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National Uranium Resource Evaluation

THE DOE/SIMPLEC MAGNETIC SUSCEPTIBILITY LOGGING SYSTEM

**Field Engineering
Corporation**

Grand Junction Operations
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March 1981

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
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ABSTRACT

The Department of Energy (DOE) and Bendix Field Engineering Corporation in conjunction with Simplec Manufacturing Company have developed a magnetic susceptibility (MS) borehole logging system. The probe employs a ferrite-core sensing coil in a basic Maxwell bridge circuit driven by a stable oscillator. Phase detectors in the surface unit independently measure the resistive (conductivity) and the reactive (susceptibility) components of the bridge output signal. System circuitry provides for minimization of temperature variations within the probe and compensation for changes in coil characteristics due to temperature variations; this is an attempt to overcome temperature drift common in previous MS systems. During controlled testing and under the extreme condition of step-function changes in temperature, the system showed abrupt MS excursions and some dependence of MS output on coil temperature and of coil temperature on borehole temperature. These observations do indicate further need for improved temperature stabilization and bridge compensation. However, under actual borehole conditions the system is more stable. Long term stability tests reveal a low-amplitude system drift that is as yet unexplained in terms of borehole or coil temperature variations.

Calibration has been achieved by using a cubic (5x5x5 ft) granite block with an assigned magnetic susceptibility value of $385 \pm 30 \mu\text{CGS}$. This block and other "models" designed to characterize the probe are available for public use at the DOE facility in Grand Junction, Colorado. The characterization models include those designed to provide borehole size correction factors, thin layer interpretation parameters, reproducibility limits, longitudinal resolution, and radius of investigation.

The DOE/Simplec system has a sensing coil with an effective length of 15 inches, and its investigation volume can be considered cylindrical. Its 99-percent radius of investigation is approximately equal to the coil length, and its 99-percent thickness of investigation is approximately two coil lengths. Observed thin-layer response curves vary from the rabbit-ears type for very thin layers (< 0.8 coil length) to the inflection-point type for greater thicknesses. Various parameters for both types of thin-layer responses are useful in estimating true MS and thickness values of isolated thin layers intersected at right angles by the borehole.

Field tests show excellent correlation of MS log values and MS core results. Logs from known uranium-favorable environments show that magnetic susceptibility measurements can give an indication of the degree of geochemical alteration, which is one of the uranium-favorable haloes sought by exploration geologists.

DOE/Bendix has acquired a new-generation system to be used in the National Uranium Resource Evaluation (NURE) program. This new system was designed by Simplec for production line manufacturing to provide lower cost, standardization of components, and easy maintainability. It incorporates improved temperature stabilization in the sensing bridge to reduce MS baseline drift due to borehole thermal gradients. The new system also incorporates provisions to interface with a computer-based data logger for both recording the measured data and controlling sensing bridge calibration and null circuitry within the probe.

INTRODUCTION

The National Uranium Resource Evaluation (NURE) program was established by the Atomic Energy Commission (now the Department of Energy) in 1974. Bendix Field Engineering Corporation, as prime contractor to the Department of Energy, has had the major responsibility for meeting the NURE program goals. These goals include provision of basic uranium resource information and development of new or improved instrumentation, facilities, and methodology for use in uranium exploration.

The magnetic susceptibility (MS) logging project evolved as part of the Bendix effort to meet the latter goal. Objectives were to develop an improved MS probe and surface electronics, design and utilize calibration and characterization facilities, and demonstrate possible use of the complete MS system in uranium exploration. This paper presents the results of that work, which include (1) the MS instrumentation with principles of operation, specifications, construction, and controlled testing, (2) design, construction, MS-value assignment, and use of MS calibration and characterization facilities, and (3) characterization of the MS system including baseline drift, reproducibility, radius of investigation, thickness of investigation, borehole size correction, and thin layer interpretation. Various field logging results are also presented.

INSTRUMENTATION

Magnetic susceptibility logging instrumentation has been discussed off-and-on in the literature since the milestone publication of Broding et al (1952). Pertinent papers are those of Veshev, et al (1957), Kal'vanskaya and Lonskii (1962), Laurila (1963), Anderson (1968), Zablocki (1974), Dowling and Savage (1975) and Scott (1976). In spite of these works, certain problems with MS logging instrumentation have persisted, at least in the United States. The most difficult of these problems is the effect of borehole temperature variations on the measured MS baseline (drift). This is especially true in environments which require that the MS logging system be used in its highest sensitivity mode.

The DOE/Simplec magnetic susceptibility system was designed to specifications developed jointly by Bendix and Simplec personnel in an effort to solve some of these problems. The specifications were based primarily on the evaluation of MS systems previously built by Simplec and Lucius Pitkin Inc., development work at Bendix, and development work by Scott (1976).

The prototype MS system discussed in this paper was designed to provide analog records of borehole magnetic susceptibility, borehole conductivity, borehole temperature, and sensing coil temperature. Magnetic susceptibility is the function of primary interest in our present program, and therefore has received the major thrust of our investigation. Conductivity will be considered more thoroughly in the future, especially in light of recent arguments that a Maxwell bridge circuit is inappropriate for conductivity measurement (George, in preparation). The two temperature measurements provide information for use in evaluating the thermal behavior of the system.

SYSTEM DESCRIPTION

The prototype MS logging system consists of a surface module incorporating control and signal processing functions and a borehole sensing unit (probe).

The probe has a 2.5-inch maximum diameter, is 10.5-feet long, weighs 67 pounds, and has a density of 3.5 gm/cm^3 . It is designed to operate with up to 6,000 feet of 4HO logging cable and withstand hydrostatic pressures up to 3,500 psi. A borehole temperature sensor is mounted in a cage on the lower end of the probe.

