann, M. W.
1973: Frequency response and resonance in acoustic logging; SPWLA, The Log Analyst, Jan.-Feb.

Dakhnov, G. V., Perel'man, A. L., Rabinovich, G. Ya., and Scherbakova, T. V.
1965: Acoustical logging laboratory of the type LAK-1; Prikladnaya Geofizika, v. 43, p. 163-176.

*Dawson-Grove, G. E.
1969: Sonar caliper applications in western Canada; Trans. SPWLA 10th ann. well log. symp., May 25-28, Houston, Texas.

Deere, D. U. and Miller, R. P.
1966: Engineering classification and index properties for intact rocks; Tech. Rept. No. AFWL-TR-65-116, Air Force Weapon Lab., Kirtland Air Force Base, New Mexico.

Denton, E. M.
1956: Continuous velocity log; Oil Gas J., Nov. 16, p. 224.

Desai, K. P., Helander, D. P., and Moore, E. J.
1970: Sequential measurements of compressional and shear velocities of rock samples under triaxial pressure; J. Pet. Tech., v. 22, no. 12.

Dushko, E. I., Muromtseva, Z. G., and Tsyrulnikova, S. S.
1961: Applications of complex logging in prospecting for iron ores in the Krivoy Rog Basin; Geolog. Zhurnal AN Ukr. S. S. R. 21(2).

Dzeban, I. P.
1970: Elastic wave propagation in fractured and vuggy media; Izv. Earth Physics, no. 10 (translated by D. G. Fly).

*Evans, H. B.
1970: Status and trends in logging; Geophysics, v. 35, p. 93-112.

*Evans, H. B. and Cotterell, C. H.
1967: Synthesis of modulus logs from acoustic parameters; some preliminary results; Trans., SPWLA 8th ann. well log. symp., Denver, Colo., June 12-14.

Fairhurst, C.
1961: Laboratory measurement of some physical properties of rocks; Proc. Fourth Symposium on Rock Mechanics, Bull. of Mineral Industry Experimental Station, Penn. State Univ.

Faust, L. Y.
1953: A velocity function including lithologic variation; Geophysics, v. 18, no. 2.

*Fons, L. C.
1969: Geological applications of well logs; Trans. SPWLA 10th ann. well log. symp., May 25-28, Houston, Texas.

Foster, M. R., Hicks, W. G., and Nipper, J. T.
1962: Optimum inverse filters which shorten the spacing of velocity logs; Geophysics, v. 27, p. 317-326.

Geertsma, J.
1960: Velocity log interpretation: The effect of rock bulk compressibility; Soc. Pet. Eng., AIME, Denver meeting, paper no. 1535-G.
1962: On Tuman's paper on "Refraction and reflection of sonic energy in velocity logging" (Geophysics, October, p. 588); Geophysics, v. 27, p. 275-276.

Geertsma, J. and Smit, D. C.
1961: Some aspects of elastic wave propagation in fluid-saturated porous solids; Geophysics, v. 26, no. 2, p. 169.

Geyer, R. L. and Myung, J. I.
1970: The 3-D velocity log: A tool for *in situ* determination of the elastic moduli of rocks; Proc. 12th Symp. Rock Mech., Univ. Miss., Rolla, Miss., Nov. 16-18.
1971: The 3-D velocity log, a tool for *in situ* determination of the elastic moduli of rocks; Proc. 12th Symp Rock Mech., Rolla., p. 71-107.

Gregory, A. R.
1963: Shear wave measurements of sedimentary rock samples under compression; Proc. the 5th Symp. Rock Mech., Minnesota.

Grosmangin, M.
1960: The cement bond log; Soc. Pet. Eng., AIME, Pasadena Meeting, Paper no. 1512-G.

---

*References cited in report 2.

*References cited in report 2.

*Guy, J.O., Youmans, A.H., and Smith, W.D.M.
1971: The sidewall acoustic neutron log; Trans. 12th ann. log. symp., Dallas, Texas, May 2-5.

Heelan, P.A.
1953: Radiation from a cylindrical source of finite length; Geophysics, v. 18, p. 685-696.

Henderson, J.B.H.
1953: Core hole velocity surveys; Geophysics, v. 18, p. 324-337.

Hicks, W.G. and Berry, J.E.
1956: Application of continuous velocity logs to determination of fluid saturation of reservoir rocks; Geophysics, v. 21, no. 3, p. 739.

Hicks, W.G.
1958: Lateral velocity variation near boreholes; Soc. Exp. Geophys. 28th Annual Meeting, San Antonio, Texas.

*Hobson, G.D. and Findlay, D.C.
1967: Down-hole geophysical studies on the Muskox Intrusion, Coppermine River area, District of Mackenzie; Geol. Surv. Can., Paper 66-44.

Hughes, D.S., Pondrem, W.L., and Mims, R.L.
1949: Transmission of elastic pulses in metal rods; Phys. Rev., v. 75, no. 10, p. 1552-1556.

Huntley, G.L.
1965: Factors affecting acoustic amplitude logs — and their evaluation; Trans., SPWLA 6th ann. well log. symp., v. 1, p. G1-G6, May 4-7, Dallas, Texas.

Ide, J.M.
1936: Comparison of statically and dynamically determined Young's modulus of rocks; Proc. Nat. Acad. Sci., v. 22.

Jaeger, J.C.
1969: Elasticity, fracture and flow; Methuen and Co. Ltd., London.

Karus, E.V. and Zuckernik, V.B.
1958: An ultrasonic apparatus for studying the physical and mechanical properties of rocks intersected by a drill-hole; Izv. Acad. Sci. U.S.S.R. Geophys. Ser., p. 1310-1322.

Kear, C.H. and Tullos, F.N.
1948: Acoustic impedance logging; Meeting Soc. Exp. Geophys., Denver, Colo.

Khalevin, N.I.
1960: Measurement of rock porosity by sonic well logging; Razvedochuaya i Promyslovaya Geofizika, v. 30, p. 3-9.

Khalevin, N.I. and Barykin, D.D.
1961: A system for acoustic investigation in boreholes; Izvest. Akad. Nauk. U.S.S.R., Ser. Geofiz., No. 1, p. 69-78.

King, M.S. and Fatt, I.
1962: Ultrasonic shear-wave velocities in rocks subjected to simulated overburden pressure; Geophysics, v. 27, no. 5, p. 590-598.

King, M.S.
1970: Static and dynamic elastic moduli of rocks under pressure; Proc. 11th Symp. Rock Mech., Berkeley, p. 329-351.

*King, M.S., Pobran, V.S., and McConnell, B.V.
1973: Acoustic borehole logging system; Presented at the 9th Can. Symp. Rock Mech., Ecole Polytechnique de Montreal, Dec. 14-15.

Kokesh, F.P.
1956: The long interval method of measuring seismic velocity; Geophysics, v. 21, no. 3, p. 724-738.

Knopoff. K. and MacDonald, G.H.F.
1958: Attenuation of small amplitude stress waves in solids; Geophysics, v. 34, no. 4, Oct.

Kokesh, F.P.
1952: Development of a new method of seismic velocity determination; Geophysics, v. 17, p. 560-573.

Kokesh, F.P. and Blizard, R.B.
1959: Geometrical factors in sonic logging; Geophysics, v. 24, p. 64-76.

Kokesh, F.P., Schwartz, R.J., Wall, W.B., and Morris, R.L.
1965: A new approach to sonic logging and other acoustic measurements; J. Pet. Tech., p. 282-286

Kolsky, H.
1963: Stress waves in solids; Dover Publication, Inc., New York.

Larocque, G.E.
1964: A sonic unit for the determination of *in situ* dynamic properties and for the outlining of fracture zones; Proc. 6th Symp. Rock. Mech., Rolla, p. 358-380.

Love, A.E.H.
1944: A treatise in the mathematical theory of elasticity; Dover Publication, New York.

---

*References cited in report 2.

*References cited in report 2.

Lawrence, H. W.
1964: *In situ* measurement of the elastic properties of rocks; Proc. 6th Symp. Rock Mech., Rolla, p. 381-390.

1965: Reflection, refraction and energy made conversion as seen on 3-D velocity logs; 35th Annual Meeting Soc. Exp. Geophys., Dallas, Texas.

Lawrence, H. W. and Baltosser, R. W.
1969: Engineering problems and downhole geophysical solution; Exploration for Mineral Resources; Circ. 101, New Mexico Bur. Mines Mineral Resourc.

Mack, H.
1966: Attenuation of controlled wave seismograph signals observed in cased boreholes; Geophysics, v. 31, p. 243-252.

Meissner, R.
1961: Wave-front diagrams from uphole shooting; Geophys. Prosp., v. 9 (4), p. 533-543.

1965: P- and sv-waves from uphole shooting; Geophys. Prosp., v. 13(3), p. 433-459.

Morlier, P.
1969: Spectre de fissuration et celerite des ondes; Revue de L'Industrie Minerale, 15 Juillet.

Morris, R. L., Grine, D. R., and Arkfeld, T. E.
1961: Using compressional and shear acoustic amplitudes for the location of fractures; J. Pet. Tech., June, p. 623-632.

1963: Using compressional and shear acoustic amplitudes for the location of fractures; Paper SPE 723, presented at the AIME Annual Meeting, New Orleans, Louisiana.

Muromtseva, Z. G.
1962: Geophysical investigations in the boreholes of the Krivoy Rog Basin; Ra zvedka i okhrana nedr, 77.

*Myung, J. I. and Baltosser, R. W.
1972: Fracture evaluation by the borehole logging method; Proc. 13th Symp. Rock Mech., Urbana, p. 31-56.

*Myung, J. I. and Helander, D. P.
1972: Correlation of elastic moduli dynamically measured by *in situ* and laboratory techniques; 13th Ann. Log Symp. Trans. SPWLA, May 7-10, Tulsa, Okla.

Myung, J. I. and Henthorne, J.
1971: Elastic property evaluation of the roof-rocks with 3-D velocity log; Solution Mining Research Institute, Atlanta, Georgia.

Nafe, J. E. and Drake, C. L.
1957: Variation with depth in shallow and deep water marine sediments of porosity, density and velocities of compressional and shear waves; Geophysics, v. 22, no. 3, p. 523.

*Norquay, I. P.
1972: Synergetic log systems, definition and application; Presented at the 4th Formation Evaluation Symposium of CWLS in Calgary, May.

*Parkhomenko, E. I.
1971: Electrification phenomena in rocks; Plenum Press, N. Y. (1971). Translated from Russian by George V. Keller, Colorado School of Mines.

Pickett, G. R.
1960: The use of acoustic logs in the evaluation of sandstone reservoirs; Geophysics, v. 25, no. 1, p. 250.

1962: Acoustic character logs and their applications in formation evaluation; Paper SPE-452 presented at the AIME Annual Meeting, Los Angeles, California.

1963: Acoustic character logs and their applications in formation evaluation; J. Pet. Tech., v. 15, p. 659-667.

*Pickett, G. R.
1970: Applications for borehole geophysics in geophysical exploration; Geophysics, v. 35, p. 81-92.

*Pirson, S. J.
1963: The elastic wave propagation logs; In Handbook of Well Log Analysis; Prentice, Hall, Inc., p. 221-236.

Pobran, V. S.
1973: Elastic-wave velocities in rocks; Unpubl. M. Sc. thesis, Univ. Saskatchewan, Saskatoon.

Price, D. G., Malone, A. W., and Knill, J. L.
1970: The application of seismic methods in the design of rock bolt systems; Proc. 1st Int. Cong; Int. Assoc. Eng. Geol., Paris, v. 2, p. 740-752.

Rinehart, J. S., Fortin, J. P., and Bergin, L.
1961: Propagation velocity of longitudinal waves in rocks; 4th Symp. Rock Mech., Bull. Mineral Ind. Experimental Station, Penn. State Univ.

---

*References cited in report 2.

*References cited in report 2.

Rodermund, C. G., Alger, R. P., and Tittman, J.
1961: Logging empty holes; Oil Gas J., v. 59, p. 119-124.

*Runge, R. J. and Powell, N. J.
1967: The effect of sampling rate on sonic log span adjustments; Trans., SPWLA 8th ann. well log. symp., Denver, Colo., June 12-14.

Sarmiento, R.
1961: Geological factors influencing porosity estimates from velocity logs; Am. Assoc. Pet. Geol., Bull., v. 45, no. 5, p. 633.

Saure, W. C.
1963: Determination of a more accurate porosity and mineral composition in complex lithologies with the use of the sonic, neutron and density surveys; J. Pet. Tech., v. 15, p. 945-959.

Saure, W. C. and Burke, J. A.
1963: Determination of true porosity and mineral composition in complex lithologies with the use of sonic, neutron and density surveys; Trans., 4th SPWLA log. symp.

*Schlumberger
1966: The Sonic Log; *in* Log Interpretation Principles, Logging Service Booklets, Schlumberger Well Surveying Corporation, Houston, Texas.

Schneider, W. C. and Burton, C. J.
1949: Determination of the elastic constants of solids by ultrasonic methods; J. Appl. Phys., v. 20, p. 48-58.

Schock, R. N.
1970: Dynamic elastic moduli of rocks under pressure; Proc. Symposium of the Engineering Nuclear Explosive, Las Vegas, Nevada.

Sherriff, R. E.
1970: Glossary of terms used in well logging; Geophysics, v. 35, p. 1116-1139.

Stowe, R. L.
1971: Comparison of *in situ* and laboratory test results on granite; Soc. Pet. Eng. of AIME, SPE 3217, Houston, Texas.

1972: Comparison of *in situ* and laboratory test results on granite; Trans. Soc. Min. Eng. AIME, v. 252, p. 194-199.

Strippling, A. A.
1958: Velocity log characteristics; J. Pet. Eng., v. 213, p. 207.

*Summers, G. C. and Broding, R. A.
1952: Continuous velocity logging; Geophysics, v. 17, p. 598-614.

Tamate, O.
1953: On the propagation of elastic waves along the infinitely long circular-cylindrical hole in an infinite solid; Techn. Reports Tohoko Univ., Sendai, Japan, v. 17, p. 91-110.

Thurber, C. H.
1960: SATA log; Soc. Pet. Eng., AIME, Denver Meeting, Paper no. 1564-G.

Thurber, C. H. and Latson, B. F.
1960: SATA log checks casing cement jobs; The Petroleum Engineer, Dec., p. B84.

Timur, A. E.
1970: A study on correlation of dynamic and static elasticity modulus determined by *in situ* and laboratory tests; 2nd Congress, Society of International Rock Mechanics, v. 1, Belgrad, Yugoslavia.

Tinch, D. H., Miller, G. K., Carpenter, B. N., and Warren, J. P.
1966: Application of magnetic tapes to well logs; J. Pet. Tech., June.

Tixier, M. P., Alger, R. P., and Doh, C. A.
1959: Sonic logging; J. Pet. Tech., v. 11, p. 106-114, May.

*Tixier, M. P., Alger, R. P., and Tanguy, D. R.
1959: New developments in induction and sonic logging; SPE of AIME 34th Annual Fall Meeting, Dallas, Texas, Oct.

1960: New developments in induction and sonic logging; J. Pet. Tech., May.

*Tixier, M. P. and Alger, R. P.
1967: Log evaluation of non-metallic mineral deposits; Trans. SPWLA 8th ann well log. symp.

1970: Log evaluation of nonmetallic mineral deposits; Geophysics, v. 35, p. 124-142.

Tixier, M. P., McVicar, B. M., and Burton, R. P.
1960: Progress in sonic log application; Presented at the First Joint Technical Meeting of the Can. Inst. Min. Met., Petroleum and Natural Gas Division and the Rocky Mountain Sections of the Society of Petroleum Engineers of AIME, in Calgary, Alberta, May 4-6.

---

[*] References cited in report 2.

[*] References cited in report 2.

Tuman, V. S.
1961: Refraction and reflection of sonic energy in velocity logging; Geophysics, v. 25, p. 588-600.

1962: Reply to discussion by J. Geertsma on "Refraction and reflection of sonic energy in velocity logging"; Geophysics, v. 27, p. 719.

*Vogel, C. B.
1952: A seismic velocity logging method; Geophysics, v. 17, p. 586-597.

Vogel, C. G. and Hubbard, W. M.
1959: The influence of geometry upon acoustic logging signals; Soc. Pet. Eng., AIME, Dallas Meeting, Paper No. 1301-G.

Walker, T. and Riddle, G.
1963: Field investigation of full wave recording of the acoustic signal; Welex Technical Bulletin, L-12.

1963: Field investigation of full wave acoustic wave recording; Presented at 4th ann. log. symp., WLA, Oklahoma City, Oklahoma.

White, J. E.
1965: Seismic waves: Radiation, transmission and attenuation; New York, McGraw-Hill, Inc.

*White, J. E.
1967: The hula log; Transactions, SPWLA 8th ann. well log. symp., Denver, Colo., June 12-14.

White, J. E. and Zechman, R. E.
1968: Computed response of an acoustic logging tool; Geophysics, v. 33, p. 302-310.

Wyllie, M. R. J., Gregory, A. R., and Gardner, L. W.
1956: Elastic wave velocities in heterogeneous and porous media; Geophysics, v. 21, no. 1, p. 41.

* 1958: An experimental investigation of factors affecting elastic wave velocities in porous media; Geophysics, v. 23, p. 459-493.

1961: Studies of elastic wave attenuation in porous media; 31st Ann. Meeting, Soc. Exp. Geophys.

Youmans, A. H., Guy, J. O., and Engle, A. W.
1970: Field tests with an experimental sidewall acoustic logging device; Paper no. 7060, Canadian Well Logging Symp. in Calgary, May 6, 7, 8.

Zablocki, G. J. and Keller, G. V.
1957: Borehole geophysical logging methods in the Lake Superior district; In Drilling Symposium, 7th Annual, Exploration drilling. Minneapolis, Minnesota Univ. Center for Continuation Study, p. 15-24.

Zanier, A. M. and Overton, H. L.
1970: Use of acoustic logging technique for determination of intergrain cementation properties; Trans. SPWLA 11th ann. log. symp., May 3-6, Los Angeles, Calif.

---

*References cited in report 2.

*References cited in report 2.

3. ELECTRICAL BOREHOLE METHODS APPLIED TO METALLIC MINERAL PROSPECTING

A.V. Dyck

INTRODUCTION

A number of electrical methods have been applied to the problem of geophysical prospecting for metallic minerals in boreholes. In these applications, the borehole not only allows the measuring equipment to approach the orebody more closely but also affords the opportunity to escape overburden effects which so often plague surface electrical methods of prospecting. Most available publications describe successful case histories dealing with unique applications of a particular method; however, several papers also deal with the techniques of borehole surveying which may have general application. For the purposes of this discussion the electrical methods are broken into three subgroups: resistivity and spontaneous polarization, induced polarization, and electromagnetic methods.

RESISTIVITY AND SPONTANEOUS POLARIZATION METHODS

Resistivity and spontaneous polarization (SP) measurements are commonly applied techniques in the well-logging industry and there are numerous papers on the subject (*see* bibliography) which are concerned with the techniques for the determination of rock properties in the vicinity of the drillhole. In fact, there are several papers describing investigations which may find application to mineral prospecting in drillholes.

Roy and Dhar (1971) have determined the radius of investigation in D. C. resistivity logging by considering cylindrical shells of ground concentric with the resistivity probe. The radius of investigation is defined as the radius of the cylindrical ground shell which makes the largest positive contribution to the signal received in a homogeneous ground. It is defined in relation to the separation L of the two farthest active (moving) electrodes. On this basis the normal array (pole-pole) has the largest radius of investigation (0. 6 L) followed by the lateral array (pole-dipole) (0. 4 L) and the Schlumberger and Wenner arrays (0. 2 L).

Buckner (1954) has considered the effects of a thin bed of different resistivity inside a homogenous isotropic medium and computed logs for two- and three-electrode devices passing through the media when the thin bed is more resistive than the host, but the expression may also be used if the bed is less resistive.

The time-domain response of wires grounded in a homogeneous medium is of interest in electrical resistivity logging whenever a commutated direct current is used. Wait (1953) has derived expressions which may be used to compute the response of a drillhole array to the sudden application of current. The response of an equispaced three-electrode array was graphically presented in the paper.

Monoelectrode and guard electrode resistance measurements are commonly employed by the well-logging industry in lithological mapping. The application of these devices to mineral prospecting in drillholes has been investigated by Bower (1968). The principle of the guard electrode (*see* for example, Guyod, 1951; Dakhov, 1962) differs from the monoelectrode only in the current distribution. Both are essentially total resistance measurements and therefore are, to some degree, dependent on varying contact resistances. At three different test sites in Quebec however, Bower (1968), found that either method was useful in locating sulphide zones intersected by the drillhole. He was also able to demonstrate an empirical relationship between continuity of the sulphide zone and ratio of background to conductor resistance in the case of the monoelectrode or ratio of background to depression current in the case of the focussed electrode.

The advantages of employing an underground electrode in D. C. resistivity work are shown in two papers. Alfano (1962) considered the difficulty, in electrical sounding, of determining the resistivity and thickness of the second layer if the top layer is, by comparison, either very conductive or very resistive. He demonstrated that, in the case of a very resistive surface layer, the problem may be overcome by injecting current directly into the second layer by means of an electrode placed very near the bottom of the surface layer. It is then necessary to perform the sounding by moving the potential electrodes only, the other current electrode being at infinity. An additional benefit of this technique is that a smaller maximum electrode spacing is needed to complete the sounding diagram than in the case of a sounding with all electrodes on the surface. The problem is not so easily solved for a conductive surface layer because it still gathers most of the current unless the electrode is buried much deeper.

Snyder and Merkel (1973) have considered the resistivity and IP response of a buried current electrode for the purposes of sounding horizontal layers as well as outlining buried three-dimensional targets. The other current electrode is removed to infinity and potentials are measured with a surface dipole. The layered models are suitable for computing the response of stratiform-type deposits, particularly in cases where a conductive overburden is shielding a more resistive, deeper IP target. The buried electrode has particular appeal when there are practical limits to the electrode separation. A survey of surface dipole measurements directed radially outward from the current pole is useful in determining direction and offset of a three-dimensional target and hence can be used to outline deep orebodies. It was observed that a current electrode buried near a target can more than double the response of the body. The IP response is enhanced particularly if the body is more resistive than the surrounding rock.

Clark and Salt (1951) used the method of images to derive an expression for the potential near a conducting sphere placed in a more resistive medium. In the technique outlined, one current electrode and a potential dipole are employed in the drillhole in a fixed- or expanding-separation mode. The other current electrode is placed at the surface in several positions which are away from but symmetric with respect to the drillhole. Any differences introduced into the borehole profile by change in azimuth of the surface current electrode is due to conductivity inhomogeneities in the rock surrounding the hole. Comparison of the two modes of movement of the downhole electrodes can separate the effects of bodies near to and distant from the hole. The technique was successfully demonstrated in a field test on the property of Lake Dufault Mines Limited, Quebec.

A method of determining orebody size by drillhole electrical prospecting has been outlined by Seigel (1952). The theoretical model considered was a flat-lying oblate spheroid. Resistivity curves were prepared for the normal (pole-pole) array and the equispaced pole-dipole array. Current distribution in the spheroid is axially-symmetric so no directional information is available. It is possible to make an estimate (within a factor of 2) of the ellipticity of the spheroid and hence decide if the encountered mineralization is a localized deposit or the fringe of a larger one.

Clark (1956) considered a similar problem for an elongated body which was represented by a prolate spheroid whose major axis lies away from the intersecting borehole. In this method one of the current electrodes lies in the intersection, the other essentially at infinity, while the potential dipole moves along the hole. It was shown that the calculated resistivity values are fairly uniform up to a distance from the current electrode which is equal to the distance the body extends away from the hole. From that point on the resistivities increase rapidly. The relationship was illustrated by a field example and was found to be useful in estimating the extension of a mineralized zone away from the hole.

Several case histories involving the application of the mise-à-la-masse technique (also referred to as applied potential) have been published. The method involves direct excitation of an ore zone by means of a current electrode making contact with it. The surface of the body becomes an equipotential surface and surrounding equipotentials are presumably concentric with it. The projection of the equipotentials on some plane of measurement is then diagnostic of the shape and size of the ore zone. The potentials may be mapped at the earth's surface or in sets of boreholes. McMurry and Hoagland (1956) have applied the method to delineate pencil-shaped zones of disseminated sulphides in a dolomite host rock at Austinville, Virginia. The resistivity contrast between host rock and mineralization varies from 10: 1 to 100: 1. The ore zones were excited by a current pole making contact in a borehole. Potentials were measured in a set of boreholes drilled in the same plane and could therefore be mapped over the plane containing the holes. High ellipticity of the equipotentials, i. e. a departure from the circular shape expected for an undisturbed spherical current distribution, was indicative of the presence of elongated mineralized zones. Displacement of the maximum potential from its expected position was also observed to be significant in locating conductive ore zones. The interpretation was supported by theoretical calculations of the current distribution.

Parasnis (1967) was also successful in applying the mise-à-la-masse technique in surveying a lead-zinc deposit in central Sweden. Geological correlation between drillholes which were numerous and closely spaced was difficult because of the irregular geometry of the deposit. The potential mapping on the surface and in boreholes revealed the dip of the orebody, established connections between different parts of the deposit and showed that it was crescent shaped. A more recent paper by Parasnis (1974) presented another field example from a zinc-pyrite orebody in northern Sweden. This survey was again able to demonstrate the continuity between ore sections encountered in adjacent holes. Two other ore sections were shown to be unrelated.

Pelton and Hallof (1971) have described a case history in which the mise-à-la-masse technique was used to outline small pods of high-grade massive sulphide mineralization near York Harbour, Newfoundland, in which surface exploration methods had been unsuccessful due to poor size-to-depth ratio of the targets and widespread disseminated mineralization. However, no alteration halo exists around the sulphide pods to aid in their detection. The technique was first tested away from mineralization to verify the spherical potential distribution under the prevailing geologic and topographic conditions. Subsequent application in the mineralized area yielded identical distortions of the potential pattern when two intersections in different holes were contacted. Thus it was shown that the two intersections are joined together and are part of a larger ore zone, a fact that was later confirmed by extensions to the underground workings.

An interesting case history described by Morrison (1971) concerns the exploration for lead deposits in flat-lying sediments in Missouri. The deposits of interest are themselves horizontal bodies of disseminated galena (2 to 3%) at depths of 700 to 800 feet. The preliminary measurements were performed with the mise-à-la-masse technique but various practical limitations dictated that the bulk of the measurements be made using only one borehole at a time. The single-hole method involved placing two points in the borehole on an equipotential surface by suitable arrangement of the two surface current electrodes on opposite sides of the hole and 1500 to 2000 feet away. In order to de-emphasize the stratigraphic effect of an overlying conductive shale layer (250 Ω-m, i. e. 40 times more conductive than the host rock of the ore), one of the potential electrodes was placed in the shale while the positions of the current electrodes were adjusted, the other potential electrode being at the bottom of the hole. Departures from the equipotential were then recorded along the hole by moving the upper electrode. The survey was also performed with the current dipole in the orthogonal position. The method was found to give good directional information to better mineralization provided the ore was within 500 feet of the hole.

The U. S. Geological Survey has been active in geophysical borehole methods (Zablocki, 1966a) as part of investigations into electrical properties of rocks. It was found by Zablocki that electrical resistivity logs could be used to distinguish enriched hematite ores from noncommercial ores. The combination of resistivity and magnetic susceptibility was found to be useful in determining the amount of magnetite necessary for a rock to appear electrically continuous (Zablocki, 1966a, b). For iron-formations of low magnetite content, the resistivity was predominantly dependent in the rock porosity. However, at higher concentrations of magnetite (8-20% by volume, depending on mode of distribution of the magnetite) the resistivity was observed to decrease sharply.

The results of experimental spontaneous-polarization (SP) measurements in drillholes for the purposes of mineral exploration have been reported by Becker and Telford (1965). They point out that the self-potentials associated with sulphide bodies, graphite and magnetite can be quite large (up to 1 volt) which is much larger than those encountered in sedimentary formations (less than 75 mv). A number of model studies indicated that in order for a body to produce the usual negative, symmetric, surface anomaly, there must be current flowing in the surrounding medium which leaves the body at depth and returns to it near the surface. Therefore the upper portion of the body must be negative with respect to the bottom. An example of a sulphide model buried at 100 feet showed no appreciable surface anomaly but did have a measurable self potential in a drillhole which missed the body by a comparable distance. It was also indicated that clay can be an efficient inhibitor of the SP effect by limiting the amount of electrochemical activity at the orebody surface and by preventing current flow at the surface.

The field measurements were made with special nonpolarizing electrodes. These were porous pots which were allowed to leak so as not to collapse under the pressures encountered in the drillhole. The potential of this single electrode was measured with respect to a fixed porous pot at the surface near the collar. A fixed-separation mode of operation with both electrodes in the hole required only that the ends of a copper wire be exposed since they were both in the same environment.

About 60 drillholes were logged near base metal deposits. Generally the SP anomalies occurred at mineral intersections described in the core logs and sometimes at minor mineral bands considered insignificant. They were typically negative but, in general, showed little correlation between amplitude and grade of mineralization. The large potentials are associated with the interfaces between barren rock and mineralization. It was recommended that, in further work, more chemical and electrical measurements be made, for example, pH and oxidation potentials. However, the routine application of the method in exploration work to obtain precise information on locations of interfaces, and indications of sulphides away from the hole, was strongly recommended.

