Mineral Deposit Signatures by Borehole Geophysics: Data from The Borehole Geophysical Test Site at The McConnell Nickel Deposit (Garson Offset), Ontario

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BACKGROUND

The success of geophysical exploration for mineral deposits is enhanced if the physical characteristics (or geophysical signature) of the deposits are known. One method of defining the signature is to document the physical properties of known deposit types (the ore, the host rock and the associated alteration), using in-situ borehole geophysical measurements. These data provide information that is fundamental for interpreting results of geophysical surveys made with existing equipment and for designing new airborne, ground and borehole geophysical equipment and methodology.

The NODA Project

The Geological Survey of Canada (GSC) has begun to compile a catalogue of geophysical signatures based on borehole geophysics, for a variety of ore deposits in the province of Ontario, that are representative of major deposit types. The project is funded under the Northern Ontario Development Agreement (NODA). Some of the test holes selected for the determination of deposit signatures will become test sites for use by industry, universities and government. Such sites will be used to evaluate new developments in geophysical exploration. Previously existing test holes and calibration facilities developed by the GSC were described by Killeen (1986) and Schock et al (1991).

Planned Logging Measurements

In the NODA project, initial measurements are to be made with the GSC's R&D logging system. These include single point resistance (SPR), induced polarization, electrical resistivity, self potential, magnetic susceptibility, natural gamma ray spectrometry (K, U, Th), spectral gamma-gamma (density, spectral gamma-gamma ratio), temperature and T-gradient and acoustic velocity. In addition, the geophysical response of the deposit to borehole 3-component magnetometer and other available instruments such as VLF (E-field and H-field) measurements will also be determined by the GSC. Other borehole geophysical data obtained by industry or universities will be added to the compilation as they become available.

Locating the first test site

The project started in 1992. A number of mining companies were contacted and one potential site, the McConnell Deposit (Garson Offset) in the Sudbury area, was selected and is identified as one of several potential test sites to be established under this project. This deposit, owned by INCO limited, is fairly representative of the nickel deposits in the Sudbury area.

THE MCCONNELL NICKEL DEPOSIT, (GARSON OFFSET), SUDBURY AREA

Geology

The McConnell nickel deposit, located in the Sudbury Breccia between norites to the north and metavolcanics to the south, is a small tabular body approximately 152 m in strike length and 610 m in depth extent. This massive sulphide deposit, comprised of pyrrhotite and pentlandite, is highly magnetic and very conductive. It has been extensively drilled and numerous drillholes remain open. A cross-section of the deposit with a fence of five holes which were geophysically logged, is shown in figure 1.

Logging at the McConnell Test Site

Preliminary multiparameter borehole geophysical measurements were made in some of these holes with the GSC's R&D logging system for an initial compilation of the geophysical signatures of the deposit and its host rock. Work to date is summarized below:

1992/1993 work

A number of holes were dummied and found to be open. Two of them were logged with the GSC R&D logging system and four were logged with the IFG Corp. 3-component magnetometer in the summer of 1992. Data were processed and presented at the OGS open house in December (Killeen and Mwenifumbo, 1992; Mwenifumbo et al, 1992) and the GSC Current Research Forum in January 1993.

1993/1994 work

The McConnell Nickel deposit was the subject of further intensified borehole geophysical surveys in the summer of 1993. Multiparameter logs were recorded in three additional holes, completing a fence of 5 holes across the deposit. Mwenifumbo et al., (1993a) provided a summary of previous work carried out in 1992/93. A description of this NODA project and its objectives was given by Killeen et al., (1993). These data will provide useful deposit signatures as well as the basis for test sites for future workers. Additional borehole 3-component magnetic measurements were made with the IFG Corp. BMP-4 probe which also provides borehole directional survey data. Experimental VLF measurements (data not shown here) were made with the new Scintrex borehole 3-component VLF system which measures both H field and E-field.

The first acoustic velocity logs were acquired in hole 78930 in the middle of the fence. This was an important step in the use of seismic methods for mineral exploration. Results of the acoustic logging which were described by Pflug et al. (1994) indicated that the massive sulphides of the McConnell deposit exhibit low velocity. These low velocities are related to the mineralogy of the ore (pentlandite and pyrrhotite) and are not necessarily to be expected in all massive sulphides. In fact the acoustic logging in the Kidd Creek area (another potential NODA test site) did not show low velocities in the massive sulphides, probably because they contain significant pyrite concentrations. Pyrite exhibits a very high acoustic velocity compared to other sulphides.

Usage of the new test site

The McConnell deposit has already been used for experimental borehole measurements by workers from INCO, Queen's University, and Ecole Polytechnique in addition to the GSC, and is on the way to becoming a widely used borehole geophysical field laboratory. Multiparameter logs in five boreholes and examples of acoustic and 3-component magnetometer and borehole orientation logs have been compiled for this release as a GSC open file. Some preliminary results illustrating hole-to-hole correlation and other uses of the test site were also described by Mwenifumbo et al. (1993b, 1993c).

Results in these holes demonstrate the possibility that logging may reduce drilling costs if it can be utilized in less expensive rotary drilled holes to supplement data from diamond core drilled holes. In addition to the fence of five holes, two holes along strike of the orebody were deepened to facilitate borehole magnetic log interpretations. One of these holes was logged (data not shown here) with the 3-component borehole magnetic logging system.

A number of oral and poster presentations illustrated results to the end of the 1994 field season, and preliminary information was published in several manuscripts (Killeen et al, 1994; Killeen, 1994).

BOREHOLE LOGGING EQUIPMENT DESCRIPTION

1. The GSC Logging System

The GSC multiparameter borehole geophysical measurements included: 1) total count (TC), potassium (K), uranium (U) and thorium (Th) natural gamma ray logs, 2) density and Spectral Gamma-Gamma (SGG) ratio logs, 3) Self Potential (SP), Single Point Resistance (SPR), normal array resistivity (R) and Induced Polarization (IP) logs, 4) Magnetic Susceptibility (MS), 5) temperature and temperature gradient logs. A general description of the GSC logging tools and the geologic features to which they respond, is given in Appendix I.
Except as noted, the following logging speeds, detector sizes etc. were used for all holes:

Temperature log:	6 m/min
MS log:	6 m/min
Gamma-ray log:	3 m/min, detector = 38 x 127 mm NaI(Tl)
Density/SGG log:	6 m/min, detector = 22 x 76 mm CsI(Na); source = 10 mCi Co-60.
IP and R:	3 m/min; (normal array)
SP:	6 m/min
SP and SPR:	6 m/min for Hole 78928

2. The Portable Logging System

The portable logging system manufactured by IFG Corp. of Brampton, Ontario, combines several geophysical measurements in a logging tool which is primarily designed to be a borehole orientation probe. The borehole survey which yields dip and azimuth of the hole, is based on measurements with 3 fluxgate magnetometers and 2 solid state tilt meters in the probe. The tool also measures resistivity, temperature and magnetic susceptibility. The magnetometer measurements are presented as the vertical, north and east components and computed total field. Additional information can be found in Appendix I.

3. The Acoustic Logging System

The acoustic logging system, manufactured by Mount Sopris Instrument Co. of Colorado uses a piezoelectric transducer for an energy source, and two piezoelectric transducer receivers. The tool can be used to determine P-wave velocities and records the full sonic waveform. The characteristics of the acoustic velocity probe were described by Pflug et al (1994). Some additional details are given in Appendix I.

RESULTS OF GEOPHYSICAL LOGGING AT THE MCCONNELL DEPOSIT

The borehole geophysical measurements made at the McConnell deposit included natural gamma ray spectrometry (total count, K, U, Th), self potential, single point resistance, electrical resistivity, induced polarization, spectral gamma gamma (density, SGG Ratio), temperature, magnetic susceptibility, borehole orientation and 3-component magnetometer. Most of the geophysical parameters give excellent responses characteristic of the deposit and its host rocks. The density, magnetic susceptibility and electrical resistivity accurately delineate the distribution of the mineralized zones along the drillholes and provide some basic physical property data to help in the interpretation and modelling of surface and airborne geophysical data. The natural gamma ray data provide useful information for mapping alteration and stratigraphy.

The geophysical logs for the five holes shown in figure 1 are presented here as a series of twenty coloured multiparameter log plots. The geology is plotted as in-fill of the area under the logs for easy comparison. The plots are tabulated below.

COLOURED MULTIPARAMETER LOG PLOTS:

Borehole	System	No. of Plots
78928	GSC R&D	1 plot
78929	GSC R&D	2 plots
78930	GSC R&D	3 plots
80555	GSC R&D	3 plots
80578	GSC R&D	5 plots
78930	Mag/Orient	3 plots
78930	Acoustic	3 plots

FUTURE PLANS FOR THE MCCONNELL DEPOSIT (GARSON OFFSET) TEST SITE

The geophysical signature of the McConnell deposit (Garson Offset) has been partially evaluated and INCO has agreed to make this deposit available as a test site as long as their plans for mining operations will permit. Any additional geophysical logs which become available, will be open filed and the physical property data, characteristic of the deposit and its host rocks, will be compiled and published in GSC 'Current Research'. A final GSC report will summarize all of the NODA project results, tying together the logs, tables, and deposit geology.

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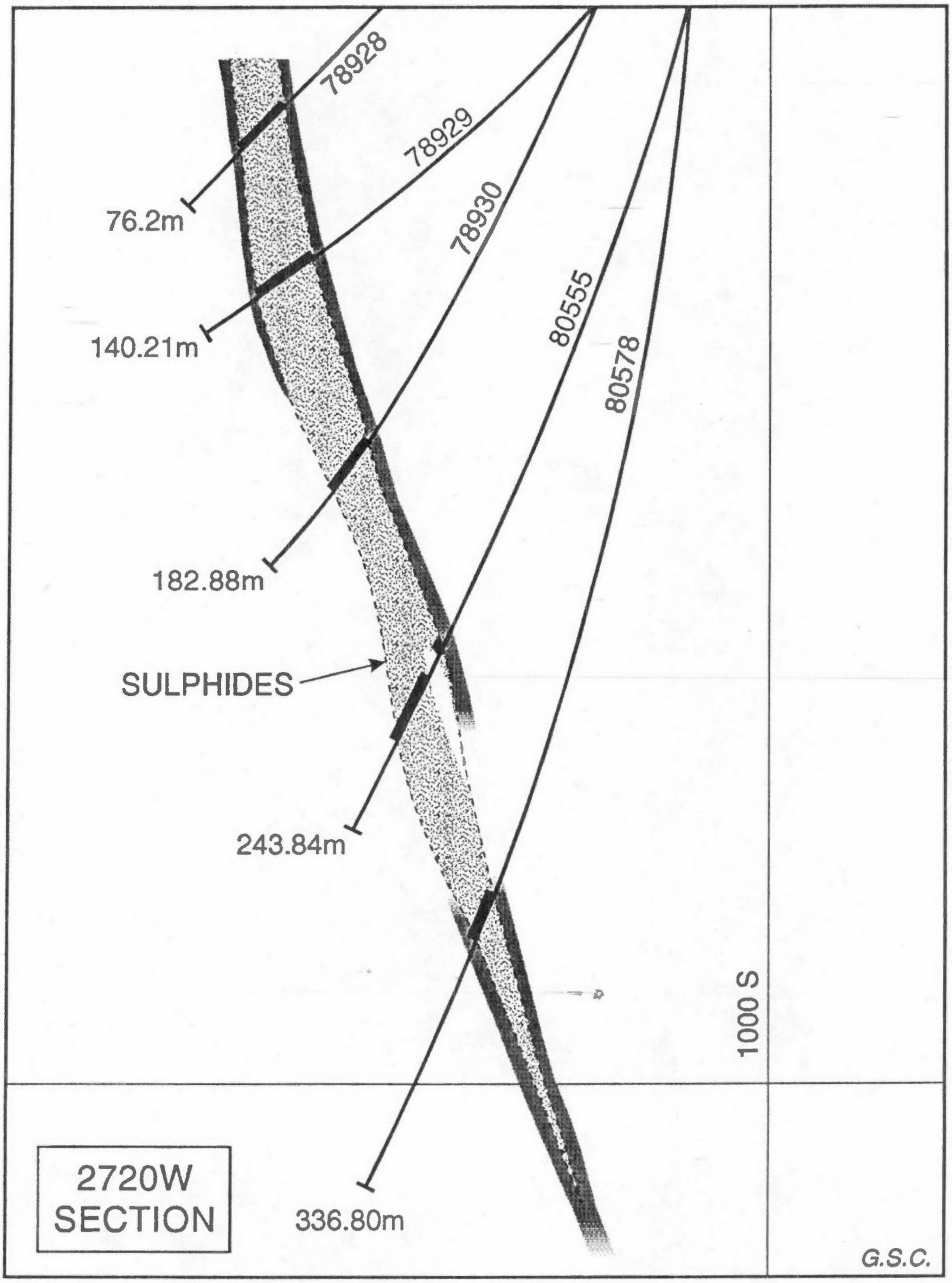

Figure 1. Vertical section through the McConnell Nickel Deposit (Garson Offset) near Sudbury, Ontario showing five boreholes which intersect the massive sulphide.