The surface unit is housed in a standard six-wide NIM with front panel meters and operating controls for both MS and conductivity. Rear panel connectors provide power inputs, signal inputs, and recorder outputs for MS, conductivity, borehole temperature, and coil temperature.

Final specifications of the prototype MS logging system, based on both design calculations and measured performance characteristics of the system, are listed in Table 1.

Table 1. Specifications for the DOE/Simplec Magnetic Susceptibility System

Magnetic Susceptibility Ranges	0-300, 1K, 5K, 10K, 100K μCGS
Minimum Detectable MS Change	$< 5 \mu\text{CGS}$
Conductivity Ranges	0-10, 100, 1000 milliohms/meter
Borehole Temperature Measurement	32°F to 200°F
Coil Temperature Measurement	32°F to 200°F
Operating Frequency	1000 Hz, crystal controlled
Operating Borehole Temperature	50°F to 167°F
Input Power	120 VAC 60 Hz 250 VDC at 250 mA
Recorder Output	100 millivolts corresponds to full scale of all MS and conductivity ranges. 25 millivolts/°F for both temperature measurements.

Principles of Operation

The DOE/Simplec MS logging system uses a ferrite-core inductor in one leg of a basic Maxwell bridge circuit to sense the effects of formation conductivity and magnetic susceptibility. The bridge circuit is thermally insulated and housed in a fiberglass shell which forms the bottom three feet of the borehole probe (except for the borehole temperature sensor) and permits inductive coupling of the sensing coil to the surrounding media.

A crystal-controlled oscillator, frequency dividers, and an active filter in the upper section of the probe (not thermally insulated) provide a stable 1-KHz sine wave for bridge excitation. This same sine wave is transmitted via a balanced pair of conductors to the surface module; there it is properly phased to provide a reference for two phase detectors which independently measure the resistive and reactive components of the bridge output signal. To a good approximation the resistive and reactive signals represent conductivity and magnetic susceptibility respectively (Kudriavtsev and Meier, 1963).

The phase detector outputs are filtered, scaled, and recorded on a strip chart recorder whose paper is moved in synchronism with the probe to provide an analog record of magnetic susceptibility and conductivity versus depth.

Test signals for checking system response and sensitivity in the field are generated through the use of an auxiliary winding on the sensing coil. Relays in the probe, which are controlled from the surface module, connect either resistors or capacitors in series with the auxiliary winding. A resistor in series with the winding will generate a resistive bridge output signal to simulate a conductivity increase. A capacitor will generate a reactive bridge output signal to simulate a magnetic susceptibility increase.

For a theoretical analysis of this type of induction logging system, the reader is referred to the work of Broding, et al (1952), whose original system concept forms the basis for our present system, and the work of Kudriavtsev and Meier (1963). Improved materials, components, and instrumentation techniques have been applied to the DOE/Simplec MS logging system to increase the sensitivity and stability to levels required for satisfactory logging in the low-MS environments.

Sensing Coil

High sensitivity was achieved through a bridge and sensing coil design which provides a high ratio of inductance to coil resistance ($Q \geq 225$). The coil is wound on a manganese-zinc ferrite core 15-inches long by 0.75-inch diameter of type MN-30 material (Ceramic Magnetics, Inc., 1976). This material was chosen for its high initial permeability and relatively constant permeability over a range of temperature in which it would normally be desirable to maintain the coil temperature; that is, temperatures higher than ambient borehole fluid temperature and lower than temperatures that cannot be conveniently maintained in a slim borehole probe. Temperature characteristics are shown in Figure 1.

Even with the good temperature stability of the MN-30 core, coil inductance and coil resistance change enough over the range of temperatures encountered in a typical borehole to severely unbalance the Maxwell bridge and offset the measurement baselines. Both compensation of bridge component temperature characteristics and stabilization of sensing coil operating temperature are employed to reduce these effects.

Bridge Compensation

Figure 2 is a schematic of the Maxwell bridge and shows the components used for compensation of temperature characteristics of the sensing coil. Both the inductance and the resistance of the coil increase with increasing temperature.

For a Maxwell bridge, Terman (1943) gives condition-of-balance equations for the coil inductance

as
$$L_d = R_a R_c C_b \quad (1)$$

and the coil resistance

as
$$R_d = R_a R_c / R_b \quad (2)$$

Figure 1. Initial permeability versus temperature for type MN-30 core material (modified from Ceramic Magnetics, Inc., 1976).

Figure 2. Sensing coil, L_d , is connected in one leg of a Maxwell bridge. Thermistors (T) and a sensistor (S) provide compensation for temperature-induced changes in coil parameters.

where terms are defined in Figure 2. From Equation (1) we see that an increase in L_d can be balanced by a corresponding increase in R_a . In the DOE/Simplec probe, this increase is provided by a 47-ohm sensistor (S in Figure 2) whose resistance also increases with temperature.

The increase of coil resistance, R_d , is also partially offset by the increase in R_a provided by the sensistor as shown by Equation (2). The remainder of the necessary compensation for the increase in R_d is provided by a decrease in R_b . This is accomplished by the two 200-kilohm thermistors whose resistance decreases with increasing temperature. The sensistor and thermistors are mounted in good contact with the ferrite core and potted with a thermally conductive epoxy to assure good tracking of coil temperature.

In Figure 2 the resistor R_c , the capacitor C_b , and the other fixed resistors were chosen for their stable temperature characteristics and do not require compensation. The 2.5-megohm potentiometer, which is a part of R_b , and the 2-megohm potentiometer, which is a part of R_a , are used to initially balance the bridge in air. The 2-megohm potentiometer is motor driven and controlled from the surface unit; this makes it easy to set the MS component to zero with the probe suspended in air just prior to logging a hole.