Further study of SP effects in drillholes was made by Bower (1958). A total of 25 holes on three different sites were surveyed using a lead-antimony electrode. It was found that the locations of the SP anomalies agree very well with the presence of sulphide intersections although, again, no correlation with degree of mineralization was evident. The shape of the SP anomaly profile was observed to be variable around massive sulphide contacts and highly erratic near disseminated sulphides.

Bølviken *et al.* (1973) have described an instrument developed at the Geological Survey of Norway for making *in situ* measurements of Eh, pH and self-potentials in diamond-drill holes. The instrument has been tested to depths of 350 m without damage to the glass electrode. A Cu-$CuSO_4$ electrode is used for measuring SP. Some SP field results from the Joma pyrite deposit, Norway, have been presented in a subsequent paper (Logan and Bølviken, 1974). SP measurements were made in 14 holes and were found to be repeatable to within 1-2 mV. All measurements were reduced to a common reference voltage. Two types of SP patterns were distinguished. One of these, termed 'electronic current potential' has an abruptly alternating pattern corresponding to the electromotive forces at interfaces of host rock and sulphides and indicates that electronic currents pass within the sulphides. The 'ionic current potential' pattern exhibits a general trend and is a consequence of ionic currents in pore water in the host rock outside the orebody. In most cases in drillholes the two potential patterns are easily separated by a simple graphical estimation. The observations are best explained by a galvanic cell model in which the pore water of the host rock constitutes the electrolyte and the upper and lower ends of the massive ore are the cathode and anode, respectively so that current in the orebody flows downwards. Distribution of potentials within the orebody can then be used to indicate direction toward the thickest part of the massive ore. Potentials outside the orebody are distributed as by a dipole source and are, therefore, useful in estimating the downward extension of an orebody and its tonnage.

These observations are corroborated in the discussion on SP measurements in drillholes by Parasnis (1974) who presents some empirical rules for estimating depth extent of an orebody. For steeply dipping tabular bodies the zero potential contour occurs nearer to the negative pole (top) and about 1/6 of the way between it and the positive pole (bottom). If the top is at appreciable depth, this fraction is somewhat larger. A field example given in this paper shows how well the underground SP pattern is developed, even though it has no surface manifestation due to short-circuiting by the highly conducting clay overburden.

INDUCED POLARIZATION

Several methods of measurement of the induced-polarization effect (IP) in boreholes have been reported in the literature. Figure 3. 1 shows some of the electrode arrays used.

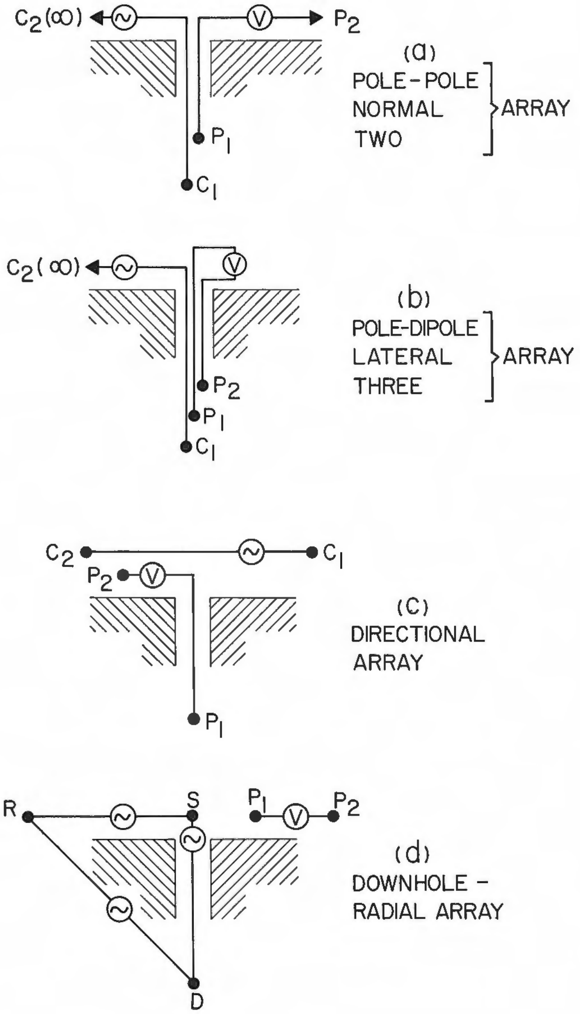


Figure 3.1: Electrode arrays used for resistivity and IP measurements in boreholes.

Keller (1967) has applied the technique to well logging, i. e. in determination of rock properties in the vicinity of the borehole. He reported that the conventional electrode arrays, such as used in resistivity logs, are commonly used for induced-polarization logging also. The array employed by Keller had three electrodes in the hole. Current was passed between the upper two (4 to 6 feet apart) while potentials were measured at the third (4 to 8 inches below) relative to a surface reference electrode. Measurements were made with time-domain equipment. If contact resistances of the inhole electrodes were 100 ohms or less, it was found that measurements could be made to depths of 2000 feet without encountering significant coupling of the current and pickup conductors in the cable. The experience gained in logging some two hundred mineral prospecting holes indicated that an induced-polarization response (integrated transient voltage normalized to the steady-state voltage) was produced by rocks rich in metallic minerals. The conclusion reached was that the induced-polarization log may be used to identify sparsely mineralized or hydrothermally altered zones which might be overlooked in core inspection or to detect sulphide concentrations missed because of poor core recovery.

Two case histories involving borehole induced polarization have been reported in the literature. In one of these, the method has been successfully applied to the search for native copper in the Osceola amygdaloidal workings in Michigan (Schillinger, 1964; Bacon, 1965). The equipment that was used operated in the time domain with a charging period of ~ 5 sec. The transient voltage could be sampled at several delay times and the IP susceptibility (ratio of transient samples to steady-state voltage i. e. chargeability) determined.

The electrode array chosen was the lateral (pole-dipole) in which the two potential electrodes (located in the hole) were separated from the downhole current electrode by 5 feet. The other current electrode was placed in a distant drillhole.

The equipment was used to assist in the exploration of the Osceola amygdaloidal footwall zone for pockets of ore-grade concentrations of native copper. It was found that the improved sampling volume achieved by using the induced-polarization technique in the boreholes allowed the prediction of location and grade of the footwall pockets.

In the other case (Mathisrud and Sumner, 1967), the technique was applied in the frequency domain (0. 3 and 2. 5 Hz) using the gradient array to the problem of locating pencil-shaped orebodies in a complex anticlinal structure occurring in Precambrian rocks of the Hanes Lake Formation, South Dakota. Current electrodes were situated at opposite ends of a drift and the potential electrodes inserted in drillholes extending outward horizontally. The choice of array was made with the aid of some scale-model results which indicated a negative PFE effect when a mineralized zone is located at the centre of a dipole-dipole array. Subsurface contour maps of apparent resistivity and PFE were, in general, quite similar. Some of the anomalies correlated with known mineralization and others were due to the presence of graphite. However, two additional ore-grade zones were located. These were missed in the primary exploration based on a 100-foot drilling interval.

There are also reports in the literature of more generalized approaches to the application of induced polarization in borehole exploration. These papers also described the interpretational aspects involved.

Wagg and Seigel (1963) described two modes of operation which can be employed in detecting and locating an orebody from its induced-polarization properties. To detect the body at depth and estimate its distance from the hole, one current electrode and one potential electrode are lowered into the hole, while the other two electrodes are located on the surface at infinite spacings from the downhole array. This is the pole-pole configuration referred to in the well-logging industry as the normal array. If a multiconductor cable is used, various downhole electrode spacings may be employed, the short spacings reflecting conditions near the hole and the longer spacings sampling up to a distance approximately equal to the spacing used. Measurements were made in the time domain. While the authors state that the frequency-domain method is equally capable of producing excellent results, they prefer the time domain because the system is more adaptable to logging isolated drillholes, presumably because coupling between current and potential conductors in the cable is less of a problem. Other advantages include inherently greater sensitivity and relative freedom from power line interference. Analysis of the downhole measurements gives an estimate of chargeability of the orebody and its distance from the hole.

Once these anomalies are obtained, the directional mode of surveying may be employed. Both current electrodes are placed at the surface on opposite sides away from the drill collar (Figure 3. 1c). Measurements are made while transmitting, in turn, in two directions orthogonal to each other. This allows an estimate of the azimuth of the ore zone with respect to the drillhole.

The authors state that borehole IP surveys should find wide application in the Precambrian Shield since steeply-dipping tabular bodies are common. The chief advantage over surface exploration is that the large dimensions of the body are presented to the line of a borehole profile. Furthermore, the size of the target is often effectively increased by a surrounding zone of alteration and disseminated sulphides and hence brought closer to the hole. An excellent example is shown of a sulphide ore zone which existed 50-100 feet away from the hole. An alteration zone intersected by the hole showed up on the short-spacing array. Increased response on the longer arrays indicated the presence of the main ore zone lying away from the hole. The directional survey indicated clearly the azimuth of the body. It was concluded that borehole IP surveys are useful for the detection of unknown sulphide deposits from an isolated, barren drillhole and for guiding drill outlining programs around a target showing high IP response. The most definite results are obtained when the survey hole is itself completely barren but useful information can be gained even if low-percentage sulphides are intersected. Steeply dipping, water-filled holes in competent rock near targets of 1-20% by volume disseminated sulphides give the best results. The much lower relative cost of borehole IP surveys relative to the drilling warrants their serious attention.

Brant *et al.* (1966) were able to define specific difficulties peculiar to induced polarization measurements in drillholes and also presented solutions to these problems. When employing multi-electrode arrays in the hole (two- and three-array), capacitive coupling between current and potential lines may be reduced by separately shielding the lines from each other. The shields must be rounded near the hole collar at less than 1000 ohm, electrode contact resistances should be kept below 10 000 ohm and, if recording in the time domain, a delay of at least 20 ms should be employed. Also discussed in this paper were expressions developed by J. R. Wait to evaluate inductive EM effects for the two- and three-arrays. Another problem arises because of resistivity contrasts between drillhole fluid and the wall rock. Graphical corrections calculated by H. O. Seigel for these 'masking' effects were presented in the paper for two-array measurements of resistivity and IP. It was pointed out that the effective hole diameter may be larger than was drilled due to wall-rock invasion. For example, 50 AX holes (1. 9 inches in diameter) drilled in gneisses at O'Okiep, South Africa had effective hole diameters varying from 6 to 12 inches. Also recommended was the use of silver-silver chloride screens as downhole potential electrodes. Mechanics of setting up the azimuthal array (similar to Wagg and Seigel, 1963) were also discussed.

Two field examples were described by Brant *et al.* (1966). In one hole sulphides were detected away from the hole with the two-array (spacings of 10, 40 and 120 feet) and their direction determined by the azimuth array. The other hole was used to illustrate corrections for the 'masking' effect of the drillhole fluid.

Hauck (1970) has described a reconnaissance borehole IP and resistivity method called the downhole-radial method. All measurements are made in the frequency domain along surface lines extending radially from the drill collar. Three current electrodes are used, a surface electrode near the collar, a remote surface electrode, and a downhole electrode. Current can be transmitted from any pair of these: downhole-remote (D-R), surface-remote (S-R), or surface-downhole (S-D) (Fig. 3. 1d).

Resistivity modelling was done with a spherical body with a resistivity contrast of 1: 13. The experiments indicated that it is possible to assign a large conductive body to a particular quadrant and demonstrated the advantage of using a downhole current electrode.

Both resistivity and IP modelling were performed on a flat-lying tabular body with a PFE of 22% and a metal factor of 28 800 mho/m and resistivity contrast of 1: 100 in a background of 75 ohm-m. The various observations are repeated here in condensed form:

1. When the source is shallow all three dipole combinations produce an anomalous response.
2. The PFE and metal factor anomaly magnitudes for the S-R dipole are comparable, the D-R PFE anomaly slightly stronger, and the D-R metal factor almost double those obtained by the conventional dipole-dipole array.
3. The S-R and S-D results are the first to lose their diagnostic variations in PFE and metal factor as the body assumes greater depths.
4. The source of the anomaly detected by the downhole survey is twice as deep as can be detected by the conventional dipole-dipole surface array.

5. When the orebody is at a distance from the drillhole, the downhole electrode must be at a greater depth than the orebody to produce a measurable IP response at the surface.
6. When an orebody is at depth close to the drillhole the D-R current sources produces, by far, the strongest response. The S-D dipole may produce a negative PFE when the downhole electrode is near the orebody. Also the D-R response can be used to estimate the far edge of the body.

Field results were also given in the paper. A zone of disseminated sulphides (0. 3 - 0. 4 per cent copper) was detected in a Precambrian environment at a depth of 1100 feet. Another test performed in a Paleozoic environment employed a downhole electrode at a depth of 1200 feet where the drill had intersected mineralized limestones containing 0. 3 - 0. 4 per cent copper. The IP results indicated an anamolous zone at a depth of 1200 feet extending to 2000 feet away from the hole. A porphyry copper deposit was also detected and its dip was determined at depths ranging from 750 to 1750 feet.

The author pointed out the limitations of the method in obtaining data near the drillhole. A technique using more inhole electrodes is better suited to this problem. He felt that the method could be applied equally well in the time domain.

Salt (1966) also performed IP measurements on the Lake Dufault Mines Ltd. property in Dufresnoy Tp., P. Q. Mechanical problems and proximity of potential and current cables lead to capacitive coupling and since measurements were made in the frequency domain, transmitting electrode and potential probes were lowered into separate holes. A peak in IP effect was observed at an electrode depth of 1100 feet, indicating the presence of a mineralized zone somewhere in the vicinity of the two holes. However, no directional information about the sulphide zone could be derived.

Theoretical calculations of borehole IP response have been reported by Merkel and Snyder (1970, abstract only). A computer program was written to calculate the apparent resistivity and IP effect of two spheres of arbitrary parameters in order to examine the effect of a secondary ore zone on three-array borehole electrical measurements.

Sumner (1965; abstract only) has reported the results of analog modelling of drillhole resistivity and IP. When used in conjunction with field results, they are useful in solving interpretative problems and in gaining worthwhile information about both general and particular situations involving complex three-dimensional potential fields.

A more recent paper by Sumner (1972) discusses and compares electrode arrays used in IP surveying and includes arrays commonly used in drillhole work. The table of comparisons is reproduced here (Table 3. 1).

ELECTROMAGNETIC METHODS

Induction logging has been routinely applied in the well-logging industry and was first considered as a method to be used in dry holes for the determination of resistivity of the rocks in the vicinity of the hole. One of the earliest papers on the interpretation of induction logs (Doll, 1949) used the 'geometrical factor' concept. The surrounding material was broken into toroidal elements for the purposes of the calculation and each toroid was considered individually as an inductive loop. The resulting in-phase voltage at the receiver coil was found to be proportional to the conductivity of the rock. This is a good approximation at low frequencies.

It should be pointed out that the well-logging industry refers to the in-phase and quadrature-phase of the induced voltage in the receiver loop relative to the transmitter current. In mining geophysics the usual practice is to refer to the phase of the secondary magnetic field (or the induced eddy current) which is 90° different in phase from the voltage induced in the receiver and therefore the terminology is interchanged. Henceforth in this discussion, in-phase and out-of-phase will refer to the components of the secondary induced field as is usual in mining geophysics.

At higher frequencies or conductivity the out-of-phase response is no longer proportional to conductivity. Furthermore there is an appreciable in-phase component of induction and the 'geometrical factor' is no longer valid because of the well known 'skin' effect. Solution of Maxwell's equations for the problem, published by Duesterhoeft (1961), Duesterhoeft *et al.* (1961), Duesterhoeft and Smith (1962) and Moran and Kunz (1962) took into account the 'skin' effect but neglected displacement currents. The out-of-phase component remained as the response measured. Anderson (1968) further extended the analysis to take into account the magnetic permeability, showing, that for low frequencies, the in-phase component is independent of conductivity but proportional to the magnetic permeability of the formation.

Roy and Dhar (1970) investigated the zone of influence of a homogeneous ground on a two-coil induction system by considering relative contribution to signal by ground elements taking account of the skin effect. They found that the contributions of the concentric-loop element are distributed in space quite differently for the real and imaginary components. Also the contributions decrease in magnitude and alternate in sign as one considers zones progressively farther from the borehole. As would be expected the contributions are frequency- and conductivity-dependent with the exception of that zone nearest the borehole. This suggests that the addition of focussing coils would be effective in controlling the zone of investigation only to the extent of desensitizing the device to the very near zone (i. e. the borehole fluid). Theoretical consideration of a coplanar- (vertical plane) coil arrangement, showed that this configuration is more strongly influenced by the near zone than is the coaxial-coil system. Fuller and Wait (1973) presented numerical results which evaluate the influence of the borehole on

Table 3. 1

Comparison of IP Survey Electrode Arrays

(after Sumner, 1972)

	Advantages	Disadvantages	Survey Speed	Signal to-Noise	EM Coupling Rejection
Parallel Field Arrays Wenner	Anomalies symmetrical Synchronous detector possible Many case histories available	Requires more wire: larger field crew Poor resolution Unfavourable in capacitive coupling situations	Fair	Good	Fair
Schlumberger	Symmetrical array Synchronous detection possible Fewer men required Works well in layered earth Type curves available	Less horizontal resolution Unsuitable for horizontal profiling Capacitive coupling possible	Fair	Fair	Fair
Gradient	Map interpretation easier Less masking by conductive overburden Penetration good; safer Communications easier Can use two or more receivers Less topographic effect Data easily contoured in plan Useful where difficulty in making good current contacts	Poor resolution with depth Poor in low resistivity areas Geometric factor varies complexly	Good	Fair	Poor
Potential-About-a-Point					
Three-Array	Good reconnaissance array Fairly good resolution	Asymmetrical More wire needed	Fair	Good	Good
Pole-Dipole, Collinear	Good resolution Good subsurface coverage	Asymmetrical Asymmetrical	Fair	Fair	Fair
Perpendicular Three-Array, Pole-Dipole, Pole-Pole	Virtually eliminates EM coupling	More wire needed	Fair to Poor	Fair	Very Good
Pole-Pole (Two-Array)	Smaller crew needed Less wire needed than for some arrays Good penetration in nonconductive overburden	Susceptible to masking by conductive over-burden	Good	Fair	Poor
PDR (Potential Drop Ratio)	Sensitive to lateral variations "Common mode" noise rejection	Complex interpretation	Fair	Good	Fair
Dipole Field Array					
Dipole-Dipole Collinear	Symmetrical, good resolution Good penetration Less survey wire needed	Slow unless equipment is portable Resistivity topographic effects Interpretation somewhat involved	Fair	Poor	Fair
Dipole-Dipole, Parallel	Special use for EM coupling interpretation	Not used for routine surveying	Poor	Poor	Fair
Down-the-Hole Arrays					
Azimuthal Array (One Potential Electrode Down the Hole)	Fair for exploration purposes Useful in finding the best search direction	Interpretation complex Negative anomalies Strong geometric effects Mainly measures changes in resistivity	Fair	Good	Good
Radial Array (One Current Electrode Down the Hole, mise-à-la-masse)	Good for exploration purposes Useful in finding the best search direction Hole need not stay open	Interpretation complex Negative anomalies Not good for obtaining rock properties	Fair	Good	Good
In-Hole Arrays (More than One Electrode in the Hole)	Good for obtaining rock properties Good for assaying Interpretation simple	Current densities may be too large Possible capacitive coupling problems Not designed for exploration purposes Special equipment, expensive	Good	Fair	Good

an induction logger and take into account propagation effects which become significant at higher frequencies. They concluded that in order for induction logging to have practical value for probing at high frequencies, the hole must be small enough that waveguide modes cannot propagate in it. This condition is met if the hole circumference is much less than a wavelength in the hole fluid. It is, of course, preferable if the hole is filled with a resistive fluid rather than a conductive one.

Belluigi (1953) has described theoretical outlines for the application of the time-domain (Matranslog) and the frequency-domain (Phase log) electromagnetic methods to borehole surveying (induction logging).

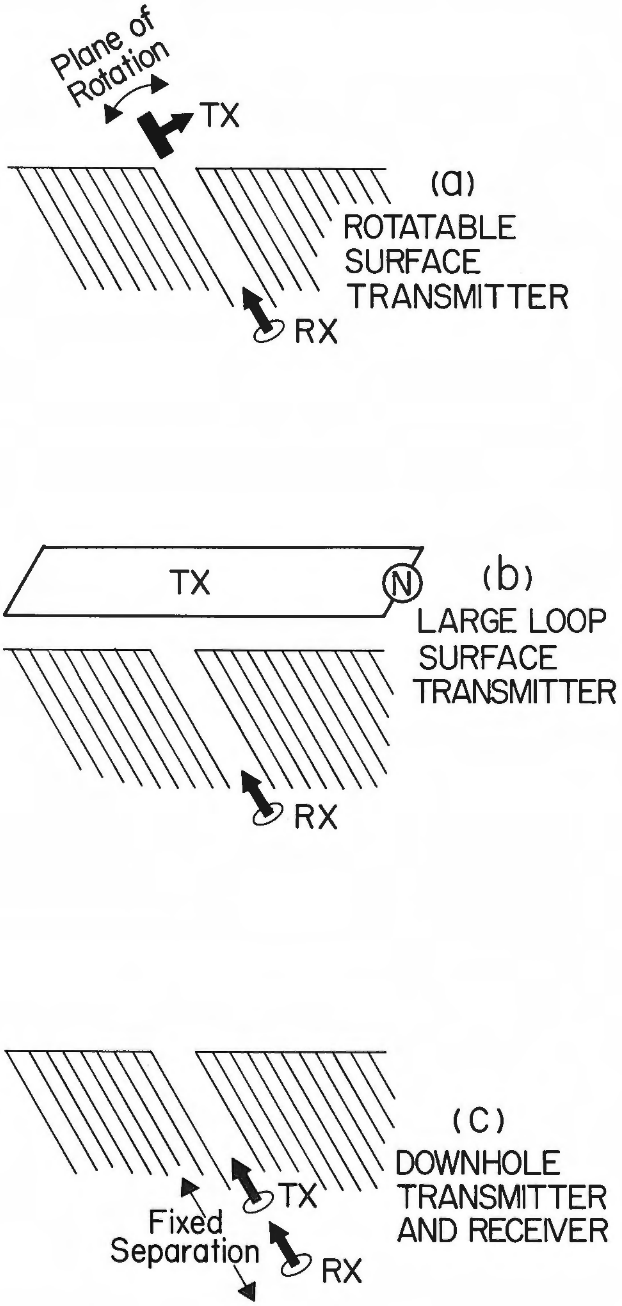


Figure 3. 2: Coil configurations used in EM surveying of boreholes.

The Telelog method has been described by Gabillard *et al.* (1971) and Bassiouni *et al.* (1972) as an electromagnetic borehole method capable of detecting resistive zones at great distances. In this method a low-frequency (12. 5 Hz or 3125 Hz) alternating field is generated by a transmitter, conductively coupled to the ground by means of surface current electrodes located on lines extending radially outward from the borehole. The vertical component of the electric field is detected at various depths in the hole. Theoretical calculations and analog tank model measurements were performed to determine apparent-resistivity profiles. The theoretical analysis was based on DC current flow and therefore did not take into account induction effects. Even with this approximation of the phenomenon the authors felt that a useful understanding was obtained. An empirical relationship was found between the near edge of a resistive zone at depth and position of a minimum in the apparent-resistivity profile. The method has been successfully applied in spotting resistive zones at great distances and locating the edge of a gas field from a development well.

Figure 3. 2 illustrates three different types of systems for the detection of conductive mineralization by electromagnetic surveying of boreholes. One of these is the subject of a paper by Ward and Harvey (1954). A unique tilt-angle method of downhole surveying was described in which the configuration is minimum coupled. The plane of the transmitting coil contains the borehole (i. e. the transmitting dipole is at right angles to the hole) and the receiver is in the borehole and coaxial with it (*see* Fig. 3. 2a). In the absence of conductive material no voltage is induced in the receiver. Any secondary-field component generated by anomalous conductive zones and detected at the receiver is nulled out by tilting a second transmitter (the vernier) whose axis of rotation is also contained in the plane of the main transmitter. The degree of tilt of the vernier is dependent on the in-phase component of the secondary field. Any residual voltage not cancelled out in the receiver is proportional to the quadrature component. It was found that the bottom of the vernier always points toward the conductor when the receiver is above the conductor and away from it when the receiver is below the conductor. A scale-model experiment with a conducting sphere verified this result and showed that the 'crossover' occurs when the receiver is opposite the centre of the sphere. The amount of tilt also depends on proximity, size and shape of the orebody. Azimuthal information about the location of the orebody may be obtained by repeating the process with the plane of the main transmitter rotated about the borehole axis until it is at right angles to the first position. For convenience in surveying inclined boreholes, one of these positions should be in the vertical plane. The method was found to be successful in accurately locating a sulphide zone from surveying two holes near the body. The range of detection of the method was estimated to be 400 feet at depths of up to 3500 feet.

The vertical-loop EM method described by Salt (1966) is almost identical except that only one transmitter is employed. This transmitter is allowed to rotate about an axis perpendicular to the borehole. The tilt-angle measurements are equivalent to those of Ward and Harvey (1954) provided that the angle is not great enough to appreciably alter the coupling between transmitter and orebody. Salt (1966) was able to detect a conducting mass and assign it to a particular quadrant. Tests in another hole did not yield any reliable directional information.

Another type of transmitter used in borehole surveying is the large, Turam-type loop laid on the surface at or near the collar (Fig. 3.2b). Noakes (1951) performed scale model experiments and field trials using a large single-frequency, surface transmitter and two different downhole receivers both of which measured the magnetic component parallel to the hole. One was a single-coil field-strength meter, the other a two-detector differential configuration. Model work with the transmitter centred about the collar of a vertical hole showed that the field strength reading produces a single peak opposite a flat lying conducting sheet. The differential measurement produces a crossover-type profile. The differential reading vastly improves detection range for horizontal sheets, rectangular blocks, and spheres and also offers better resolution of multiple conductors. Thin conducting sheets give the largest anomaly when flat lying and no anomaly at all when dipping at 90° and lying close to the hole. Azimuth experiments with a smaller loop lying in each quadrant showed that a conducting sphere gives a much larger anomaly when situated directly under the transmitter.

Field tests were performed with a loop approximately 1400 feet square transmitting at 1200 Hz at two test sites in Quebec. At the MacDonald Mines property the hole which was surveyed intersected massive pyrite mineralization and the downhole detector was therefore surrounded by high conductivity material. The only anomaly was due to a non-conductive lamprophyre dyke which had been intersected by the hole. At the Waite Amulet property a number of anomalies were obtained. However all of these were attributed to small occurrences of sulphide mineralization at or near the drillhole. The drillhole EM surveys showed no evidence of larger conductive zones lying away from the hole.

Salt (1966) also tested a horizontal-loop EM method. A large surface transmitting loop was laid just to one side of the hole. In-phase and quadrature measurements were made in a downhole receiver coaxial with the borehole. Better response can be observed when the transmitter lies on the same side of the hole as the conductive zone, so that it should be possible to determine direction to the conductor by employing the transmitter in several positions. Field results seemed to indicate that a rough estimate could be made.

A third type of coil configuration employed in borehole-EM surveys is the two-coil fixed-separation coaxial method with both transmitter and receiver in the hole (Fig. 3.2c). Elliot (1961, 1966) has described such a system which operates at a frequency of 1230 Hz. It measures the in-phase and quadrature-phase components of the secondary fields with a sensitivity of 100 ppm in EX holes (diameter 1.5 in.) to depths as great as 2000 feet. Each of the components is measured separately using multi-method circuitry. A number of field examples presented in the paper demonstrate that the system is useful in determining whether or not an intersection is due only to localized sulphides. Detection range for sulphides lying away from the hole was estimated to be as large as 200 feet from the hole for economically interesting sulphide bodies.

Smith and Hallof (1971, abstract only) has reported the development of a similar system for surveying NX boreholes (diameter 3 in.) to a maximum depth of 8000 feet. This system measures in-phase and quadrature components of the secondary field at frequencies of 200 Hz and 1200 Hz and with five coil separations ranging from 100 to 500 feet.

Interpretation of the fixed-separation coaxial EM method is greatly aided by the use of scale-model results. An estimate of the magnitude of the response to be expected from sheet-like bodies perpendicular to the drillhole can be made from the phasor diagram published by Brant *et al.* (1966) for the coaxial, helicopter-borne EM system flying over a vertical dyke. It can be seen from these curves that, for a system capable of measuring a 1 per cent anomaly, the maximum range of detection is about one-half of the coil separation. Detection range would, of course, be improved if the sheet lay parallel to the hole. A suite of scale model profiles has been collected by Drinkrow (1974, 1975) for planar, half-plane, tabular and disc-shaped orebodies which were either intersected or missed by the drillhole. While magnitude only (no phase information) was recorded, the type curves show highly recognizable features characteristic of probe-to-orebody geometry. Visual interpretation of body size, dip and conductivity should be possible with the aid of these curves.

The VLF method has been applied in boreholes by Lesnisse *et al.* (1974). The system employs a magnetic component reference on surface and a moving magnetic component sensor in the borehole and measures phase difference and amplitude ratio between the two. It has been successfully tested on mining problems using two transmitting stations at right angles to each other.