Table of contents

APPENDIX I

THE LOGGING SYSTEM

The GSC Borehole Geophysical Logging System

General Description of GSC Logging Tools and Geologic Responses

1. GAMMA-RAY SPECTRAL LOGGING
    1.1 Theory
    1.2 Principle of Gamma-Ray Spectral Logging
    1.3 The GSC Gamma-Ray Spectral Logging Equipment
2. DENSITY/SPECTRAL GAMMA-GAMMA (SGG) LOGGING
3. IP/R/SP LOGGING
    3.1 Geological interpretation of IP/R/SP Logs
        3.1.1 INDUCED POLARIZATION (IP)
        3.1.2 RESISTIVITY (R)
        3.1.3 SELF POTENTIAL (SP)
    3.2 The IP Logging Tool Description
        3.2.1 Induced Polarization (IP)
        3.2.2 Self Potential (SP)
        3.2.3 Resistivity (R)
4. MAGNETIC SUSCEPTIBILITY LOGGING
5. TEMPERATURE/TEMPERATURE-GRADIENT LOGGING
6. ACOUSTIC TOOL DESCRIPTION
7. 3-COMPONENT MAGNETIC / ORIENTATION TOOL DESCRIPTION
    Selected Bibliography on Borehole Geophysical Logging

APPENDIX I

THE LOGGING SYSTEM

The GSC Borehole Geophysical Logging System

Applications of geophysical logging encompass both mining exploration and geotechnical problems. These include: delineating ore zones, identifying and mapping alteration associated with ore, lithologic interpretation and hole-to-hole stratigraphic correlation for unravelling complex structures. Also possible is in situ assaying of ore, and in situ determination of physical rock properties for use in calculating geotechnical (rock strength) parameters. Groundwater flow patterns in joints and fractures intersected by the holes can be detected as well.

The primary components of the GSC R&D digital logging system are: 1. The borehole probe containing the geophysical sensor; 2. The logging cable and winch for sending the signal to the surface instruments, and for sending power down to the probe; 3. A depth counter attached to a wellhead pulley for keeping track of the location of the probe in the hole; 4. An analog-to digital converter (ADC) to convert the signal to digital form for recording; 5. A computer keyboard and display monitor to sort out and record the signals and display information; 6. A 9-track magnetic tape recorder; 7. A multi-pen chart recorder to provide a hard copy in the field.

Most modern 'slim-hole' tools are 38 to 50 mm diameter, designed to run in BQ holes or larger. The logging speed is usually about 6m/minute and unless otherwise indicated, can be run in either air or water-filled holes. Data sampling rate ranges from 1 to 5 samples per second, providing a measurement every 2 to 10 cm in the hole.

The truck-mounted system has five logging tools (probes) with different sensors that in total can measure up to twelve parameters. The characteristics of the logging tools and their measuring principles are briefly described below.

General Description of GSC Logging Tools and Geologic Responses

1. GAMMA-RAY SPECTRAL LOGGING

1.1 Theory

Gamma-ray measurements detect variations in the natural radioactivity originating from changes in concentrations of the trace elements, uranium (U) and thorium (Th) as well as changes in concentration of the major rock forming element potassium (K). Gamma-ray logs are important for detecting alteration zones, and for providing information on rock types.

In sedimentary rocks, potassium-40 is in general the principal source of natural gamma radiation, primarily originating from clay minerals such as illite and montmorillonite. Since the concentrations of these naturally occurring radioelements vary between different rock types, natural gamma-ray logging provides an important tool for lithologic mapping and stratigraphic correlation. For example, in sedimentary rocks, sandstones can be easily distinguished from shales due to the low potassium content of the sandstones compared to the shales. In unconsolidated sediments, sand can be distinguished from clay for the same reason.

In igneous and metamorphic geologic environment the three sources of natural radiation may contribute equally to the total number of gamma-rays detected by the gamma probe. Often in base metal exploration areas, the principal source of the natural gamma radiation is potassium-40 because alteration, characterized by the development of sericite (sericitization) is prevalent in some of the lithologic units. Sericitization results in an increase in the element potassium and hence a corresponding increase in the potassium-40 isotope. This renders sericitized zones excellent targets for gamma-ray logging. The presence of feldspar porphyry sills which contain increased concentrations of K-feldspar minerals would also show higher than normal radioactivity on the gamma-ray logs. During metamorphism and hydrothermal alteration processes, uranium and thorium may be preferentially concentrated in certain lithologic units. The gamma-ray spectral logs can delineate zones of increased radioactivity, and in addition, identify which radioelements are present.

1.2 Principle of Gamma-Ray Spectral Logging

A gamma-ray probe's sensor is usually a sodium iodide or cesium iodide scintillation detector and logging occurs while lowering or raising the probe in the hole at about 3 m/minute. Unlike an ordinary gamma-ray tool which only counts the gamma rays, the spectral gamma-ray tool also measures the energy of each gamma ray detected. K, U and Th produce gamma rays with characteristic energies so geophysicists can estimate the individual concentrations of the three radioelements.

Potassium decays into two stable isotopes (argon and calcium) which are no longer radioactive. Uranium and thorium, however, decay into daughter-product isotopes which are unstable (i.e. radioactive). The decay of uranium forms a series of about a dozen radioactive elements in nature which finally decay to a stable form of lead. The decay of thorium forms a similar series of radioisotopes. As each isotope in the disintegration series decays, it is accompanied by emissions of alpha or beta particles or gamma rays. These gamma rays have specific energies associated with the decaying radioisotope. The most prominent of the gamma rays in the uranium series originates from decay of ^{214}Bi (bismuth), and in the thorium series originates from decay of ^{208}Tl (thallium).

Because there should be an equilibrium relationship between the daughter product and parent, it is possible to compute the quantity (concentration) of parent uranium (^{238}U) and thorium (^{232}Th) in the decay series by counting gamma rays from ^{214}Bi and ^{208}Tl respectively, if the probe has been properly calibrated (Killeen, 1982).

During each second of time while the probe is moving down the hole, the gamma-ray energies are sorted into an energy spectrum in a computer memory. The number of gamma rays in three pre-selected energy windows centred over peaks in the spectrum is computed, as is the total gamma-ray count. These four numbers represent potassium, uranium, thorium and Total Count (TC) detected during that one second counting time.

These data (including depth) are recorded and also displayed on the chart recorder to produce gamma-ray spectral logs. Although the raw gamma-ray spectral logs (Total Count log, K log, U log and Th log) provide more information than a non-spectral (gross count) log, it is possible to convert them to quantitative logs of percent K, ppm U and ppm Th. This requires that the probe be calibrated in model boreholes with known concentrations of K, U and Th such as the models constructed by the GSC at Bells Corners near Ottawa (Killeen, 1986).

Because gamma rays can be detected through steel, it is even possible (at a slight decrease in sensitivity) to log inside drill rod or casing.

1.3 The GSC Gamma-Ray Spectral Logging Equipment

The GSC R&D logging system utilizes gamma-ray spectral data acquisition equipment similar to that found in modern airborne gamma-ray spectrometers. Full 256 channel gamma-ray spectra are recorded from a scintillation detector in the probe. The recording media is a 9-track magnetic tape. Scintillation detectors of different materials, and of different sizes are used by the GSC. These include:

Name	Composition	Density (g/cm^3)
Cesium Iodide	CsI (Na)	4
Sodium Iodide	NaI (Tl)	3.67
Bismuth Germanate (BGO)	$Bi_4\,Ge_3\,O_{12}$	7.0

Probe housings of outside diameter 1.25" (32 mm), 1.5" (38 mm) or 2" (50 mm), contain detectors of sizes ¾" x 3", 1" x 3", and 1.25" x 5" respectively for use in AQ, BQ, and NQ holes respectively. The selection of probe (and detector) for logging is determined by the hole diameter. The largest diameter probe that will safely fit in the borehole is selected to maximize the count rate and provide good counting statistics. For smaller probes, the higher density (higher efficiency) materials are chosen. (These are also higher cost.) If the count rate is too low due to the extremely low concentrations of K, U and Th, such as is often the case in limestones for example, it may not be possible to produce a K log, U log and Th log. In that case only the Total Count log is produced which is the count rate of all gamma rays above a preselected threshold energy (usually 100 KeV or 400 KeV). A number of factors determine the logging speeds and sample times during the acquisition of gamma-ray data. The critical factors are the anticipated levels of radioactivity and the size of detector in the probe. Gamma-ray spectral logging is usually done at 3 m/minute but can be done as fast as 6 m/minute or as slow as 0.5 m/minute for more detailed information. The volume sampled is about 0.5 cubic metres of rock surrounding the detector, at each measurement (i.e. 10 to 30 cm radius depending on the rock density).

2. DENSITY/SPECTRAL GAMMA-GAMMA (SGG) LOGGING

The Density/SGG Ratio log or heavy element indicator log is derived from the spectral gamma-gamma probe that also provides the density (Killeen and Mwenifumbo, 1988). The SGG/density tool is essentially a spectral gamma-ray logging tool with the addition of a weak (10 millicurie = 370 MBq) gamma-ray source (e.g. ^{60}Co) on the nose of the probe. The tool has a 23 mm by 76 mm (0.9" x 3") cesium iodide detector which measures gamma rays from the source that are backscattered by the rock around the borehole.

Complete backscattered gamma-ray spectra are recorded in 1024 channels over an energy range of approximately 0.03 to 1.0 MeV. Density information is determined from the count rate in an energy window above 200 keV while information about the elemental composition or heavy element content is derived from the ratio of the count rates in two energy windows (spectral gamma-gamma ratio, SGG); one at high energy (above 200 keV) and one at low energy (below 200 keV). When there is a change in the density of the rock being measured, the count rates recorded in both windows will increase or decrease due to the associated change in compton-scattered gamma rays reaching the detector. However, if there is an increase in the content of high Z (atomic number) elements in the rock, the associated increase in photoelectric absorption (which is roughly proportional to Z^5) will cause a significant decrease in count rate in the low energy window with relatively little change in the high energy window. Since the low energy window is affected by both density and Z effect while the high energy window is mainly affected by density, the ratio of counts in the high-energy window to the counts in the low-energy window can be used to obtain information on changes in Z. This ratio increases when the probe passes through zones containing high Z materials. Thus the log can be considered as a heavy element indicator, and can be calibrated to produce an assay tool for quantitative determination of the heavy element concentration in situ along the borehole, without resorting to chemical assaying of the core (Killeen and Mwenifumbo, 1988).

The sample volume is smaller than for natural gamma ray logging since the gamma rays must travel out from the probe, into the rock and back to the detector. A 10 to 15 cm radius around the probe is "seen". Data are acquired with a logging speed of 6.0 m/minute with a sample time of 1 second, giving a measurement every 10 cm.

The density of the rock is affected by porosity, water content and chemical composition. Most of the density variations within igneous and metamorphic rocks are due to variations in mineralogical composition. Rocks with higher percentages of mafic minerals (Fe, Mg silicates) have higher densities than those with higher percentages of felsic minerals (Ca, Na, K, Al silicates). The presence of minerals containing heavy elements such as base metals tend to increase the overall density of the host rock. In sedimentary rocks, density variations may be a result of differing degrees of compaction (induration) rather than changes in elemental composition.

In ore tonnage and reserve computations, one of the parameters used is the specific gravity and hence a knowledge of in-situ densities of the rocks may provide valuable information for ore reserve estimations. Open fractures intersected by the borehole often appear as low density zones on the density log (Wilson et al, 1989).

3. IP/R/SP LOGGING

The Induced Polarization (IP) tool consists of an assembly of electrodes which are placed in the borehole, usually including current electrodes and potential (measurement) electrodes. A square wave current with an 'off' time between positive and negative parts of the waveform is transmitted (waveforms may be from 1 second to 8 seconds duration). Potential measurements made at selected times in the waveform can be related to the IP effect (chargeability of the rocks), the resistivity (R) of the rocks, and to self-potentials (SP) generated in the rocks. The transmitter is a constant current source located at the surface. A detailed explanation of the IP probe will be given below.

3.1 Geological interpretation of IP/R/SP Logs

3.1.1 INDUCED POLARIZATION (IP)

In time domain IP measurements, the rate of decay of the measured voltages during the current off-time is related to the electrical polarizability of the rock and is called chargeability. A high chargeability response is an indication of the presence of metallic sulfides and oxides or cation-rich clays such as illite and montmorillonite (Mwenifumbo, 1989). One of the major alteration processes within a number of base metal and gold mining camps is pyritization and this is a target for most IP logging.