Temperature Stabilization

Stabilization of the sensing coil operating temperature is perhaps the most critical step in achieving the desired stability of operation. Figure 3 shows the sensing coil assembly which is insulated by a ceramic-fiber blanket and mounted inside the fiberglass outer shell. The coil is heated by bifilar-wound copper heaters which are embedded in slots in a fiberglass form that fits snugly over the ferrite core.

The sensing coil is wound over the coil form/heater assembly and is thoroughly impregnated with thermally conductive epoxy. A Faraday shield covers the coil and the auxiliary winding is wound overall.

Sensing thermistors are embedded in the coil assembly in good thermal contact with the core; they sense coil temperature and control the heater-amplifier circuit. The temperature set-point can be adjusted by a potentiometer in the heater amplifier and is usually set at about 150°F, which is well above temperatures normally encountered in uranium-oriented logging operations.

TEMPERATURE TESTS

Controlled temperature tests were conducted to determine the effectiveness of the component compensation and coil temperature stabilization employed and to characterize overall thermal stability of the system. These tests included measurement of warm-up time during which the sensing coil reaches a stable temperature and the MS output becomes relatively stable, measurement of long term stability for a stable borehole environment, and measurement of response to step-function temperature changes.

To determine warm-up time in a constant temperature environment, the probe was suspended on the sidewall at a fixed depth in the water-filled,

Figure 3. A thermostatically-controlled heater maintains the sensing coil at a constant operating temperature which is higher than expected borehole temperatures. A thermally conductive epoxy bonds coil, core, heater into a single isothermal unit. Non-metallic materials are used in housing and coil-mounting hardware.

4.5-inch diameter hole of the borehole size correction model, discussed in the System Characterization section below. MS output was measured from the time power was applied until the coil temperature became constant and the MS drift declined to a small value. Warmup times were in the range of 45 to 75 minutes depending on borehole water temperature. MS output drift dropped from several hundred $\mu\text{CGS}/\text{minute}$ at turn-on to about 4 $\mu\text{CGS}/\text{minute}$ after warm-up.

Long-term stability was measured with the probe positioned at the bottom (29 ft) of the same hole used in the warm-up test. Coil temperature, borehole temperature, and MS output were recorded as a function of time for about 85 hours. Both temperatures were quite stable and never varied more than 1°F above or below the initial temperature; however, MS output continuously drifted in the negative direction, regardless of the direction of any temperature variation, and gradually decreased in amplitude to about 0.1 $\mu\text{CGS}/\text{minute}$ at the end of the test.

A temperature step-function test was conducted with the probe suspended on the sidewall in the 6-inch diameter hole of the borehole size correction model. The probe was allowed to reach thermal equilibrium (coil temperature of 151°F and MS value of 612 μCGS) with the borehole water whose ambient temperature was 65°F .

Figure 4 schematically represents observed variations in MS, borehole temperature, and coil temperature during the time when crushed ice was dumped into the hole and the water/ice mixture was circulated throughout the hole. A decrease in borehole temperature from 65°F to 32°F took place during about two minutes of circulation.

The MS output response to the negative 33°F temperature step was a negative excursion to a value of 446 μCGS after 2 minutes. The response then changed direction, returning to the original value of 612 μCGS in another 9 minutes. It overshoot the original value and finally stabilized at 704 μCGS after another 30 minutes.

Coil temperature began a slow, steady decline about two minutes after the borehole temperature step and finally stabilized at 146°F after 30 minutes.

Forty minutes after the start of the temperature test, the probe was removed from the 32°F water in the 6-inch borehole and plunged into the 4.5-inch borehole which contained water at 50°F . The MS output rose immediately to 828 μCGS , and then began a slow decline to 675 μCGS which it reached after 27 minutes. The coil temperature finally stabilized at 149°F after approximately 30 minutes.

Analysis of Results

In Figure 5, the equilibrium values of magnetic susceptibility and coil temperature, as observed in the two step-function temperature tests (Figure 4), are plotted against one another. It is evident from this figure that during these rather severe temperature tests MS output varied with coil temperature, indicating a need for improved sensing coil compensation.

In Figure 6, sensing coil temperature at thermal equilibrium is plotted against borehole temperature. The rather drastic fall-off at the cold end

Figure 4. Response of the DOE/Simplec logging system to two step-function changes in borehole fluid temperature. Magnetic susceptibility in the 6-inch diameter borehole has been corrected to the standard 4.5-inch borehole using the sidewall data in Figure 11.

Figure 5. Magnetic susceptibility variation with coil temperature as obtained from Figure 4.

Figure 6. Coil temperature variation with borehole temperature as obtained from Figure 4.

suggests the need for improved coil insulation or a heating system capable of greater output, at least when extreme temperature changes are expected. It is shown below in the sections on Log-Core Comparison and Field Results that under some field conditions the system drift is negligible, while under others it is small but perceptible at 1-2 μ CGS/min.

Using data similar to those presented in Figures 5 and 6, one may be able to develop a method to correct MS values on the basis of measured coil temperature and/or borehole temperature. Currently, however, we are looking to a new-generation system to provide better temperature stabilization and bridge compensation.

NEW GENERATION SYSTEM

DOE/Bendix has acquired a new-generation magnetic susceptibility logging system to be used in the NURE program. This system was designed by Simplec for production line manufacturing to include standardization of components, easier maintainability, and improved temperature compensation and temperature stabilization. The probe is 7 feet 4 inches long weighs 45 pounds and does not include a borehole temperature sensor. Other specifications are similar to those of the prototype system described above.