SUMMARY AND CONCLUSIONS

It is apparent from the published literature that a variety of techniques have already been investigated and that these techniques have been applied successfully in certain instances. For example, the results of an experiment which integrated several methods (Dolan, 1969, abstract only) will be mentioned briefly here. Successful results were obtained in downhole electrical prospecting for large low-grade copper deposits. The downhole methods used were: DC mise-à-la masse, DC resistivity, time-domain IP, spontaneous polarization, and time-domain EM. The surveys detected and located a deposit at a depth of 1900 feet which consisted of about 600 feet of greater than one per cent copper.

Overall, the techniques can be grouped into two categories. The first group of techniques are simply downhole adaptations of surface methods and are applied in the same in line manner as is usual for a surface profile. The only difference in procedure is that the profile is into the earth. In this configuration all system elements are confined to the borehole and the entire system has cylindrical symmetry. This type of survey is useful for detection purposes but does not give any information about the direction to the anomalous zone. The zone of exploration is somewhat less than the array spacing.

Directional information is available only if some asymmetry is introduced into the configuration. This is usually accomplished by placing one or more of the system elements on the surface in a location away from the drill collar. These methods form the second group. For example, the EM transmitter may be a large loop laid on the ground with the borehole axis outside of it, or the IP current electrodes may be deployed on the surface in orthogonal pairs. These systems have quite often been successful in estimating the azimuth of an orebody away from the borehole. An increased radius of exploration is more practically achieved for this type of method.

Further discussion of the relative merits of the two classes of systems should include the influence of surface interference and effects due to conductive stringers intersected by the hole. Wagg and Quinn (1972) indicated that an EM system employing a surface transmitter is extremely vulnerable to interference from localized conductors (usually conductive overburden) near the transmitter and that fixed-separation EM systems are less susceptible. Furthermore they point out that interpretation procedures for the fixed-separation system can make better use of parametric scale-modelling results. Effects due to unknown deviations of the borehole are also minimized.

It seems that masking of larger, more distant orebodies by small stringers intersected by the hole is less likely with a surface transmitter since a more uniform primary field is set up thus enhancing the secondary response of the larger body. However neither approach enjoys a clear-cut advantage.

Ease of survey operations is also a factor. For example Wagg and Quinn (1972) are of the opinion that IP drillhole work is more complicated than surface work both logistically and from an interpretive point of view. Fountain (1969) claims that EM drillhole surveys are generally more reliable and present fewer problems than drillhole IP surveys especially at great depths. This, of course, should not be the deciding factor since some orebodies will respond to one method and not to the other.

Salt (1966) also tested several methods on the Lake Dufault Mines property in Dufresnoy Township, Quebec. Details of these surveys (EM, IP and resistivity) have already been discussed. He suggested that it is probably easier to determine effective range of a particular technique using model experiments rather than using real orebodies. His chief conclusion was that it would be advisable to use each of the three basic techniques (EM, IP and resistivity) as the results of each survey should complement one another.

The literature survey has revealed that borehole electrical methods can significantly extend the sampling volume of a drillhole and be helpful in detecting unknown ore zones, outlining known ones and completing systematic investigation of a block of ground. It is obvious that there are methods which will work in particular areas. Further evaluation of the effects of the various system parameters outlined here can be properly conducted only by field testing those systems currently available. It is essential that the tests with each technique be performed systematically in a variety of known geological environments. Such a program, initiated in 1974, has been undertaken on a cooperative basis by the Geological Survey of Canada and several members of the Canadian mining industry (Dyck, 1975).

Acknowledgments

The author wishes to express his appreciation to Mr. L. S. Collett who contributed a large part of the bibliography and many of the references and to Dr. A. K. Sinha who critically read the manuscript.

REFERENCES

NOTE: Topics of discussion in each of the references is indicated by the numbers which follow the reference according to these headings:

1. Resistivity and/or mise-à-la-masse
2. Spontaneous polarization
3. Induced polarization
4. Electromagnetic induction

Alfano, Luigi
1962: Geoelectrical prospecting with underground electrodes; Geophys. Prospect., v. 10, p. 290-303. (1)

Anderson, W. L.
1968: Theory of borehole magnetic susceptibility measurements with coil pairs; Geophysics, v. 33, p. 962-971. (4)

Bacon, L. O.
1965: Induced-polarization logging in the search for native copper; Geophysics, v. 30, p. 246-256. (3)

Bassiouni, Z. A. F., Gabillard, R. L. A., Desbrandes, R., and de Gelis, E. F.
1972: A new application of Telelog: Locating oil or gas field limits; Trans. SPWLA 13th Ann. Symp. (4)

Becker, A. and Telford, W. M.
1965: Spontaneous polarization studies; Geophys. Prospect., v. 13, no. 2, p. 173-188. (2)

Belluigi, Arnaldo
1953: Theoretical outlines of new methods of borehole prospecting by physical methods: the Matranslog and the Phaselog; Geofisica Pura Applicata, v. 25, p. 29-36. (4)

Bølviken, B., Logn, Ø., Breen, A., and Uddu, O.
1973: Instrument for *in situ* measurements of Eh, pH and self-potentials in diamond drill holes; Geochemical Exploration 1972, M. J. J. Jones (Editor), Proc. Symp. Geochem. Expl. 4th, Lond., 1972. Inst. Min. Met., London, p. 415-420 (2)

Bower, E. J.
1968: Resistivity and self-potential logging studies in sulfide zones; unpubl. M. Eng. thesis, McGill Univ. (1, 2)

Brant, A. A., Dolan, W. M., and Elliot, C. L.
1966: Coplanar and coaxial EM tests in Bathurst area, New Brunswick, Canada, 1956; Min. Geophys., Soc. Exp. Geophys., v. 1, p. 130-141. (4)

Brant, A. A. and the Newmont Exploration Staff
1966: Examples of induced polarization field results in the time domain; Min. Geophys., Soc. Exp. Geophys., v. 1, p. 289-305. (1, 3)

Buckner, G. O.
1954: Sub-surface electrical measurements about two plane interfaces; Geophysics, v. 19, p. 297-309. (1)

Clark, A. R. and Salt, D. J.
1951: Earth resistivities near a diamond drill hole; Geophysics, v. 16, p. 659-665. (1)

Clark, A. R.
1956: The determination of the long dimension of conducting orebodies; Geophysics, v. 21, p. 470-478. (1)

Dolan, W. M.
1969: Downhole electrical prospecting for large low-grade copper occurrences; A successful application; Abstract (39th Annual SEG Meeting, Calgary, Alberta); Geophysics, v. 34, p. 1015. (1, 2, 3, 4)

Doll, H. G.
1949: Introduction to induction logging and application to logging of wells drilled with oil base mud; J. Pet. Tech., v. 1, no. 6, p. 148-162. (4)

Drinkrow, R. L.
1974: Modelling results for down-hole EM; Abstract *in* Geoexploration, v. 12, p. 228. (4)

Drinkrow, R. L. (cont.)
1975: Scale model studies of a down-hole EM probe; Mineral Research Laboratories, CSIRO, Investigation Report 108. (4)

Duesterhoeft , W. C. Jr.
1961: Propagation effects in induction logging; Geophysics, v. 26, no. 2, p. 192-204. (4)

Duesterhoeft, W. C. Jr., Hartline, R. E., and Thomsen, H. S.
1961: The effect of coil design on the performance of the induction log; J. Pet. Tech., v. 13, p. 1137-1148. (4)

Duesterhoeft, W. C. Jr. and Smith, H. W.
1962: Propagation effects on radial response in induction logging; Geophysics, v. 27, p. 463-469. (4)

Dyck, A. V.
1975: Borehole Logging (Electrical); *in* Report of Activities, Geol. Surv. Can., Paper 75-1A, p. 81-82. (1, 3, 4)

Elliot, C. L.
1961: An electromagnetic drill hole instrument for the detection of conductive sulfide bodies; presented at 31st Ann. Int. Meeting, Soc. Exp. Geophys., Denver, Colorado. (4)

1966: Electromagnetic method and apparatus of Geophysical Exploration; Canadian Patent No. 743, 665. (4)

Fountain, D. K.
1969: The uses of geophysics in mineral exploration in the Northwestern U. S. and southern B. C., McPhar Geophysics Limited, Don Mills, Ont. (1, 3, 4)

Fuller, J. A. and Wait, J. R.
1973: Mutual electromagnetic coupling of coaxial loops in a borehole; Radio Sci., v. 8, no. 5, p. 453-457. (4)

Gabillard, R. L. A., Louage, F. C. J., Bassiouni, Z. A. F., and Desbrandes, R.
1971: Telelog, an electromagnetic method of directional exploration at great distances from boreholes; Trans. SPWLA 12th Ann. Symp. (4).

Hauck III, A. M.
1970: A reconnaissance downhole induced polarization and resistivity survey method: presented at 40th Annual Soc. Exp. Geophys. Meeting, New Orleans, La. (3)

Keller, G. V.
1968: Induced polarization well logging: SPWLA 8th Ann. Logging Symp., Denver, Colo., Trans. (3)

Lesnisse, A., Millen, R., and Zahaczewski, M.
1974: New equipment for underground exploration by using the electromagnetic VLF method in drill-holes; Abstract, Annual EAEG Meeting (Madrid, Spain), Geophys. Prospect., v. 22, no. 3, p. 584.

Logn, Ø. and Bølviken, B.
1974: Self-potentials at the Joma Pyrite Deposit, Norway; Geoexploration, 12, p. 11-28. (2)

Mathisrud, G. C. and Sumner, J. S.
1967: Underground I. P. surveying at Homestead Mine; Min. Cong. J., v. 53, no. 3, p. 66-69. (3)

McMurry, H. V. and Hoagland, A. D.
1956: Three dimensional applied potential studies at Austinville, Virginia; Bull. Geol. Soc. Am., v. 67, p. 683-696. (1)

Merkel, R. H. and Snyder, D. D.
1970: The effect of secondary resistivity and polarization anomalous zones in well logging; Abstract (40th Annual Soc. Exp. Geophys., New Orleans, La.) Geophysics., v. 35, p. 1165. (1, 3)

Moran, J. H. and Kunz, K. S.
1962: Basic theory of induction logging and application to study of two-coil sondes; Geophysics, v. 27, p. 829-858. (4)

Morrison, B. C.
1971: Electrical potential method used at a single hole to indicate direction to better mineralization; Trans. AIME, v. 250, p. 337-340. (1)

Nabighian, M. N. and Davidson, M. J.
1969: The Electromagnetic Pulse (EMP) Method-Theory and Interpretation; Abstract (39th Annual Soc. Exp. Geophys. Meeting, Calgary Alberta) Geophysics, v. 34, p. 1017. (4)

Noakes, J.
1951: An electromagnetic method of geophysical prospecting for application to drill holes; unpubl. Ph. D. thesis, Univ. Toronto. (4)

Parasnis, D. S.
1967: Three dimensional electric mise-à-la-masse survey of an irregular lead-zinc-copper deposit in Central Sweden; Geophys. Prospect., v. 15, p. 407. (1)

1974: Some present-day problems and possibilities in mining geophysics; Geoexploration, v. 12, p. 97-120. (1, 2)

Pelton, W. H. and Hallof, P. G.
1971: The applied potential method in the search for massive sulphides at York Harbour, Newfoundland; Presented at the AIME Annual Meeting, New York, N. Y., Reprint, McPhar Geophysics Ltd., Toronto, Canada. (1)

Roy, A. and Dhar, R. L.
1970: Relative contribution to signal by ground elements in two-coil induction logging system; Geophys. Prospect., v. 18, p. 389-404. (4)

1971: Radius of investigation in DC resistivity well logging; Geophysics, v. 36, p. 754-760. (1)

Salt, D. J.
1966: Tests of drill hole methods of geophysical prospecting on the property of Lake Dufault Mines Ltd., Dufresnoy Twp., Quebec; Min. Geophys. Soc. Exp. Geophys., v. 1, p. 206-226. (1, 3, 4)

Schillinger, A. W.
1964: Calumet successfully uses I. P. probe underground to boost ore discoveries; Min. Eng., Nov., p. 83-88. (3)

Seigel, H. O.
1952: Ore body size determination in electrical Prospecting; Geophysics, v. 17, p. 907-914. (1).

Smith, R. J. and Hallof, P. G.
1971: A new deep drill-hole electromagnetic system; Abstract, 41st Ann. Soc. Exp. Geophys. Meeting (Houston, Texas), Geophysics, v. 36, p. 1280. (4)

Snyder, D. D. and Merkel, R. M.
1973: Analytic models for the interpretation of electrical surveys using buried current electrodes; Geophysics, v. 38, p. 513-529. (1, 3)

Sumner, J. S.
1965: Interpretation of underground resistivity and induced polarization results from analog modelling; Abstract (35th Annual Soc. Exp. Geophys. Meeting, Dallas, Texas), Geophysics, v. 30, p. 1246. (1, 3)

1972: Comparison of electrode arrays in IP surveying; Trans. AIME, v. 252, p. 447-452. (3)

Wagg, D. M. and Seigel, H. O.
1963: Induced polarization in drill holes; Can. Min. J., v. 84, p. 54-59. (1, 3)

Wagg, D. M. and Quinn, F.
1972: Drill hole geophysics; Geoterrex Ltd., Ottawa. (1, 3, 4)

Wait, J. R.
1953: Transient coupling in grounded circuits; Geophysics, v. 18, p. 138-141. (1, 3)

Ward, S. H. and Harvey, H. A.
1954: Electromagnetic surveying of diamond drill holes; Can. Min. Manual, p. 19-30; Published by National Business Publications, Gardenvale, Que. (4)

Zablocki, G. J.
1966a: Some applications of geophysical logging methods in mineral exploration drill holes; Trans. 7th Int. Well Log. Symp., SPWLA, May 8-11. (1, 3)

1966b: Electric properties of some iron formations and adjacent rocks in the Lake Superior region; Min. Geophys., Soc. Exp. Geophys., v. 1, p. 465-492.

BIBLIOGRAPHY

NOTE: These papers are grouped by the subject for which they make useful additional reading and are listed alphabetically under the following headings:

1. Electrical Resistivity Methods
2. Spontaneous Polarization Methods
3. Electromagnetic Methods
4. General

1. Electrical Resistivity Methods

Al'pin, L. M.
1964: On a solution of the fundamental problem of resistivity logging; Bull. (Izv) Acad. Sci. USSR, Geophys. Ser., no. 2, p. 131-2.

Arps, Jan L.
1964: An introduction to continuous electric logging while drilling; Gulf Coast Assoc. Geol. Soc., Trans., v. 14, p. 133-136.

Atkins, E. R.
1961: Techniques of Electric Log Interpretation; J. Pet. Tech., v. XIII, p. 118-123.

Blakeman, E. R.
1962: A method of analyzing electrical logs recorded on a logarithmic scale; J. Pet. Tech., v. 14, p. 844-850.

Bliamptis, E. E.
1972: A new method for determining the physical parameters of large soil and rock samples *in situ;* Air Force Cambridge Research Laboratories, United States Air Force, Environmental Research Papers, no. 425, AFCRL-TR-72-0734.

Bondarev, V. I.
1963: The field of a disc electrode located in a borehole; Bull. (Izv) Acad. Sci., USSR, Geophys. Ser., no. 3, p. 295-298.

Bowsky, M. C.
1942: The effect of mud resistivities on the intensities of electrical logs; Geophysics, v. 7, p. 82-89.

Broding, R. A. and Rummerfeld, B. F.
1955: Simultaneous gamma ray and resistance logging as applied to Uranium exploration; Geophysics, v. 20, p. 841-859.

Brown, D. L.
1971: Techniques for quality-of-water interpretations from calibrated geophysical logs, Atlantic coastal area; Groundwater, v. 9, no. 4, p. 25-38.

Chaterji, G. C. and Sinha, S. C.
1963: Single-point electrical logging in subsurface geological correlation of unconsolidated and semi-consolidated sediments in India; India Natl. Inst. Sci. Proc., v. 29, pt. A, no. 3, p. 347-358.

Chombart, L. G.
1960: Well logs in carbonate reservoirs; Geophysics, v. 25, p. 779-853.

Colombo, U., Salimbini, G., Sironi, G., and Veneziani, I.
1959: Differential electric log; Geophys. Prospect., VII, p. 91-118.

De Witte, L., Fournier, K. P., and Tejada-Flores, H.
1957: Calculation of guard electrode response curves; Geophysics, v. 22, p. 67-74.

De Witte, L. and Gould, R. W.
1959: Potential distribution due to a cylindrical electrode mounted on an insulating probe; Geophysics, v. 24, p. 566-579.

Doll, H. G.
1951: The Laterolog: A new resistivity logging method with electrodes using an automatic focussing system; Trans. AIME, v. 192, p. 305-316.

Enslin, J. F.
1955: Some applications of Geophysical Prospecting in the Union of South Africa; Geophysics, v. 20, p. 886-913.

Foster, J. B. and Whalen, H. E.
1966: Estimation of formation pressures from electrical surveys - offshore Louisiana; J. Pet. Tech., XVIII, no. 2, p. 165-171.

Frimpter, M. H.
1969: Casing detector and self-potential logger; Ground Water, v. 7, no. 6, p. 24.

Guyod, H.
1955: Electric analogue of resistivity logging; Geophysics, v. 20, p. 615-629.

1964: Factors affecting the responses of Laterolog type logging systems (LL3 and LL7); J. Pet. Tech., v. 16, no. 2, p. 211-219.

1966: Interpretation of electric and gamma ray logs in water wells; The Well Log Analyst, Jan.-Mar.

Haines, B.M. and Emerson, D.W.
1972: Aspects of mud properties in geophysical logging of shallow water bores; Asut. Soc. Expl. Geophys., v. 3, no. 2, p. 33-52.

Hansen, H.J.
1967: The electric log: geophysics' contribution to ground water prospecting and evaluation; Maryland Geol. Surv., Info. Circ. 4.

Hitchon, B.
1964: The effect of differences in interpretation on the lithological evaluation of electric logs; Bull. Can. Pet. Geol., v. 12, no. 3, p. 754-769.

Hobson, G.D. and Findlay, D.C.
1967: Down-hole Geophysical Studies on the Muskox Intrusion, Coppermine River area, District of Mackenzie; Geol. Surv. Can., Paper 66-44, 37 p. (Can. contribution to the International Upper Mantle Project no. 135).

Horn, M.K. and Slack, H.A.
1962: Comlog - A comprehensive Computer System for Log Interpretation; J. Pet. Tech., v. 14, p. 1109-1114.

Jeffries, F.
1964: Wireline logs have untapped potential; Can. Pet. Eng., v. 5, no. 9, p. 36-40.

Jones, P.H. and Buford, T.B.
1951: Electric logging applied to ground-water exploration; Geophysics., v. 16, no. 1, p. 115-139.

Keller, G.V.
1964: Compilation of electrical properties from electrical well logs; Color. Sch. Mines, Q., v. 59, no. 4, p. 91-110.

1971: Electrical characteristics of the earth's crust; *in* Electromagnetic probing in geophysics, J.R. Wait, ed.; The Golem Press, Boulder, Colorado, p. 13-76.

Keller, G.C. and Frischknecht, F.C.
1966: Chapter II. Electrical Well Logging; *in* Electrical Methods in Geophysical Prospecting, Pergamon Press, p. 61-89.

Korzhev, A.A., Dunchenko, I.A., and Morgunov, V.D.
1965: On the use of three-electrode lateral logging on the coal deposits of the Donets Basin; Razved. Geofizika, no. 6, p. 84-88.

Kovalenko, P.P.
1965: Determination of the specific resistivity of drilling mud from three-layer laterology sounding curves; Razved. Geofizika, no. 6, p. 80-83.

Krol, G. and Gordon-Welsh, J.F.
1962: A contact electrode system for electrical borehole logging; Ann. Geol. Surv. S. Afr., v. 1, p. 235-37.

Kunz, K.S. and Moran, J.H.
1958: Some effects of formation anistropy on resistivity measurements in boreholes; Geophysics, v. 23, p. 770-794.

Lao, C., Peterson, F.L., and Cox, D.C.
1969: Application of electric well logging and other well logging methods in Hawaii; Water Resources Research Center, Univ. Hawaii. Tech. Rep. No. 21, 108 p.

Martin, M., Murray, G.H., and Gillingham, W.J.
1938: Determination of the potential productivity of oil-bearing formations by resistivity measurements; Geophysics, v. 3, p. 258-272.

McKelvey, J.G. Jr., Southwick, P.F., Spiegler, K.S., and Wyllie, M.R.J.
1955: The application of a three-element model to the S.P. and resistivity phenomena evinced by dirty sands; Geophysics, v. 20, p. 913-931.

Owen, J.E. and Greer, W.J.
1951: The Guard Electrode Logging System; Trans. AIME, v. 192, p. 347-356.

Patten, E.P. Jr. and Bennett, G.D.
1963: Application of electrical and radioactive well logging to ground-water hydrology; U.S. Geological Survey Water-Supply Paper 1544-D, Pennsylvania Ground Water Report W 19, Reprinted 1967.

Perkins, F.M., Osoba, J.S., and Ribe, K.H.
1956: Resistivity of sandstones as related to the geometry of their interstitial water; Geophysics, v. 21, p. 1071-1086.

Perkov, N.A.
1965: On interpretation of laterolog results obtained by means of laterolog instrument ABK-3 (Laterolog-3); Oil Nat. Gas Comm. (India), Bull., v. 2, no. 1, p. 43-48.

Peterson, F.L. and Lao, C.
1970: Electric well logging of Hawaiian basaltic aquifers; Ground Water, v. 8, no. 2, p. 11.

Schlumberger, C., Schlumberger, M., and Leonardon, E.G.
1934: A new contribution to subsurface studies by means of electrical measurements in drill holes; Trans. AIME, v. 110, p. 237.

Smith, H.D. and Blum, H.A.
1954: Microlaterolog versus Microlog for formation factor calculations; Geophysics, v. 19, p. 310-320.

Southwick, S.H. and Adair III, T.W.
1964: Digital computer programming for automatic analysis of well logs; J. Pet. Tech., v. 26, p. 35-40.

Tixier, M.P.
1958: Symposium on Subsurface Geology in Petroleum Exploration; edited by J.D. Haun and L.W. LeRoy, Colo. Sch. Mines., Chap. 15, Electric Logging, p. 267-328.

Vonhof, J.A.
1966: Water quality determination from spontaneous-potential electric log curves; J. Hydrology, v. 4, p. 341-347.

Wyllie, M.R.J.
1957: The fundamentals of electric log interpretation; Academic Press, 2nd Edition.

1960: Log interpretation in sandstone reservoirs; Geophysics, v. 25, p. 748-778.

Zhuraulev, V.P., Popov, V.K., and Ternovskaya, L.A.
1965: Determination of the resistivity of layers of average thickness; Razved. Geofizika, no. 4, p. 120-128. Geop. Abs. 231-080.

Zhuraulev, V.P., Vasil'yev, G.P. and Novikov, Ye, N.
1965: On the choice of optimum three-electrode sonde lateral logging; Razved. Geofizika, no. 7, p. 51-72.

Zublin, C.W.
1964: Why electric log water wells?; Ground Water, v. 2, no. 2, p. 32-34.

2. Spontaneous Polarization Methods

Dickey, P.A.
1944: Natural potentials in sedimentary rocks; Trans. AIME, v. 155, p. 39.

Doll, H.G.
1949: The SP Log: Theoretical analysis and principles of interpretation; Trans. AIME, v. 179, p. 146.

Doll, H.G. (cont.)
1955: The invasion process in high permeability sands; Pet. Eng., Jan.

Gondouin, M., Tixier, M.P., and Simard, G.L.
1957: An experimental study on the influence of the chemical composition of electrolytes on the SP curve; Trans. AIME, v. 210, p. 58.

Gondouin, M. and Scala, C.
1958: Streaming potential and the SP Log; Trans. AIME, v. 213, p. 170.

Guyod, H.
1964: An investigation of the factors affecting the SP in soft formations; 5th Ann. SPWLA Logging Symp., Midland, Texas, Trans., p. A1-A18.

Hill, H.J. and Anderson, A.E.
1959: Streaming potential phenomena in SP log interpretation; Pet. Trans., v. 216, p. 203.

Hill, H.J. and Milburn, J.D.
1956: Effect of clay and water salinity on electrochemical behaviour of reservoir rocks; Trans. AIME., v. 207, p. 65.

Mounce, W.D. and Rust, W.W.
1944: Natural potentials in well logging; Trans. AIME, v. 155, p. 49.

Salisch, H.A.
1954: An experimental investigation of factors affecting the electrokinetic component of the SP curve; unpubl. M.Sc. thesis, Univ. Okla.

Schenck, K.D.
1955: An investigation of the streaming potential developed in formations of low permeability; unpubl. M.Sc. thesis, Univ. Okla.

Segesman, F.
1962: New SP correction charts; Geophys., v. 27, p. 815-828.

Segesman, F. and Tixier, M.P.
1959: Some effects of invasion on the SP curve; Trans. AIME, v. 216, p. 138-146.

Vonhof, J.A.
1966: Water quality determination from spontaneous-potential electric log curves; J. Hydrology, v. IV, no. 4, p. 341.

Wyllie, M.R.J.
1949: A quantitative analysis of the electrochemical component of the SP curve; Trans. AIME, v. 186, p. 17.

1951: An investigation of the electrokinetic component of the self-potential curve; Trans. AIME, v. 192, p. 1.

3. Electromagnetic Methods

Andreeva, M.M. and Kaufman, A.A.
1965: Method of calculating multicoil focussing probes used in induction logging; Izv. Acad. Sci. USSR, Physics of the Solid Earth, no. 9, p. 643-646.

Dumanoir, J.L., Tixier, M.P., and Martin, M.
1957: Interpretation of the induction-electrical log in fresh mud; J. Pet. Tech., v. 9, p. 202-217.

Edwards, J.M. and Stroud, S.G.
1964: Field results of the electromagnetic casing inspection log; J. Pet. Tech., v. XVI, no. 4, p. 377-382.

Gawin, A.
1972: Electromagnetic well logging in anisotropic rock medium; Geol. Trans. of the Polish Acad., Warsaw, p. 93. (Russian and English abstracts in Econ. Geol., v. 68, no. 2, p. 289, 1973.)

Holser, W.T., Brown, R.J.S., Roberts, F.A., Fredriksson, O.A., and Unterberger, R.R.
1972: Radar logging of a salt dune; Geophysics, v. 37, p. 889-906.

Kaufman, A.A. and Sochelnikov, V.V.
1964: Contribution to the theory of induction logging in strata of limited thickness; Bull. (Izv) Acad. Sci., USSR, Geoph. Ser., no. 7, p. 610-616.

Marsh, C.R. and Parizek, R.R.
1968: Induction-tuned method to determine casing lengths in hydrogeologic investigations; Ground Water, v. 6, no. 6, p. 11-17.

Nikitina, V.N.
1960: The general solution of an axially symmetrical problem in induction logging theory; Izvest. Geophys. Ser., p. 607-616.

Ponomarchuk, T.F.
1965: Use of the induction method for determining the productivity of low-resistivity reservoirs of the Kuma Plain; Razved. Geofizika, no. 5, p. 116-124.

Tixier, M.P., Alger, R.P., and Tanguy, D.R.
1960: New developments in induction and sonic logging; J. Pet. Tech., v. XII, no. 5, p. 79-87.

Vaniyan, L.L. and Thiep, L.K.
1969: On the discrepancy in the results of induction logs and electric lateral well logs; Izv. Acad. Sci., USSR, Phy. of the Solid Earth, no. 8.

Veksler, V.I. and Plyusnin, M.I.
1957: Low frequency electromagnetic investigations of drill hole surroundings; Akad. Nauk. USSR Izv. Ser. Geofiz., no. 7, p. 834-9.

Zenor, H.M. and Oshry, H.I.
1962: Modification of the induction log geometric factor due to propagation; Third annual logging symposium, May 17-18, Soc. Prof. Well Log Analysts.

Zverev, G.N., Kresov, V.A., and Batanin, V.A.
1965: A magnetic dipole in a three-layered conducting medium; Izv. Acad. Sci. USSR, Physics of the Solid Earth, no. 9, p. 618-623.

4. General

Anderson, W.B.
1973: Potential uses for borehole logs in mineral exploration; Can. Min. Metall. Bull., v. 67, no. 743, p. 164-168.

Anpilogov, A.P. and Orlov, L.I.
1964: Interpretation of geophysical logging information according to data of preserved cores; Pet. Geol., v. 5, no. 6, p. 324-8.

Baltosser, R.W. and Lawrence, M.W.
1970: Application of well logging techniques in metallic mineral mining; Geophysics, v. 35, no. 1, p. 143-152.

Branisa, F.
1974: Filtering of well-log curves; Geophysics, v. 39, p. 545-549.

Broding, R.A.
1958: Symposium on subsurface geology in petroleum exploration; editors J.D. Haun and L.W. LeRoy, Colo. Sch. Mines., Chap. 22, Magnetic Well Logging, p. 427-436.

Callaghan, W.H. and McMurry, H.V.
1970: Geophysical exploration of Mississippi Valley - Appalachian type strata-bound zinc-lead deposits; Mining and Groundwater Geophysics, Geol. Surv. Can., Econ. Geol. Ser., no. 26, p. 350-360.

Crain, E.R. and Anderson, W.B.
1966: Quantitative log evaluation of the Prairie Evaporite Formation in Saskatchewan; J. Can. Pet. Tech., v. 5, p. 145-152.

Crosby, I.W. III and Anderson, J.V.
1971: Some applications of geophysical well logging to basalt hydrogeology; Ground Water, v. 9, no. 5, p. 12-20.