3.1.2 RESISTIVITY

The electrical resistivity of rocks depends on several factors including the presence of conductive minerals such as base metal sulfides or oxides and graphite in the rock. Most rocks without these minerals are usually poor conductors and their resistivities are governed primarily by their porosity and salinity of the pore water and to a lesser extent by the intrinsic minerals that constitute the rock. Some alteration processes such as silicification and carbonatization tend to reduce the porosity of the rock and hence increase the resistivities of the rocks. Thus in rocks where no significant amounts of conductive minerals occur, the most important factors affecting the resistivities are fracturing, porosity, the degree of saturation of pore spaces and the nature of the electrolytes in the pore fluids. The resistivity log is, therefore, useful mainly in mapping conductive minerals and fracture zones. In sedimentary rocks, the resistivity log is frequently used in lithologic mapping because changes in lithology are often associated with changes in porosity.

3.1.3 SELF POTENTIAL (SP)

SP anomalies are mainly an indication of the presence of graphite and/or high concentrations of base metal sulfides including pyrite. Large self potentials observed within and around sulfide and graphite bodies are mainly caused by electrochemical processes (Sato and Mooney, 1960, Hovdan and Bolviken, 1984). Low resistivity anomalies correlating with SP and IP anomalies are, therefore, good indications of the presence of conductive minerals. Also SP anomalies can be generated by fluid flow in porous media (electrokinetic or streaming potentials - Bogoslovsky and Ogil'vy, 1970, 1972) and heat flow (thermal electric coupling - Corwin and Hoover, 1979).

3.2 The IP Logging Tool Description

The transmitter on surface is a constant current source capable of supplying up to 250 mA. There are 4 selectable pulse times for the current waveforms: 0.25s, 0.5s, 1s and 2s (i.e. full waveforms of 1 second to 8 seconds duration). The long pulse times would mean logging at very low speeds in order to avoid errors that may be introduced in smearing measurements over large depth intervals. The volume of rock sampled is roughly related to the electrode spacings. The full waveform is recorded (digitized at 4ms intervals) on 9-track magnetic tape. Logging speed varies in the range 1 to 6 m/min according to the chosen pulse length (waveform duration). Sample interval is dependant on the chosen logging speed and chosen waveform period. Typically, a 1 second period with a logging speed of 6m/min results in sampling every 10 cm along the borehole.

3.2.1 Induced Polarization

The standard IP parameter is the chargeability determined during the early middle or center of the 'off' time of the decaying waveform. The apparent chargeabilities can be measured with 3 types of electrode arrays: 40 cm normal array, lateral array (pole-dipole array) and the 10 cm Dakhnov micronormal. The downhole current and potential electrodes are gold-plated brass cylinders, 40 mm in diameter.

3.2.2 Self Potential (SP)

The self potential is determined during the late 'off' time of the IP decay waveform. SP measurements are carried out either in the gradient mode with the same arrays as are used in the IP/Resistivity measurements, or in the Potential mode with a single Pb or $Cu/CuSo_4$ electrode downhole and a reference electrode on the surface. SP can be measured simultaneously with the IP/Resistivity measurements or in a separate logging run with current off. The latter is the preferred approach.

3.2.3 Resistivity (R)

The resistivity measurements are derived from the waveforms received during the constant current 'on' time of the square waveform, after the initial IP charging effects are over.

4. MAGNETIC SUSCEPTIBILITY LOGGING

The magnetic susceptibility (MS) of a volume of rock is a function of the amount of magnetic minerals, mainly magnetite, and pyrrhotite, contained within the rock. MS measurements can provide a rapid estimate of the ferromagnetism of the rock. These measurements can be interpreted to reflect lithological changes, degree of homogeneity and the presence of alteration zones in the rock mass. During the process of hydrothermal alteration, primary magnetic minerals (e.g. magnetite) may be altered (or oxidized) to weakly- or non-magnetic minerals (e.g. hematite). Anomalously low susceptibilities within an otherwise homogeneous high susceptibility (ferromagnetic) rock unit may be an indication of altered zones.

The volume of investigation or 'sample volume' is roughly a sphere of 30 cm radius, surrounding the sensing coil in the probe. The sensing coil forms part of a balanced electrical circuit. When the coil passes near ferromagnetic material, the inductance changes causing a phase shift in the current in the coil. The probe is calibrated so that this shift is converted into a measurement of the magnetic susceptibility. Logging is carried out at 6 m/minute and a measurement is taken every second or each 10 cm along the hole.

Basic flows and diabase dikes containing higher concentrations of magnetic minerals can be easily outlined from magnetic susceptibility measurements when they occur within a sedimentary sequence which normally contain little or no magnetic minerals. Susceptibilities within the range from 0 to 200000 microSI can be measured with this tool. Since the measurements are made inductively (ie with e.m. fields not electrodes), the tool can be used inside plastic casing and in dry holes.

5. TEMPERATURE/T-GRADIENT LOGGING

Temperature measurements are used to detect changes in thermal conductivity of the rocks along the borehole or to detect water flow through cracks or fractures. Fractures or shear zones may provide pathways for groundwater to flow if hydrologic gradients exist within the rock mass. Groundwater movements produce characteristic anomalies and their detection may provide information on the location of the fractured rock mass and hence aid in the structural interpretation of the area. The temperature gradient log amplifies small changes in the temperature log, making them easier to detect.

Large concentrations of metallic sulphides and oxides may perturb the isothermal regime locally since metallic minerals have very high thermal conductivities. This perturbation may be delineated with the high sensitivity temperature logging system. This, however, would be observed only in a thermally quiet environment. In areas where there are numerous fracture zones with ground water movements, thermal anomalies due to ground water movements are much larger than those that would be observed due to perturbation caused by the presence of metallic minerals.

The ultra-high sensitivity temperature probe designed at the GSC has a 10 cm long tip of thermistor beads with sensitivity of 0.0001 degrees Celsius. Changes in temperature of the fluid in the borehole are measured and sent as a digital signal to the surface. The signal is then converted into true temperature after correcting for the effect of the thermistor time constants; the temperature gradients are computed from the temperature data. All temperature logging is carried out during a downhole run so the sensor is measuring the temperature of the undisturbed fluid. The usual logging speed is 6 m/minute with data sampled every 1/5 of a second (approximately every 2 cm). This high spatial resolution of data is necessary if accurate temperature gradients are to be determined from the temperature data.

6. ACOUSTIC TOOL DESCRIPTION

The Borehole Geophysics Section of the GSC conducts acoustic velocity logging using a tool with a piezoelectric transducer for an energy source, and two piezoelectric transducer receivers separated by 30 cm. The difference in arrival times of the compressional waves (P-waves) at the two fixed receivers is converted to a velocity measurement. In addition, the amplitude of the first arrival is recorded as an amplitude log, which can be used to give a qualitative measurement of the attenuation factor (Q). The equipment, manufactured by Mount Sopris Instrument Co. of Colorado, records the full sonic waveform, making it possible to reprocess the field data to improve the precision of the first arrival picks, or in some cases, to pick the arrival time of the slower S waves which will provide additional information on the mechanical properties of the rocks.

By pulsing the energy source every half second and recording alternately with the 2 receivers, an average velocity is obtained every second, which, at a logging speed of 3 m/minute, represents a sample every 5 cm in the borehole.

The physical characteristics of the acoustic velocity probe were described by Pflug et al (1994). The 45 mm diameter probe consists of 2 sections; the transmitter section, and the receiver section, separated by a flexible acoustic isolator 0.5 m long. The manufacturer recommends a logging speed of less than 40 ft/minute (12 m/minute).

The acoustic logging tool can be used to determine P and S wave velocities which can be combined with data from the Density logging tool to calculate Poisson's ratio, Young's modulus, bulk modulus and shear modulus which are parameters important to any mining operation. It requires a water-filled hole to make good acoustic 'contact' with the walls of the hole. Some special modifications to the probe are possible (still experimental) for use in air-filled holes.

7. 3-COMPONENT MAGNETIC / ORIENTATION TOOL DESCRIPTION

A major problem in exploration drilling is knowing exactly where a drillhole goes since they often deviate from the planned path by significant amounts, both in direction (azimuth) and dip. The GSC has helped to support the development (by IFG Corp. of

Brampton, Ontario) of a new borehole orientation probe based on measurements with a 3-component fluxgate magnetometer and solid state tilt meters in the probe. The probe, continuously monitors its movement in dip and direction as it moves down the hole at about 6 m/minute sending the data to the up-hole electronics for recording and display on a PC. Because the borehole orientation data are recorded every few centimeters in the hole, noisy parts of the record which may occur due to magnetic anomalies can be easily edited to provide accurate survey results. Most of the older techniques which relied on magnetic measurements were recorded at largely separated points in the hole and anomalous readings were hard to detect and ambiguous to interpret.

The 3-component magnetometer measurements are themselves of interest in mineral exploration for detecting the presence of magnetic bodies at some distance from the hole. The prototype version of the probe being used by the GSC, contains two sets of 3-component magnetometers and the application of borehole magnetic gradiometer measurements are also being investigated.

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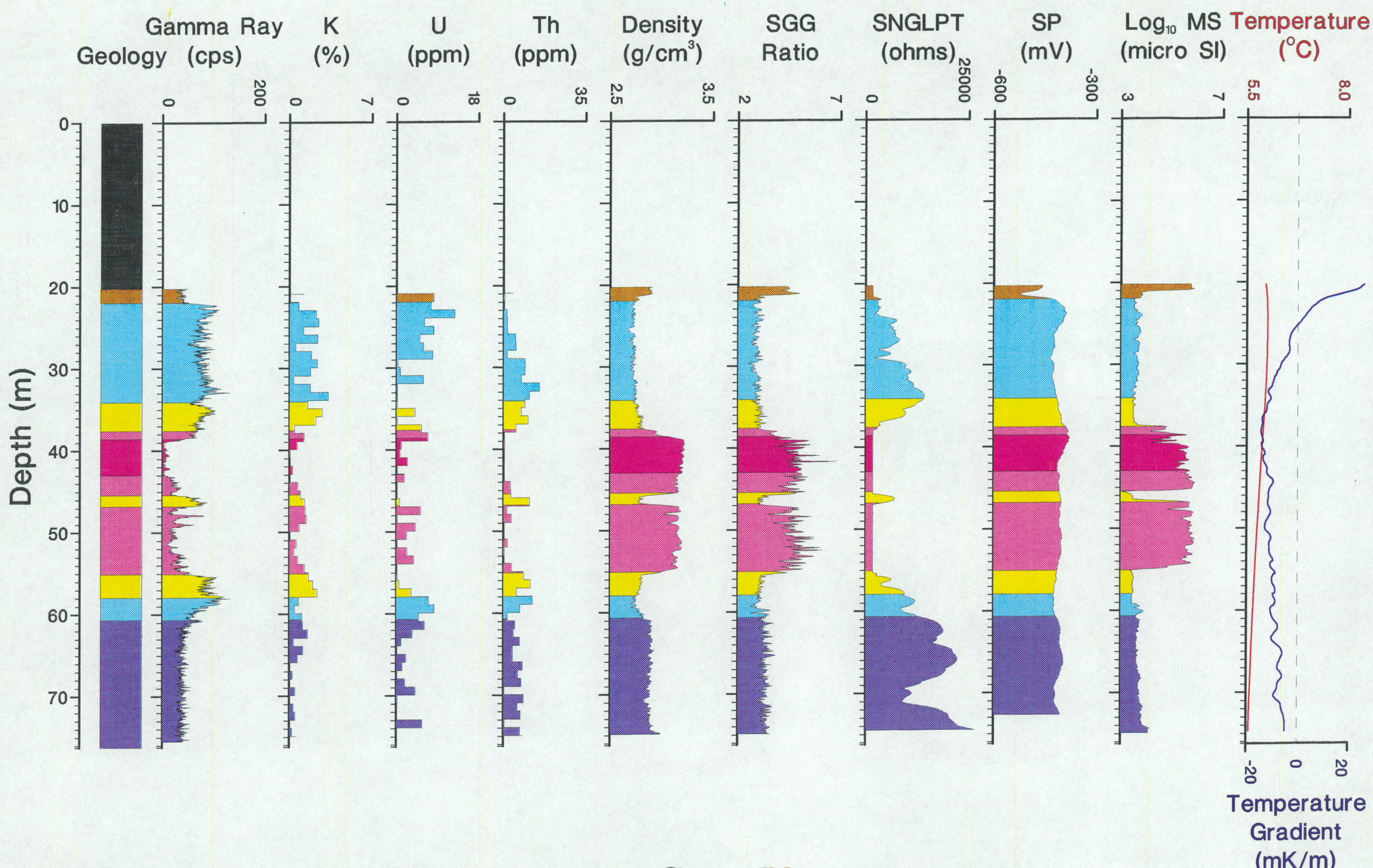
MCCONNELL DEPOSIT (GARSON OFFSET)
(GSC Research and Development Probes)

Latitude (46°33'13"), Longitude (80°52'28")