Bridge Compensation

The new probe uses the same basic sensing-coil compensation method described previously; however, all the major components of the Maxwell bridge are housed within the temperature controlled environment. Only the two balance potentiometers, a small trimming capacitor, and some fixed bridge-trimming resistors are housed in the upper section of the probe. Initial tests have revealed a problem with the metallized polycarbonate bridge capacitors which did not follow the manufacturer's temperature performance specifications. Simplec is replacing them with another style polycarbonate capacitor which has been shown to be considerably more stable during laboratory temperature tests.

Temperature Stabilization

The new probe uses the same basic method of heating the sensing coil and sensing its temperature with thermistors embedded in the thermal epoxy coil encapsulant. Improvements have been made in the insulation and in the temperature control amplifier.

Tests have shown that the temperature stabilization system in the new probe can maintain coil temperature within 1°F of its set-point when a probe, which has stabilized in 98°F air, is plunged into a borehole containing a 32°F water/ice mixture.

Other Improvements

The new system incorporates remotely controlled, motor driven, null potentiometers in both legs of the Maxwell bridge, permitting the zeroing of conductivity as well as MS when the probe is suspended in air prior to logging. In the prototype system previously described, only the MS component could be zeroed conveniently in the field.

A solid state temperature sensor and improved temperature amplifier circuit provide a more accurate readout of sensing coil temperature. In addition, modular construction employing printed circuit cards containing functional subsystems makes the new probe more reliable and easier to maintain and troubleshoot.

A digital data downlink provides remote control for nulling the Maxwell bridge and for generation of MS and conductivity sensitivity test signals using the auxiliary winding. The data-link system has provisions to interface with the minicomputer in the Bendix digital logging systems if we should ever wish to use computer control of bridge nulling or test signal generation.

High level (± 10 volts full scale) outputs are provided from the surface module to interface with our computer-based digital logging systems. Digitally coded signals transmit range switch settings to the computer for automatic scaling of MS and conductivity data.

Since the new Simplec system employs the same basic sensing coil geometry, bridge excitation, and phase detection as the DOE/Simplec prototype system, the calibration and characterization studies reported below should be valid for it as well as for the prototype system. However, thorough testing of the new system is planned for the future.

SYSTEM CALIBRATION

The DOE/Simplec magnetic susceptibility logging system has the capability (using auxiliary winding mentioned above) to internally check whether or not the system has gone out of calibration. However, the initial absolute calibration must be done in specially designed external models of known magnetic susceptibilities. The United States Bureau of Mines (USBM) (Snodgrass, 1976) constructed models designed for that purpose. However, none of these has a 4.5-inch diameter borehole, which is standard to the uranium exploration industry. Therefore, we have supplemented the USBM models in Denver with a granite block model in Grand Junction. This block (Figures 7 and 8) is above ground, has a 4.5-inch uncased borehole, and has a wooden superstructure and steps to facilitate access and probe positioning.

The borehole of the granite block was obtained by coring. The resulting core was subsequently cut into several 3-inch sections and six of these were further cored to obtain six smaller cores of 1.28-inch diameter. The magnetic susceptibility of these small-diameter cores was measured on three Bison MS bridges (Bison, 1970) at the Geochemical Analysis Department of Bendix. The average MS was 385 ± 30 μ CGS at the 95-percent confidence level.

Six cores do not constitute a thorough sampling of the granite block and hence a 95-percent confidence level for the entire block. In an effort to further validate the assignment of 385 ± 30 μ CGS, we calibrated the logging system to 385 μ CGS for the probe sidewalled on the north sidewall (of the four cardinal-direction sidewalls the north one always had an MS value closest to the average of all four). After this calibration, the south, west, and east sidewalls were logged to provide a more integrated sampling of the block. The differences of those MS log peak values from that of the north sidewall was never more than 25 μ CGS, thus giving credibility to a 95-percent confidence level of ± 30 μ CGS for the entire block. The absolute calibration value of

GRANITE BLOCK

THIN LAYER

RADIUS OF INVESTIGATION

BOREHOLE SIZE CORRECTION

Figure 7. Plan view of models used for calibration and characterization of magnetic susceptibility logging systems. Figure is not to scale.

BOREHOLE SIZE CORRECTION

Figure 8. Cross sections of models used for calibration and characterization of magnetic susceptibility logging systems. Boreholes in the granite block and borehole size correction models are uncased. Boreholes in the thin-layer and radius-of-investigation models are PVC plastic pipe with a 4.5-inch OD and a 4-inch ID. The borehole size correction model is concrete with the "ore zone" being a blend of concrete and uranium ore. Figure is not to scale.

385 μ CGS was checked by calibrating our MS system to 385 μ CGS (on the sidewall) and then logging the USBM models (Snodgrass, 1976) as well as the Grand Junction thin-layer and radius-of-investigation models where we had some laboratory knowledge of the models' magnetic susceptibilities. The MS values from the calibrated probe agreed to within 10 percent with the laboratory-assigned MS values for those models.

Thus, we feel fairly comfortable in assigning a magnetic susceptibility value of 385 ± 30 μ CGS to the granite block--our primary calibration model.

This calibration is expected to be linear "for all practical purposes" up to about 20,000 μ CGS according to Kudriavtsev and Meier (1963). As a check, we calibrated the DOE/Simplec system using the granite block and then logged the USBM calibration model A6 which has an assigned value of 9,090 μ CGS (Snodgrass, 1976). The peak value of our log of A6, after correcting for the 3-inch diameter borehole, agreed with the assigned value for A6 within the uncertainty of the assigned value of the granite block, confirming linearity to about 9,000 μ CGS.

The recommended procedure for calibrating in the granite block is to log both down and up the north sidewall at 5 ft/min. The down and up logging allows elimination of the effect of system drift by using the average amplitude of the two logs. Figure 9 shows both the down and up logs obtained from the granite block; a slight negative drift is evident. The abrupt decrease in MS near the bottom of the model is due to a steel run-pipe which extends into the ground. This pipe does not affect the peak value of the log, which is due solely to the granite block.