Dyck, J. H., Keys, W. S. and Meneley, W. A.
1972: Application of geophysical logging to ground water studies in southeastern Saskatchewan; Can. J. Earth Sci., v. 9, no. 1, p. 78-94.

Doll, H. G., Tixier, M. P., and Segesman, F.
1964: Recent developments in well logging in U. S. A.; World Petroleum Congress, Proc., sec. 1, p. 887-905.

Evans, H. B.
1970: Status and trends in logging; Geophysics, v. 35, no. 1, p. 93-112.

Gaskell, T. F. and Threadgold, P.
1960: Borehole Surveying: *in* Methods and techniques in Geophysics; Interscience Publishers, p. 62-103.

Geophysics
1960: Logging issue; G. E. Archie, ed., v. 25, no. 4.

George, C. F. Jr., Smith, H. W., and Bostic, F. X. Jr.
1964: Application of inverse filters to induction log analysis: Geophysics, v. 29, no. 1, p. 93-104. (5).

Ivanhoe, L. F.
1965: Short note-conversion of electric logs for seismic time sections; Geophysics, v. 30, p. 1141-1143.

Johnson, H. M.
1962: A history of well logging; Geophysics, v. 27, p. 507-527.

Kelley, D. R.
1969: A summary of major geophysical logging methods; Penna. Geol. Surv., Bull. M 61, 82 p.

Keys, W. S.
1967: Well logging in ground-water hydrology; Presented at Eighth Annual Logging Symposium, Society of Professional Well Log Analysis, Denver, Colo.

Keys, W. S. and MacCary, L. M.
1971: Application of borehole geophysics to water-resources investigations; U. S. Dept. Int., Geol. Surv., Book 2, Chap. EL.

Lindseth, R. O.
1966: Application of signal theory to well-log interpretation; Transactions, SPWLA 7th Annual Logging Symposium. (5)

Lytle, R. J.
1973: Measurement of earth medium electrical characteristics: Techniques, results and applications; Lawrence Livermore Laboratory, Univ. Calif., UCRL-51479.

Moore, E. J.
Application of borehole geophysics to mining exploration; Penn. State Univ., College of Mineral Industries Contribution, p. 57-18.

*Parasnis, D. S.
1973: Mining Geophysics; 2nd Edition, Elsevier Scientific Publishing Co.

Pickett, G. R.
1970: Applications for borehole geophysics in geophysical exploration; Geophysics, v. 35, no. 1, p. 81-92.

Pirson, S. J.
1963: Handbook of well log analysis; Prentice-Hall.

1970: Geologic well log analysis; Gulf Publishing Co., Houston, Texas.

Reeves, D. R.
1971: *In-situ* analysis of coal by borehole logging techniques; Can. Min. Metall. Bull., v. 64, no. 706, p. 67-75.

Schlumberger Ltd.
1972: Log Interpretation; v. 1 and 2, Schlumberger Ltd., Houston, Texas.

Scott, J. H.
1973: Prediction of geologic and hydrologic conditions ahead of rapid excavation operations by inhole geophysical technique; U. S. Dept. Interior, Bur. Mines, Final Technical report - in-house research.

Segesman, F., Soloway, S., and Watson, M.
1962: Well logging - the exploration of subsurface geology; Proc. IRE, v. 50, p. 2227-2243.

Sherriff, R. E.
1970: Glossary of terms used in well logging; Geophysics, v. 35, p. 1116-1139.

Tarkhov, A. G.
1965: Some methods of underground geophysical prospecting; J. Indian Geophys. Un., v. 2, no. 3, p. 107-120.

Threadgold, P.
1960: Advances in well logging; Inst. Pet. Res., v. 14, no. 168, p. 389-391.

Tixier, M. P. and Alger, R. P.
1970: Log evaluation of nonmetallic mineral deposits; Geophysics, v. 35, no. 1, p. 12-142.

Volosyuk, G. K. and Safranov, N. I. (Editors)
1971: Skvazinnaya Rudnaya Geofizika, (Borehole Mining Geophysics) NEDRA, Leningrad, 535 p. (*in* Russian).

4. BOREHOLE GRAVIMETRY

A. Overton

INTRODUCTION

Gravity measurements in mine shafts and boreholes have long been recognized as the most effective means of determining average rock densities for different layers of the crust, and for the earth itself (Airy, 1856; Lorenz, 1938; Jung, 1939). Smith (1950) described in detail the potential uses of borehole gravity measurements, and gave an account of analytical procedures, accuracy requirements, and limitations of the method. Three applications of borehole gravimetry are generally recognized in the literature:

1. Density control for precise interpretation of surface gravity surveys.
2. Interpretation of seismic data.
3. Interpretation of borehole geology.

A fourth application is the estimation of formation porosity (McCulloh, 1965). The advantage of borehole gravimetry in the interpretation of surface gravity surveys is that precise Bouguer corrections are possible using borehole gravity measurements, giving rise to more precise gravity anomalies which in turn may be accurately interpreted using the density-depth function given by the measurements.

Although the literature contains many references describing the usefulness of borehole gravity measurements, development of the precise borehole gravity meter has been slow. Dolbear (1959) described problems and objectives in the design of the borehole gravity meter, and McCulloh (1965) also discussed design requirements of a practical meter. Working models have evolved into two basically different types, one using an astatized balance, and the other a vibrating string element. McCulloh *et al.* (1967) described the LaCoste and Romberg astatized spring type. Howell *et al.* (1966), Oil and Gas Journal (1966), and Goodell and Fay (1964) described vibrating string models. The greatest difference in using the two different models appears to be in the reading time with 3 to 5 minutes being required for the astatized spring models and about 20 minutes for the vibrating string models. To date borehole gravimetry has not been widely applied (Century Geophysical, 1974, pers. comm.), and at least one logging company is still in the early stages of development of their borehole gravimeter (Schlumberger, of Canada, pers. comm.). One reason for this slow development may be that the fundamental parameter, the density-depth function, given by the borehole gravimeter finds its primary use in surface gravity interpretations. Its use therefore depends upon the degree to which surface gravity surveys have been used in oil exploration, and also the degree to which substitutes may be utilized for the density-depth function as from core samples, backscattered gamma density logs or densities from acoustic logs.

The alternative density logging devices are particularly sensitive to borehole conditions such as caving, fractures and drilling fluid invasion into the borehole wall, and are also ineffective in cased boreholes. The borehole gravity meter is much less sensitive to these conditions and can be run in cased boreholes, giving bulk density estimates for very large rock volumes represented by the order of the cube of the chosen sampling interval. Smith (1950) and McCulloh (1965) point out that a detailed gravity log, which may be desired for correlations with electrical, acoustic, or scattered gamma density logs, requiring gravity determinations at six-foot intervals and density estimates as good as .05 g/cm^3, would require a gravity meter precision of .002 mgal. The lower precision of available borehole gravity meters, approximately .01 mgal, therefore precludes detailed logging. Moreover, the lengthy reading times require that the degree of detail be compromised to produce results within the allowable time for the survey.

High sensitivity borehole gravity surveys must take into account borehole conditions such as caving, variable mud cake thickness, casing shoes, and particularly drift which requires differential latitude and terrain corrections.

Specifications for two models of recent development are given in the following table (LaCoste and Romberg, Inc., 1974, pers. comm.). They are of the astatized spring type.

	Prototype (USGS)	Improved Model
Operating temperature °C	100	112
Reading accuracy mgls.	.01	.01
Reading time, minutes	3-5	3-5
Maximum diameter, inches	5.5	4.75
Gravity range, mgls.	7000	7000
Required cable (armored) conductors	13	7
Allowable hole deviation, degrees	6.5	10
Levelling accuracy, seconds	6	6
Input power required, volts	115AC & 48DC	115

By comparison published specifications for the vibrating string type of gravity meter (Goodall and Fay, 1964; Howell *et al.*, 1966; and Oil and Gas Journal, 1966) differ most notably in their reading times of about 20 minutes, and costs which are about one quarter that for the astatized spring type (Jones, 1972 quotes \$80,000 for the astatized spring type and \$18,000 for the vibrating string type).

Gravity meters of both types require large diameter boreholes. Development of smaller gravity meters will only be stimulated by demand (LaCoste and Romberg, Inc., 1974, pers. comm.).

APPLICATIONS TO MINING PROBLEMS

Bulk density estimates for volumes approximately equal to the cube of the sampling interval may be applied toward the location of orebodies which have been missed by the borehole. The mean density ρ between two sampling depths separated by h metres with a difference in gravity readings g mgal is given by:

$$\rho = 3.686 - 11.94\, g/h$$

In the absence of a directional sense to the density determination, positional information requires a pattern of determinations in an array of boreholes surrounding the orebody. The dense, massive types of orebodies lend themselves most readily to detection by borehole gravity methods. The detection sensitivity for less dense and disseminated ores decreases commensurate with the density contrast and volume of the ore compared to host rock within the measured volume, and upon the instrument sensitivity.

The accurate determination of Bouguer corrections by the borehole gravity method allows maximum utilization of precise surface gravity surveys in delineating orebodies.

Acknowledgments

The author wishes to thank Dr. P. G. Killeen for suggestions and critically reading the manuscript.

BIBLIOGRAPHY

*Airy, G. B.
1856: Account of pendulum experiments undertaken in the Harton Colliery for the purpose of determining the mean density of the earth; R. Soc. London, Phil., Trans., v. 146, no. 14 and 15, p. 297, 342 and p. 343-355.

Beyer, L. A.
1968: Recent tests of the U. S. Geological Survey La Coste and Romberg borehole gravimeter system; Presented at the 38th Ann. Int. Soc. Exp. Geophys. Meeting, Denver, Colorado, Oct. 2., 1968.

1971: Vertical gradient of gravity in vertical and near vertical boreholes; Open file report, U. S. Geol. Surv.

Cook, A. H. and H. I. S. Thirlaway
1951: A gravimeter survey in the Bristol and Somerset coalfields; Geol. Soc. London. J., v. 107, pt. 3, p. 255-286.

*Dolbear, D. W. N.
1959: Design considerations of a bore-hole gravimeter; Geophys. Prospect., v. 7, p. 196-201.

Domzalski, W.
1954: Gravity measurements in a vertical shaft; Inst. Min. Met., London, Trans., Bull. 571, v. 63, p. 429-445.

1955a: Three dimensional gravity survey; Geophys. Prospect., v. 3, p. 15-55.

1955b: Relative determination of the density of surface rocks and the mean density of the earth from vertical gravity measurements; Geophys. Prospect., v. 3, p. 212-227.

Eckhardt, E. A.
1938: Gravity difference benchmarks for gravimeter calibration and control thereof; Geophysics, v. 3, p. 160.

Evjen, H. M.
1936: The place of the vertical gradient in gravitational interpretations; Geophysics, v. 1, p. 127-137.

Farlay, D. G.
1971: Application of the downhole gravity meter for porosity determination; Libyan Assoc. Pet. Technologists, 7th Ann. Meeting, Preprint, p. 1-20.

Gilbert, R. L. G.
1949: A dynamic gravimeter of novel design; Proc. Phys. Soc. B., v. 62, p. 445-454.

1952: Gravity observations in a borehole; Nature, v. 170, p. 424-425.

*Goodell, R. R. and Fay, C. H.
1964: Borehole gravity meter and its applications; Geophysics, v. 29, p. 774-782.

Hammer, S.
1938: Investigation of the vertical gradient of gravity; Trans. Am. Geophys. U., Pt. 1, p. 72-82.

1950: Density determinations by underground gravity measurements; Geophysics, v. 15, p. 637-652.

1963a: Gravity interpretation by stripping; Geophysics, v. 28, p. 369-378.

---

*References cited.

*References cited.

Hammer, S. (cont.)
1963b: Rock densities and vertical gradient of gravity in the earth's crust; J. Geophys. Res., v. 68, p. 603-604.

1965: Density determinations by underground gravity measurements - sequel; Geophysics, v. 30, p. 1133-1134.

Hearst, J.R.
1968: Terrain corrections for borehole gravimetry; Geophysics, v. 33, p. 361-362.

*Howell, L.G., Heintz, K.O., and Barry, A.
1966: The development and use of a high-precision downhole gravity meter; Geophysics, v. 31, p. 764-772.

*Jones, B.R.
1972: The use of downhole gravity data in formation evaluation; SPWLA, 13th ann. log. symp., p. 1-13.

*Jung, H.
1939: Dichtebestimmung im anstehenden gestein durch messung der schwerebeschleunigung in verschiedenen tiefen unter tage; Zeitschr. Geophsik, v. 15, p. 56-65.

Kazinskiy, V.A.
1963: Methods of developing and ways of solving problems of subsurface gravimetry; Akad. Nauk. S.S.S.R. Izv., Sci. Geofiz, p. 748-765.

Kumagai, N., Abe, E., and Yoshimura, Y.
1960: Measurement of vertical gradient of gravity and its significance; Boll. Geophisica, v. 2, no. 8, p. 607-630.

*Lorenz, H.
1938: Bietrage zur theorie des erdaufbaus; Zeitschr. Geophysik, v. 14, p. 142-152.

Lukavchenko, P.I.
1962: Observations with gravimeters in boreholes and mine shafts; Rasvedochnaya i Promyslovaya Geofizika, no. 43, p. 52-64.

*McCulloh, T.H.
1965: A confirmation by gravity measurements of an underground density profile based on core densities; Geophysics, v. 30, p. 1108-1132.

1966: The promise of precise borehole gravimetry in petroleum exploration and production; U.S. Geol. Surv., Circ. 531, p. 1-12.

*McCulloh, T.H. (cont.)
1967: Borehole gravimetry: New developments and applications; Seventh World Petroleum Congress, Mexico City, Apr. 2-8, p. 735-744.

McCulloh, T.H., LaCoste, L.J.B., Schoellhamer, J.E., and Pampeyan, E.H.
1967: The U.S. Geological Survey - LaCoste and Romberg precise borehole gravimeter system - instrumentation and support equipment; U.S. Geol. Surv. Prof. Paper 575-D, p. D92-D100.

McCulloh, T.H., Schoellhamer, J.E., Pampeyan, E.H., and Parks, H.B.
1967: The U.S. Geological Survey - LaCoste and Romberg precise borehole Gravimeter system - test results; U.S. Geol. Surv. Prof. Paper 575-D, p. D101-D112.

McCulloh, T.H., Schoellhamer, J.E., and Kandle, J.R.
1968: Application of gravity measurements in wells to problems of reservoir evaluation; Trans. 9th Ann. Logging Symp., SPWLA, p. 01-029.

Miller, A.H. and Innes, M.J.S.
1953: Application of gravimeter observations to the determination of the mean density of the earth and rock densities in mines; Can. Dom. Obs. Publ., v. 16, no. 4, p. 3-17.

*Oil and Gas Journal
1966: ESSO licenses down-hole gravity meter; Oil Gas J., v. 64, no. 26, p. 101-102.

Rogers, G.R.
1952: Subsurface gravity measurements; Geophysics, v. 17, p. 365-377.

Secors, G.B., Meyer, H.J., and Hinze, W.J.
1963: A density determination by underground gravity measurements in Michigan; Geophysics, v. 28, p. 663-664.

*Smith, N.J.
1950: The case for gravity data from boreholes; Geophysics, v. 15, p. 605-636.

Thyssen-Bornemisza, S.
1963: The vertical gravity gradient in borehole exploration; Geophysics, v. 28, p. 1072-1073.

1964: Determination of Bouguer density in shallow holes; Geophysics, v. 29, p. 445-446.

1965a: Determination of the vertical density gradient in a borehole; Geophysics, v. 30, p. 439-440.

1965b: The anomalous free air vertical gradient in borehole exploration; Geophysics, v. 30, p. 441-443.

---

* References cited.

* References cited.

Thyssen-Bornemisza, S. and Stackler, W. F.
1956: Observing vertical gravity gradient; Geophysics v. 21, p. 771-779.

Van Melle, F. A., Fass, D. L., Kaufman, S., Postma, G. W., and Seriff, A. J.
1963: Geophysical research and progress in exploration; Geophysics, v. 38, p. 466-478.

Vaschilov, Yu. N.
1964: Allowance for the effects of the relief of the locality in gravimetric observations in underground workings and boreholes; Razvedochnaya i Promyslovaya Geofizika, v. 51, p. 71-75. Translated by J. E. Bradley.

Wyckoff, R. D.
1941: The Gulf gravimeter; Geophysics, v. 6, p. 13-33.

5. MAGNETIC DRILLHOLE MEASUREMENTS IN MINERAL EXPLORATION

P. J. Hood and A. V. Dyck

In the past determination of magnetic parameters in drillholes has been performed either by the measurement of magnetic susceptibility of the rocks surrounding the drillhole using electromagnetic induction or by measurement of the distortion of the earth's magnetic field due to susceptibility contrasts and/or remanent magnetism.

MAGNETIC SUSCEPTIBILITY MEASUREMENTS

Two types of instrument have been used for making susceptibility measurements in boreholes. The well-logging arm of the oil exploration industry has made good use of electromagnetic induction to determine electrical rock properties of intersected strata (induction logging). This induction tool employs basically a transmitting and receiving coil operating in the audio-frequency range. The quadrature component of the induced secondary field is taken as a measure of the rock conductivity. For low conductivities, the in-phase component is controlled entirely by the magnetic susceptibility of the surrounding medium. Theoretical aspects of susceptibility measurements by induction logging with two-coil instruments have been discussed by Kaufman (1966) and Anderson (1968).

In the single-coil induction tool, on the other hand, the self-inductance of the coil is measured with an impedance bridge. For example, Broding *et al.* (1952) employed a single coil induction tool in sedimentary rocks where the susceptibility logs were found to have "considerable lithological character".

Application of susceptibility logging to mineral exploration has been discussed by Zablocki (1966a, b). Using an induction logging device similar to that of Broding *et al.* (1952), Zablocki measured magnetic susceptibility in holes drilled in iron-formations. The susceptibility logs were found to be of considerable value in evaluating magnetite content. They also facilitated the selection of core samples for assay purposes in cases where the visual estimation of the grade was difficult. Furthermore the general geological conditions in a drillhole could be more quickly visualized from a susceptibility log than from a detailed core description.

Zablocki (1974) has reported that the commercial instrument which was described by Laurila (1963) is used routinely by iron-mining companies in development programs. This instrument is an air-cored, long, narrow, flat-wound coil whose axis is perpendicular to the borehole. Self-inductance of the coil is measured at a frequency of 1 kHz. Several new coil designs were described by Zablocki (1974). These are similar to that of Laurila (1963) in that they are rectangular in cross-section. However, instead of being flat-wound, the windings are divided into sections which differ in azimuth from each other. The vertical-wire sections of the coils subtend an angle of 275° in order to provide more magnetic flux coupling to the wall rock. Also the operating frequency was lowered to 400 Hz. The probes were designed to be used in blast holes with a diameter of 12. 25 inches. Measurement of susceptibility was found to be indicative within a standard error of 1. 2 of the weight per cent iron occurring as magnetite in experiments performed in the Minntac open-pit taconite mine in Minnesota. The method was considered to be useful in establishing cut-off boundaries between ore and waste.

MAGNETIC FIELD MEASUREMENTS

Broding *et al.* (1952) described experiments in which the total magnetic field was measured with a saturable-core magnetometer. The total field element was aligned parallel to the magnetic vector by means of two orthogonal sensors and a feedback-servo system. The main field was biased out allowing measurements to be made with a sensitivity of 1 gamma (1 α = 1 nanotesla). The instrument was used to record total field logs going into and through igneous plugs. It was concluded that the total field log raised as many questions as it answered and was, therefore, limited in use.

During more recent years, much development work has been undertaken in Scandinavia in the development of reliable instrumentation for surveying in slim drillholes. The outcome of the work carried out in Sweden by the Swedish Geological Survey and the Swedish Mining Association was the Hetona 3-component fluxgate drillhole magnetometer. Various models of this instrument have been described by Zuber (1962), Bergdahl (1963) and Hood (1969, 1970). A similar instrument has been produced in Finland for use at the Otanmaki mine in an approximately parallel development (*see*, for example, Levanto, 1959).

Basically the instrument measures three orthogonal components of the total magnetic field, X, Y and Z using miniaturized fluxgate elements and dip of the borehole with an inclinometer, all housed in a probe small enough to be used in an EX (36 mm) hole. Measuring accuracy is 50 - 150 γ and maximum range is ± 300 000 γ. The assembly of fluxgates is mounted so that it is free to rotate about the axis of the borehole. The direction of the borehole and the direction of the gravity vector are used as frames of reference. The X-component is parallel to the borehole axis and the other two perpendicular to it, with the Y-component always horizontal (i. e. perpendicular to gravity). The Z-component is then in the vertical plane which contains the borehole. Provided that the azimuth of the borehole is also known the orientation of the three elements can be determined. If, however, the borehole axis is vertical (or nearly so) the pendulum which orients the Y-component is constrained to move in a horizontal plane and is, therefore, useless. In this case the direction of the X-component only can be determined.

The three-component borehole magnetometer has seen extensive use in Scandinavia for iron-ore

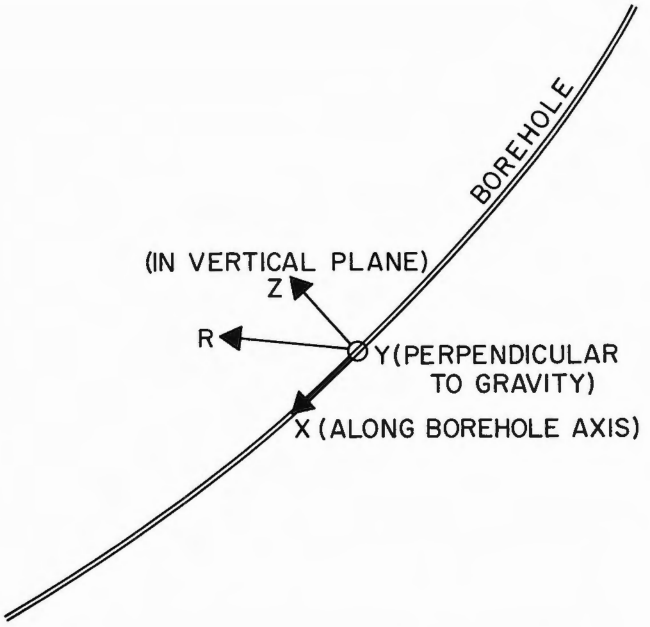


Figure 5. 1: Components measured by borehole magnetometer.

prospecting. As a result a number of field examples and methods of interpretation have been published (Levanto, 1959; Paarma and Levanto, 1960; Zuber, 1962; Levanto, 1963 and Lantto, 1973).

A simple method for display of borehole magnetic data is the vector approach as described by Levanto (1959, 1963) and Paarma and Levanto (1960). The contribution of the normal field must first be removed and then the resultant (R) of the anomalous X and Z components is plotted in the vertical section defined by the borehole (Fig. 5. 1). The value of the anomalous Y-component (which is perpendicular to this plane) is recorded on the section as a number. As a first approximation the magnetic sources can be considered a simple pole whose position can be determined by visualizing the location of the magnetic flux lines. As the magnetic measurements are strongly affected by magnetic materials near the drillhole, it is important to map the field at points distant from the ore-bearing zones. The ease of interpretation by visual inspection was illustrated by examples from the Raajärvi and Otanmäki iron mines in Finland.

A more accurate interpretation of borehole magnetic measurements requires better knowledge of the magnetic fields created by magnetic deposits of various shapes and sizes. Parasnis (1973) has demonstrated the borehole magnetic profile to be expected when the hole passes near or through a spherical magnetic zone of homogeneous composition. The anomalous field inside the sphere is constant and opposite in direction to the magnetizing field. A set of formulae has been presented by Zuber (1962) for the shape and magnitude of the fields due to poles, dipoles, spherical and plate-like orebodies. This method is sufficient in most cases for the purpose of determining position and approximate size of a single magnetic body. In cases where more than one orebody is involved, Zuber proposed that the potential calculation method be used. The magnetic potential at a given point, x, in the hole is:

$$V = -\int_0^x X \cdot dx \text{ which can be determined graphically.}$$

Calculation of V in several boreholes relative to a common reference point permits the construction of a potential contour map, the form of which indicates the position and shape of the magnetic zone. Several examples were presented by Zuber to illustrate the success of his methods in magnetic ore prospecting.

Lantto (1973) has presented a general interpretation procedure called the characteristic curve method. This method is based on the characteristic points of a profile where either the horizontal or vertical field components are zero. Standard curves given in the paper are for models which can be represented by two parallel infinite line poles (long tabular bodies) or a dipole (rod-shaped bodies). The standard curves were applied to determining the depth of the bottom of an iron-ore deposit at the Otanmäki mine in Finland using characteristic points located on the surface and in two boreholes.

Levanto (1963) has discussed the errors inherent to borehole magnetic measurements. These errors are due to uncertainty in the direction of the hole, misalignment of the probe in the hole, and orientation error of the sensing elements. In Scandinavia the measurement error is 50 γ/degree of azimuth error and 150 γ/degree of dip angle error. As a result an accuracy of 500 - 1000 γ is a realistic estimate to be expected under normal conditions. The reading accuracy of the instrument should therefore be about 100 - 200 γ. Anomalies below 300 - 500 γ are best measured using single-element instruments.

SUMMARY AND CONCLUSIONS

There is no doubt that borehole measurements of magnetic susceptibility by induction logging and of the total magnetic field by three-component magnetometers are useful in iron-ore prospecting.

Susceptibility measurements have proven to be useful in determining the amount of iron present in the vicinity of the drillhole in the form of magnetite. The larger volume sampled by an *in situ* bulk measurement is preferable to the volume of core usually measured in the laboratory.

Magnetic field intensities measured in boreholes are useful in the direct detection of iron-ore deposits.

In this application anomalous magnetic fields are often of the order of several thousand γ and occasionally as large as the earth's normal field even at points away from the orebody. In the search for ore deposits of base metals other than iron, i. e. sulphide deposits, success of the magnetic method in boreholes would usually depend on the presence of pyrrhotite. It is difficult to predict the size of anomaly to be expected due to a pyrrhotite source and how this anomaly would compare in magnitude to the noise inherent in measurement as well as the "geological" noise of undesirable magnetic sources. The only known application of borehole magnetic vector mapping near a sulphide body (pyrite-pyrrhotite composition) did not yield any conclusive information apparently due to the lack of susceptibility contrast between the deposit and the host rock (Malmqvist, 1958). A test program such as that undertaken by Dyck (1975) would be most helpful in assessing the method in the sulphide exploration environment under a variety of conditions.

Acknowledgments

The authors wish to thank Mr. P.H. McGrath for reviewing the manuscript.

BIBLIOGRAPHY

*Anderson, W.L.
1968: Theory of borehole magnetic susceptibility measurements with coil pairs; Geophysics, v. 33, no. 6, p. 962-971.

*Bergdahl, S.G.
1963: The drill hole magnetometer and its use for magnetic prospecting; Colo. Sch. Mines, Q., v. 58, no. 4, p. 253-258.

Briden, J.C. and Ward, A.W.
1966: Analysis of magnetic inclination in borecores; Pure Appl. Geophys., v. 63, p. 133-152.

*Broding, R.A., Zimmerman, C.W., Somers, E.V., Wilhelm, E.S., and Stripling, A.A.
1952: Magnetic well logging; Geophysics, v. 17, no. 1, p. 1-26.

*Dyck, A.V.
1975: Borehole Logging (Electrical); *in* Report of Activities, Geol. Surv. Can., Paper 75-1A, p. 81-82.

*Hood, P.
1969: Mineral exploration trends and developments in 1968; Can. Min. J., v. 90, no. 2, p. 157-180.

*1970: Magnetic surveying instrumentaion; a review of recent advances; Proceedings of the Canadian Centennial Conference on Mining and Groundwater Geophysics, Niagara Falls, October 22-27th, 1967; Mining and Groundwater Geophysics 1967, Editor L.W. Morley, Geol. Surv. Can., Econ. Geol. Ser., no. 26, p. 3-31.

*Kaufman, A.A.
1966: Effect of magnetic permeability in induction logging; Int. Geol. Rev., v. 8, no. 4, p. 480-488.

Kristjánsson, L.
1965: Geomagnetic measurements in drill holes through layered strata; Geoexploration, v. 13, p. 45-55.

Kudryavtsev, Y.I. and Meyer, V.A.
1963: Interpretatsiya diagram karotazha magnitnoy vosprumchivosti (Interpretation of the diagrams of magnetic susceptibility logging); Leningrad Univ. Uchenyye Zapishi, Voprosy Geofizihi, no. 320, p. 134-161.

*Lantto, V.
1973: Characteristic curves for interpretation of highly magnetic anomalies in borehole measurements; Geoexploration, v. 11, no. 2, p. 75-85.

*Laurila, E.
1963: On the measurement of the susceptibility and conductivity of the rock surrounding a bore; Acta Polytechnica Scandinavica, Physics, no. 25, p. 1-24.

*Levanto, A.E.
1959: A three-component magnetometer for small drill-holes and its use in ore prospecting; Geophys. Prospect., v. 7, no. 2, p. 183-195.

*1963: On magnetic measurements in drill holes; Geoexploration, no. 2, p. 8-20.

*Malmqvist, D.
1959: The geophysical case history of the Kankberg ore deposit in the Skellefte district; *in* Geophysical Surveys in Mining, Hydrological and Engineering Projects, EAEG, The Hague, p. 32-54.