Borehole
78928



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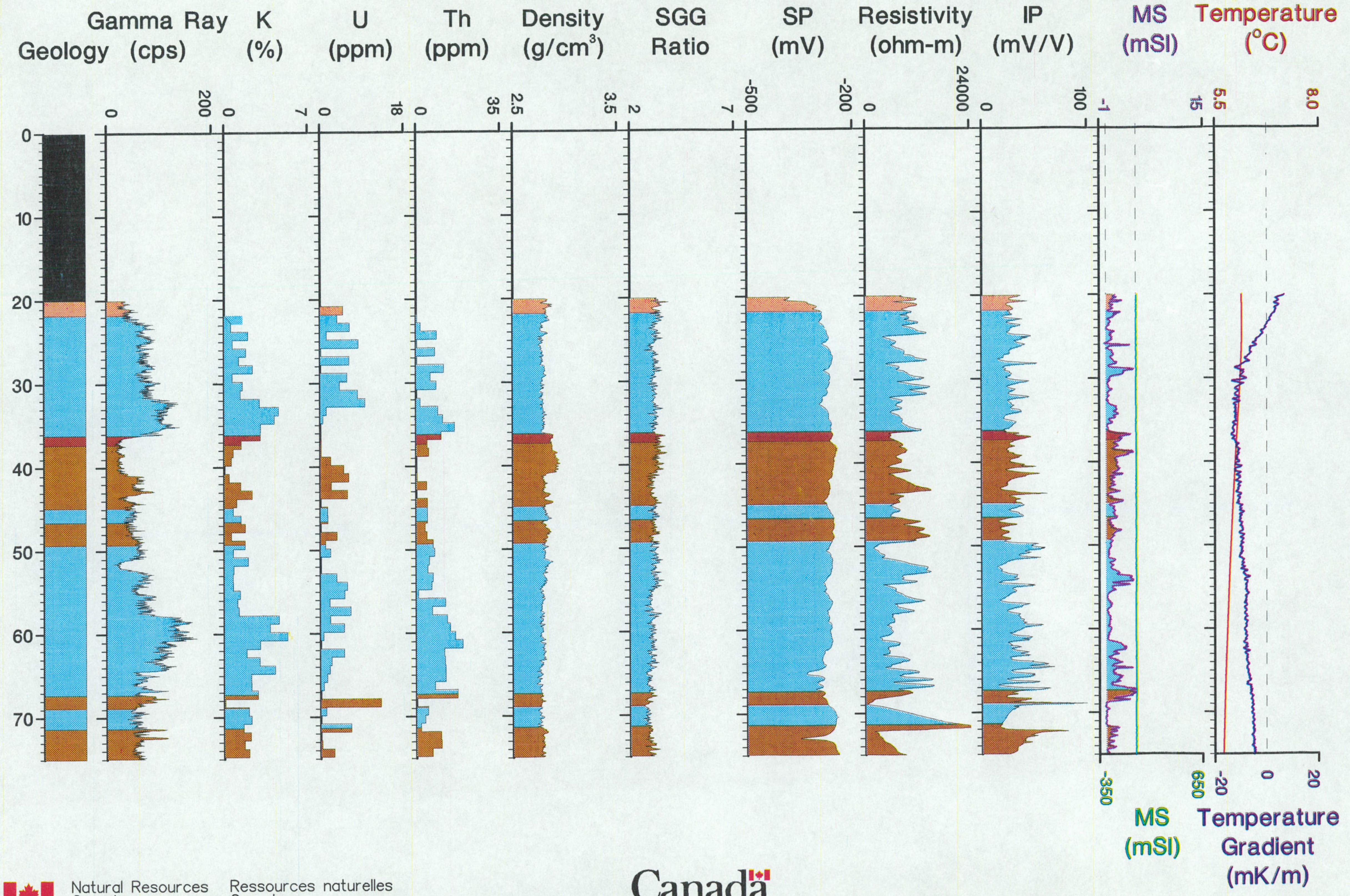
MCCONNELL DEPOSIT (GARSON OFFSET)
(GSC Research and Development Probes)
Latitude (46°33'12"), Longitude (80°52'28")

Borehole
78929
Plot 1 of 2



LEGEND

- Casing
- Metasediment
- Metagabbro
- Sudbury Breccia
- Metabasalt
- Massive Sulphide
- Conglomerate
- Incl. Massive Sulphide
- Quartz Diorite Dyke

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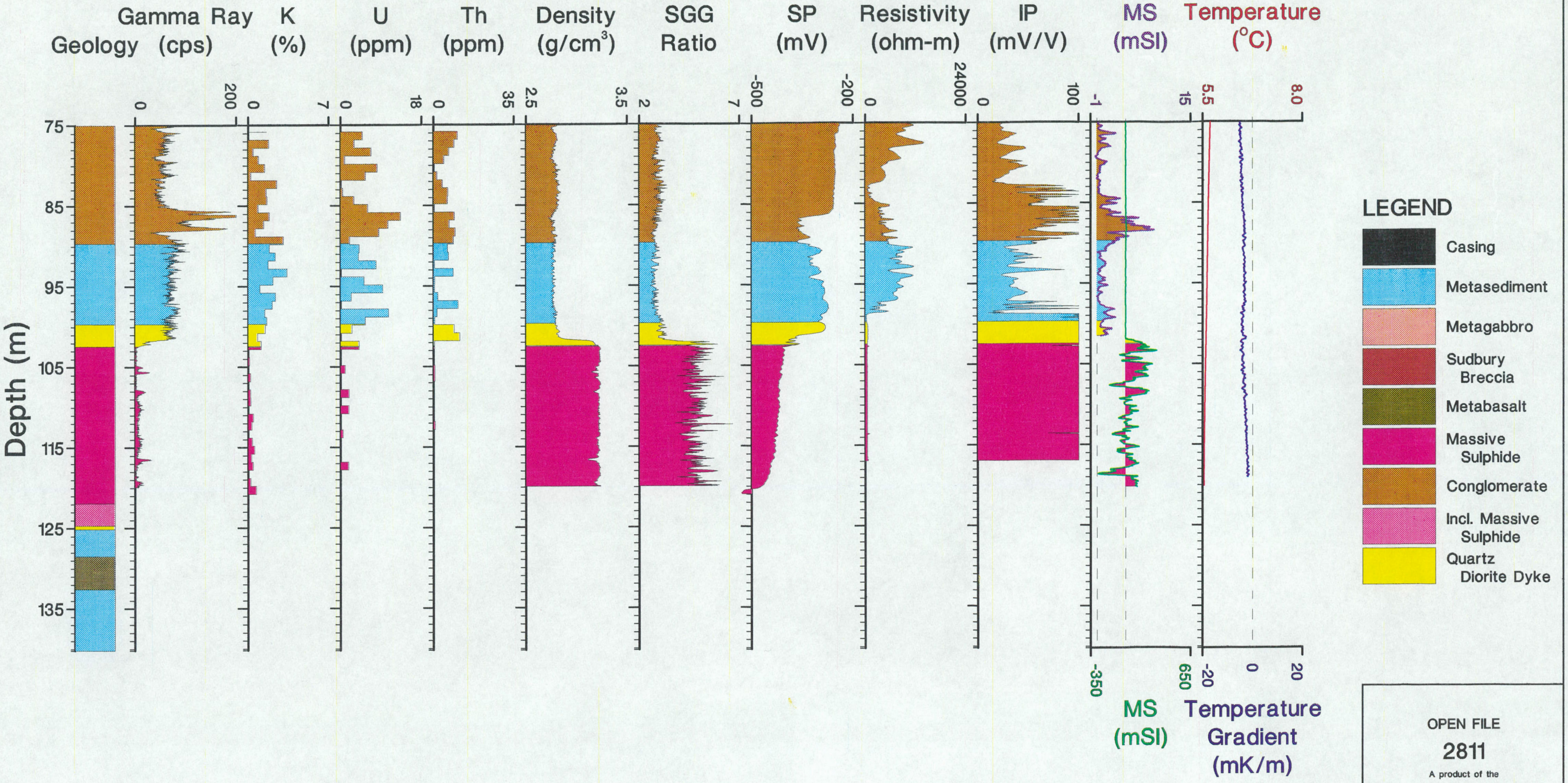
Latitude (46°33'12"), Longitude (80°52'28")

Borehole 78929
Plot 2 of 2



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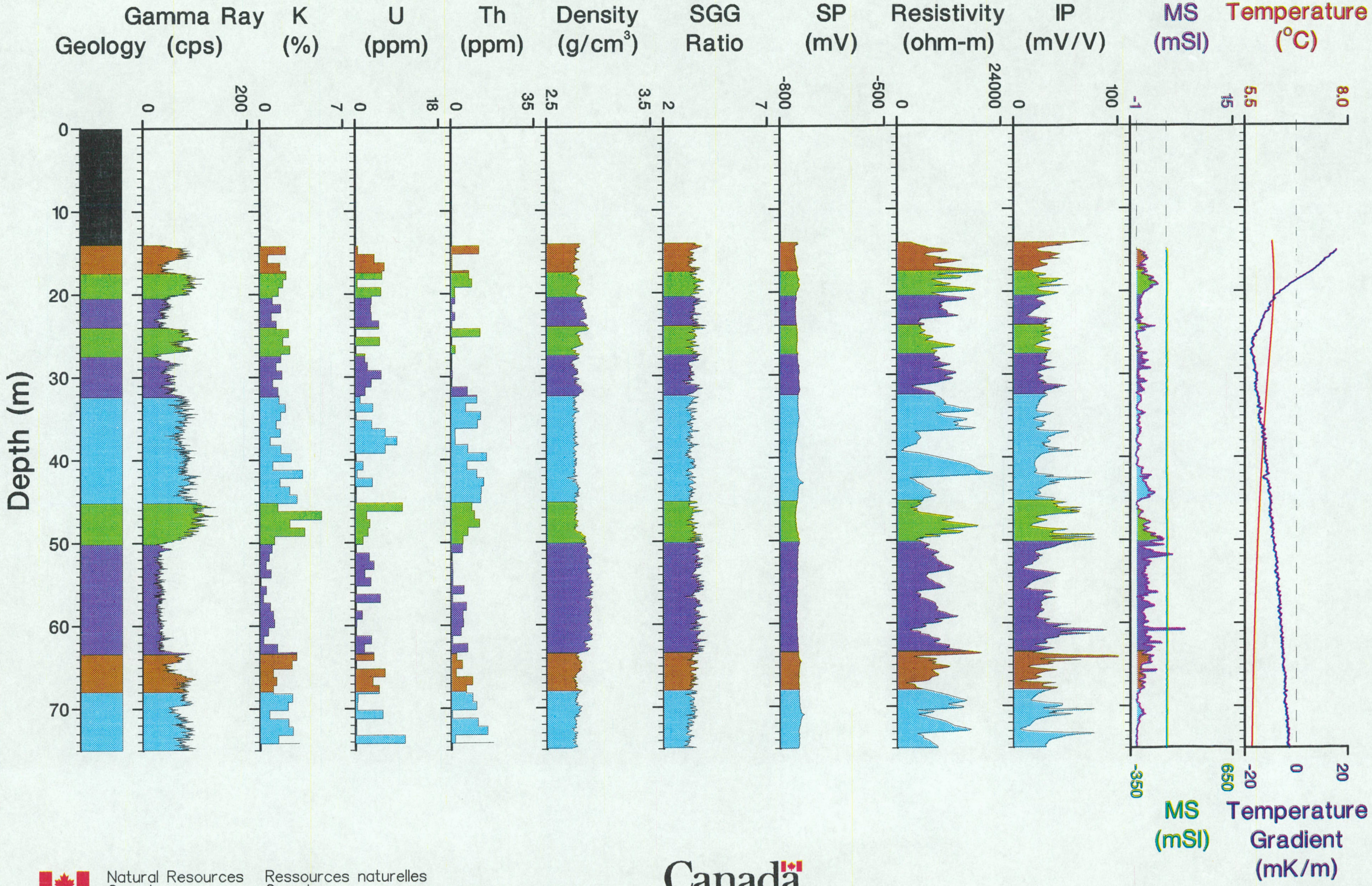
(GSC Research and Development Probes)

Latitude (46°33'12"), Longitude (80°52'28")

Borehole 78930
Plot 1 of 3



LEGEND

- Casing
- Conglomerate
- Schist
- Amphibolite
- Metasediment
- Quartz Diorite Dyke
- Incl. Quartz Diorite Dyke
- Massive Sulphide
- Incl. Massive Sulphide
- Meta. Sudbury Breccia