SYSTEM CHARACTERIZATION

Geoscientists must be aware of the sampling characteristics of the magnetic susceptibility logging system in order to relate the measurements to subsurface geology. Also, except for the crudest of applications, the data should be free from the effects of human-caused variations in the geometry of the measurement environment.

In this section, we present data that characterize the DOE/Simplec MS logging system and allow more meaningful use of its measurements. The standard measurement environment is in a 4.5-inch diameter, open borehole that intersects all geologic variations at right angles.

BOREHOLE SIZE CORRECTION

Since magnetic susceptibility is a volume measurement it is quite sensitive to variations in the volume of rock material sampled. These variations are most commonly encountered and especially critical when the borehole diameter differs from that of the standard borehole diameter (4.5 inches) because of a different bit size, rugosity, or washouts of the sidewall. Corrections for these differences from the standard borehole can be made using experimentally determined borehole size correction factors.

Fortunately, we have been able to make use of an existing characterization model in Grand Junction to determine MS borehole size corrections. The concrete model (Figures 7 and 8) was originally constructed to estimate

Figure 9. Magnetic susceptibility logs (down and up) from the granite block primary calibration model.

borehole size effects on fission neutron logs. It has four zones intersected by seven uncased boreholes of different sizes that are 2 degrees off vertical. A sidewall log from the 3-inch borehole (Figure 10) shows the strong contrasts in the model that allow good borehole size correction data to be obtained.

Data for both a centered and a sidewalled probe are shown in Figure 11. The former are only for the MS contrast between air and the upper zone of the model and the latter makes use of all three major contrasts shown in Figure 10. The second order polynomials in Figure 11 are least-squares fits to the data and were forced to equal unity for the standard borehole diameter of 4.5 inches. We should note that the MS contrasts between the ore zone and the barren zones are due to the very low MS of the uranium ore that was used in the ore zone in place of the high-MS barren zone material.

The data in Figure 11 behave as expected. For a sidewalled probe the correction factor approaches a constant value of about 1.6, while for a centered probe it approaches infinity. In the case of boreholes with sidewall washouts, a centered probe is more suitable because the correction factor does not depend on the azimuthal variation of the washout (azimuth information is not normally obtained with a caliper log). For boreholes with uniform diameter different than 4.5 inches, a sidewalled probe is preferred because the correction factor is small.

In general, we prefer to use a sidewalled probe and use a caliper log to "flag" erroneous MS data due to detected washouts. Data from uniform boreholes are easily corrected by multiplication with the sidewall correction factors in Figure 11.

At the present time no sidewalling device is mounted on the probe. Thus, to obtain relatively constant contact with the sidewall we log up the hole at about 25 ft/min and rely on the fact that no hole is perfectly vertical. It is appropriate to point out that logging speed tests in our plastic-cased, 300-ft borehole at Grand Junction showed no significant differences between MS logs taken at 5 and 50 ft/min. In open boreholes, though, 25 ft/min seems to be a good compromise between speed of operation and insured sidewall contact.

RADIUS OF INVESTIGATION

Authors such as Broding, et al (1952), Kal'varskaya (1959), and Kudriavtsev and Meier (1963) have considered the volume of investigation of various magnetic susceptibility logging systems to be cylindrical, and through use of theoretical calculations and laboratory experiments they have determined the radius of investigation. Our approach was to construct a series of radius-of-investigation models of different diameters, "infinite" thickness, and with 4.5-inch diameter boreholes (Figures 7 and 8) for actual logging by the DOE/Simplec MS system.

The models rest on the ground, have boreholes of 4.5-inch OD PVC pipe, and the external cylinders are of non-conductive, non-magnetic material. The cylinders are filled with commercially-bagged "play sand" which, in a gross sense (as sampled by the probe), is quite homogeneous.

Figure 10. Magnetic susceptibility log of the 3-inch borehole in the borehole size correction model (Figures 7 and 8).

Figure 11. Borehole size correction factors for the magnetic susceptibility probe both centered and sidewalled in the borehole size correction model (Figures 7 and 8).

The peak amplitudes of the MS logs for the radius-of-investigation models are shown plotted in Figure 12. They have been normalized to the amplitude of the largest diameter model. The consistently high values for the 36-inch model are as yet unexplained; however, this does not significantly affect the experiment. On the basis of the data in Figure 12, we can say that for standard borehole logging conditions the DOE/Simplec system receives 99 percent of its MS response from material within one coil length (15 inches) of the sidewalled probe.

The latter statement must be qualified on the basis of the work by Kudriavtsev and Meier (1963). They found both theoretically and experimentally that the radius of investigation in MS logging increases with an increase in borehole diameter; consequently it decreases with an increase in the magnetic susceptibility of the material surrounding a borehole of fixed diameter. Therefore, our experimental result presented in the previous paragraph is valid for standard logging conditions in a geologic environment with MS similar to that of the play sand (about 400 μ CGS). However, it must be used with caution when logging in boreholes that are of nonstandard or highly variable diameter or when logging in geologic environments with MS significantly different than that of the play sand.

The granite block calibration model has a magnetic susceptibility of 385 μ CGS and has a smallest radial dimension of 30 inches or two coil lengths. Thus we can feel quite confident that the DOE/Simplec system sees the block as being infinite in the radial direction.

RESOLUTION AND THIN LAYER INTERPRETATION

Equally as important as knowledge of the radius of investigation in characterizing the MS system is knowledge of its response to thin layers and its ability to resolve these layers (thickness of investigation). To obtain this information, we have constructed a thin-layer model (Figures 7 and 8) that allows the logging of different thicknesses of material.