Meyer, V.A., Kudryavtsev, Y.I., and Shulgin, V.A.
1967: Apparatura karotazha magnitnoy vosprumchivosti s dvukhatushechnyni zondom (Magnetic susceptibility logging apparatus with two-coil sonde); Geofi. Apparatura, no. 32, p. 44-51.

*Paarma, H. and Levanto, A.
1960: On the use of magnetic measurements in ore prospecting; 21st Int. Geol. Cong. Copenhagen, Part II, p. 98-110.

*Parasnis, D.S.
1973: Mining Geophysics; 2nd Edition, Elsevier Scientific Publishing Co.

Ponomarev, V.N. and Bakhvalov, A.N.
1964: Determination of the attitude of a thin bed from internal magnetic field measurements; Bulletin (Izvestiya), Academy of Sciences, USSR, Geophysics Series, no. 3, p. 214-219, p. 360-369 (Russian).

---

* References cited.

* References cited.

Stadukkin, V. D.
1963: The determination of the magnetic susceptibility of rocks and ores by measurement of the magnetic field intensity in artificially magnetized bore-holes for the purpose of location and evaluation of iron-ore deposits; Bulletin Izvestiya, no. 9, p. 1381-1385, p. 845-847. (Eng.).

Volocyula, G. K. and Safranova, H. I. (Editors)
1971: Borehole Mining Geophysics; Nedra, Leningrad, 535 p. (in Russian).

*Zablocki, C. J.
1966: Some applications of geophysical logging methods in mineral exploration drill holes; Trans. 7th Ann. Logging Symp., SPWLA, May 8-11.

*Zablocki, C. J. (cont.)
1966: Electrical properties of some iron formations and adjacent rocks in the Lake Superior region; *in* Min. Geophys., v. 1, S.E.G., p. 465-492.

*1974: Magnetic assays from magnetic susceptibility measurements in taconite production blast holes, northern Minnesota; Geophysics, v. 39, p. 174-189.

*Zuber, J. A.
1962: Magnetische Bohrlochmessungen als Hilfsmittel bei der Erzprospektierung. (Magnetic well logging as a tool in ore prospecting); Berg- und Huttenm. Monatsh, v. 107, p. 299-306.

---

* References cited.

* References cited.

6. NUCLEAR TECHNIQUES FOR BOREHOLE LOGGING IN MINERAL EXPLORATION

P.G. Killeen

INTRODUCTION

Nuclear borehole logging techniques have been used in coal, potash and uranium exploration programs as well as in petroleum exploration. However, their application to base metal exploration can be considered to be still in the experimental stage. This is partially due to the fact that it is only in the last few years that the field of electronics has developed to the point where the necessary miniaturization of electronic equipment to fit mineral exploration boreholes could be achieved. In addition, several advances in physics have been made, such as the development of the Californium-252 neutron source and the high resolution Ge(Li) gamma-ray detector. Also the background for neutron-activation analysis has been firmly established, and its capability of determining concentrations of selected elements such as copper, silver or gold, is directly applicable to mineral exploration.

This review, therefore, will cover the more firmly established nuclear techniques, which may have application to base metal borehole logging, in addition to nuclear techniques which have definite mineral exploration applications but which are presently under development or in experimental stages.

Nuclear borehole logging techniques may be considered to be either passive or active. In the former, the natural radiation in the hole is measured by an appropriate detector while in the latter, both a radioactive source and a detector are placed in the borehole. The radiation which reaches the detector from the source is modified by the physical properties of the rock, and the radiation detected can be translated into a measure of rock density, moisture content, etc.

In either case, the effective radius of investigation is proportional to the mean path length of the radiations involved.

As a rule of thumb, 90 per cent of the natural gamma rays come from within a 9-inch radius of the detector (Gregory and Horwood, 1961). The mean path of neutrons from commonly available sources is 8 to 24 inches depending on porosity and H_2O content of the rock Pirson, 1963). Thus the volume of rock being sampled is increased by at least an order of magnitude over core samples, and a sample which is more truly representative of the rock through which the borehole penetrates is assured.

A. PASSIVE SYSTEMS

The gamma (γ) log

The gamma log is a measurement of the intensity of the total natural gamma radiation of rocks, emitted by the Uranium and Thorium decay series and by Potassium-40. The γ-rays are most commonly detected by a scintillation counter using a sodium iodide (NaI(T1)) crystal detector. The gamma log, introduced in 1939, was one of the first nuclear techniques developed for lithological correlation. It was of great interest to the oil industry because cased holes could be logged since the gamma-rays could penetrate the casing.

A large volume of data has accumulated during oil exploration concerning the natural gamma radiation of rocks such as shale, sandstone and limestone. This information has been of tremendous use in lithologic correlation and for interpretation of geological structure.

Unfortunately a relatively small amount of data is available on the natural gamma radiation of rocks of interest to mineral exploration such as rhyolites, andesites, greenstones and igneous and metamorphic rocks in general. There is a need to obtain such a data base on which to build methods of interpretation of gamma-logs for mining geophysics.

The natural gamma log has been used extensively in uranium exploration. Scott *et al.* (1961) described a method for determining the grade and thickness of mineralized zones penetrated by a borehole, using gamma-ray logs. Scott (1963) presented a method of computer analysis of gamma-ray logs for uranium exploration. Several other papers on logging and interpretation in uranium prospecting are those by Dodd (1966), Dodd *et al.* (1967), Hawkins and Gearhart (1968) and Sprecher and Ryback (1974). More recently Dodd (1974) estimated that in 1973, drilling in the United States for uranium exploration amounted to about 16 million feet and most of that was logged using the natural gamma log.

A somewhat different drillhole probe based on the geiger counter, and presently in use at Eldorado Nuclear's uranium mine in northern Saskatchewan, has been described by Peebles (1969). The natural gamma-log has also been used to evaluate potash deposits in Saskatchewan (Edwards *et al.*, 1967; Costello and Norquay, 1967).

The gamma-ray spectral log

In certain types of uranium deposits, the variability of thorium concentration reduces the value of the natural gamma log, and a technique that can distinguish the difference between gamma-rays from thorium and uranium is needed. Also the problem of radioactive disequilibrium in some deposits will require a more sophisticated logging technique.

The gamma-ray spectral log is a measurement of the natural gamma radiation of rocks, with the added capability of energy discrimination. The thorium, uranium and potassium components of the natural radiation can be determined because of their characteristic gamma-ray energies. The results from the log are obtained by using a gamma-ray spectrometer, and therefore the Th, U, K, U/Th, U/K and Th/K measurements are available for borehole lithology determinations and correlation.

Lock and Hoyer (1971) discussed the technique of natural gamma-ray spectral logging and some of its applications. Rhodes and Mott (1966) in a more theoretical paper, computed factors required to take into account the effects of properties of the borehole itself such as diameter, mud density and casing, on gamma-ray spectral logs. Dodd and Eschliman (1972) reviewed the possibilities for determining the state of radiometric equilibrium of uranium using the gamma-ray spectral log.

In addition to the obvious application to uranium and potash exploration, there appears to be a high potential for base metal exploration. The relationship between petrology and Th/U ratios in granitic rocks has been investigated (Whitfield *et al.*, 1959), and Moxham *et al.* (1965) reported on gamma-ray spectrometer studies of hydrothermally altered rocks. Bennett (1971) reported on the relation between the radioelements and hydrothermal mineralization. More recently Davis and Guilbert (1973) reported on the distribution of Th, U and K in porphyry copper deposits. There is the possibility of measuring significant changes in Th and U distributions as haloes around mineral deposits (Gross, 1952; Mero, 1960). Wright *et al.* (1960) reported on the association of uranium with pyrite, sphalerite and galena, and Rekharsky (1959) and Melnikov and Berzina (1974) found molybdenite to be associated with increased uranium. Further investigations are needed to more closely define the relationship between Th, U and K distributions and deposits of base metals.

The gamma-ray spectral technique of measurement also forms the basis of the activation logs (Caldwell *et al.*, 1963) which are discussed later in this report.

B. ACTIVE SYSTEMS

Active logging systems involve the use of a source of radiation. These may be in the form of a radioactive source produced artificially in a nuclear reactor and sold commercially, or in the form of an electronic source such as an X-ray tube or neutron generator. The latter sources have the advantage that they can be turned off when not in use, but the disadvantage of being rather bulky for small boreholes. The detected radiation can be of two types: (1) the original source radiation which has been modified by the physical properties of the rock through which it travelled, or (2) a secondary radiation emitted from the rock after excitation by the primary source radiation.

The gamma-gamma log (γ-γ)

The gamma-gamma log is a measurement of the density of the rock in the borehole wall, obtained by detecting gamma rays from a radioactive source after they have undergone scattering in the region between the source and detector.

It is also known as the scattered γ-ray log, the formation density log (FDL) or the density log. Two radioactive sources commonly used are Cobalt-60 (1.17 and 1.33 Mev γ-rays), and Cesium-137 (0.66 Mev γ-rays). The source is collimated and shielded from the detector to prevent radiation from reaching the detector directly.

Figure 6.1 shows the path through the rock from the source to the detector taken by the Compton-scattered gamma rays (after Tittman and Wahl, 1965). With a suitable source and detector the only rock property affecting the detector response is the density of electrons which cause the Compton scattering. The bulk density of the rock can then be calculated. When properly calibrated the density log can also be a direct measure of porosity (Pirson, 1963). A method which will compensate for effects of mud cake or wall rugosity has been described by Wahl *et al.* (1964). The compensation is computed from the measurement made by two detectors, one close to the source, which is primarily affected by the mud cake, and one farther from the source which is affected by both the rock and the mud cake. A diagram of a compensated density log tool (dual-spacing log) after Cameron and Clayton (1971) is also shown in Figure 6.1. Density measurements can be made to within an accuracy of ± 1 or 2 per cent.

The selective gamma-gamma log

This measurement technique is similar to the gamma-ray spectral log except that a gamma source is used instead of natural gamma rays. At energies below about 0.2 Mev, the photoelectric effect becomes more important than the Compton effect, and the detector response is not a simple function of the bulk density as in the gamma-gamma density log. The chemical composition of the rock has a large influence on the resulting gamma-ray distribution at low energies and leads to the possibility of determining the heavy element concentration and chemical composition of the rock with the γ-γ log. This selective γ-γ log has a great potential for base metal borehole logging, but is presently not developed to an advanced stage. Czubek (1966) discussed the possibilities of selective γ-γ logging in mining. Czubek (1971) summarized the Russian and European work in this field and indicated that the method can be used to evaluate coal, Zn, Pb, Fe, Hg, Cu and Mn content. The technique has also been applied to evaluation of uranium concentrations in boreholes (Czubek and Dumesnil, 1969). Simon (1969) described the use of γ-γ logging in the determination of tin concentrations in Czechoslovakia. He indicated accurate analyses could be produced for monometallic deposits, and qualitative ore-indications for polymetallic ore.

This appears to be a method with high potential and warrants investigation by the mining industry.

The neutron log

The several types of neutron logs are measurements of rock properties made by utilizing neutron sources. The basic principle of the neutron log is that the neutrons emitted by the source are slowed down and scattered by collisions with atomic nuclei. The maximum energy loss in a collision occurs when the target nucleus has a mass similar to the neutron. Thus

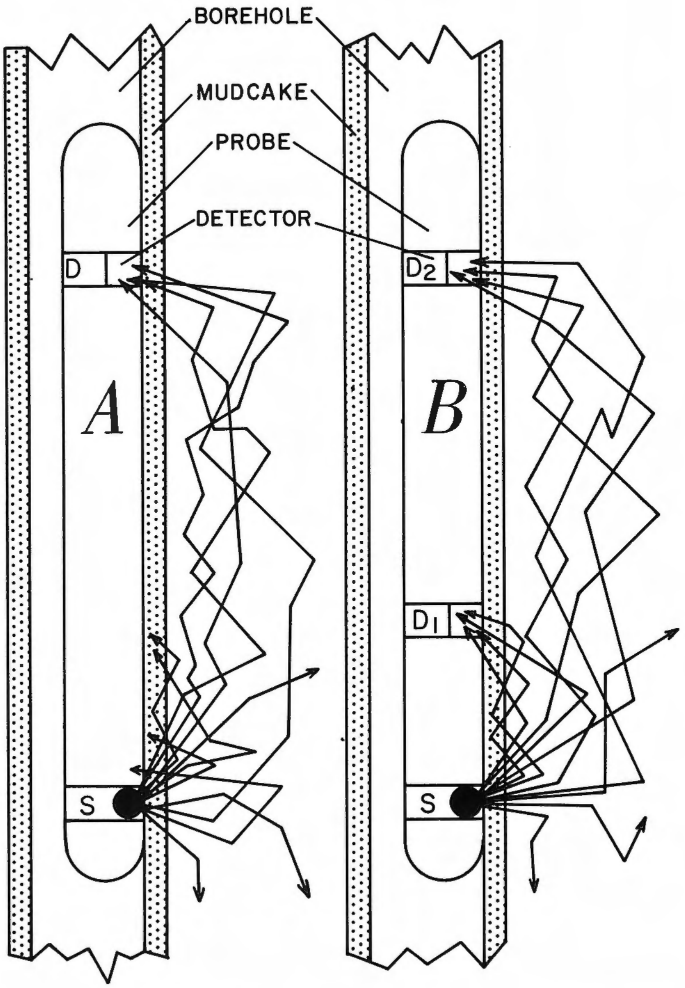


Figure 6.1: Gamma-gamma (γ, γ) probe A (left) showing the scattering of gamma rays in the borehole wall between the source (S) and detector (D). Probe B (right) is a compensated gamma-gamma logging tool with two detectors: D_1 (short spacing) and D_2 (long spacing).

the hydrogen atom has the greatest effect in slowing down the neutrons to thermal energies after which they are soon captured. The neutron log has been often referred to as the hydrogen log. The elements B, Hg, Mn and Cd have high absorption cross-sections and may also be measured in this way. Upon capture of a neutron the excited target nucleus emits a gamma-ray. There are three possible measurements that can be made: a) the fast neutrons using a short source-detector spacing (n, n epithermal); b) the slow neutrons using a long source-detector spacing (n, n thermal); c) the capture gamma-rays (n, γ or prompt γ).

The detector response in all three cases is proportional to the hydrogen content of the rock, usually in the form of water in pores, and is therefore a measure of porosity. The source detector spacings vary between one and two feet and logging probe diameters of under two inches are available. Generally the measurement of capture gamma-rays is made at a long spacing so that a high hydrogen content will cause most of the captures to occur close to the source, and a low hydrogen content allows captures to take place farther from the source, i.e. nearer the gamma-ray detector. Thus there is an inverse relationship between the gamma-ray detector response and the hydrogen content.

It should also be mentioned that an ordinary gamma-ray log should be run in conjunction with the (n-γ) log, to enable the natural gamma radiation background to be subtracted from the neutron-induced gamma radiation. In an effort to eliminate or minimize effects of borehole conditions, several variations exist in the measurement techniques for (n-γ) logging. The borehole probe can have dual-spaced detectors, and be either centred in the hole or pressed against the sidewall. The SNP probe (sidewall neutron porosity) is an example of the latter.

A variation on the (n-γ) log is possible if a spectrometer is included such that the energy of the capture γ-rays (or prompt γ) is measured. This has been done to produce a "chlorine log" wherein characteristic γ-rays of chlorine are measured (Dewan *et al.*, 1960). In principle this technique can be extended to determine the elemental composition of ores, although the difficulties involved are considerable. The application of this method to Ni in laterites and porphyry Cu is being studied by several groups including Scintrex Ltd. (Nargolwalla, 1973) and the U.S. Geological Survey (Senftle *et al.*, 1971).

The neutron γ-ray spectral method appears to be a promising field for further investigation since there are several advantages to the measurement of these prompt or capture γ-rays. Many of the γ-ray energies are high (above 3 Mev) and therefore the effective radius of penetration or sampling volume is large. Borehole effects are therefore minimized, and the natural radiation background is negligible since it is of lower energy. It is also possible to measure the energies of activation γ-rays emitted by the decaying unstable isotope produced by the capture of the neutrons. These γ-rays are emitted after a short time which is the half-life of the particular isotope involved, and they have energies characteristic of the emitting element. The disadvantage is that the energy is usually less than 3 Mev, so the natural background radiation may produce interference, and the effective radius of penetration is smaller than for most prompt or capture γ-rays. The measurement of these activation γ-rays however has been very highly developed in the laboratory environment, and a great deal of literature is available on the various energies and half-lives of the different activated elements.

A third type of γ-ray besides the capture (prompt) and activation γ-rays exists. These are γ-rays produced during the slowing down of the neutrons by inelastic scattering (n, nγ). During inelastic scattering the nucleus of the atom involved in the collision becomes excited and a γ-ray with a characteristic energy is emitted. The nuclear data presently available on the various energies is rather limited. These γ-rays are emitted early in the life of the neutron, which leads to the requirement of timed measurements. However, this is only possible with a pulsed neutron source which can be shut off intermittently. Therefore isotopic neutron sources cannot be used for these timed measurements.

The above mentioned neutron logging techniques may be termed "conventional" as opposed to the pulsed-neutron techniques to be described below.

The introduction of the pulsed-neutron generator, an electronic device, made it possible to make any of the above measurements at specific times after the pulse or burst of neutrons is over. Thus the γ-rays from inelastic scattering (n, nγ) could be measured during the first 50 μ seconds, then several neutron counting measurements could be made to determine the shape of the decay curve of the neutrons (i. e. the die-away curve), and similarly for the capture γ-rays which would die away with a half-life dependent on the hydrogen content of the rock, and finally the half-life of the activation γ-rays could be determined by making several successive measurements of γ-ray counts at specific energies. An analogy in base metal exploration geophysics is the airborne Input system which makes several measurements of a decay curve after the primary electromagnetic field is turned off.

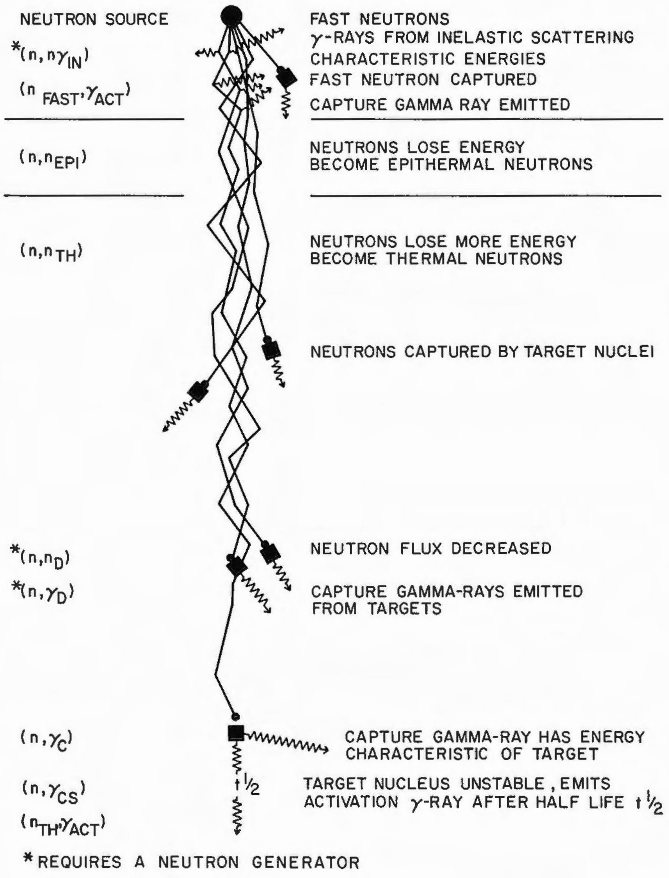


Figure 6. 2: Neutron logging methods summarized by illustration of possible events during about 1000 microseconds in the life of a neutron (IN = Inelastic, ACT = Activation, EPI = Epithermal, TH = Thermal, D = Die away, C = Capture, CS = Capture Spectrometry).

The effects of borehole fluids and casing can be eliminated by these timed measurements since the half-life of the neutrons in the borehole and casing is different from the surrounding rock. If measurements are taken 500 μs after the pulse, the results are entirely dependent on the rock properties as interactions in the borehole are over by that time. The several variants of times and types of measurements have been called Neutron Lifetime Log (MLL) and Thermal-neutron Decay Time Log (TDT).

Figure 6. 2 summarizes the neutron logs.

It should be noted that there is some confusion in the literature concerning the use of the word 'prompt' to describe γ-rays. It is generally used to refer to a capture γ-ray as the radiation is prompt radiation as opposed to the later activation γ-ray from the same atom. The confusion arises in describing the γ-rays emitted by atoms during an inelastic collision with a neutron. Such γ-rays are truly 'prompt' also, and not the delayed result of radioactive decay.

The possibilities for application of pulsed neutron logging to borehole mineral exploration are considerable.

Cyclic activation has also been made possible with the development of pulsed neutron generators. In this case the activity of a very short-lived activation product can be measured at the appropriate time after each of several neutron pulses, yielding a much higher count rate than if only one measurement were made. This should make it possible to do continuous activation borehole logging by measuring very short-lived activities. Small-diameter neutron-lifetime tools have been developed for use in 2 1/8 and 1 11/16-inch tubing (Caldwell *et al.*, 1969).

Gamma-ray nuclear resonance

This is a relatively new element analysis technique at present in the experimental stage, Sowerby (1971), Sowerby and Ellis (1973).

Basically the technique involves the use of a radioactive gamma-ray source to bombard the rock which then re-emits gamma rays of the same energy if conditions are right for nuclear resonance. The "right condition" occurs when the energy of the incident gamma ray is exactly that which can excite a stable nucleus of an element. This energy is different for different elements. At present the best means of producing the correct energy of incident gamma ray is to use a radioactive isotope that decays via the excited state of the element to be analyzed. This source requirement puts a limitation on the number of elements which can be determined with the technique. Sowerby and Ellis (1973) listed the elements most suited to analysis by gamma-ray resonance scattering. They include Cu, Ni, Cr, Hg, W, Ti, Li, V, Ge, As, Cd, Cs and Tl. For certain specific elements such as Cu or Ni, this technique may prove to be more favourable than neutron activation methods.

Photoneutron activation

A high energy γ-ray can eject a neutron from the nucleus in a (γ, n) reaction. This has been used in the construction of a beryllium detector. Czubek (1971) described the Russian application of this technique to logging of 3 types of beryllium deposits. To the author's knowledge no other borehole tests of (γ, n) equipment have been reported although its surface use was described by Bisby (1959).

X-ray fluorescence

The X-ray fluorescence drillhole probe has been described by Rhodes *et al.* (1969) and by Clayton (1969, 1971). The technique uses an isotopic source of γ-rays to irradiate the borehole wall which in turn emits X-rays with energies characteristic of the elements in the rock. The technique can still be considered in the experimental stages as far as exploration borehole logging is concerned although several thousand feet of AX (1 7/8 inch) and BX (2 3/8 inch) test holes have been logged using a 1 3/4 inch diameter probe. The advantages of the technique are that it is applicable to a wide variety of elements, the sensitivity is high and the technique of XRF is well documented. The main disadvantage appears to be the fact that the low energies involved permit only a very small radius of penetration (in effect a "surface" analysis for elements below $z = 40$ in the periodic table) and the borehole conditions have a large effect on the results. The low energies detected also require a relatively thin window over the detector, which is vulnerable under borehole conditions. It has been suggested that its main application may be in development drilling to locate ore-grade cutoff.

NEUTRON SOURCES (Isotopic)

There are four commonly used radioactive sources available in addition to the isotope Californium-252 which is presently available only in limited quantities. One curie of Californium-252 yields 4.4×10^{9} neutrons per second by spontaneous fission with an effective half-life of 2.65 years. Keys and Boulogne (1969) described its use in well logging.

Advantage - high neutron yield, small size
Disadvantage - expensive, limited availability
- moderately short half-life

The other sources utilize an (α, n) reaction to produce neutrons e.g. an alpha-particle source bombards the element Beryllium which then emits neutrons.

1. Radium-Beryllium (1 curie yields 1.5×10^{7} n/sec)

   Advantage - half-life is long (1620 years) and therefore needs no recalibration with time
   Disadvantage - emits γ-rays as well as neutrons and these may cause interference in measurements.

2. Polonium-Beryllium (1 curie yields 3.0×10^{6} n/sec)

   Advantage - no γ-rays emitted
   Disadvantage - short half-life of 140 days and therefore requires frequent recalibration.

3. Plutonium-Beryllium (1 curie yields 2.0×10^{6} n/sec)

   Advantage - no γ-rays
   - half-life = 89 years
   Disadvantage - expensive.

4. Americium-Beryllium (1 curie yields 2.0×10^{6} n/sec)

   Advantage - half-life = 458 years
   Disadvantage - relatively large volume compared to the other sources.

CALIBRATION

As nuclear logging for oil exploration increased, it became necessary to establish a common base on which to calibrate the various proliferating arrays of logging equipment. This standardization would permit correlation and comparison of data from one logging service company to another and from instrument to instrument. It would also present the possibility of developing a more quantitative measurement capability.

In 1956 the American Petroleum Institute appointed a committee to develop the required standardization.

By 1959 a standard calibration system had been developed, and two calibration pits had been constructed at the University of Houston (Belknap, 1963).

Calibration for lithological correlation purposes

The API Gamma-Ray Unit

This unit is defined as 1/200 of the difference in log deflection between zones of high and low radiation in the gamma-ray calibration pit at the University of Houston. The 24-foot-deep pit contains three zones of homogeneous radioactivity concrete, four feet in diameter and eight feet thick. The high activity centre zone contains 13 ppm U, 24 ppm Th, and 4 per cent K. The level of radioactivity is then about twice that of an average shale.

The API Neutron Unit

This unit is defined as 1/1000 of the difference between instrument zero and the log deflection opposite a 6-foot zone of Indiana limestone in the neutron calibration pit at the University of Houston. The 24-foot-deep neutron test pit consists of four zones as follows: six feet of water, 6 feet of limestone (Carthage Marble) of 1.9 per cent porosity, 6 feet of Indiana limestone of 19 per cent porosity, and 6 feet of Austin limestone of 26 per cent porosity.

By 1963, most of the logging companies had voluntarily converted to the API standards, realizing it was in their best interests to do so. The API units were defined fifteen years ago primarily for standardization and correlation purposes. In the light of advances made in nuclear techniques and instrumentation it is perhaps time to define some new units for nuclear logging which would be more amenable to quantitative interpretation.

SECONDARY CALIBRATION STANDARDS

In addition to these downhole calibration facilities, a number of portable log calibration facilities are in use. These secondary standards usually consist of reference sources placed at a fixed distance from the detector. They can provide a check on the primary calibration of logging equipment. Various secondary and tertiary calibration standards for logging equipment have been described by Bosworth (1972).

Calibration for Uranium exploration purposes

Similarly, there was a need for calibrating logging equipment for uranium exploration. About 16 million feet of borehole logging was carried out in the United States alone in 1973 for uranium exploration purposes. The USAEC established test pits for calibration purposes at various centres. (Grand Junction, Colorado; Casper, Wyoming; Grants, New Mexico and George West, Texas). The model hole facilities at Grand Junction are rather elaborate compared to the other test pit facilities. They include test holes for determination of hole size - water factors and casing factors in addition to grade-thickness factors.

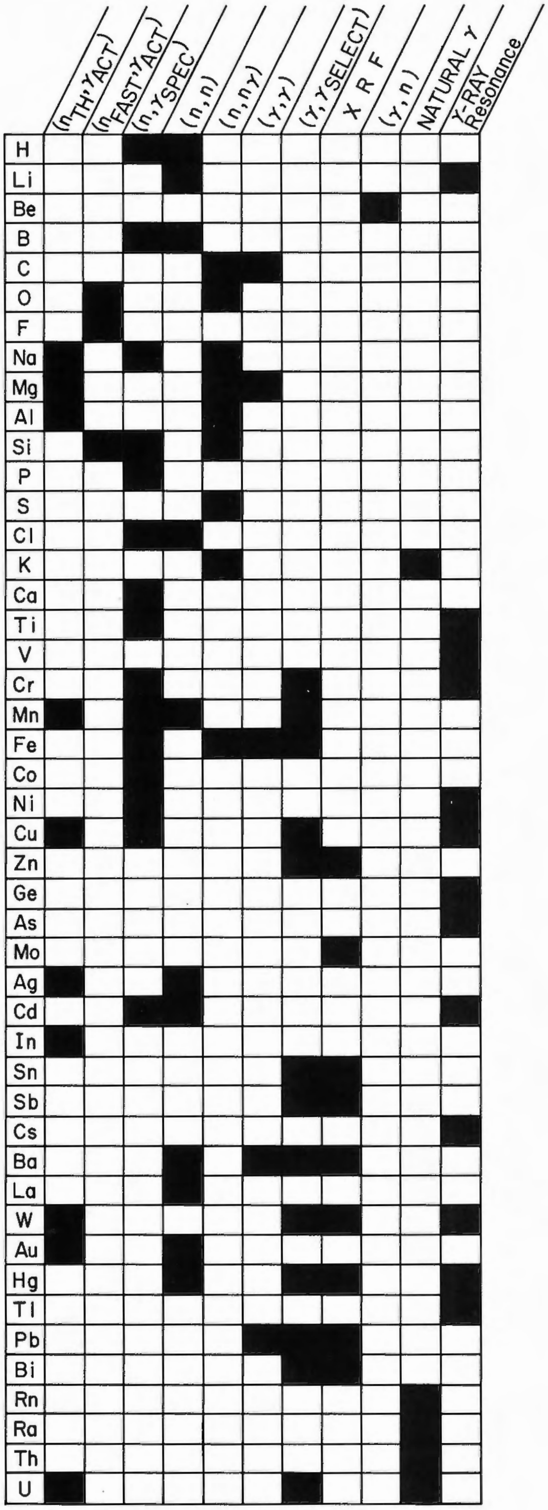
Typical grades used in the test holes range from about 0. 2 per cent U_3O_8 to 2. 0 per cent U_3O_8, with thickness ranging from 0. 5 feet to about 4 feet. The use of these pits for uranium exploration grade-thickness determinations has been described by Scott *et al.* (1961) and Scott (1963). A method of utilizing results obtained in two test pits for calibration purposes, which improves the accuracy of the calibration, has been described by Crew and Berkoff (1969).