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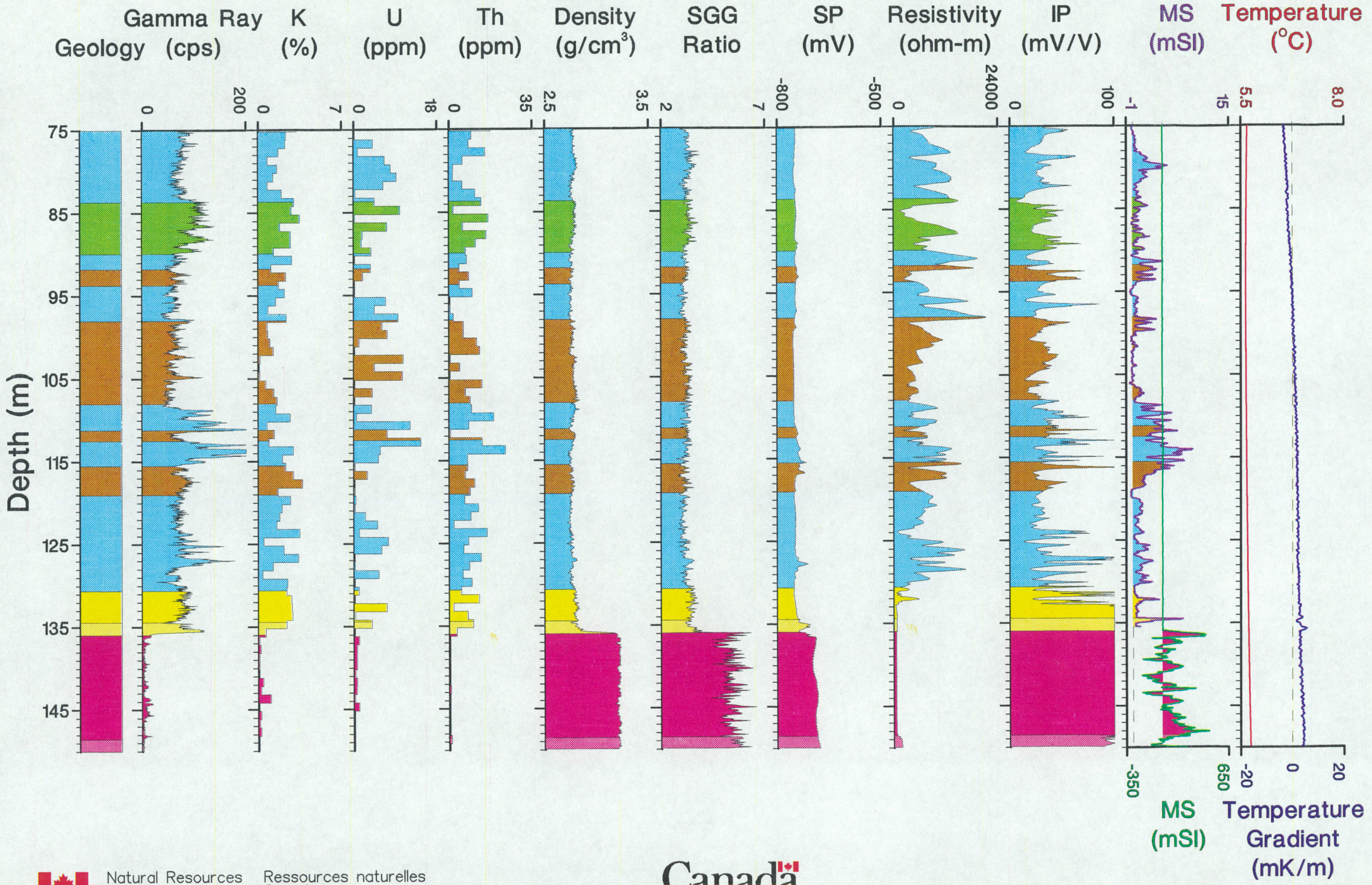
Latitude (46°33'12"), Longitude (80°52'28")

Borehole 78930



LEGEND

- Casing
- Conglomerate
- Schist
- Amphibolite
- Metasediment
- Quartz Diorite Dyke
- Incl. Quartz Diorite Dyke
- Massive Sulphide
- Incl. Massive Sulphide
- Meta. Sudbury Breccia

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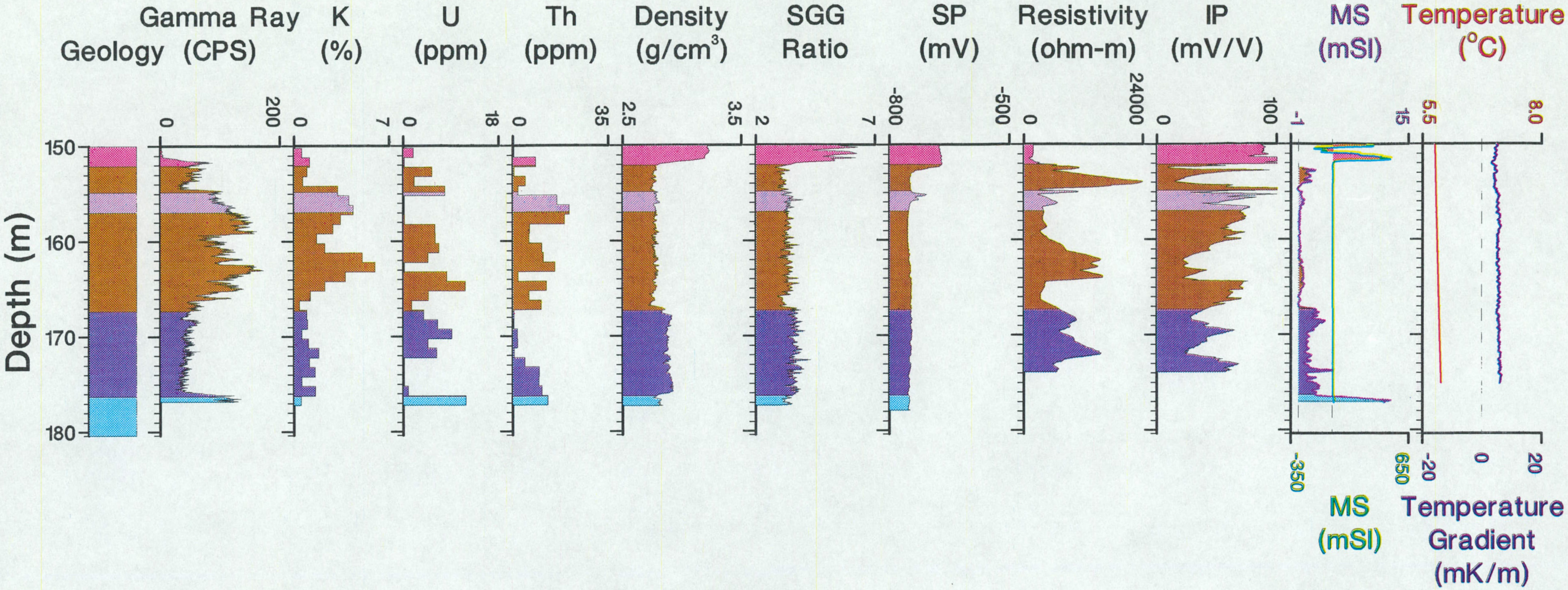
Latitude (46°33'12"), Longitude (80°52'28")

Borehole
78930
Plot 3 of 3



LEGEND
- Casing
- Conglomerate
- Schist
- Amphibolite
- Metasediment
- Quartz Diorite Dyke
- Incl. Quartz Diorite Dyke
- Massive Sulphide
- Incl. Massive Sulphide
- Meta. Sudbury Breccia

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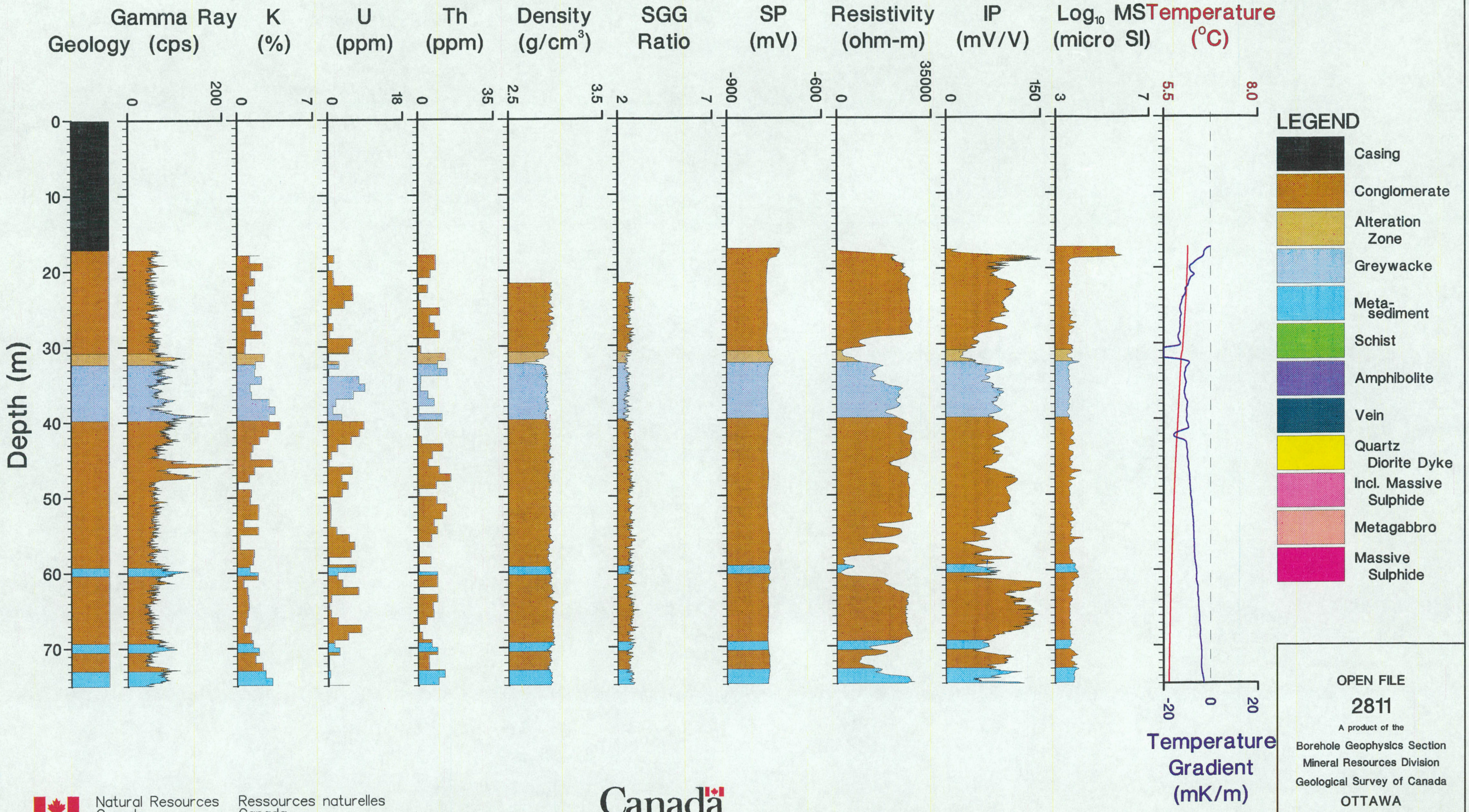
Latitude (46°33'12"), Longitude (80°52'28")

Borehole 80555
Plot 1 of 3



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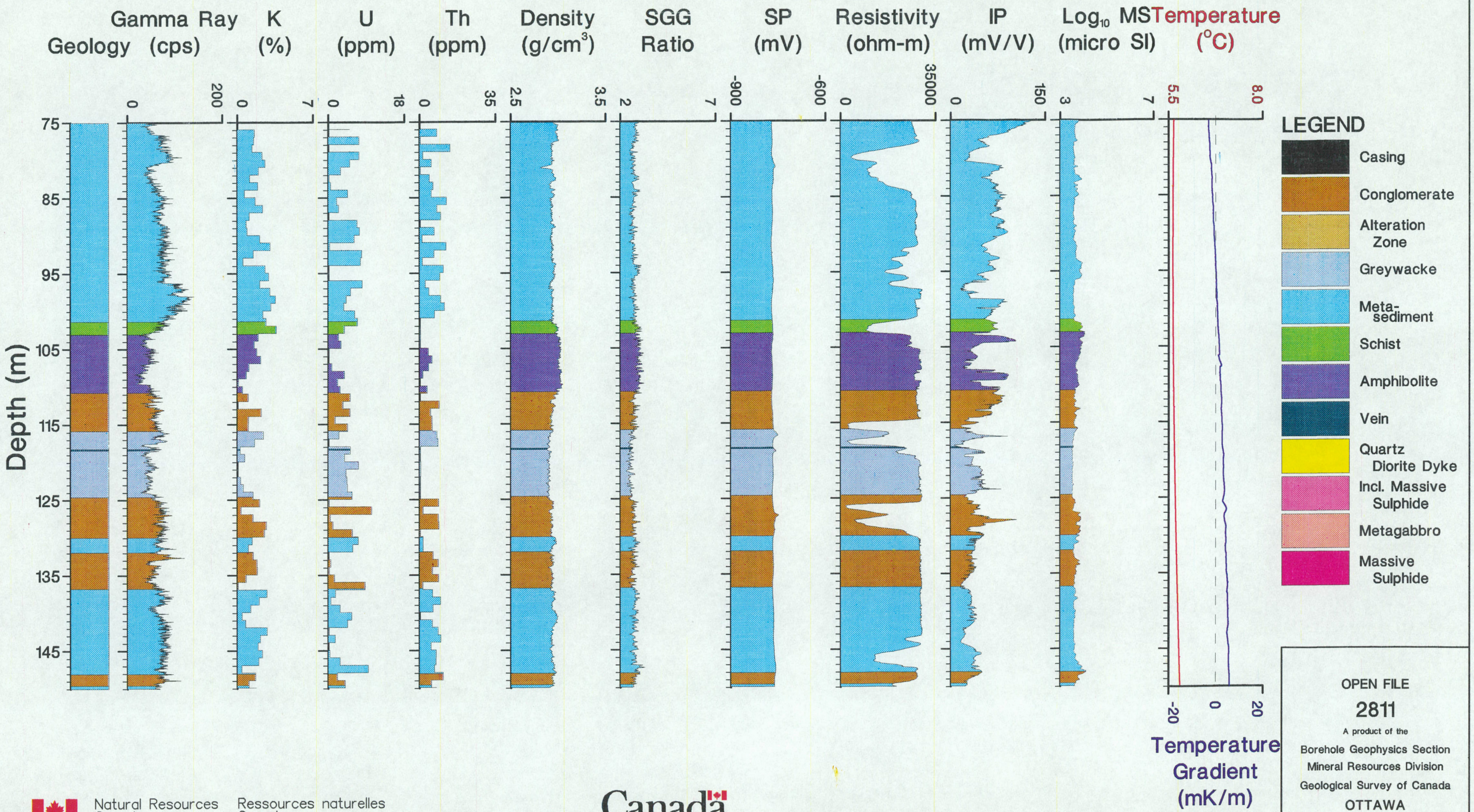
Latitude (46°33'12"), Longitude (80°52'28")