As with the radius-of-investigation models, we use play sand that is homogeneous enough for the purposes of the experiment. The model is first logged empty, then a thin layer of sand is placed into the model with our "scientific" shovel and another log taken, and so on to a maximum thickness of 36 inches. A representative set of MS logs from this model is shown in Figure 13. The two distinct types of responses produced are called the rabbit-ears type and the inflection-point type. Similar responses have been described by Laurila (1963) and Kudriavtsev and Meier (1963) for single-coil probes and by Sochel'nikov (1965) for a double-coil probe.

Full-width-at-half-maximum (FWHM) is a parameter used commonly in the interpretation of log data. Figure 14 shows this parameter plotted against layer thickness; data are from three separate experiments with the thin-layer model. The FWHM gives a direct indication of layer thickness only for thicknesses greater than about two coil lengths; Kudriavtsev and Meier (1963) showed a similar result. Figure 14 may be used to estimate layer thickness for thinner layers, but it is ambiguous for thicknesses between 10 and 20 inches.

Figure 12. Magnetic susceptibility amplitude as a function of model diameter. The amplitude has been normalized to that of the 69-inch diameter model.

Figure 13. Magnetic susceptibility logs from the thin-layer model shown in Figures 7 and 8. Layer thickness is shown at the left. For ease in presentation two scales are used with the 11.5-inch thickness common to both. A small, negative drift has been removed from the data.

Figure 14. Variation of the full-width-at-half-maximum of a magnetic susceptibility log as a function of layer thickness.

Inflection-point responses yield a parameter that would seem quite useful in determining the true magnetic susceptibility of a thin layer. This parameter, E, plotted in Figure 15 and described in Figure 16, is the MS difference between the baseline and the inflection point of the curve. The E scale is greatly expanded in Figure 15 to show the increased scatter for smaller thicknesses where the inflection point is more difficult to pick. It is evident from Figure 15 that, for isolated inflection-point responses, the parameter E should be measured and doubled to obtain the true MS of the layer.

Figure 16 shows further parameters that can be used to interpret MS responses for layers less than about two coil lengths in thickness. The B/A and D/E ratios allow determination of the true thickness. This thickness can then be used in conjunction with the normalized amplitude curve to determine true magnetic susceptibility.

On the basis of these model studies, we see that the DOE/Simplec MS logging system has a 99-percent thickness of investigation equal to about two coil lengths (Figure 16) and produces responses that can be interpreted to give true magnetic susceptibility and thickness for thinner layers. For responses that are not isolated, the interpreter should follow the suggestion of Zablocki (1974) and deconvolve the log using a thin-layer response, such as shown for the 2.5-inch layer in Figure 13, to obtain true variations in magnetic susceptibility.

The same qualification made for the radius-of-investigation results must be made here. That is, the thickness of investigation increases with borehole diameter (Kudriavtsev and Meier, 1963), and consequently it decreases with increasing magnetic susceptibility. The above results should, therefore, be rigorously used only in environments with magnetic susceptibilities similar to that of the play sand (400 μ CGS).

The granite block calibration model has a magnetic susceptibility of 385 μ CGS and is 5 ft thick (four coil lengths). It is evident from the granite block log (Figure 9) and the above considerations, that the DOE/Simplec system sees the block as being infinite in the longitudinal direction.

REPRODUCIBILITY

The degree to which a logging system can reproduce a log is important to know when formulating one's confidence in the data. We chose to test the reproducibility of the DOE/Simplec system in the 300-ft test borehole at Grand Junction. This hole is cased with ABS plastic pipe, has cement grout from TD to about 130 ft, and has pea gravel behind the casing from 130 ft to the surface. Radium-foil strips implanted into stainless steel sleeves encircle the casing at various depths and are used for testing gamma-ray probes.

Portions of the two MS logs from the hole are shown in Figure 17. These were taken on the same day and with no change in the logging system configuration; logs have been off-set to facilitate comparison.

The interface between the pea gravel and grout behind the casing is marked by a 400 μ CGS step-function anomaly and a radium-foil strip at 85 ft sends the log off scale in a negative direction (this is normal for a highly conductive circuit closed around the probe). The pea gravel is heterogenous with numerous MS anomalies on the order of 5 μ CGS.

Figure 15. Variation of the parameter E (see Figure 16) with layer thickness. E is normalized to the true magnetic susceptibility of the thin-layer model material.

Figure 16. Normalized magnetic susceptibility amplitude (right scale) as a function of layer thickness. Variation of the parameter ratios A/B and D/E (left scale) with layer thickness.

Figure 17. Consecutive magnetic susceptibility logs taken in the 300-ft test borehole at Grand Junction. Logs have been off-set for clarity.

Comparison of the logs in Figure 17 shows that for these ideal conditions the log reproducibility is excellent with only minor muting in some cases and the same anomalies of 1-2 μ CGS present on both logs. Under the less ideal conditions of open-hole logging in the field, we have found reproducibility at least as good as 5 μ CGS and feel that the system allows resolution of very subtle and meaningful anomalies in the sedimentary environment.

LOG-CORE COMPARISON

The DOE/Simplec system was used to log USGS core hole GM-1 (Stuckless, et al, 1977) in the Granite Mountains near Jeffrey City, Wyoming. The data, shown in Figures 18 and 19, were acquired in analog form, digitized at a 0.5-ft interval, and corrected for the 3-inch diameter borehole. At the time of logging, the final calibration value of 385 μ CGS had not been assigned to the granite block (500 μ CGS was used); therefore, log values in Figures 18 and 19 are about 30 percent higher than those that would be obtained from a properly calibrated system.