At present no test holes for uranium logging purposes exist in Canada. With the increasing demand for uranium and the likelihood of consequent logging programs, such calibration facilities should be considered an important development towards aiding uranium exploration.

Calibration for base metal exploration purposes

In order to facilitate the development and use of nuclear techniques for borehole logging with respect to mineral exploration, a series of model boreholes similar to those described above should be constructed.

These model holes would have to be designed to provide the proper testing ground and calibration standards required to make gamma-ray, neutron, X-ray and other nuclear measurements on massive and disseminated sulphides, and other common base metal ore-forming minerals. They would also have to contain



	(n_{TH}, γ_{ACT})	(n_{FAST}, γ_{ACT})	(n, γ_{SPEC})	(n, n)	$(n, n\gamma)$	(γ, γ)	$(\gamma, \gamma_{SELECT})$	X R F	(γ, n)	NATURAL γ	γ-RAY Resonance
H			■	■							
Li				■							■
Be									■		
B			■	■							
C					■	■					
O		■			■						
F		■									
Na	■		■		■						
Mg	■				■	■					
Al	■				■						
Si		■	■		■						
P			■								
S					■						
Cl			■	■							
K					■					■	
Ca			■								
Ti			■								■
V											■
Cr			■				■				■
Mn	■		■	■			■				
Fe			■		■	■	■				
Co			■								
Ni			■								■
Cu	■		■				■				■
Zn							■	■			
Ge											■
As											■
Mo								■			
Ag	■			■							
Cd			■	■							■
In	■										
Sn							■	■			
Sb							■	■			
Cs											■
Ba				■		■	■	■			
La				■							
W	■						■	■			■
Au	■			■							
Hg				■			■	■			■
Tl											■
Pb						■	■	■			
Bi							■	■			
Rn										■	
Ra										■	
Th										■	
U	■						■			■	

Figure 6. 3: Eleven nuclear techniques applicable to mineral exploration, and the forty-six elements which they can be used to detect.

zones of background rock types such as greenstone in which the ore-forming minerals occur. The distribution of the model test holes could follow a similar pattern to that of the USAEC test holes for uranium exploration. An elaborate set of holes for measuring many variables could be established at some main location such as Ottawa, and a smaller number of model holes could be located near areas of active base metal exploration such as Timmins, Ontario; Chibougamou, Quebec; Bathurst, New Brunswick; Thompson, Manitoba and in the Highland Valley of British Columbia.

At present the only known Canadian model test hole facilities for nuclear techniques related to base metal exploration are those of Scintrex Ltd. in Toronto.

DISCUSSION

In summary, there are several nuclear methods directly applicable to mining exploration, and several with great potential if further developed. Figure 6. 3 indicates the elements reported in the literature as being detectable by nuclear techniques, many of which can and have been adapted for borehole logging. It appears that the most recent and most highly developed nuclear logging techniques for mining exploration have been developed in Russia and Europe. Unfortunately much of the work is not translated into English, and is therefore available only with some difficulty. The development of borehole geochemical logging (or *in situ* multi-element analysis with continuous logging) is a definite future possibility. The available literature on borehole logging has been primarily concerned with sedimentary rock such as sandstone, shales, limestones and dolomite, having low concentrations of the heavy elements, high porosity, and many other rock properties which are entirely different in "hard rock" logging. The physical foundations for the measurement techniques have been laid, but there is a dearth of knowledge on the subject of logging in hard rock. Simple things such as the natural γ-ray flux in base metal exploration boreholes are still a matter of conjecture based on surface measurements. It might be very worthwhile to establish a data base even at the expense of drilling some larger diameter holes, to evaluate existing nuclear logging equipment in the hardrock environment. These holes would also be useful in evaluation of other borehole-geophysics techniques such as the electrical methods.

REFERENCES

Bennett, R.
1971: Exploration for hydrothermal mineralization with airborne γ-ray spectrometry; Can. Inst. Min. Met. Spec., v. 11, Proc. 3rd Int. Geochem. Expl. Symp., Toronto, p. 475-478.

Belknap, W. B.
1963: A. P. I. standards for nuclear logs; The Log Analyst. v. 4, no. 2, Aug.-Sept., p. 7-10.

Bisby, H.
1959: Nucleonic instrumentation for the detection and assay of beryllium minerals; A. E. R. E.-R 3021 United Kingdom Atomic Energy Authority.

Bosworth, A. F.
1972: Log calibrations, surface and downhole; Can. Well Log Soc. J., v. 5, no. 1, Dec., p. 39-68.

Caldwell, R. L., Baldwin, W. F., Bargainer, J. D., Berry, J. E., Salita, G. N., and Sloan, R. W.
1963: Gamma-ray spectroscopy in well logging; Geophysics. v. 28, no. 4, p. 617-632.

Caldwell, R. L., Mills, W. R., and Givens, W. W.
1969: Advances in nuclear geophysical methods in oil geology and rock analysis; *in* Nuclear Techniques and Mineral Resources, IAEA, Vienna, p. 397-414.

Cameron, J. F. and Clayton, C. G.
1971: Mining and quarrying; *in* Radioisotope Instruments, part 1, p. 75-147. Pergamon Press, Toronto.

Clayton, C. G.
1969: Review paper: Applications of radioisotope X-ray fluorescence analysis in geological assay, mining and mineral processing; *in* Nuclear Techniques and Mineral Resources, IAEA, Vienna, p. 293-321.

1971: Application of radioisotope X-ray fluorescence analyzers in metalliferous mineral exploration and mining; *in* Nuclear Techniques for Mineral Exploration and Exploitation, IAEA, Vienna, p. 27-35.

Costello, J. T. and Norquay, I. P.
1967: Logging the prairie evaporite formation in Saskatchewan; *in* Mining and Groundwater Geophysics, Geol. Surv. Can., Econ. Geol. Rept. no. 26, p. 492-496.

Crew, M. E. and Berkoff, E. W.
1969: Twopit, a different approach to calibration of gamma-ray logging equipment; USAEC Grand Junction Office, Mining Division, Colorado.

Czubek, J. A.
1966: Physical possibilities of γ-γ logging; *in* Radioisotope Instruments - Industry and Geophysics, v. 2, IAEA.

1971: Recent Russian and European developments in nuclear geophysics applied to mineral exploration and mining; The Log Analyst, v. 12, no. 6, p. 20-34.

Czubek, J.A. and Dumesnil, P.
1969: Radiocarottage gamma naturel selectif; *in* Nuclear Techniques and Mineral Resources, IAEA, Vienna, p. 223-248. (in French)

Davis, J.D. and Guilbert, J.M.
1973: Distribution of the radioelements Potassium, Uranium and Thorium in selected porphyry copper deposits; Econ. Geol., v. 68, no. 2, p. 145-160.

Dewan, J.T., Stone, O.L., and Morris, R.L.
1960: Results of chlorine logging in closed holes; Paper 1561-G presented at 35 Ann. Fall Meeting of APE of AIMMPE in Denver, Oct. 2-5, (publ. in J. Pet. Tech).

Dodd, P.H.
1966: Quantitative logging and interpretation systems to evaluate uranium deposits; SPWLA 7th ann. logging symp. (Paper P)

1974: Geophysical exploration for uranium - A review of methods and economics; Paper presented at the 103rd Annual Meeting, A.I.M.E., Dallas, Texas, Feb. 25.

Dodd, P.H., Droullard, R.F., and Lathan, C.P.
1967: Borehole logging methods for exploration and evaluation of uranium deposits; *in* Mining and Groundwater Geophysics 1967; Geol. Surv. Can., Econ. Geol. Rept. no. 26, p. 401.

Dodd, P.H. and Eschliman, D.H.
1972: Borehole logging techniques for uranium exploration and evaluation; *in* Uranium Prospecting Handbook, ed. by S.H.W. Bowie, M. Davis and D. Ostle Inst. Min. Metall., London.

Edwards, J.M., Ottinger, N.H., and Haskell, R.E.
1967: Nuclear log evaluation of potash deposits; SPWLA 8th Ann. Symp. (Paper L)

Gregory, A.F. and Horwood, J.L.
1961: A laboratory study of gamma-ray spectra at the surface of rocks; Dept. Energy, Mines and Resources, Ottawa, Mines Br., Res. Rept. no. R 85.

Gross, W.H.
1952: Radioactivity as a guide to ore; Econ. Geol., v. 47, p. 722-742.

Hawkins, W.K. and Gearhart, M.
1968: Use of logging in uranium prospecting; SPWLA 9th ann. log. symp. (Paper T)

Keys, W.S. and Boulogne, A.R.
1969: Well logging with Californium-252; The Log Analyst, v. 10, no. 6, p. 11-24.

Lock, G.A. and Hoyer, W.A.
1971: Natural gamma-ray spectral logging; The Log Analyst, v. 12, no. 5, p. 3-9.

Melnikov, I.V. and Berzina, I.G.
1974: Some characteristic features of the behaviour of uranium in the formation of uranium-molybdenum deposits; Soviet Atomic Energy, Jan. 1974, a translation of Atomnaya Energiya, v. 35, no. 1, 1973, p. 615-621.

Mero, J.L.
1960: Uses of the gamma-ray spectrometer in mineral exploration; Geophysics, v. 25, no. 5, p. 1054-1076.

Moxham, R.M., Foote, R.S., and Bunker, C.M.
1965: Gamma-ray spectrometer studies of hydrothermally altered rocks; Econ. Geol., v. 60, no. 4, p. 653-671.

Nargolwalla, S.S.
1973: Nuclear technique for borehole logging of Geologic Materials; Scintrex Ltd. Applications Brief 73-1, 222 Snidercroft Rd., Concord, Ontario.

Peebles, G.A.
1969: Radiometric instrumentation and techniques at Eldorado's Beaverlodge operation; Can. Inst. Min. Met., Trans., v. 72, p. 311-316.

Pirson, S.J.
1963: Handbook of well log analysis for oil and gas formation evaluation; Prentice-Hall Inc.

Rekharsky, V.I.
1959: On the regularities of distribution of molybdenum and uranium in mineralized zones; Bull. Acad. Sci. U.S.S.R., Geol. Ser., p. 17-27.

Rhodes, J.R., Furuta, T., and Berry, P.F.
1969: A radioisotope X-ray fluorescence drill hole probe; *in* Nuclear Techniques and Mineral Resources, IAEA, Vienna, p. 353-364.

Rhodes, D.F. and Mott, W.E.
1966: Quantitative interpretation of gamma-ray spectral logs; Geophysics, v. 31, no. 2, p. 410-418.

Scott, J.H.
1963: Computer analysis of gamma-ray logs; Geophysics, v. 28, no. 3, p. 457-465.

Scott, J.H., Dodd, P.H., Droullard, R.F., and Mudra, P.J.
1961: Quantitative interpretation of gamma-ray logs; Geophysics, v. 26, no. 2, p. 182-191.

Senftle, F.E., Wiggins, P.F., Duffey, D., and Philbin, P.
1971: Nickel exploration by neutron capture gamma rays; Econ. Geol., v. 66, p. 583-590.

Simon, L.
1969: Quantitative evaluation of ore mineralization in drill holes by gamma-gamma logging; Can. Min. J., v. 90, no. 7, p. 57-59.

Sowerby, B.D.
1971: A new method of element analysis using nuclear resonance scattering of gamma-rays; Nucl. Instrum. Methods, v. 94, p. 45-51.

Sowerby, B.D. and Ellis, W.K.
1973: Industrial on-stream analysis using gamma-ray resonance scattering; *in* Nuclear Techniques in the Basic Metal Industries, IAEA, Vienna.

Sprecher, C. and Rybach, L.
1974: Design and field test of a scintillation probe for γ-logging of small diameter boreholes; Pure Appl. Geophys., v. 112, p. 563-570.

Tittman, J. and Wahl, J.S.
1965: The physical foundations of formation density logging (gamma-gamma); Geophysics, v. 30, no. 2, p. 284-294.

Wahl, J.S., Tittman, J., Johnstone, C.W., and Alger, R.P.
1964: The dual spacing density log; J. Pet. Tech., v. 16, p. 1411.

Whitfield, J.M., Rogers, J.J.W., and Adams, J.A.S.
1959: The relationship between the petrology and the thorium and uranium contents of some granitic rocks; Geochim. Cosmochim. Acta, v. 17, p. 248-271.

Wright, H.D., Smith, C.M., and Hutta, J.J.
1960: Role of trace amounts of uranium in some base metal sulphides from vein deposits; *in* Int. Geol. Cong. (21st), pt. 16, p. 248-260.

BIBLIOGRAPHY

Allen, L.S., Mills, W.R., Desai, K.P., and Caldwell, R.L.
1972: Some features of dual-spaced neutron porosity logging; *in* The Log Analyst, v. 13, no. 4, p. 22-27.

Baltosser, W.R. and Lawrence, H.W.
1970: Application of well logging techniques in metallic mineral mining; Geophysics, v. 35, no. 1, p. 143-152.

Beckerley, J.G.
1960: Nuclear methods for subsurface prospecting; *in* Annual Review of Nuclear Science, ed. by E. Segre, G. Friedlander and W. Meyerhof, v. 10, p. 425-460.

Berry, C.G. and Inwood, R.
1968: New methods in exploration and evaluation using mechanical logs; Ont. Pet. Inst. 7th Ann. Conf. Windsor, Ont., Oct. 30-Nov. 1; Tech. Session. no. 3; 25 p.

Bond, L.O., Alger, R.P., and Schmidt, A.W.
1969: Well log applications in coal mining and rock mechanics; Soc. Min. Eng. of AIME; Reprint no. 69-F-13. S.M.E. 345 East 47th St., N.Y., 10017.

Caldwell, R.L.
1967: Well logging in the U.S.S.R.; SPWLA 8th ann. Logging Symp. (Paper C)

Caldwell, R.L., Allen, L.S., and Mills, W.R.
1966: Theoretical and experimental model results in neutron life-time logging; *in* Radioisotope Instruments in Industry and Geophysics, v. 2, I.A.E.A.

Clayton, C.G.
1967: A survey of the application of radiation techniques in oil and mineral boreholes; United Kingdom Atomic Energy Authority report A.E.R.E.-R 5368.

Crandall, J.L.
1970: Survey of applications for ^{252}Cf; Isotopes and Radiation Technology; v. 7, no. 3.

Culver, R.B., Hopkinson, E.C., and Youmans, A.H.
1973: Carbon oxygen (C/O) Logging Instrumentation; Soc. Pet. Eng. of AIME, Paper no. 640 presented at 48th ann. fall meeting in Las Vegas, Sept. 30.

Czubek, J.A. and Guitton, J.
1966: Application de la methode γ-γ à la determination sur place de la densite des mineraes d'Uranium; *in* Radioisotope Instruments in Industry and Geophysics, v. 2, IAEA.

Dewan, J.T.
1956: Neutron log correction charts for borehole conditions and bed thickness; J. Pet. Tech., Feb., 9 p.

Dewan, J.T., Johnstone, C.W., Jacobson, L.A., Wall, W.B., and Alger, R.P.
1973: Thermal neutron decay logging using dual detection; The Log Analyst, v. 14, no. 5, p. 13-26.

Dibbs, H.P. and Dalton, J.L.
1973: Neutron methods for on-line analysis; Can. Min. Metall. Bull., v. 66, no. 737, p. 61-69.

Dodd, P.H. and Droullard, R.F.
1966: A logging system and computer program to determine rock density of uranium deposits; *in* Radioisotope Instruments in Industry and Geophysics, v. 2, I.A.E.A.

Dorin, A.H., Norquay, I.P., and Everett, R.V.
1969: Field compatible-scale overlay system an aid to wellsite log interpretations; Ont. Petm. Inst., 8th Ann. Conf. Toronto, Oct. 15-17, Tech. Session no. 3, 27 p.

Eisler, P.L., Huppert, P., and Wylie, A.W.
1971: Logging of copper in simulated boreholes by gamma spectrometry; Geoexploration, v. 9, no. 4, p. 181-194.

Evans, H.B.
1970: Status and trends in logging; Geophysics, v. 35, no. 1, p. 93-112.

Fertl, W.H.
1971: Occurrence of the neutron absorbing trace element boron. Pt. I: Boron in Rocks; The Log Analyst, v. 12, no. 5, p. 10-13.

Fons, L.
1969: Geological applications of well logs; SPWLA 10th ann. log. symp. (Paper AA)

Gallagher, M.J.
1970: Portable X-ray spectrometers for rapid ore analysis; *in* Mining and Petroleum Geology, v. 2, ed. by M.J. Jones, Inst. Min. Met., London.

Gardner, R.P., Dunn, W.L., and McDougall, F.H.
1971: A quality factor concept for evaluation of the surface type gamma-ray backscatter soil density gauge; Nuclear Engineering and Design, v. 16, p. 399-407.

Givens, W.W., Caldwell, R.L., and Mills, W.R. Jr.
1968: Cyclic activation logging; The Log Analyst, v. 9, no. 3, p. 18-21.

Goldsmith, L.H.
1966: Some fundamentals of potash geology as a guide to exploration; SPWLA 7th ann. symp.

Granberry, R.J., Jenkins, R.E., and Bush, D.C.
1968: Grain density values of cores from some Gulf Coast formations and their importance in formation evaluation; SPWLA 9th ann. symp. (Paper N)

Heslop, A.
1970: Log analysis using a time-share computer; Can. Well Logging Soc. J., v. 3, no. 1, Dec., p. 123-46.

1971: Mixed-lithology analysis using MN product; Can. Well Logging Soc. J., v. 4, no. 1, Dec., p. 85-93.

1972: Gamma-ray log response of shaly sandstones; Can. Well Logging Soc. J., v. 5, no. 1, Dec., p. 29-37.

Hilchie, D.W., Mills, W.R., Dennis, C.L., and Givens, W.W.
1968: Some aspects of pulsed neutron logging; SPWLA 9th ann. log. symp. (Paper Q); also *in* The Log Analyst, v. 10, no. 2, p. 7-17.

Homilius, J. and Lorch, S.
1957: Density determination on near-surface layers by gamma absorption; Geophys. Prospect., v. 5, no. 4, p. 449-468.

Hoyer, W.A. and Lock, G.A.
1972: Logging for copper by *in situ* neutron activation analysis; AIME Annual Meeting, San Francisco, Calif., Feb. 20-22, Reprint no. 72-L-28, *in* Trans. Soc. Min. Eng., AIME, v. 252, no. 4, Dec., p. 409-417.

Itoh, T.
1971: Pulse neutron well-logging techniques; Proc. 8th World Petrol. Cong., v. 3, p. 37-44.

Jenkins, J.C.
1969: Practical applications of well logging to mine design; Soc. Min. Engin., AIME, reprint no. 69-F-73.

Jones, W.B. and Carpenter, R.A.
1967: Element detection by a non dispersive X-ray fluorescent analysis system; The Log Analyst, v. 8, no. 2, p. 3-10.

Keller, G.V.
1966: Geophysical well logging in the Soviet Union - A Review; SPWLA 7th ann. log. symp. (Paper D)

Keys, W.S.
1967: Well logging in groundwater hydrology; SPWLA, ann. symp. (Paper K)

Kokesh, F.P.
1951: Gamma-ray logging; Oil Gas J., July 26, 7 p.

Landstrom, O., Christell, R., and Koski, K.
1972: Field experiments on the application of neutron activation techniques to *in situ* borehole analysis; Geoexploration, v. 10, no. 1, p. 23-39. (Feb.)

Lauber, A. and Landstrom, O.
1971: A Ge(Li) borehole probe for *in situ* gamma-ray spectrometry; AB Atomenergi, Studsuik, Sweden, Rt. AE-444, 26 p.

Lawson, B.L. and Cook, C.F.
1970: A theoretical and laboratory evaluation of Carbon Logging: Part II - Theoretical evaluation of oxygen interference; SPWLA 11th Ann. log. symp. (Paper B)

Lindseth, R.O.
1966: Application of signal theory to well log interpretation; SPWLA 7th ann log. symp.

Lobanov, E.M., Novikov, A.P., Nikanorov, G.S., and Khaidarov, A.A.
1966: Determining copper content in exploration drill-hole sections by activation logging; Min. Minerals Eng., v. 2, no. 8, p. 303-308.

Lobanov, E.M., Novikov, A.P., Nikanorov, G.S., Romanov, O.M., and Khaidarov, A.A.
1966: The efficiency of locating copper sulphide ores in drill-hole cores by neutron activation logging; Min. Minerals Eng., v. 2, no. 7, p. 261-264.

Lock, G.A. and Hoyer, W.A.
1973: Carbon-oxygen (C/O) log: Use and interpretation; Paper 4639 of Soc. of Petrol. Engineers of AIME, presented at 48th ann. meeting in Las Vegas, Sept. 30.

Marchant, L.C. and White, E.J.
1968: Comparison of log and core analysis results for an extremely heterogeneous carbonate reservoir; SPWLA 9th ann. log. symp. (Paper L)

McDougall, F.H., Dunn, W.L., and Gardner, R.P.
1971: Studies of the surface type γ-ray backscatter soil density gauges using collimation and spectrometry techniques; *in* Nuclear Engineering and Design, v. 16, p. 415-421.

McFadzean, T.B.
1972: Cross-plotting, a neglected technique in log analysis; Can. Well-Log. Soc. J., v. 5, no. 1, p. 69-99.

Nargolwalla, S.S., Rehman, A., St. John-Smith, B., Legrady, O., Strever, J., and Seigel, H.O.
1974: *In situ* borehole logging for minerals by neutron capture - prompt gamma measurements; Paper presented at 103rd AIME ann. mtg. in Dallas, Feb. 24-28.

Paap, H.J. and Scott, H.D.
1970: The use of ^{252}Cf as a neutron source for well logging; Paper presented at the "Symposium on application of Radioisotopes", American Institute of Chemical Engineers, 63rd Annual Meeting Nov. 29-Dec. 3, Chicago, Illinois.

Pickett, G.R.
1970: Applications for borehole geophysics in geophysical exploration; Geophysics, v. 35, no. 1, p. 81-92.

Pickett, G.R. and Artus, D.S.
1970: Prediction from logs of recoverable hydrocarbon volume, Ordovician carbonates: Williston Basin; Geophysics, v. 35, no. 1, p. 113-123.

Pirson, S.J.
1969: Environmental logging and mapping in the search for minerals; SPWLA 10th ann. log. symp. (Paper I)

Pirson, S.J., Alparone, N., and Avadisian, A.
1966: Implications of log-derived radioactivity anomalies associated with oil and gas fields; SPWLA 7th ann. log. symp.

Radioisotope Instruments in Industry and Geophysics v. 2, I.A.E.A.
1966: Copy of abstracts in English of 11 papers in Russian on subjects related to borehole nuclear geophysics;

Rasmussen, N.C.
1969: The potential of prompt activation analysis in industrial processing; Analysis Instrumentation, v. 7, p. 186-192. Instrument. Soc. Am., 580 William Penn Place, Pittsburgh, Pa., presented at the 15th AID Symposium, New Orleans, May.

Reeves, D.R.
1971: *In situ* analysis of coal by borehole logging techniques; Can. Min. Metall. Bull., Feb., also in Can. Inst. Min. Met. Trans., v. 74, p. 61-69.

Rhodes, J.R.
1969: Applications of neutron activation to on-stream analysis; Isotopes and Radiation Technology; v. 6, no. 4, p. 359-368.

Riboud, J. and Schuster, N.A.
1971: Well logging techniques; Proc. 8th World Pet. Cong., v. 3, p. 327-337.

Richardson, J.E.
1971: A method of calculating the capture cross section of oil for use with pulsed neutron capture logs; SPWLA 12th ann. log. symp. (Paper I), p. 7.

Savinski, D.
1962: Some analytical and statistical rules for the gamma-testing of naturally occurring deposits containing radioactive elements and for gamma-logging; Izv. Geophys. Ser., p. 659-663. translated by F. Goodspeed.

Scott, H.D. and Smith, M.P.
1973: The aluminum activation log; The Log Analyst, v. 14, no. 5, p. 3-12.

Seaborg, G.T.
1968: Radioisotope with 'Fantastic' practical applications; S. Afr. Min. Eng. J., Nov. 8, p. 1103-1108.

Senftle, F.E.
1970: Mineral exploration by nuclear techniques; Min. Cong. J., Jan., 6p.

Senftle, F.E., Evans, A.G., Duffey, D., and Wiggins, P.F.
1971: Construction materials for neutron capture gamma-ray measurement assembly using ^{252}Cf; Nuclear Tech., v. 10, Feb., p. 204-210.

Senftle, F.E., Philbin, P.W., and Sarigianis, P.
1968: Use of ^{252}Cf for mineral exploration: Comparison with accelerators for *in situ* neutron activation of silver; Isotopes Radiation Tech., v. 7, no. 4, p. 411-418.

Senko-Bulatnyi, I.N.
1964: Continuous gamma-spectrometer activation logging of Bauxite deposits; Izv. Geophys. Ser. No. 7, p. 1030-1036, translated by S.B. Dresner.

Simmons, G.
1966: Temperature logging and heat flow; SPWLA 7th ann. symp.

Snyder, D.
1974: Application of well logging to the exploration of porphyry copper systems; Paper presented at the 103rd AIME annual meeting in Dallas, Feb. 24-28.

Tanner, A.B., Moxham, R.M., and Senftle, F.E.
1972: A probe for neutron activation analysis in a drill hole using ^{252}Cf and a Ge(Li) detector cooled by a melting cryogen; Nuclear Instruments and Methods, 100, April, p. 1-7.

Threadgold, P.
1970: Applications of well-logging techniques to mining exploration boreholes; *in* Mining and Petroleum Geology, v. 2, ed. by M.J. Jones, Inst. Min. Met., London.

Threadgold, P. (cont.)
1971: Interpretation of thermal neutron die-away logs: Some useful relationships; SPWLA 12th ann. log. symp. (Paper L)

Tittle, C.W.
1961: Theory of neutron logging I; Geophysics, v. 26, no. 1, p. 27-39.

1966: Applications of radioisotope instruments in geophysics; in Radioisotope Instruments in Industry and Geophysics, v. 2, IAEA.

Tittle, C.W. and Allen, L.S.
1966: Theory of neutron logging II; Geophysics, v. 31, no. 1, p. 214-224.

Tittman, J., Sherman, H., Nagel, W.A., and Alger, R.P.
1966: The sidewall epithermal neutron porosity log; J. Pet. Tech., Oct.

Tixier, M.P. and Alger, R.P.
1970: Log evaluation of nonmetallic mineral deposits; Geophysics, v. 35, no. 1, p. 124-142 (also in SPWLA 8th ann. log. symp.).

Trombka, J.I., Senftle, F., and Schmadebeck, R.
1970: Neutron radiative capture methods for surface elemental analysis; Nuclear Instruments and Methods, 87, p. 37-43.

Truman, R.B., Alger, R.P., Connell, J.G., and Smith, R.L.
1972: Progress report on interpretation of the dual-spacing neutron log (CNL) in the U.S.; (in The Log Analyst, v. 13, no. 4, p. 3-21.)

Walters, E.J.
1968: Statistical study of neutron logs for correlation studies; SPWLA 9th ann. log. symp. (Paper F)

Whitaker, S.H.
1972: Lignite exploration in the Ravenscrag Formation of Southern Saskatchewan; Proc. 1st Geol. Conf. on Western Canadian Coal.; Res. Counc. Alta., Inf. Ser., no. 60.

Wichmann, P.A.
1971: Neutron activation for elemental determination in boreholes; SPWLA 13th ann. logging symp., May, (Paper G) also presented as paper at CWLS meeting May 1970 as "Elemental Deter. by neut. act. half life analysis" Reprint no. 7506.

1972: Notes on the accuracy of the neutron lifetime measurement; SPWLA 13th ann. log. symp. (Paper A) 15 p.

Wichmann, P.A., Hopkinson, E.C., and Youmans, A.H.
1967: Advances in nuclear production logging; SPWLA ann. log. symp. (Paper T)

Wichmann, P.A. and Webb, R.W.
1970: Neutron activation logging for silicon to aluminum ratios; J. Pet. Techn., Feb., p. 201-6

Wiggins, P.F., Duffey, D., and Senftle, F.E.
1970: Detection and analysis of titanium ore using $^{252}\mathrm{Cf}$; Trans. Am. Nuclear Soc. 13, no. 2, 490.

Youmans, A.H., Bishop, W.D., and Wichmann, P.A.
1970: Applications of the neutron lifetime log in new wells; SPWLA 11th Ann. log. symp. (Paper N)

Youmans, A.H., Hopkinson, E.C., and Wichmann, P.A.
1966: Neutron lifetime logging in theory and practice; SPWLA 7th ann. log. symp. (Paper Q)

Youmans, A.H. and Zimmerman, C.W.
1959: Recent advances in the use of nuclear physics in oil well surveys; World Petroleum Congress (5th), paper 17, sec. X, p. 207-214.