Borehole 80555
Plot 2 of 3



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Borehole 80555
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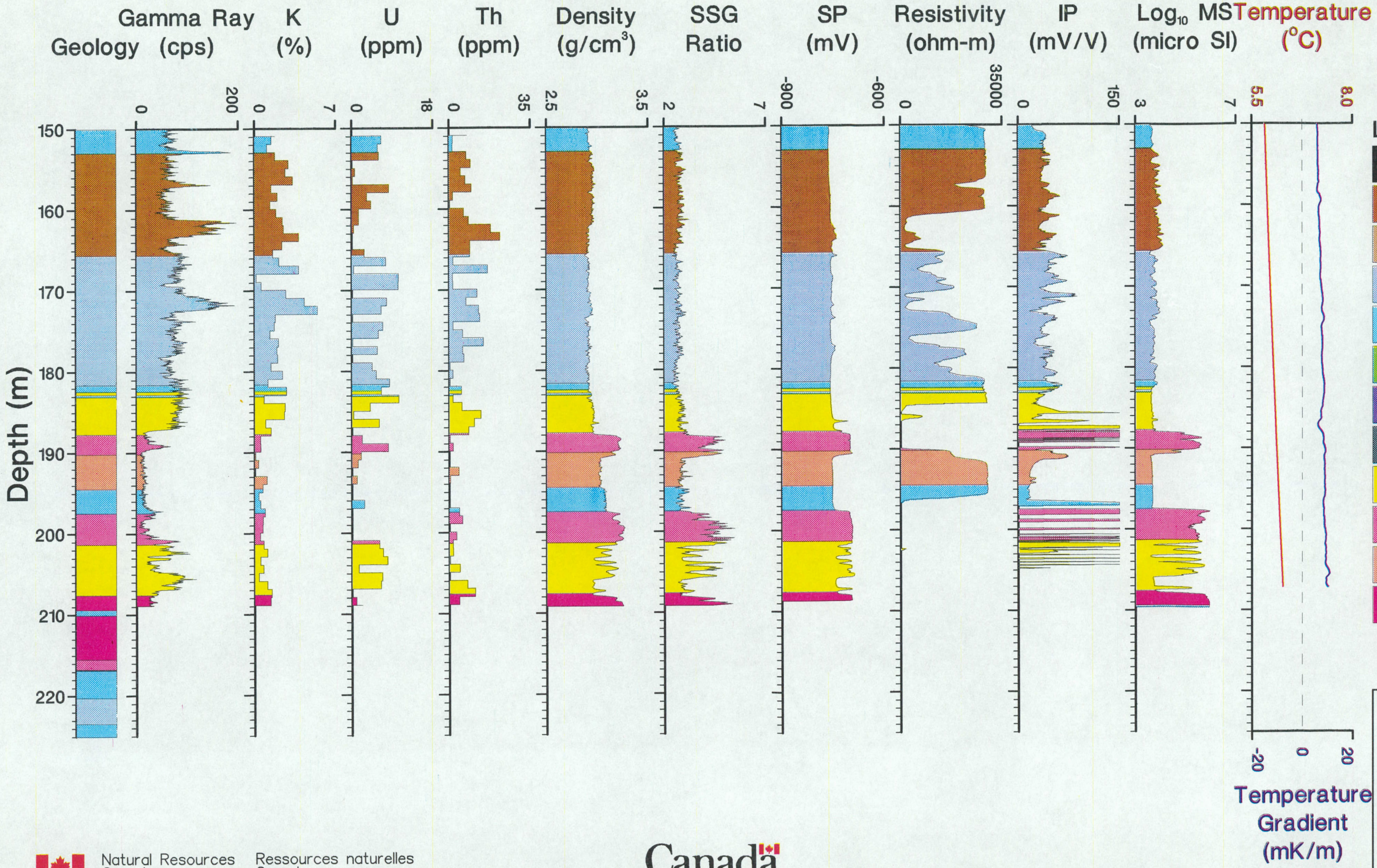

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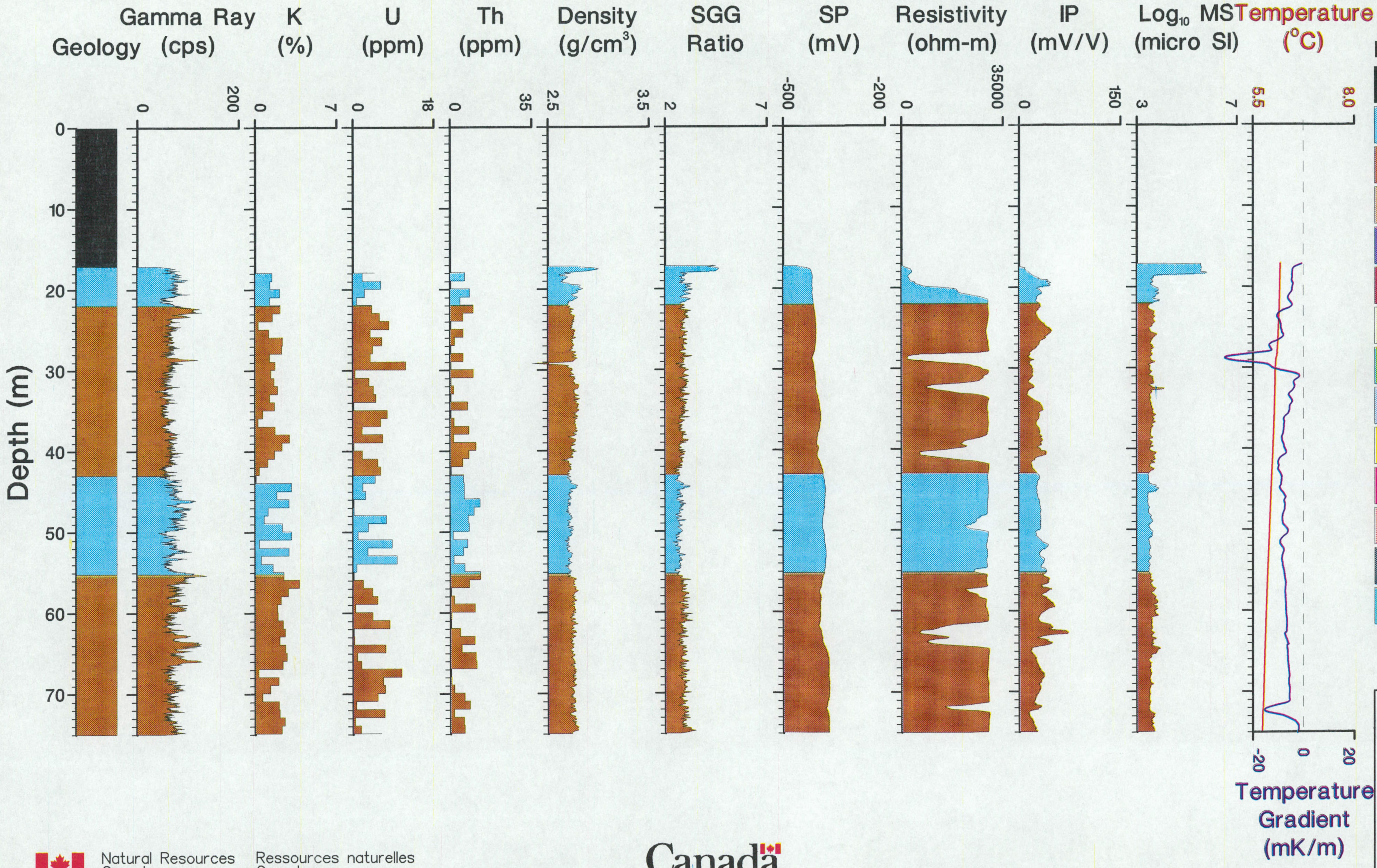

LEGEND

- Casing
- Metasediment
- Conglomerate
- Alteration Zone
- Amphibolite
- Sudbury Breccia
- Quartzite
- Schist
- Greywacke
- Quartz Diorite Dyke
- Massive Sulphide
- Metagabbro
- Vein
- Structure

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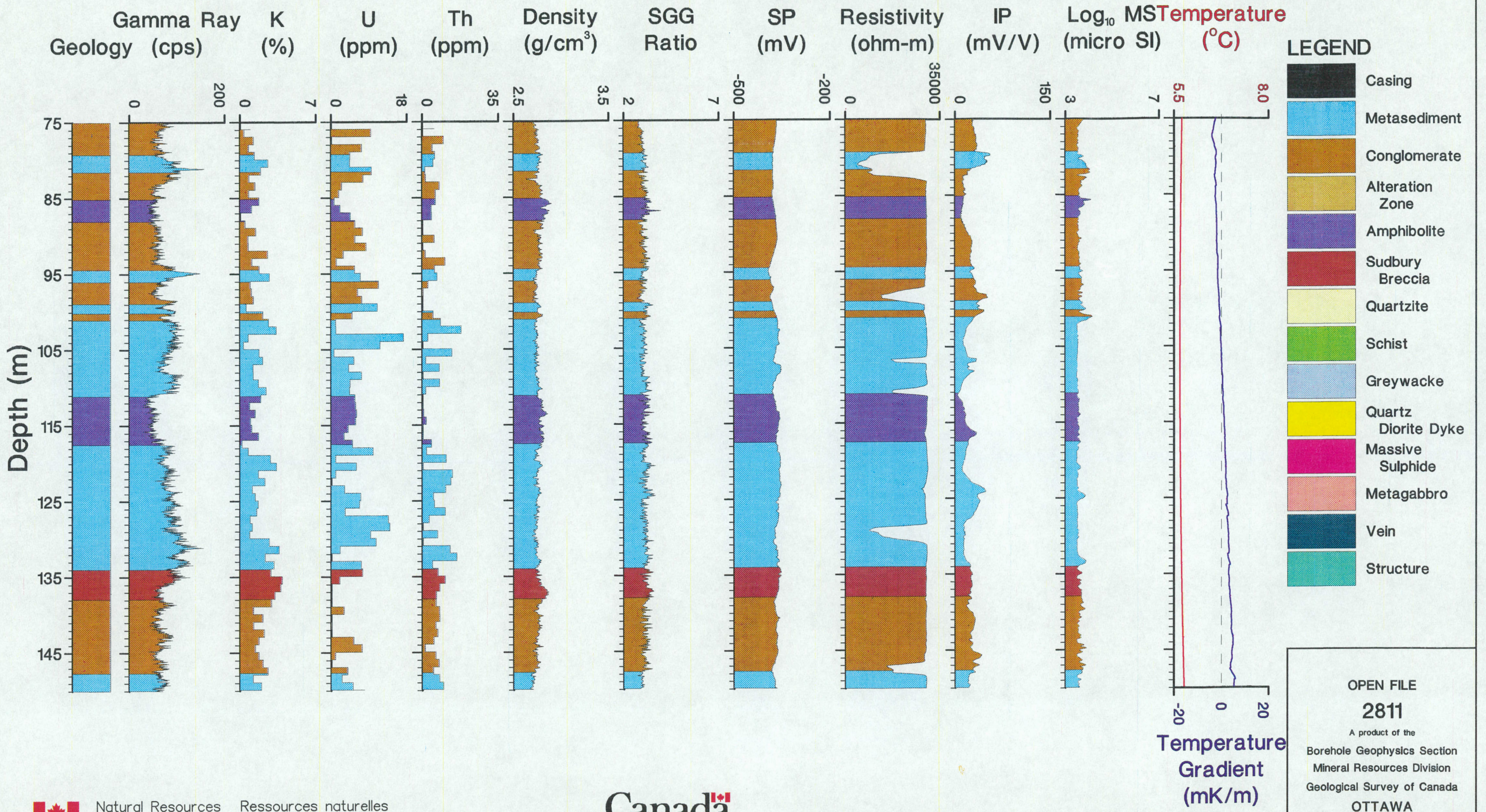
(GSC Research and Development Probes)
Latitude (46°33'12"), Longitude (80°52'28")