The magnetic susceptibility of core obtained from hole GM-1 was measured at approximately 1-ft intervals (Stuckless, et al, 1977) using a Bison laboratory bridge with a 2-inch diameter external coil attachment (J. Scott, J. Stuckless, personal communication, 1978). These data, shown in Figures 18 and 19, show that the magnetic susceptibility log and core values exhibit the same character throughout the hole. Figure 19 allows a more detailed comparison of the two data sets.

The difference in sample volume between core and log is evident in Figures 18 and 19. The magnetite within the section is in relatively small zones that are not precisely delineated by the logging system. Deconvolution using the system's thin-layer response would not be valid in this case, however, because of the unlikelihood of layering in the granite.

FIELD RESULTS

The paucity of magnetite in association with uranium deposits has been well documented in the literature (Adler, 1973; Harshman, 1974; Adams, et al, 1974) and various authors have observed the expected negative correlation with magnetic susceptibility measurements (Ellis, et al, 1968; Hafen, et al, 1976; Scott and Daniels, 1976; Bramlett, et al, 1979). In this section, we present two examples of DOE/Simplec magnetic susceptibility logs taken in uranium-favorable environments with associated zones of magnetite depletion.

The first example (Figure 20), modified from Bramlett, et al (1979), is from the Copper Mountain uranium district in central Wyoming. This is a granitic environment where uranium is normally found concentrated in fractured, brecciated, and altered granite rocks (Yellich, et al, 1978). In Figure 20, the magnetic susceptibility log on the left, taken in relatively unaltered granite, shows high-amplitude variations in magnetic susceptibility indicative of the presence of undisturbed magnetite. The log on the right, taken in altered, uranium-favorable granite, is relatively featureless and reflects the alteration of magnetite to less magnetic minerals. This zone of altered granite was shown by Bramlett, et al (1979) to correspond to suppressed values of the earth's total magnetic field at the surface.

Figure 18. Comparison of log and core magnetic susceptibility values from hole GM-1, Granite Mountains, Wyoming. Note the negligible drift in the log.

Figure 19. Detailed comparison of log and core magnetic susceptibility values from hole GM-1, Granite Mountains, Wyoming.

Figure 20. DOE/Simplec magnetic susceptibility logs from the Copper Mountain uranium district in Wyoming. Note difference in MS scales for the two logs and the negligible drift.

The second log example (Figure 21) is from the Grants uranium district in northwestern New Mexico. This is a sedimentary environment where most uranium occurs in the Westwater Canyon Member of the Jurassic Morrison Formation (Brookins, 1976).

Hafen, et al (1976) extensively studied the mineralogy and magnetic susceptibility of the Westwater Canyon Member and found that MS could be related to the alteration of the sandstone, in particular the destruction of magnetite-ilmenite, and that down-hole MS measurements correlated well with the distribution of magnetite-ilmenite in drill-hole cuttings. Figure 21 is similar to Hafen's Figure 4 and shows: 1) lower magnetic susceptibility in the mineralized sands of the upper Westwater Canyon Member, 2) higher magnetic susceptibility in the barren lower sands, and 3) higher magnetic susceptibility in the shale horizons within the Westwater Canyon Member.

A negative drift in the MS baseline is evident in the data in Figure 21. For the section of hole shown (2,300-2,000 ft), borehole temperature was constant at 86°F and coil temperature remained at $145 \pm 0.5^\circ\text{F}$. Drift direction (negative) and rate (approximately 1 $\mu\text{CGS}/\text{min}$) are consistent with drift observed during the long-term stability test described in the Instrumentation section.

In the portion of the hole from 2,000 to 600 ft, borehole temperature decreased from 86 to 61°F and coil temperature decreased from 145 to 143°F. The drift of the MS baseline changed to a positive direction and continued at a slightly non-linear rate of 1-2 $\mu\text{CGS}/\text{min}$. These observed relationships between MS drift, coil temperature, and borehole temperature follow the characteristics observed during the temperature tests and plotted in Figures 5 and 6. Similar behavior has been observed on all the MS and temperature logs recorded in the Grants district using the DOE/Simplec system.

The baseline drift observed in the field logs is a reflection of imbalance in the bridge circuit. Under the borehole conditions observed in the field this imbalance biases the MS response, but does not significantly alter system sensitivity (George, in preparation). Practically, this means that absolute values of magnetic susceptibility are sometimes difficult to determine on the logs, but relative values are as good as the initial calibration.

SUMMARY

A magnetic susceptibility logging system has been developed which is relatively stable under normal field logging conditions and which produces logs that accurately represent in situ variations in magnetic susceptibility. However, both field and laboratory tests indicate the need for further improvement of temperature stabilization and bridge compensation; a new generation system designed by Simplec may fill that need.

A cubic granite block with a magnetic susceptibility of 385 μCGS is designated as the primary calibration standard and is available for public use at the DOE facility in Grand Junction, Colorado. Models are also available for characterization of magnetic susceptibility systems. These include models to provide borehole size correction factors, thin layer interpretation parameters, reproducibility limits, longitudinal resolution, and radius of investigation.

Figure 21. Logs from the Westwater Canyon Member of the Morrison Formation, Grants uranium district, New Mexico. All logs were acquired in analog form and subsequently digitized at a 1-ft interval. Sandstone and shale are shaded and unshaded respectively.

The DOE/Simplec system has a 99-percent radius of investigation, approximately equal to the coil length (15 inches), and a 99-percent thickness of investigation, approximately equal to two coil lengths. The true magnetic susceptibility and thickness of isolated layers less than two coil lengths in thickness can be obtained through use of parameters measured from their log responses.

Field tests show that the system has a reproducibility of at least 5 μ CGS and that logging at 25 ft/min is a good compromise between speed of operation and keeping the probe on the sidewall. Comparison of log and core magnetic susceptibility measurements confirms the fact that the logging system samples a rather large volume and that interpretive aids are necessary to unfold the true variation of magnetic susceptibility with depth.