APPENDIX

The following list of nuclear borehole equipment is primarily designed to include those with the greatest possibility of being useful in mining geophysics. The information was compiled mainly from replies to enquiries sent to companies listed in the annual Geophysical Equipment and Services Directory published by the Society of Exploration Geophysicists.

It is hoped that at the time of writing at least the list will give a fairly complete and representative idea of the present state-of-the-art equipment and services available for nuclear borehole logging which are applicable to mineral exploration. The author apologizes for any possible omissions.

(1) ABEM, Geosearch Consultants, Suite 1114,
100 University Avenue, Toronto, Ontario,
M5J 1V6

- gamma spectral log
- gamma-gamma log
- depth to 1000 m
- detector 1" diam x 0.5 to 2.0 inches length NaI(T1)
- probe diameter 43 mm
- also semiconductor detector, 20-60 cc Ge(Li) with 20 times the resolution of a NaI(T1)

(2) AUSTRAL EXPLORATION SERVICES, Box 16,
Clarence Gardens, Edwardstown SA 5039,
Australia

- gamma spectral log
- depth to 600 m

(3) B.P.B. INDUSTRIES LTD., East Leake,
Nr. Loughborough, Leicestershire, England

- slimline tools operate in holes to 1¾" diameter
- depths to 6000 feet
- gamma ray probe 1½" O.D.
- neutron probe 1½" O.D. by 6 feet long
- offer complete service, including interpretation
- experience logging coal, potash, uranium, iron, evaporites and salt

(4) DATA PROBE LOGGING LTD., 3133 Doverville
Crescent S.E., Calgary, Alberta

- tools to run in size (AX) hole, depths 3000 feet plus
- natural gamma combined with single point resistivity
- γ-γ density and single point resistivity
- neutron

(5) DRESSER ATLAS, P.O. Box 1407, Houston, Texas
77001, U.S.A.

- NLL 1 11/16" O.D. by 22 feet (55 pounds weight)
- gamma ray 1 11/16" O.D. by 18 feet (50 pounds)

(6) EKCO Borehole Logger (X.R.F.) available
through INSTRONICS TECHNO-PRODUCTS LTD.,
Stittsville, Ontario

- primarily for use in mines
- depth (length) to 50 feet
- probe head mounted in flexible hose
- probe/hose diameter 1¾"
- recommend 2" diameter holes
- experience in tin mines in Cornwall, England
- can be set up to analyze for various elements

(7) EXPLORANIUM LIMITED, 436 Limestone Crescent, Downsview, Ontario

- 3 channel portable γ-ray spectrometer for logging
- probe 1¼" O. D. by 57" (or larger size)
- scintillation crystal ¾" x 3" = 1. 32 in^3.

(8) GEARHART-OWEN INDUSTRIES INC., P. O. Box 1939, Fort Worth, Texas 76101, U. S. A.

- γ-ray tool 1 11/16" diameter with ¾" x 1" NaI(T1) crystal also 7/8" x 4" crystal available also 1 3/8" x 18" geiger detector available
- other diameter tools 7/8", 1", 1 3/8" and larger
- dual detectors and combination tools available
- neutron tool 1 7/16" diameter (also 1 11/16" and larger)
- tool lengths about 10 feet, weight about 40 lb
- WIDCO Model 1200 portable logger (165 lbs) has a γ-ray tool 2" diameter by 37" long

(9) HALLIBURTON SERVICES LTD. (WELEX), 275 Bentall Bldg., 44 - 7th Avenue S. W., Calgary, Alberta

- γ-ray and neutron tool combined 1 5/8" O. D. by 20 feet (80 pounds)
- γ-ray tool 1 5/8" O. D. and 1. 66" by 13 feet (weight 50 pounds)

(10) MOUNT SOPRIS INSTRUMENT CO., Box 449, Delta, Colorado 81415, U. S. A.

- gamma log probe diameter 36 mm combined with electrical logs
- two detector gamma combined with electrical logs (42 mm)
- automatic dead-time correction circuitry
- depth to 1000 m

(11) SCHLUMBERGER LTD., 1250 Elveden House, Calgary, Alberta

- neutron logging tools 1 11/16" diameter
- CNL dual spacing, thermal neutron detector
- GNT detects high energy capture gamma rays and thermal neutrons
- γ-ray log
- TDT pulsed neutron, several γ-ray measurements after each pulse

(12) SCINTREX LTD., 222 Snidercroft Road, Concord, Ontario

- γ-ray spectral logging, to depths over 600 meters
- GSD-3 probe, ¾" x 2" crystal = 0. 88 in^3

(13) SYSTEMS DEVELOPMENT INCORPORATED, 1700 Surveyor Blvd., Carrollton, Texas 75006, U. S. A.

- combination tool called ACCUR-LOG
- probe 1 5/8" O. D. by 55" long
- γ-ray detector 7/8" x 1 1/4" NaI(T1)
- combined with S. P. and single point resistivity

7. DIRECTIONAL SURVEYING OF BOREHOLES

A.V. Dyck

Boreholes usually deflect to a greater or lesser extent away from the direction in which they are started. This can occur because the drill string is quite flexible over a distance which is very large compared to its diameter. Deflection is caused by the angle of the drill bit relative to the dip angle of the rocks being penetrated, the extent to which there is layering in the rock, and the extent to which layers differ in hardness. It then becomes important to determine the dip and orientation of the hole at any point along its length. There are several reasons why this is necessary. For example, it may be desirable to straighten the hole by inserting wedges since excess curvature causes large frictional forces on the drill rods; also, unknown deviations from the desired direction can lead to uncertainties in the interpretation of the geology. Our interests fall into the latter category in that proper interpretation of borehole geophysical surveys requires knowledge of the geometry of the hole.

Measurement of the dip and orientation of the hole must be made relative to some reference direction. Commonly used references are: 1) the earth's magnetic field, 2) the direction of the force of gravity, and 3) the direction determined by gyroscopic rotation. The magnetic field direction is not a convenient reference to use where magnetic rock formations cause local distortions of the field. The vertical as defined by gravity has been used as a reference by several different types of instruments. The oldest of these is probably the fluid-operated device which records the horizontal permanently by means of acid etching. Another method of obtaining a permanent recording is to photograph the position of a pendulum at various locations in the hole. The disadvantage of either type of instrument is that the record does not become available until the device is withdrawn from the hole. Furthermore only the dip of the hole is determined, but not its orientation. Krebs (1964) described an instrument which uses a pendulum to measure dip of the hole and a compass to measure the direction. The two measurements are recorded photographically at intervals down the hole by means of a timed, multiple-exposure system. Another instrument (Holm, 1964) employs a similar pendulum-compass arrangement but their positions are measured by electrical means and can therefore be recorded remotely at the surface. The diameter of this instrument is 35 mm and is capable of surveying to a depth of about 600 m.

Another type of device measures both dip and orientation by means of a single pendulum (Roxstrom, 1959; Holz, 1961). This instrument must be lowered into the hole by means of a torsionally rigid rod so that its azimuth with respect to the borehole axis can be controlled from the surface. The pendulum is constrained to move in a plane which contains the borehole axis. When this plane coincides with the vertical the pendulum either swings free or exerts a maximum force on a compensating mechanism whose output is recorded electrically at the surface. At this point the pendulum indicates the dip of the hole and the azimuth of the torsionally rigid rod projecting from the hole at the surface gives an indication of the orientation of the hole. The Craelius EM borehole dip indicator (Roxstrom, 1959) is suitable for surveying an EX hole to a depth of 300 m and can determine dip to within ± 0.2° and orientation to within ± 2°.

More recent developments in borehole surveying employ a gyroscopic reference. The dip and orientation of the probe are determined relative to a gyroscopically stabilized platform and monitored at the surface. Any drift which may occur in the instrument can be compensated by making spot checks while withdrawing the instrument from the hole. Some of the models available are sufficiently small to survey EX holes.

It is also possible to measure accumulated dip and orientation of a drillhole relative to its direction at the collar. A device which accomplishes this is the REFLEX-FOTOBOR (Hood, 1975). Dip and orientation are determined by measuring the bending of a long (12 m) flexible probe as it passes along the hole. The amount of flexing as indicated by the positions of three rings relative to the optical axis and the vertical as indicated by a bubble are recorded simultaneously by photographic means. The path of a hole may be determined with an accuracy of 0.1 per cent. Since there are no delicate moving parts, the instrument is much more robust than other types. Holes with a minimum diameter of 46 mm have been surveyed to depths as great as 1325 m.

In any program of geophysical exploration from boreholes it would be wise to include a directional survey. For example, in Sweden, small diameter (EX) drillholes have been known to deviate as much as 100 m over a 200 m length (Holm, 1964). A rapid, accurate survey of a borehole drilled in a mining environment, where there are likely to be magnetic sources, is probably most easily achieved with either a gyroscopic instrument or one of the flexing-rod type.

Acknowledgments

The author wishes to thank Dr. P.G. Killeen for critically reading the manuscript.

REFERENCES

Holm, A.
1964: An instrument for the determination of drill hole geometry; Geoexploration, v. 2, no. 1, p. 20-27.

Holz, P.
1961: New electronic instrument to survey boreholes; Can. Min. J., v. 82, no. 1, p. 45-46.

Hood, P.J.
1975: Mineral exploration: Trends and developments in 1974; Can. Min. J., v. 96, no. 2.

Krebs, E.
1964: Modern borehole surveying; Min. Mag., v. 3, no. 4, p. 220-233.

Roxstrom, E.
1959: Craelius EM bore-hole dip indicator; Can. Min. J., v. 80, no. 11, p. 78-84.

8. TEMPERATURE MEASUREMENT IN BOREHOLES FOR THE MINING INDUSTRY

A. M. Jessop and A. S. Judge

TEMPERATURE MEASUREMENTS

There are two quite different styles in the measurement of temperature in boreholes. One of these is employed regularly by the oil and gas industry and is readily available as a logging service. These logs are run shortly after the end of drilling; the temperatures recorded are of low accuracy and are representative of no more than the mud in the well. However, the log is continuous and the variations of temperature within the hole yield much valuable information to drilling engineers. The second style is used by geophysicists, in slim holes as well as in large wells, and provides a series of spot readings to a high accuracy. In order that the readings should reflect the true undisturbed temperature of the rock, it is necessary for some time to elapse between drilling and measuring. The high accuracy of these measurements is particularly useful in the delineation of permafrost boundaries. The remainder of this section will deal with the second style only.

Most of the temperature measurements in boreholes in the last century and the first half of this century were made by means of glass thermometers. Since a thermometer must be recovered for each reading, this was a very tedious process. Several other kinds of sensors have been tried, but only the thermistor has become popular as a high-resolution borehole thermometer. The main requirements of a borehole thermometer are: a fast response, and accuracy to 10 mK; in-place reading; simple calibration and associated instrumentation; and a portable and rugged nature. All temperature sensors lack one or more of these attributes except the thermistor but even that requires careful calibration and a detailed analysis of the results for the best precision. The thermistor has become the standard sensing element for precise measurement of temperature in boreholes.

The thermistor is used as an electrical resistance thermometer. It has a nominal resistance, normally specified at 25°C, of anything between a few hundred and a few million ohms. The temperature coefficient of resistance is negative and is about 4 per cent per degree. Early thermistors gave some trouble with calibration drift, but this problem is now very rare. The most convenient thermistors are encapsulated in a glass envelope, which is about 12 mm long and about 2 mm wide at the end containing the thermistor.

Thermistors must be calibrated before use, preferably against a good platinum thermometer system. A series of temperature-resistance pairs is produced for each thermistor. For an accuracy of 10 mK at all temperatures, an interval of no more than 5 K between calibration temperatures is permissible. The relation between resistance R and absolute temperature T is usually represented by:

$$R = A \exp(B/(T + C))$$

The parameters A, B and C are supposedly constant, but in practice they are slightly temperature-dependent. Analysis of the results of calibration is best done by computer, and read-out tables may be prepared. If an accuracy of 0.1 K is acceptable, thermistors can be bought ready-calibrated and matched, and the process of calibration can be avoided.

In use, the thermistor usually forms one arm of a Wheatstone bridge, but whatever measuring circuit is used, there will be an electric current through the thermistor. This electric current generates heat through normal resistive dissipation, and the thermistor is warmed by the act of measurement. The extent to which warming occurs is described by the 'dissipation constant' of the thermistor, and is usually expressed in mW/K, or the amount of power that will produce a temperature rise of 1 K when the thermistor is surrounded by still air. In practice the situation of the thermistor is always more favourable than suspension in still air. A current meter is used as a null-detector in the bridge, and the bridge voltage must be sufficiently high to provide sufficient current. Since the voltage required is proportional to the resistance of the bridge, the power dissipated is also proportional to the resistance, and so a low resistance thermistor is favoured.

For the purpose of borehole logging the thermistor is attached to the end of a long cable, and so two long leads are included in the arm of the bridge. The resistance of the leads can amount to a few hundred ohms, and this must be subtracted from the measured resistance before the calculation of temperature. Leakage resistance between the wires of the cable can also occur. The resistance of the leads varies during the course of logging, owing to changes of temperature of the cable, and these changes can be monitored by means of a short-circuit loop. Errors from resistance in the leads can be kept to acceptable levels by keeping the thermistor resistance high compared with the cable resistance, but low compared with the leakage resistance of the cable. In use, the resistance of the thermistor is derived from the equation:

$$R = R_m - R_s + R_m^2/R_o$$

where R_m = measured resistance of thermistor and cable (usually 5 kΩ to 25 kΩ)

R_s = resistance of short-circuit loop of leads (a few hundred ohms)

R_o = open-circuit resistance of leads (should exceed 100 MΩ)

The resistance chosen for the thermistor is a compromise between these different restrictions and it is usually possible to achieve 0.01 K accuracy with little difficulty.

There are two different ways of using thermistors in the field. One is to install several thermistors into a multi-conductor cable, and to leave the cable in a borehole. The second involves the use of a single thermistor in a probe on the end of a three- or four-conductor cable, which may be lowered to a series of positions within a borehole. These two methods each have their own advantages and disadvantages. The multi-thermistor cable is useful in a hole where there is a risk of blockage, since once it is installed it can remain in place. It also yields good data on the change of temperature at the measuring points. It can be read quickly and easily, and the reader need only transport his bridge to the site. On the other hand, the measuring points must be decided in advance, and are then permanently fixed. Also a new cable must be made for each hole thereby increasing the work load. Furthermore it has been found by experience that an unarmoured cable will not survive in a large-diameter mud-filled cased hole freezing in permafrost. The single thermistor method has the advantages that one cable may be used many times at different locations, the thermistor may be recalibrated, and there is complete flexibility in the choice of measurement intervals. The disadvantages are the risk of holes becoming blocked, and the inability to return the thermistor to exactly the same points in the hole. The extra equipment to transport is not very important since a 1000 m cable weighs only about 10 kg.

The single-thermistor configuration is usually favoured over the multi-thermistor cable. The thermistor is usually connected to the cable by a plug, to ensure ease of interchange and removal for recalibration, and is inserted into a thin tube that projects below the bottom of a pressure-tight probe, to ensure good contact with unstirred water. A film of oil gives good contact between the thermistor and the enclosing tube. The adjustment to the new temperature and the dissipation of the thermal mass of the probe are achieved within about one minute, which is about the time required to make a reading. Measurements are always made when the probe is on the downward journey, since the movement of probe and cable stir the fluid in the hole, and reliable results can only be achieved before this occurs.

A set of equipment is shown in Figure 8.1. The equipment as illustrated, can be carried by one man, and can be used to depths of about 1000m. At greater depths a stronger and heavier cable is required, and a power driven winch becomes necessary. The pressures encountered by the probe are also greater, and a better seal between the probe and cable is needed. Nevertheless, the majority of measurements in slim holes are at depths less than 1000 m, and it is only occasionally that equipment in excess of that shown is needed.

APPLICATIONS

The above section has described the technology of temperature measurement in some detail. A bibliography on thermistors, their application and suitable measuring circuits for them, is given in Bibliography I. The questions to ask at this stage concern the practical value of measuring underground temperatures and determining local and regional heat flux. The earliest observations on the earth's internal temperature were made in the underground mines of Europe. Robert Boyle in 1671 summarized an account by Morinus "who above forty-five years ago, visited the deep Hungarian-mines ...., and takes notice .... that when they had descended about 80 fathoms beneath the surface of the earth, he began to feel a breath of an almost luke-warm air; which warmth increased upon him, as he descended lower". Such observations sparked some of the earliest speculations on the nature and origin of the earth and which led to the heat flow studies conducted today. Boyle concluded from some of these early observations that; "For it seems probable to me, that in these yet inpenetrated Bowells of the Earth, there are great store-houses of either actual Fires, or places considerably Hot, or, (in some Regions) of both; from which Reconditories (if I may so call them) or magazines of hypogeall heat, that quality is communicated, especially by Subterraneall Channells, Clefts, Fibres or other Conveyances, to the less deep parts of the Earth, either by a propagation of heat through the substance of the interposed part of the Soil (as when the upper part of an Oven is remisly heated by the same Agents that produce an intense heat in the Cavity,) or by a more easy diffusion of the Fire or heat through the above mentioned Conveyances as may be exemplified by the pipes that convey heat in some Chymicall structures: Or else, (which is perhaps that most usuall way,) by sending upward shot mineral Exhalations and Steams".

As mines were pushed deeper considerable problems arose with the problems of heat and ventilation and the most important practical use of rock temperatures has been in ventilation design in mines (Cleland, 1933). Measured temperature gradients across Canada vary from $5^{\circ}C\ km^{-1}$ to as high as $80^{\circ}C\ km^{-1}$ leading to underground temperatures across Canada which may be as low as $-17^{\circ}C$ in the far north to as high as $100^{\circ}C$ in western Canada within the top kilometre of the earth's crust. Bibliography II is a bibliography of published underground temperature measurements across Canada which used together with the prediction techniques suggested by Judge (1973) should provide useful base data for such problems. Other environmental mining problems partially thermal in origin have arisen as mining development is pushed north into the permafrost regions of Canada. The presence or absence of frozen ground is important in the design of open pit walls and in setting explosive charges. At Schefferville, within the discontinuous zone of permafrost, subsurface temperatures are used as a tool to map the distribution of permafrost (Nicholson and Granberg, 1973; Nicholson and Thom, 1973). Within the continuous zone the presence of permafrost can be beneficial provided its integrity is maintained, particularly in rocks with high permeability when unfrozen, such as occur at the Polaris Mine on Little Cornwallis Island in the Canadian Arctic (Judge, in prep.). This requires special ventilation design for underground operations, in which a balance must be achieved between environmental and human concerns. The rate of penetration into the rock walls of the thermal disturbance due to ventilation effects can be determined using the method proposed by Jaeger and Le Marne (1963). Similarly, if underground vertilation temperatures are maintained above $0^{\circ}C$ in a permafrost area, the rate of penetration of

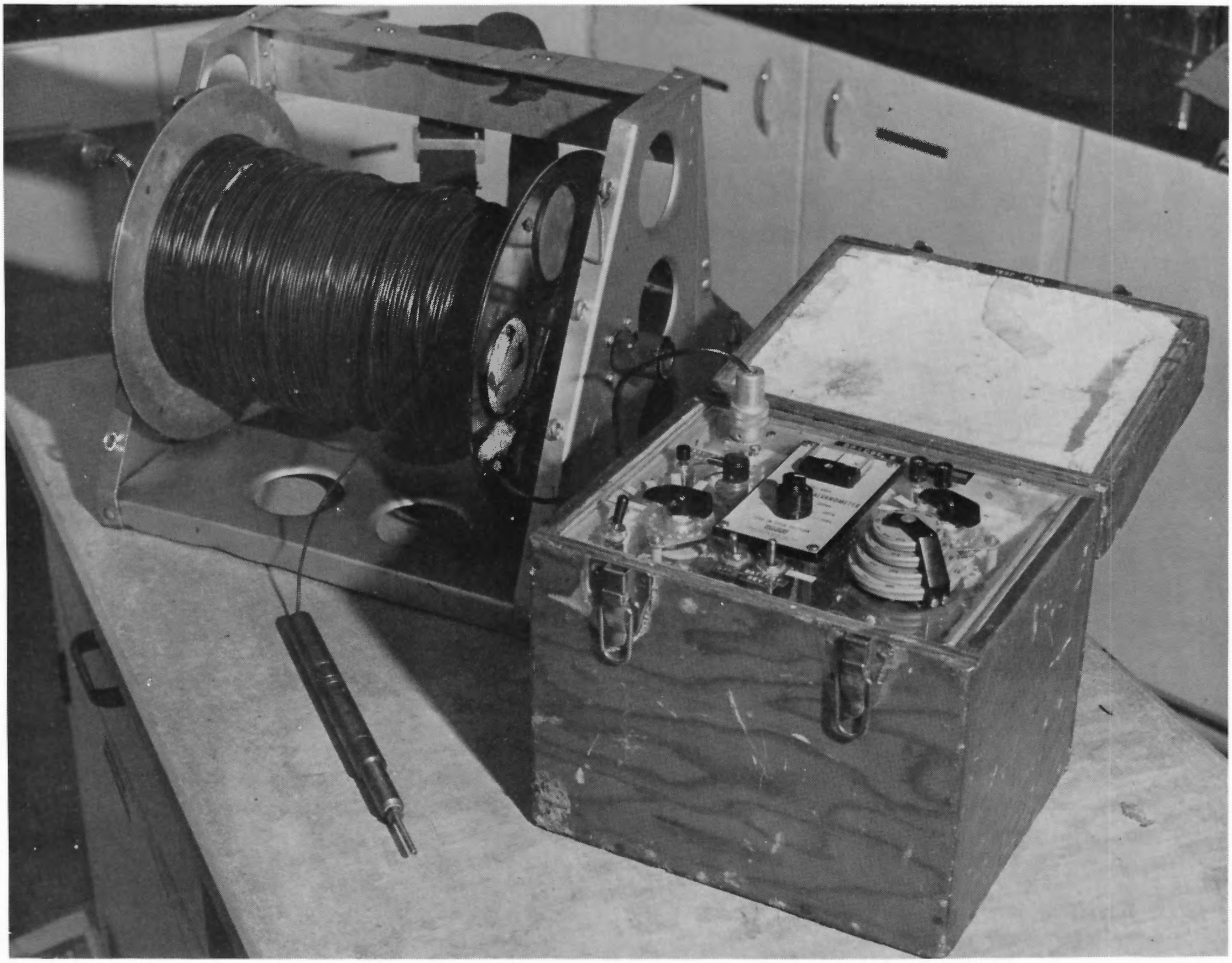


Figure 8.1. Temperature measurement equipment.

thaw into the rock wall can also be assessed.

Temperature measurements, coupled with isotope studies, of water in fracture zones within the mine may assist in locating fracture systems and their relationship to each other and to the surface (Beck and Neophytou, 1968), and may thus be of use in "dewatering" mines and in locating oxidizing sulphides.

A rather different application is to use temperature observations as a prospecting tool to locate new orebodies. Several papers have attempted to correlate underground temperatures with mineral bodies e.g. Stainer (1923), Lovering (1948), Lazar (1963). Such identifications can be caused by relatively few mechanisms: i) heat refraction as a result of the thermal conductivity contrast between the ore and the surrounding rocks; ii) local heat generation contrasts resulting from abnormally high levels of uranium, thorium and potassium in the ore zone (this of course may constitute the ore) or from the oxidation of sulphides; iii) recent intrusion of felsic volcanics with which the ore is associated; iv) ore-associated fracture zones along which water is moving at a different temperature to normal rock temperature at that location.

Temperature anomalies associated with these mechanisms may vary by several orders of magnitude but generally the largest will be associated with water movements, young intrusives or oxidizing sulphides. Anomalies associated with radioactive heat generation from an orebody could approach $1^{\circ}C$ whereas those associated with heat refraction in the vicinity of large sulphide bodies are unlikely to exceed $0.2^{\circ}C$.

Examples of related work which may be of value in assessing such prospects are Blackwell and Baag (1973), Emmons (1915), Irvine (1970), Jaeger (1964), Lewis (1969), Lovering (1935, 1948, 1955), McBirney (1963), Sass *et al.* (1968), Simmons (1961, 1967), Van Orstrand (1932, 1934). The rapid penetration of ventilation effects in an underground drift or stope must be taken into account in attempting to analyze such results (Jaeger and Le Marne, 1963).

Bibliography III lists a selection of papers considered of value for mineral prospecting, both surface and underground, by geothermal methods.

Recent regional studies of heat flow are starting to outline the thermal structure of the continents and hence provide an insight into the location of mining belts (Birch *et al.*, 1968; Roy *et al.*, 1968; Blackwell, 1971).

BIBLIOGRAPHY I

A selected bibliography on thermistors and their use for temperature measurements

The numbers in brackets after each entry refer to the subject headings for which the paper makes useful reading according to the following code:

1. Manufacture and construction.
2. Calibration and characteristic curves.
3. Stability.
4. Measuring circuits for.

Baker, H. D., Ryder, E. A., and Baker, N. H.
1961: Temperature measurement in engineering; v. 2, p. 5, Wiley and Sons. (3)

Beakley, W. K.
1951: The design of thermistor thermometers with linear calibration; J. Sci. Instr., v. 28, p. 176-179. (4)

Beck, A. E.
1956: The stability of thermistors; J. Sci. Instr., v. 33, p. 16-17. (3)

1963: Lightweight borehole temperature measuring equipment for resistance thermometers; J. Sci. Instr., v. 40, p. 452-454. (4)

1965: Techniques of measuring heat flow on land; Chap. 3 in Terrestrial Heat Flow, Geophys. Monogr. no. 8 NAS-NRC Publ. no. 1288. (4)

1966: Problems in measuring temperature and terrestrial heat flow in deep boreholes; *in* Drilling for scientific purposes, ed. Findlay and Smith; Geol. Surv. Can., Paper 66-13, p. 77-84. (4)

Becker, J. A., Green, C. B., and Pearson, G. L.
1946: Properties and uses of thermistors-thermally sensitive resistors; Am. Inst. Elec. Eng. Trans., v. 65, p. 711-725. (2, 3)

Black, J. S.
1957: A temperature-controlled tank for calibrating reversing thermometers; U. S. Navy Elect. Lab. Rep. no. 784. (2)

Bosson, G., Gutmann, F., and Simmons, L. M.
1950: A relationship between resistance and temperature of thermistors; J. Appl. Phys., v. 21, p. 1267-1268. (2)

Clark, J. A. and Kobayashi, Y.
1967: Properties of thermistors; C. R. R. E. L. Tech. Rep. no. 188, p. 28. (1, 3)

Diment, W. H. and Robertson, E. C.
1963: Temperature, thermal conductivity and heat flow in a drilled hole near Oak Ridge, Tennessee; J. Geophys. Res., v. 68, p. 5035-5047. (3)

Doig, R., Saull, V. A., and Butler, R. A.
1961: A new borehole thermometer; J. Geophys. Res., v. 66, p. 4263-4264. (4)

Droms, C. R.
1962: Thermistors for temperature measurements *in* temperature, its measurement and control in science and industry; Am. Inst. Phys., v. 3, p. 339-346. Reinhold. (3, 4)

Fenwall Electronics Inc.
Methods for designing linear temperature read-out circuits; Thermistor Application Notes no. AN-1, Fenwall Electronics. (4)

Capsule thermistor course; Fenwall Electronics no. L-3. (1, 4)

Stability and reliability characteristics; Fenwall Electronics no. TD-1. (3)

Fridberg, S. A.
1955: Semiconductors as thermometers *in* Temperature its Measurement and Control in Science and Industry; Am. Inst. Phys., v. 2, p. 359-380, Reinhold. (1, 2, 3)

Harvey, M. E.
1968: Precision temperature-controlled water bath; Rev. Sci. Instr., v. 39, p. 13-18. (2)

Jessop, A. M.
1964: A lead-compensated thermistor probe; J. Sci. Instr., v. 41, p. 503-504. (4)

Johnson, P. R.
1970: A new temperature resistance relationship for thermistors; Inst. Arctic Envir. Eng., Univ. Alaska Publ. N-7003, p. 6. (2)

Jones, E.W.
1965: Calibration techniques for thermistors; Instr. Control Systems, v. 38, p. 123-124. (2)

Judge, A.S.
1972: Geothermal measurements in a sedimentary basin; Unpubl. thesis, Univ. Western Ontario 380 p. (1, 2, 3, 4)

1973a: Ground temperature measurement using thermistors; *in* Proc. Permafrost Thermal Regime Seminar, Saskatoon 1972, Tech. Mem. no. 108, Assoc. Comm. Geotech. Res., NRC p. 13-25. (1, 2, 3, 4)

1973b: Measurement of the thermal regime, Section 2, p. 12-27 *in* Thermal Regime of the Mackenzie Valley: Observations of the Natural State; Environmental and Social Comm. Northern Pipelines Rept. 73-38. (2, 3, 4)

Kljucec, N.M. and Telford, A.S.
1972: Well temperature monitoring with thermistor cables through permafrost; Paper no. 7256 presented at Pet. Soc., Can. Inst. Min. Met., Meeting, April. (4)

Misener, A.D. and Beck, A.E.
1960: The measurement of heat flow over land; Chap. 2 *in* Methods and Techniques in Geophysics, ed. Runcorn, S.K. 1, Interscience. (4)

Misener, A.D. and Thompson, L.G.D.
1952: The pressure coefficient of resistance of thermistors; Can. J. Tech., v. 30, p. 89-94. (4)

Muller, R.H. and Stalten, H.J.
1953: Use of thermistors in precise measurement of small temperature differences; Anal. Chem., v. 25, p. 1103-1106. (3)

Neilson, K.E.C.
1959: Temperature measurements with thermistors in concrete; Swedish Cement Concrete Res. Inst. Bull. 34, p. 44. (3)

Olson, J.R. and Brumley, D.F.
1961: Optimum parameters for linearising thermistor temperature bridges; U. S. Navy Electron. Lab. Tech. Memo no. TM-460. (4)

Osterkamp. E.
1970: Thermistors for temperature measurement; Inst. Arctic Envir. Eng., Univ. Alaska Publ. B7003, p. 9. (2, 3)

Raspet, R., Swartz, J.H., Lillard, M.E., and Robertson, E.C.
1966: Preparation of thermistor cables used in geothermal investigations; U.S. Geol. Surv. Bull., 1203-C, p. 1-11. (2)

Robertson, E.C., Raspet, R., Swartz, J.H., and Lillard, M.E.
1966: Properties of thermistors used in geothermal investigations; U.S. Geol. Surv. Bull. 1203-B, p. 1-34. (1, 2, 3)

Staley, R.C.
1952: Performance characteristics of Sanborn rod thermistors; Am. Meteorol. Soc. Bull., v. 33, p. 67-72. (3)

Steinhart, J.S. and Hart, S.R.
1968: Calibration curves for thermistors; Deep Sea Res., v. 15, p. 497-503. (2)

Swartz, J.H.
1954: A geothermal measuring circuit; Science, v. 120, p. 573-574. (4)

Swartz, J.H. and Raspet, R.
1961: Thermal shock and its effect on thermistor drift; Nature, v. 190, p. 875-878. (3)

Tavernier, P. and Prache, P.
1952: Influence de la pression sur la résistivité d'une thermistance; J. Physique et Radium, v. 13, p. 423-426. (3)

Victory Engineering
1966: High reliability thermistors; Veco Tech. Bull. V1142A, p. 6. (3)

1967a: Thermistor bridges; Veco Tech. Bull. V369. (4)

1967b: Handbook of thermistor applications; Veco Tech. Bull. V1133. (1, 2, 3, 4)

Weaver, J.G.
1967: Geothermal temperature measurements using oscillators; unpubl. M.Sc. thesis, Univ. Toronto. (4)

BIBLIOGRAPHY II

Selected Bibliography of Heat Flow Measurements and Subsurface Temperatures in Canada

Anglin, F.M.
1964: Subsurface temperature in Western Canada; Unpubl. M.Sc., Univ. Western Ontario.