Borehole 80578
Plot 2 of 5



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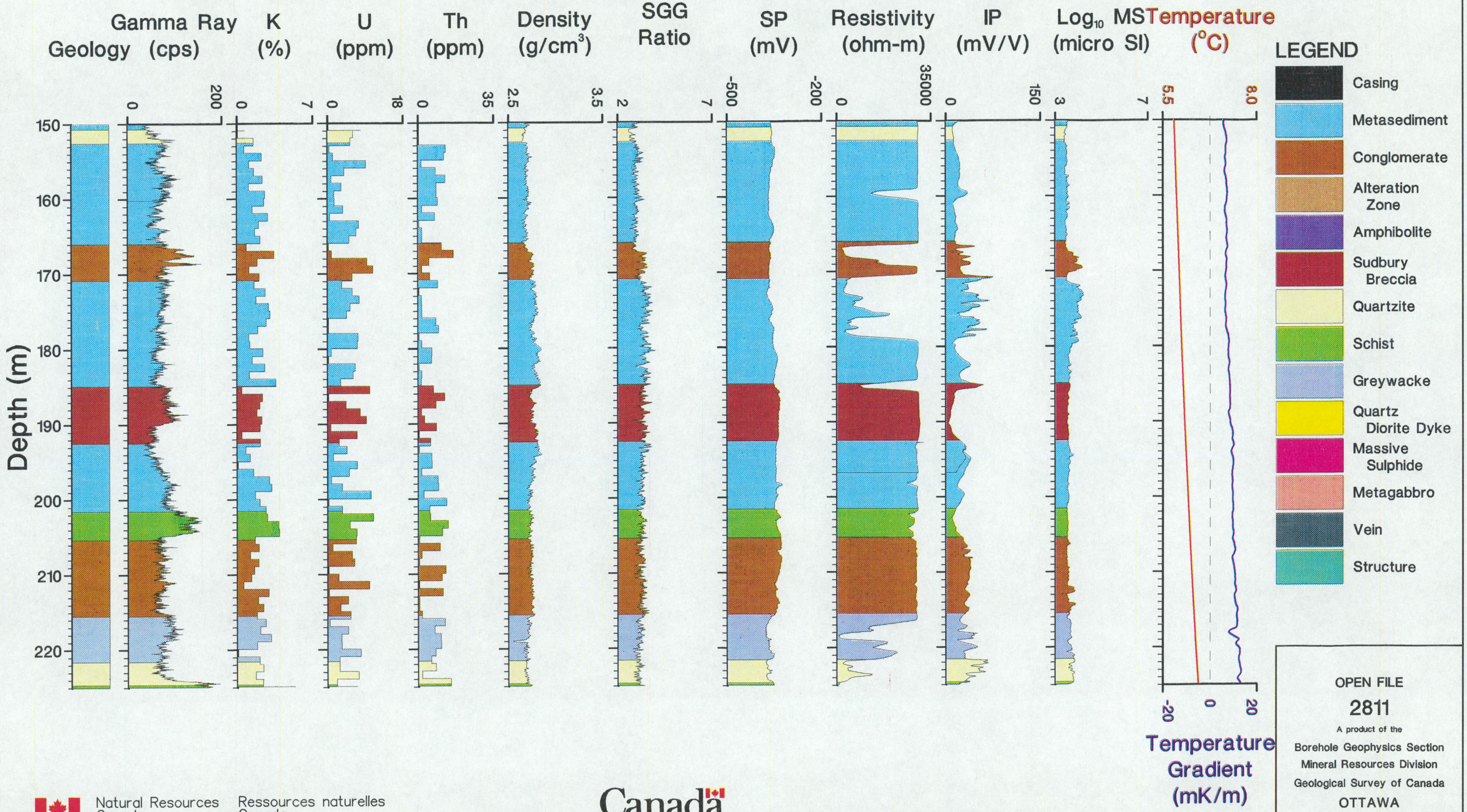
Borehole 80578
Plot 3 of 5



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Borehole 80578
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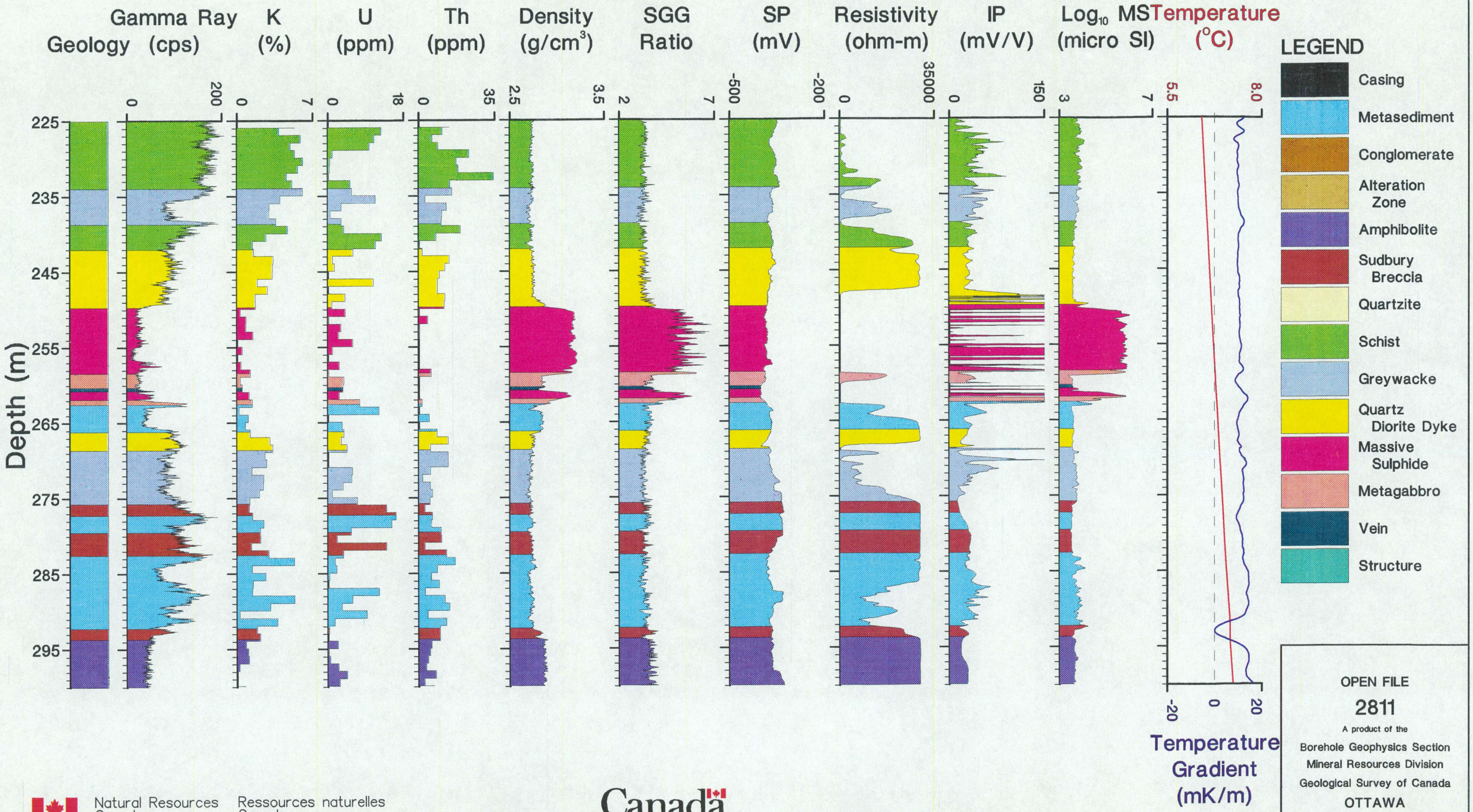

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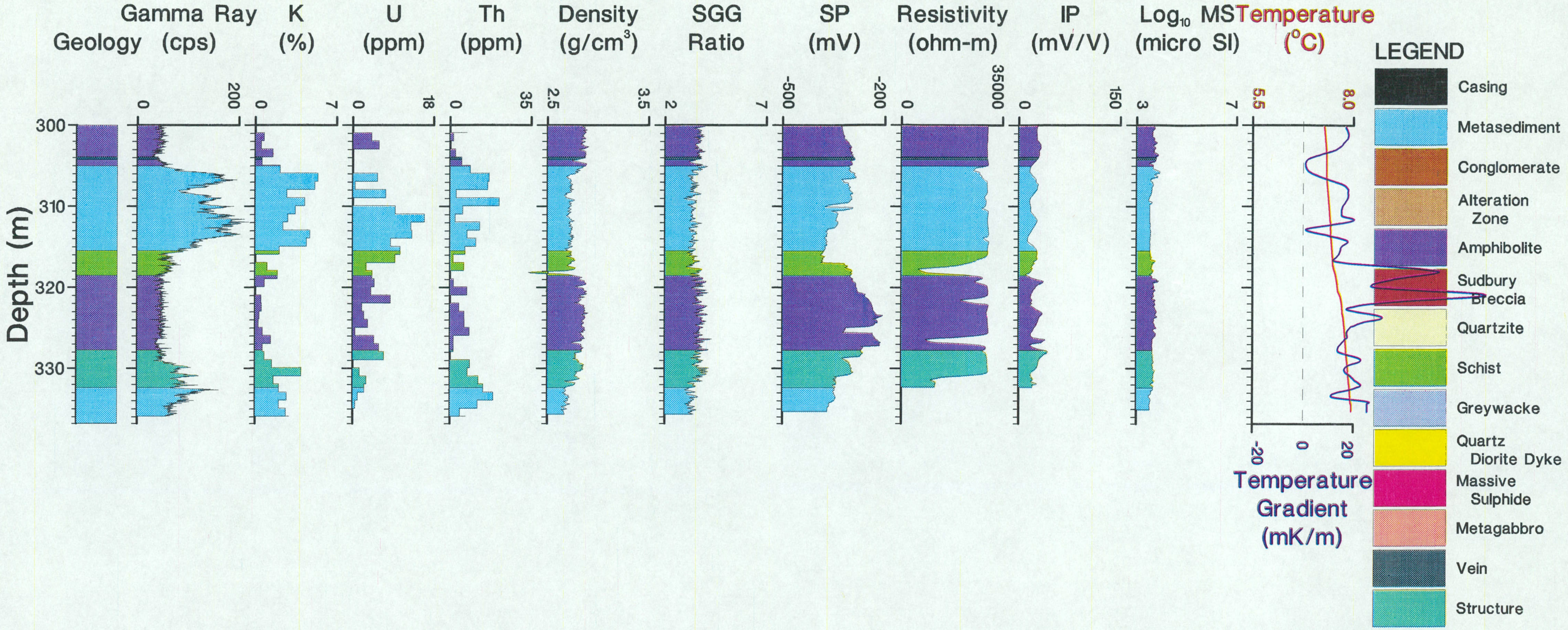
Latitude (46°33'12"), Longitude (80°52'28")