Finally, logs from known uranium-favorable environments show that magnetic susceptibility measurements can give an indication of the degree of geochemical alteration, which is one of the uranium-favorable haloes sought by exploration geologists.

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REFERENCES

- Adams, S. S., Curtis, H. S., and Hafen, P. L., 1974, Alteration of detrital magnetite-ilmenite in continental sandstones of the Morrison Formation, New Mexico: in Formation of Uranium Ore Deposits (IAEA Symposium, Athens), p. 219-253.
- Adler, H. H., 1973, Exploration for uranium in sandstones: geochemical, remanent magnetic, and sulfur-isotope applications: in Uranium Exploration Methods (IAEA Symposium, Vienna), p. 155-169.
- Anderson, W. L., 1968, Theory of borehole magnetic susceptibility measurements with coil pairs: Geophysics, v. 33, p. 962-971.
- Bison Instruments, Inc., 1970, Manual on magnetic susceptibility system Model 3101, 12 p.
- Bramlett, L. B., Czarnecki, R. F., Emilia, D. A., Pacer, J. C., Sadowski, R. M., and Schmidt, J. S., 1979, Uranium geophysics, Copper Mountain, Wyoming: SME-AIME preprint no. 79-336, 9 p.
- Broding, R. A., Zimmerman, C. W., Somers, E. V., Wilhelm, E. S., and Stripling, A. A., 1952, Magnetic well logging: Geophysics, v. 17, p. 1-26.
- Brookins, D. G., 1976, Uranium deposits of the Grants, New Mexico, mineral belt: USERDA open file report no. GJBX-16(76), 153 p.
- Ceramic Magnetics, Inc., 1976, Engineered Ferrites Brochure.
- Dowling, D. J., and Savage, K. D., 1975, Magnetic susceptibility logging apparatus for distinguishing ferromagnetic materials: U.S. Patent No. 3,890,563.
- Ellis, J. R., Austin, S. R., and Drouillard, R. F., 1968, Magnetic susceptibility and geochemical relationships as uranium prospecting guides: USAEC, R.I.D. Rep. 4, GJO, Grand Junction, Colorado, 21 p.
- George, D. C., in preparation, Comments on the performance of the Maxwell bridge circuit for magnetic susceptibility and conductivity measurements.
- Hafen, P. L., Adams, S. S., and Secor, G. B., 1976, Application of magnetic susceptibility measurements to uranium exploration in sandstones: in Exploration for Uranium Ore Deposits (IAEA Symposium, Vienna), p. 367-378.
- Harshman, E. N., 1974, Distribution of elements in some roll-type uranium deposits: in Formation of Uranium Ore Deposits (IAEA Symposium, Athens), p. 169-183.
- Kal'var'skaya, V. P., 1959, Magnetic susceptibility logging curves by using models: Uchenye Zapiski LGU, Ser. fiz. i geolog. nauk, v. 11, no. 278, p. 143-148.

- Kal'varskaya, V. P., and Lonskii, A. V., 1962, An apparatus for logging magnetic susceptibility: Prikl. Geofiz. Vses. Nauchn.-Issled. Inst. Geofiz. Metodov Razvedki, Sb. Statei no. 33, p. 213-224.
- Kudriavtsev, Iu. I., and Meier, V. A., 1963, Interpretation of magnetic susceptibility logs: Uchenye Zapiski LGU, Ser. fiz. i geolog. nauk, v. 14, no. 320, p. 134-161.
- Laurila, E., 1963, On the measurement of the susceptibility and conductivity of the rock surrounding a bore: Acta Polytechnica Scandinavica, ser. 25, 24 p.
- Scott, J. H., 1976, USGS non-nuclear geophysics R&D projects: in Uranium Geophysical Technical Symposium, U.S. Energy Research and Development Administration, Grand Junction, Colorado, p. 243-252.
- Scott, J. H., and Daniels, J. J., 1976, Non-radiometric borehole geophysical detection of geochemical haloes surrounding sedimentary uranium deposits: in Exploration for Uranium Ore Deposits (IAEA Symposium, Vienna), p. 379-390.
- Scott, J. H., and Stuckless, J. S., personal communication, 1978, U.S. Geological Survey, Denver Federal Center, Denver, Colorado.
- Snodgrass, J. J. 1976, Calibration models for geophysical borehole logging: U.S. Bureau of Mines Report of Investigations, no. 8148, 21 p.
- Sochel'nikov, V. V., 1965, Fundamentals of the approximate theory of magnetic logging using spaced pickups in weakly magnetic rocks: Geol. i Geofiz. Akad. Nauk SSSR, Sibirsk. Otd., no. 10, p. 106-117.
- Stuckless, J. S., Bunker, C. M., Bush, C. A., Doering, W. P., and Scott, J. H., 1977, Geochemical and petrological studies of a uraniferous granite from the Granite Mountains, Wyoming: Jour. Research U.S. Geol. Survey, v. 5, no. 1, p. 61-81.
- Terman, F. E., 1943, Radio Engineers Handbook, McGraw-Hill Book Co., Inc., p. 903-905.
- Veshev, A. V., Meir, V. A., Larionov, L. V., and Barkhatov, D. R., 1957, The logging of the magnetic susceptibility of weakly magnetic rocks: in Problems of ore geophysics, Gosgeolizdat, v. 1 p. 69-78.
- Yellich, J. A., Cramer, R. T., and Kendall, R. G., 1978, Copper Mountain, Wyoming, Uranium Deposit - Rediscovered: in Wyoming Geological Association Guidebook, Wind River Basin, p. 311-327.
- Zablocki, C. J., 1974, Magnetite assays from magnetic susceptibility measurements in taconite production blast holes, northern Minnesota: Geophysics, v. 39, p. 174-189.