Anglin, F.M., Beck, A.E.
1964: The use of terrestrial heat flow data in interpreting regional geology; Proc. Third Ann. Conf. Ont. Pet. Inst.

1965: Regional heat flow pattern in Western Canada; Can. J. Earth Sci., v. 2, p. 176-182.

Annersten, J.L.
1964: Permafrost studies in Labrador-Ungava; ed. J.B. Bird, McGill Sub-Arctic Res. Paper no. 16.

Aston, D.
Average soil temperature based on the period 1960 to 1968; Canada, Dep. Transport, Meteorol. Br. C.D.S. no. 5 -69.

Baillie, A.D. and Veesey, G.E.
1968: Metamorphism in a Middle Devonian reef complex; rev. H. Heise, Oilweek, Feb. 12, p. 10-12.

Ballard, T.M.
1972: Subalpine soil temperature regimes in southwestern British Columbia; J. Arctic Alpine Res., v. 4, p. 139-146.

Beck, A.E.
1962: Terrestrial flow of heat near Flin Flon, Manitoba; Nature, v. 195, p. 368-369.

1964: Flusso Di Calore Terrestre Ed Energia Geotermica; *in* Italian, La Scuola in Azione San Donato Milanese, ente Nazionale Idrocarburi, E.N.I., p. 165-189.

1970: Non-equivalence of oceanic and continental heat flows and other geothermal problems; Comments Earth Sci. Geophys., v. 1, p. 29-34.

Beck, A.E. and Logis, Z.
1963: Terrestrial flow of heat in the Brent Crater; Nature, v. 201, p. 383.

Beck, A.E. and Judge, A.S.
1969: Analysis of heat flow data-detailed observations in a single borehole; R. Astron. Soc., Geophys., v. 18, p. 145-158.

Beck, A.E. and Neophytou, J.P.
1968: Heat flow and underground water flow in the Coronation Mine area; Geol. Surv. Can., Paper 68-5, p. 229-239.

Beck, A.E. and Sass, J.H.
1966: A preliminary value of heat flow at the Muskox Intrusion near Coppermine, N.W.T., Canada; Earth Planet. Sci. Lett., v. 1, p. 123-129.

Beck, A.E., Anglin, F.M., and Sass, J.H.
1971: Analysis of heat flow data - *in situ* thermal conductivity measurements; Can. J. Earth Sci., v. 8, p. 1-19,

Bremmer, P.C.
1955: Diamond drilling in permafrost at Resolute Bay, N.W.T.; Can., Dom. Obs., v. 16, p. 365-390.

Brown, R.J.E.
1956: Permafrost investigations in the Mackenzie Delta; Can. Geograph, no. 7, p. 21-26.

1965: The relation between mean annual air and ground temperatures in the permafrost region of Canada; Proc. Int. Permafrost Conf. NAS-NRC Publ. 1287, p. 241-247.

1965: Some observations on the influence of climate and terrain features on the Permafrost at Norman wells, N.W.T.; Can. J. Earth Sci., v. 2, p. 15-31.

1967: Comparison of permafrost conditions in Canada and the U.S.S.R.; Polar Record, v. 13, p. 741-752.

1967: Permafrost Map of Canada; Nat. Res. Counc. (NRC 9769) and Geol. Surv. Can. (Map 1246A).

1970: Permafrost in Canada; Univ. Toronto Press, 234 p.

1972: Permafrost in the Canadian Arctic Archipelago; A. Geomorphol. Suppl., v. 13, p. 102-130.

1973: Influence of climatic and terrain factors on ground temperatures at three locations in the permafrost region of Canada; *in* Permafrost: North American Contrib. Second. Int. Conf., NAS ISBNO-309-02115-4, p. 27-34.

Brown, R.J.E. and Péwé, T.L.
1973: Distribution of permafrost in North America and its relationship to the environment: A review 1963-1973; *in* Permafrost: North American Contrib. Second Int. Conf.; NAS, Washington, p. 71-100.

Brown, W.G., Johnston, G.H., and Brown, R.J.E.
1964: Comparison of observed and calculated ground temperatures with permafrost distribution under a northern lake; Can. Geotech. J., v. 1, p. 147-154.

Butler, R.B.
1961: Terrestrial heat flow in the St. Lawrence Lowland of Quebec; unpubl. M.Sc. thesis, McGill Univ., 49 p.

Cermak, V.
1971: Underground temperature and inferred climatic temperature of the past millenium; Palaeogr. Palaeoclimatol. Palaeoecol., v. 10, p. 1-19.

Cermak, V. and Jessop, A.M.
1971: Heat flow, heat generation, and crustal temperature in the Kapuskasing area of the Canadian Shield; Tectonophysics, v. 11, p. 287-303.

1972: Heat flow and heat production in the Canadian Shield; Geothermics, v. 1, p. 70-72.

Cleland, R.H.
1933: Rock temperatures and some ventilation conditions in the mines of Northern Ontario; Can. Inst. Min. Met., Trans., p. 379-407.

Cook, F.A.
1955: Near surface soil temperature measurements at Resolute Bay, N.W.T.; Arctic, v. 9, p. 237-249.

1958: Temperatures in permafrost at Resolute, N.W.T.; Geogr. Bull., v. 12, p. 5-18.

Crain, I.K.
1967: The influence of Post-Wisconsin climatic change; unpubl. M.Sc. thesis, McGill Univ.

1968: The glacial effect and the significance of continental terrestrial heat flow measurements; Earth Planet. Sci. Lett., v. 4, p. 69-72.

1969: A simple method of calculating climatic corrections to heat flow measuremnts; Can. J. Earth Sci., v. 6, p. 499-502.

Doig, R.
1961: A further study of terrestrial heat flow in the St. Lawrence Lowlands of Quebec; unpubl. M.Sc. thesis, McGill Univ.,

Fou, J.T.K.
1969: Thermal conductivity and heat flow at St. Jerome, Quebec; unpubl. M.Sc. thesis, McGill Univ.

French, H.M.
1970: Soil temperature in the active layer, Beaufort Plain; Arctic, v. 23, p. 229-239.

Garland, G.D., and Lennox, D.H.
1962: Heat flow in Western Canada; J.R. Astr. Soc. Geophys., v. 6, p. 245-262.

Goguel, J.
1956: Influences des Variations de la Température Superficielle sur le Degré Géothermique, en Particulier dans le Cas d'un Sol Gelé Permanent; Annales Géophys., v. 12, p. 183-201.

Gough, D.I. and Porath, H.
1970: Long-lived thermal structure under the southern Rocky Mountains; Nature, v. 226, p. 837-839.

Gray, J.T.
1966: Permafrost studies at Knob Lake, central Labrador-Ungava 1964 - 1965; McGill Sub-Arctic Res. Paper no. 21.

Hamza, V.M.
1973: Vertical distribution of radioactive heat production in the Grenville geological province and the sedimentary sections overlying it; unpubl. Ph.D. thesis, Univ. Western Ontario.

Hemstock, R.A.
1949: Permafrost at Norman Wells, N.W.T.; Imperial Oil Ltd., Calgary.

Hobson, G.D., Beck, A.E., and Findlay, D.C.
1966: Notes on geophysical logs and borehole temperature measurement from the Muskox Drilling Project; *in* Drilling for Scientific Purposes, ed. Findlay and Smith, Geol. Surv. Can., Paper 66-13, p. 108-122.

Jacobsen, G.
1963: Deep permafrost measurement in North American; Polar Record, v. 11, p. 595-596.

1964: Geothermal research in Canada; Can. Min. Metall. Bull., v. 67, p. 1-4.

1968: Three measurements of heat flow in Eastern Canada; Can. J. Earth Sci., v. 5, p. 61-68.

1970: Depth of permafrost; Oilweek, Jan. 12, p. 22-25.

1971: The distribution of glacial perturbation of heat flow in Canada; Can. J. Earth Sci., v. 8, p. 162-166.

1972: Heat flow and permafrost; Can. Min. Met. Bull., v. 65, p. 45-48.

Jessop, A.M. and Judge, A.S.
1971: Five measurements of heat flow in southern Canada; Can. J. Earth Sci., v. 8, p. 711-716.

Johnston, G.H. and Brown, R.J.E.
1964: Some observations on Permafrost Distribution at a lake in the Mackenzie Delta, N.W.T., Canada; Arctic, v. 17, p. 163-175.

Judge, A.S.
1972: Geothermal measurements in a sedimentary basin; unpubl. Ph.D. thesis, Univ. Western Ontario.

1972: Predicting the depth of permafrost; Oilweek, July 19th.

1973: The prediction of permafrost thickness; Can. Geotech. J., v. 10, p. 1-11.

1973: Deep temperature observations in the Canadian North, in Permafrost; North American Contrib. Second Int. Conf. Nat. Acad. Sciences ISBN 0-309-02115-4, p. 35-40.

1973: Thermal regime of the Mackenzie Valley; Observations of the natural state; Environmental-Social Comm. Northern Pipelines Rep. no. 73-38, p. 170.

1974: Geothermal measurements in Northern Canada; in Geology of the Canadian Arctic G.A.C./C.S.P.G., Spec. Vol., p. 301-311.

1974: The occurrence of offshore permafrost in northern Canada; *in* Beaufort Sea Symposium Arctic. Inst. North America (in press).

Judge, A.S. and Beck, A.E.
1967: An anomalous heat flow layer at London, Ontario; Earth Plan. Sci. Lett., v. 3, p. 167-170.

1973: Analysis of heat flow data - Several boreholes in a sedimentary basin; Can. J. Earth Sci., v. 10, p. 1494-1507.

Lachenbruch, A.H.
1957: Thermal effects of the ocean on permafrost; Bull. Geol. Soc. Am., v. 68, p. 1515-1529.

Lachenbruch, A.H. and Marshall, B.V.
1969: Heat flow in the Arctic; Arctic, v. 22, p. 300-311.

Law, L.K., Patterson, W.S.B., and Whitham, K.
1965: Heat flow determinations in the Canadian Arctic Archipelago; Can. J. Earth Sci., v. 2, p. 59-71.

Leith, T.H.
1952: Heat flow at Kirkland Lake; Am. Geophys. Trans., v. 33, p. 435-443.

Lewis, T.J.
1969: Terrestrial heat flow at Eldorado, Saskatchewan; Can. J. Earth Sci., v. 6, p. 1191-1197.

Mackay, J.R.
1967: Permafrost depths, lower Mackenzie Valley, N.W.T.; Arctic, v. 20, p. 21-26.

1971: The origin of massive icy beds in permafrost western Arctic Coast Canada; Can. J. Earth Sci., v. 4, p. 397-422.

1972: The world of underground ice; Ann. Assoc. Am. Geogr., v. 62, p. 1-22.

1972: Offshore permafrost and ground ice, southern Beaufort Sea, Canada; Can. J. Earth Sci., v. 9, p. 1550-1561.

Mathews, W.H.
1972: Geothermal data from the Granduc areas, northern Coast Mountains of British Columbia; Can. J. Earth Sci., v. 9, p. 1333-1337.

Misener, A.D.
1949: Temperature gradients in the Canadian Shield; Can. Inst. Min. Met. Trans., v. 52, p. 125-132.

1955: Heat flow and depth of permafrost at Resolute Bay, Cornwallis Island, N.W.T., Canada; Am. Geophys. U. Trans., v. 36, p. 1055-1060.

Misener, A.D. and Cleland, R.H.
1949: Temperature gradients in Kirkland Lake mines; Ont. Dept. Mines, v. 57, p. 60-62.

Misener, A.D. and Thompson, L.G.D.
1950: Temperature gradients in Ontario and Quebec; Can. Inst. Min. Met. Trans., v. 53. p. 368-371.

Misener, A.D., Thompson, L.G.D., and Uffen, R.J.
1951: Terrestrial heat flow in Ontario and Quebec; Am. Geophys. U. Trans., v. 32, p. 729-738.

Misener, A.D., Bremner, P.C., and Hodgson, J.H.
1956: Heat flow measurements in permafrost at Resolute Bay, N.W.T.; J. R. Astron. Soc. Can., v. 50, p. 14-24.

Mustonen, E.D.
1967: A micro-geothermal survey, Lake Dufault, Quebec; unpubl. M.Sc. thesis, Univ. Western Ontario.

Nicholson, F.H. and Granberg, H.B.
1973: Permafrost and snowcover relationships near Schefferville; in Permafrost North American Contrib. Second. Int. Conf. NAS, Washington, p. 151-158.

Nicholson, F.H. and Thom. B.G.
1973: Studies at the Timmins 4 Permafrost experimental sites; in Permafrost: North American Contrib. Second. Int. Conf. NAS, Washington, p. 159-165.

Paterson, W.S.B.
1968: A temperature profile through the Meighen Ice Cap, Arctic Canada; I.U.G.G. Int. Assoc. Scient. Hydrol. Snow and Ice Comm. Reports and Discussion (IASH no. 49), p. 440-449.

Paterson, W.S.B. and Law, L.K.
1966: Additional heat flow determinations in the area of Mould Bay, Arctic Canada; Can. J. Earth Sci., v. 3, p. 237-246.

Pye, G.B. and Hyndman, R.D.
1972: Heat flow measurements in Baffin Bay and the Labrador Sea; J. Geophys. Res., v. 77, p. 938-945.

Rankin, D.S.
1973: Heat flow-heat production studies in Nova Scotia; unpubl. Ph.D. thesis, Dalhousie Univ.

Rankin, D.S. and Hyndman, R.D.
1971: Shallow water heat flow measurements in Bras d'Or Lake, Nova Scotia; Can. J. Earth Sci., v. 8, p. 96-101.

Rao, R.U.M. and Jessop, A.M.
1974: A comparison of the thermal characters of shields; Can. J. Earth Sci. (in press).

Sass, J.H., Killeen, P.G., and Mustonen, E.D.
1968: Heat flow and surface radioactivity in the Quirke Lake Syncline near Elliot Lake, Ontario, Canada; Can. J. Earth Sci., v. 5, p. 1417-1428.

Sass, J.H., Lachenbruch, A.H., and Jessop, A.M.
1971: Uniform heat flow in a deep hole in the Canadian Shield and its paleoclimatic implications J. Geophys. Res., v. 76, p. 8586-8596.

Saull, V.A., Clark, T.H., Doig, R.P., and Butler, R.B.
1962: Terrestrial heat flow in the St. Lawrence Lowland of Quebec; Can. Min. Metall. Bull., v. 65, p. 63-66.

Taylor, A.E. and Judge, A.S.
1974: Canadian geothermal data collection-Northern Wells 1955 to February 1974; Geothermal Series, no. 1, Can., Earth Phys. Br., 171 p.

Thompson, A. and Bremner, P.C.
1952: Permafrost drilling and soil temperature measurements at Resolute, Cornwallis Islands, Canada; Nature, v. 170, p. 705-706.

Wright, J.A.
1968: Geothermal investigations using *in-situ* techniques; unpubl. Ph.D. thesis, Univ. Toronto.

BIBLIOGRAPHY III

Selected Bibliography of Applied Geothermal Methods in Exploration and Mining

Shallow Geothermal Prospecting

Bouwhuijsen, J.N.A. v.d.
1934: The thermocouple proves useful on a geophysical survey; Eng. Min. J., v. 135.

Dedkova, D., Halousek, J., Kremar, B., and Prihoda, K.
1970: Geothermal prospecting in shallow holes and its limitations; Geothermics Spec. Issue no. 2, p. 1244-1249.

Drummond, J.E. and McNabb, A.
1962: On the analysis of surface temperature surveys; N.A. J. Geol. Geophys., v. 5, p. 3-17.

Geertsma, J.
1971: Finite element analysis of shallow temperature anomalies; Geophys. Prospect., v. 19, p. 662-681.

Jakosky, J.J.
1950: Thermal methods; Chap. 9, p. 983-985, *in* Exploration Geophysics, Trija, California.

Kappelmeyer, O.
1957: The use of new surface temperature measurements for discovering anomalies due to causes at depth; Geophys. Prospect., v. 5, p. 239-259.

Kremar, B. and Masin, J.
1970: Prospecting by the geothermic method; Geophys. Prospect., v. 18, p. 255-260.

Lovering, T.S. and Goode, H.D.
1963: Measuring geothermal gradients in drillholes less than 60 ft. deep, East Tintac District Utah; U.S. Geol. Surv., Bull. 1172, p. 48.

Paul, M.
1939: Experience with a new geothermal method of prospecting; Zeitschr. Geophysik, v. 15, p. 88-93.

Poley, J. Ph. and Van Steveninck, J.
1970: Delineation of shallow salt domes and surface faults by temperature measurements at a depth of 2 meters; Geophys. Prospect., v. 19, p. 666-700.

Poley, J. Ph. and Van Steveninck, J.
1971: Thermal near-surface expression of shallow geological features; Geophys. Prospect., v. 19, p. 695-697.

Strangway, D.W. and Holmer, R.C.
1965: Infrared geology; p. 293-320, *in* Proc. 3rd Sympos. Remote Sensing, Univ. Michigan.

Terry, M.C. and Burney, J.H.
1941: Thermal prospecting for oil;. p. 1011-1013, *in* Temperature American Institute of Physics.

Thompson, G.E.K.
1960: Shallow temperature surveying in the Wairekei-Tampo area; N.Z. J. Geol. Geophys., v. 3, p. 553-562.

Geothermal Anomalies, Structure and Detection of Orebodies

American Petroleum Institute
1930: Earth temperatures in oil-fields; Bull. 205.

Birch, F.
1950: Flow of heat in the Front Range, Colorado; Bull. Geol. Soc. Am., v. 61, p. 567-630.

Birch, F., Roy, R.F., and Decker, E.R.
1968: Heat Flow and thermal history in New England and New York; p. 437-451, *in* Studies of Appalachian Geology, Interscience.

Blackwell, D.D.
1971: The thermal structure of the continental crust; *in* Structure and physical properties of the earth's crust, ed. J. Heacock, Am. Geophys. U. Monogr. 4, p. 169-184.

Blackwell, D.D. and Baag, C.G.
1973: Heat flow in a "blind" geothermal area, near Marysville, Montana; Geophysics, v. 38, p. 941-956.

Byerly, E.P.
1965: Geothermal surveys in sedimentary rocks near Grants and Laguna, New Mexico; Geophysics, v. 30, p. 369-402.

Carslaw, H.S. and Jaeger, J.C.
1959: The conduction of heat in solids; Oxford Press, 467 p.

Cleland, R.H.
1933: Rock temperatures and some ventilation conditions in the mines of Northern Ontario; Can. Inst. Min. Met. Trans., p. 379-407.

Drescher-Kaden, F.K. and Heller, S.
1961: Reibungswarme als Energiequelle hydrothermaler Vorgange Berichte der Geologischen; Gesellschaft in der D.D.R., v. 6, p. 3-13.

Emmons, H.W.
1915: On temperatures that obtain in zones of chalcocitization; Econ. Geol., v. 10, p. 151-160.

Grossling
1959: Temperature variations in geosynclines; Bull. Geol. Soc. Am., v. 70, p. 1253-1282.

Heiland, A.
1963: Temperature measurements; Chap. 11, p. 837-862 *in* Geophysical Exploration, Prentice Hall, New York.

Heroy, W.B.
1968: Thermicity of salt as a geologic function; Geol. Soc. Am., Spec. Paper 88, p. 619-629.

Horai, K. and Nur, A.
1970: Relationship among terrestrial heat flow, thermal conductivity and geothermal gradient; J. Geophys. Res., v. 75, p. 1985-1991.

Ingersoll, L.R., Zobel, O.J., and Ingersoll, A.C.
1954: Heat conduction; Univ. Wisconsin Press, 325 p.

Irvine, T.N.
1970: Heat transfer during solidification of layered intrusions 1. Sheets and sills; Can. J. Earth Sci., v. 7, p. 1031-1061.

Jaeger, J.C.
1943: Theoretical aspects of heat developed in faulting; J. Proc. R. Soc. N.S.W., v. 76, p. 203-204.

1964: Thermal effects of intrusions; Rev. Geophys., v. 2, p. 443-466.

1965: Application of the theory of heat conduction to geothermal measurements; Chap. 2, p. 7-23 *in* Terrestrial Heat Flow, Geophys. Monogr. no. 8, Am. Geophys. U.

Jaeger, J.C. and Le Marne, A.
1963: The penetration of ventilation cooling around mine openings and extrapolation to virgin rock temperatures; Austral. J. Science, v. 14, p. 95-108.

Jakosky, J.J.
1950: Thermal methods; Chap. 9, p. 966-986, *in* Exploration Geophysics, Trija, Calif.

Kappelmeyer, O. and Haenel, R.
1974: Geothermics; Geoexploration Monogr. Ser. 1, no. 4, Geopublication Assoc.

Lazar, I.R.
1963: Moznost' vyuzitia geotermickych merani k prospeckcii sulfidickych lozisk; Rudy 11, p. 21-22 (Translation Earth Physics Br. 1974).

Lewis, T.
1969: Terrestrial heat flow at Eldorado, Saskatchewan; Can. J. Earth Sci., v. 6, p. 1191-1197.

Lovering, T. S.
1935: Theory of heat conduction applied to geological problems; Bull. Geol. Soc. Am., v. 46, p. 69-94.

1948: Geothermal gradients, climatic changes and rate of sulphide oxidation in the Dan Manuel district, Arizona; Econ. Geol., v. 43, p. 1-20.

1955: Temperatures in and near intrusions; Econ. Geol., v. 50, p. 249-281.

McBirney, A. R.
1963: Conductivity variations and terrestrial heat flow distribution; J. Geophys. Res., v. 68, p. 6323-6329.

Nutting, P. G.
1929: Deformation and temperature; Wash. Acad. Sci. J., v. 19, p. 109-115.

Ovnatanav, S. and Tamrazyan, G. P.
1970: Thermal studies in subsurface structural investigations; Apsheron Pen., Azerbaijan, U. S. S. R. Am. Assoc. Pet. Geol. Bull., v. 54, p. 1677-1685.

Roy, R. F., Blackwell, D. D., and Birch, F.
1968: Heat generation of plutonic rocks and continental heat flow provinces; Earth Planet. Sci. Lett., v. 5, p. 1-12.

Sass, J. H., Killeen, P. G., and Mustonen, E. D.
1968: Heat flow and surface radioactivity in the Quirke Lake syncline near Elliot Lake, Ontario, Canada; Can. J. Earth Sci., v. 5, p. 1417-1428.

Selig, F. and Wallick, G. S.
1966: Temperature distribution in salt domes and the surrounding sediments; Geophysics, v. 31, p. 346-361.

Simmons, G.
1961: Anisotropic thermal conductivity; J. Geophys. Res., v. 66, p. 2269-2270.

1967: Interpretation of heat flow anomalies 1. Contrasts in heat production; Rev. Geophys., v. 5, p. 43-52.

1967: Interpretation of heat flow anomalies 2. Flux due to initial temperature of intrusives; Rev. Geophys., v. 5, p. 109-119.

Stainer, X.
1923: Sur l'origine de certaines anomalies de degres geotheomique en Belgique; Ann. Mines Belgique, v. 24, p. 979.

Van Orstrand, C. E.
1932: On the flow of heat from a rock stratum in which heat is being generated; Wash. Acad. Sci. J., v. 22, p. 529-539.

1934: The application of geothermics to geology; Bull. Am. Assoc. Pet. Geol., v. 18, p. 13-38.

9. BOREHOLE GEOPHYSICAL METHODS IN PERMAFROST

J.A. Hunter

METHODS

Very little work has been done with borehole geophysical methods in permafrost conditions. The studies done to date have been oriented towards investigating the engineering properties of soils and rocks as an aid to road and pipeline construction and mining of frozen ore.

Wyder *et al.* (1973) applied geophysical techniques in boreholes near Tuktoyaktuk, N.W.T. to determine whether they could be used to 1) detect the presence of massive ground ice bodies, 2) to identify frozen surficial deposits, 3) to determine the ice content of frozen materials. Sondes used were neutron thermal neutron, decentralized gamma-gamma, caliper, and natural gamma. In addition, uphole and wavefront seismic methods were applied. Both logging and seismic methods were successful in mapping large ice bodies and major changes in lithology.

Uphole seismic techniques have been used by Kurfurst *et al.* (1974) to map the boundary between frozen and thawed surficial materials in areas of thermal disturbance of permafrost. Hunter (1974) has applied seismic uphole techniques to mapping of thermal anomalies in iron-formation at Schefferville, Quebec. Although the results are not conclusive, there are indications that temperature anomalies result in seismic velocity anomalies which are larger than those associated with lithology changes.

Recent publications from the U.S.S.R. contain papers on borehole techniques in permafrost. Akimov (1973) has used electrical seismic, nuclear and thermometric techniques to obtain physico-mechanical properties of frozen soils. Strength and deformational properties, ice content, lithology and temperature variations have been measured. Zykov and Baulin (1973) have used ultra sonic logging to measure longitudinal and Rayleigh waves in dry boreholes and have correlated these values with changes in porosity, lithology and temperature. Irbe (1973) has used mechanical logging, caliper, natural radioactivity, acoustic logging, natural field potentials, and temperature measurements in West Siberia to map the upper and lower boundaries of permafrost and to map the occurrence of taliks (unfrozen) zones.

BIBLIOGRAPHY

Akimov, A.T.
1973: Logging in shallow dug boreholes for studying Geotechnical and Geodynamic characteristics of frozen soils; IInd International Conference on Permafrost, Lectures and Deposits, no. 6: Yakutsk Press, Yakutsk, p. 18-25.

Hunter, J.A.
1974: Seismic up-Hole wave front experiments in permafrost, Schefferville, Quebec; *in* Report of Activities, Pt. B.; Geol. Surv. Can., Paper 74-1, Pt. B., p. 83-86.

Irbe, N.A.
1973: Differentiation of frozen soils and fluids co-occurring with them in Territory of West Siberian Lowland by Industrial-Geophysical Techniques; in IInd International Conference on Permafrost, Lectures and Reports, no. 6: Yakutsk Press, Yakutsk, p. 100-104.

Kurfurst, P.J., Isaacs, R.M., Hunter, J.A., and Scott, W.J.
1974: Permafrost studies in the Norman Wells Region, Northwest Territories; in Proceedings of the Symposium on the Geology of the Canadian Arctic, Geol. Assoc. Can., Saskatoon, May 1973, p. 277-299.

Meissner, R.
1961: Wave-front diagrams from uphole shooting; Geophys. Prospect., v. 9, p. 533-543.

Wyder, J., Junter, J., and Rampton, V.
1973: Geophysical investigations of surficial deposits at Tuktoyaktuk, N.W.T.; Geol. Surv. Can., Open File Rept. no. 128.

Zykov, Uy. D. and Baulin, Y.I.
1973: Potentialities of Seismo-Acoustic Techniques in Engineering Geologic Investigations of Construction on Permafrost; in IInd International Conference on Permafrost, Lectures and Reports, no. 6: Yakutsk Press, Yakutsk, p. 78-82.