Borehole
80578
Plot 5 of 5



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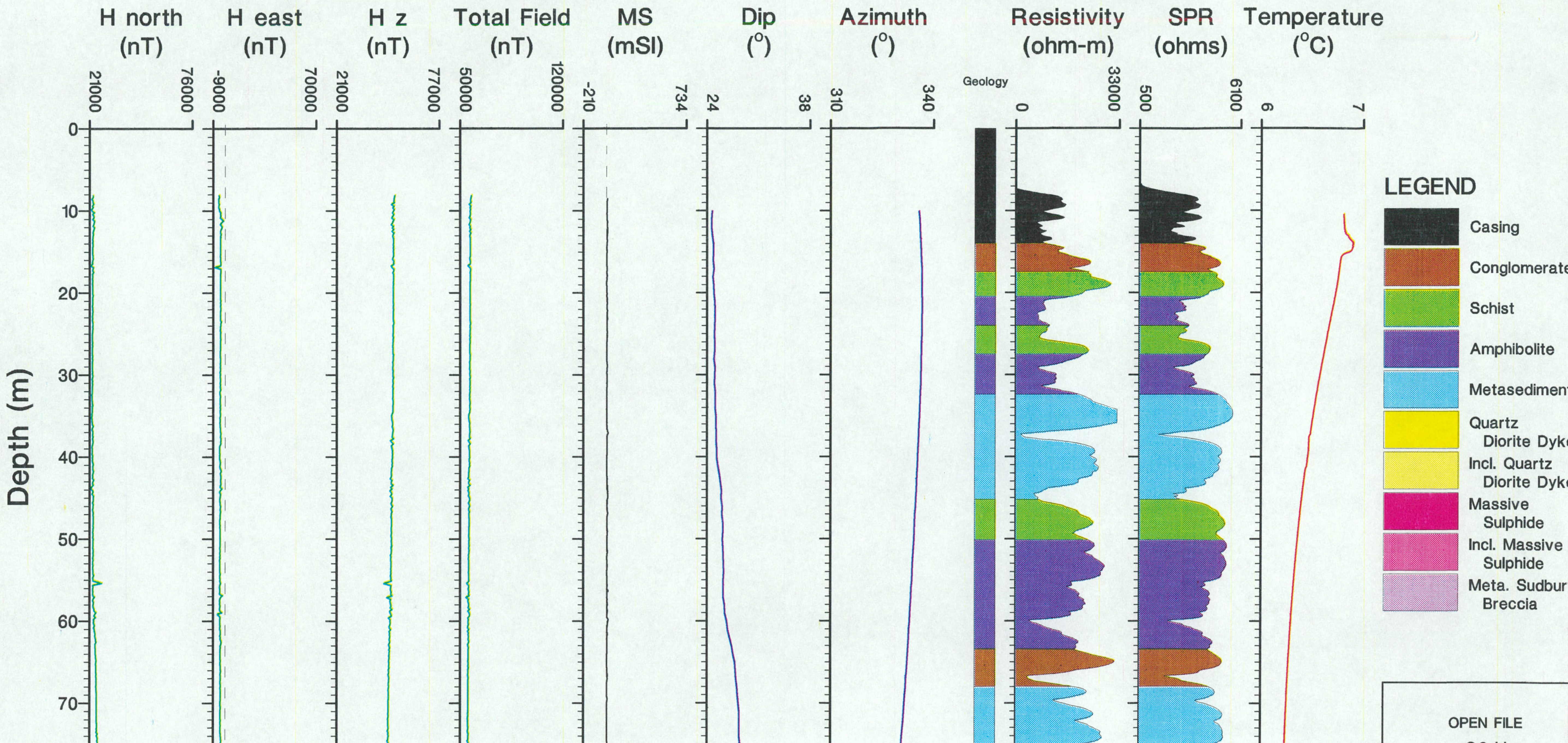
MCCONNELL DEPOSIT (GARSON OFFSET)
(Magnetometer/Orientation Tool)
Latitude (46°33'12"), Longitude (80°52'28")

Borehole 78930
Plot 1 of 3



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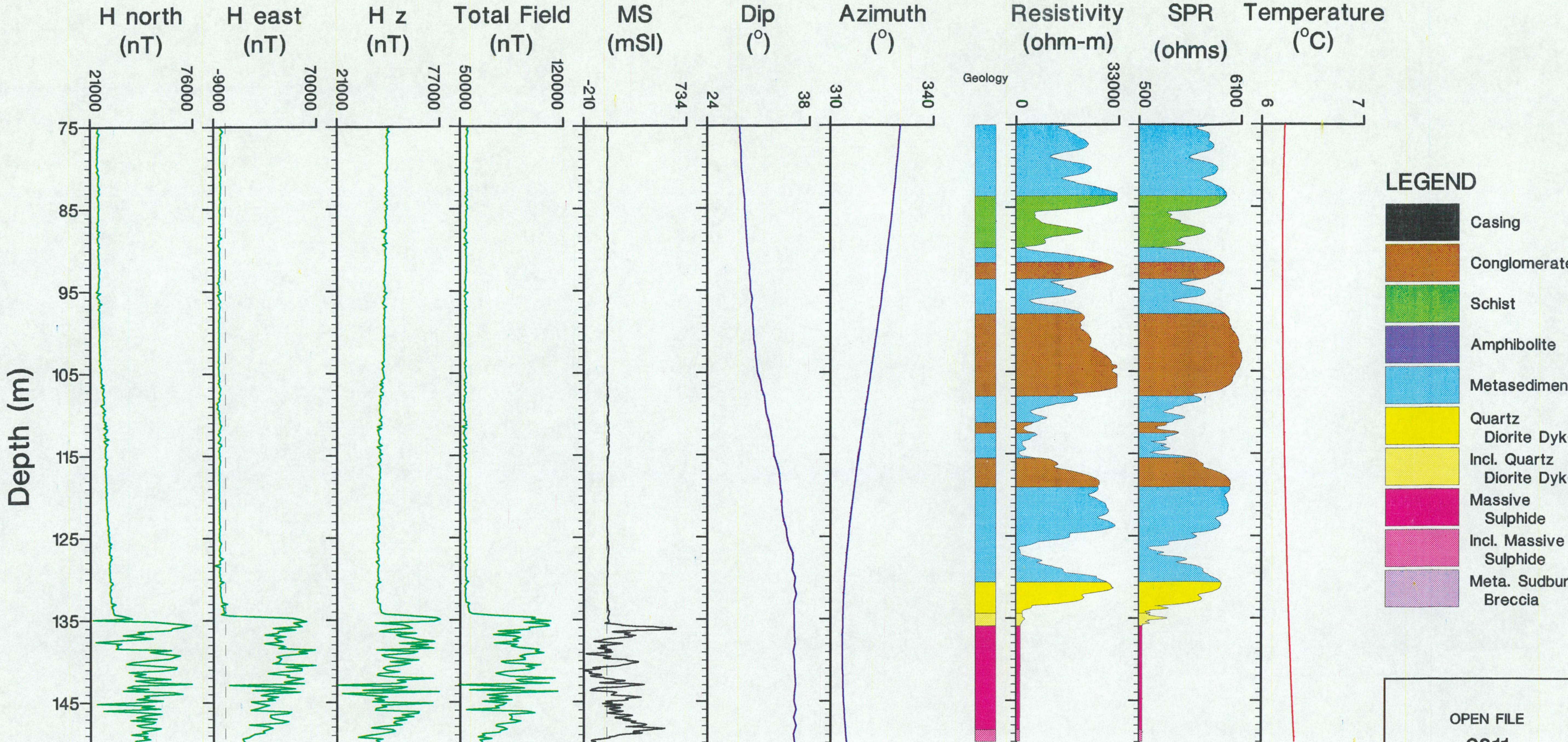

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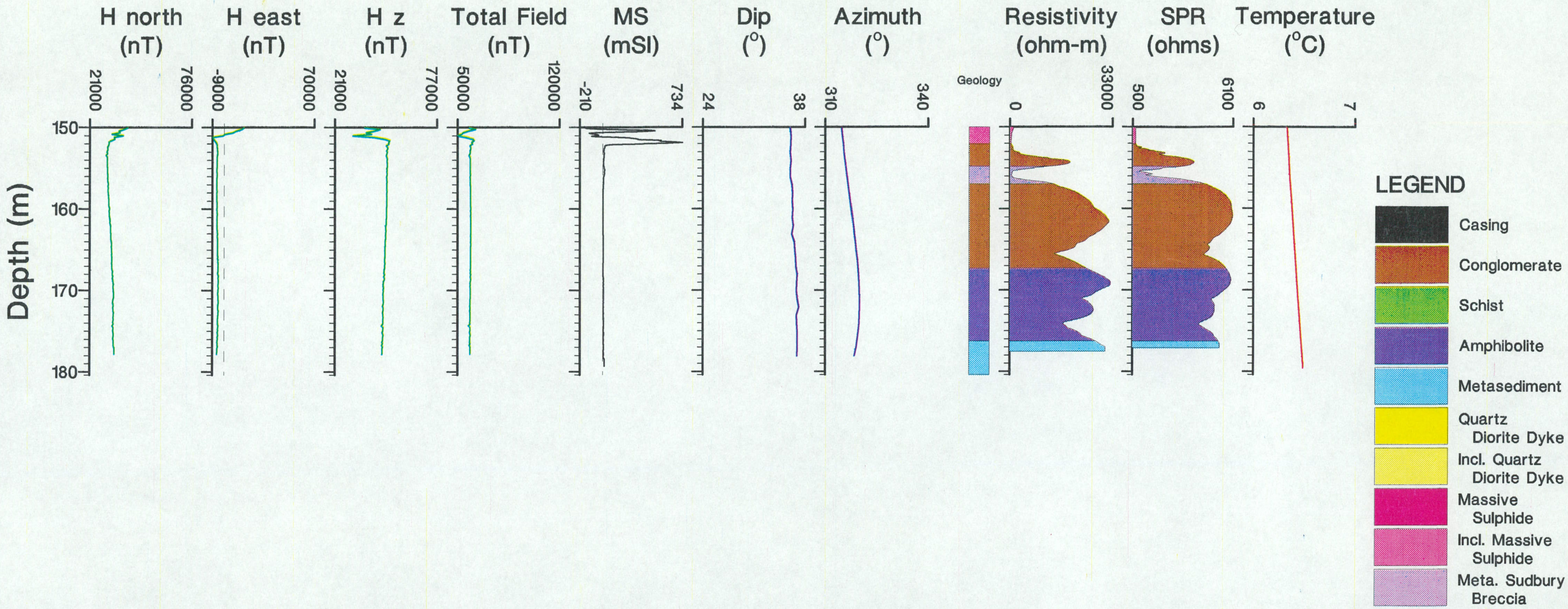

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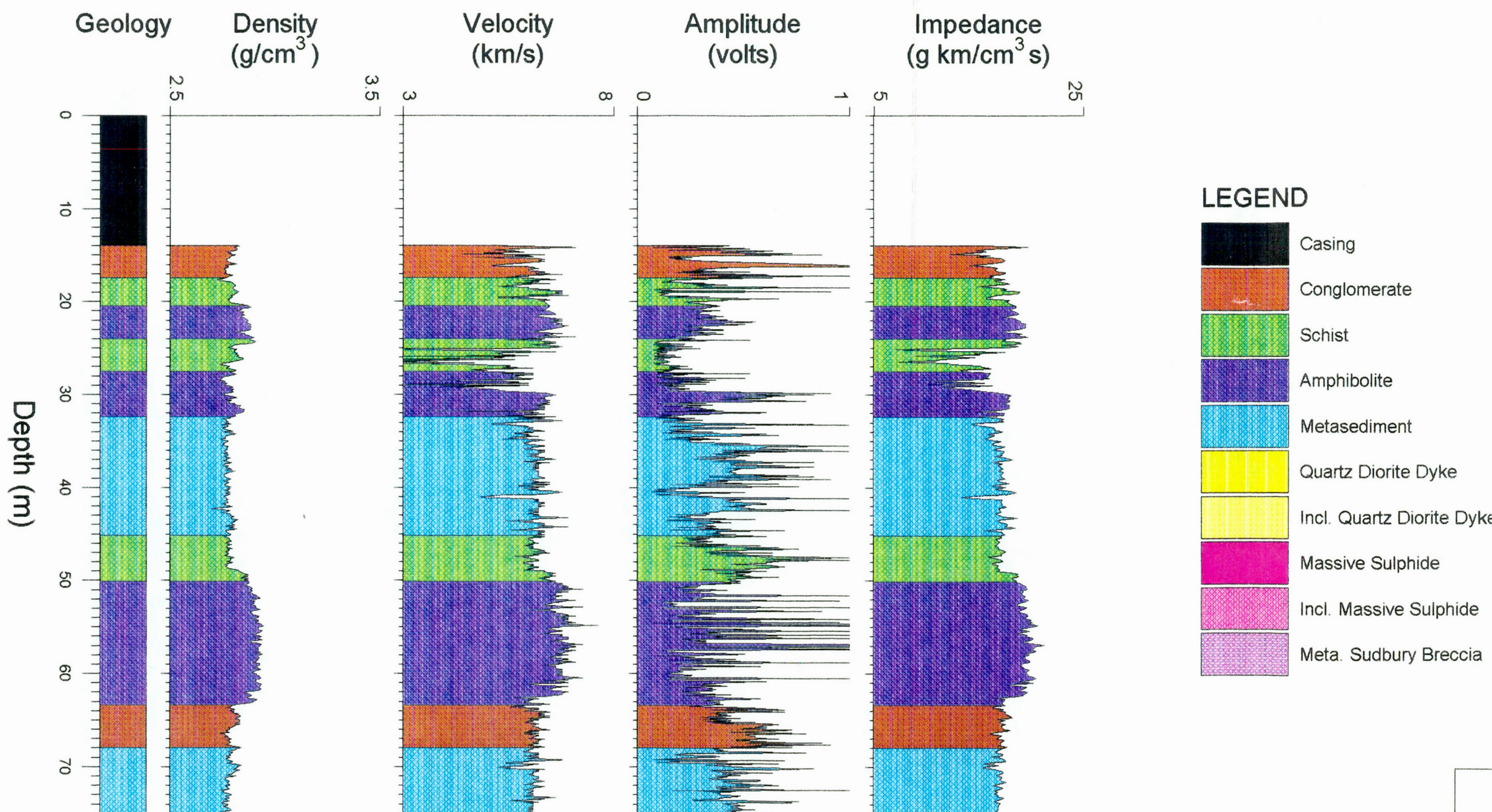
MCCONNELL DEPOSIT (GARSON OFFSET)
(Acoustic and Density Logs)
Latitude (46°33'12"), Longitude (80°52'28")

Borehole
78930
Plot 1 of 3



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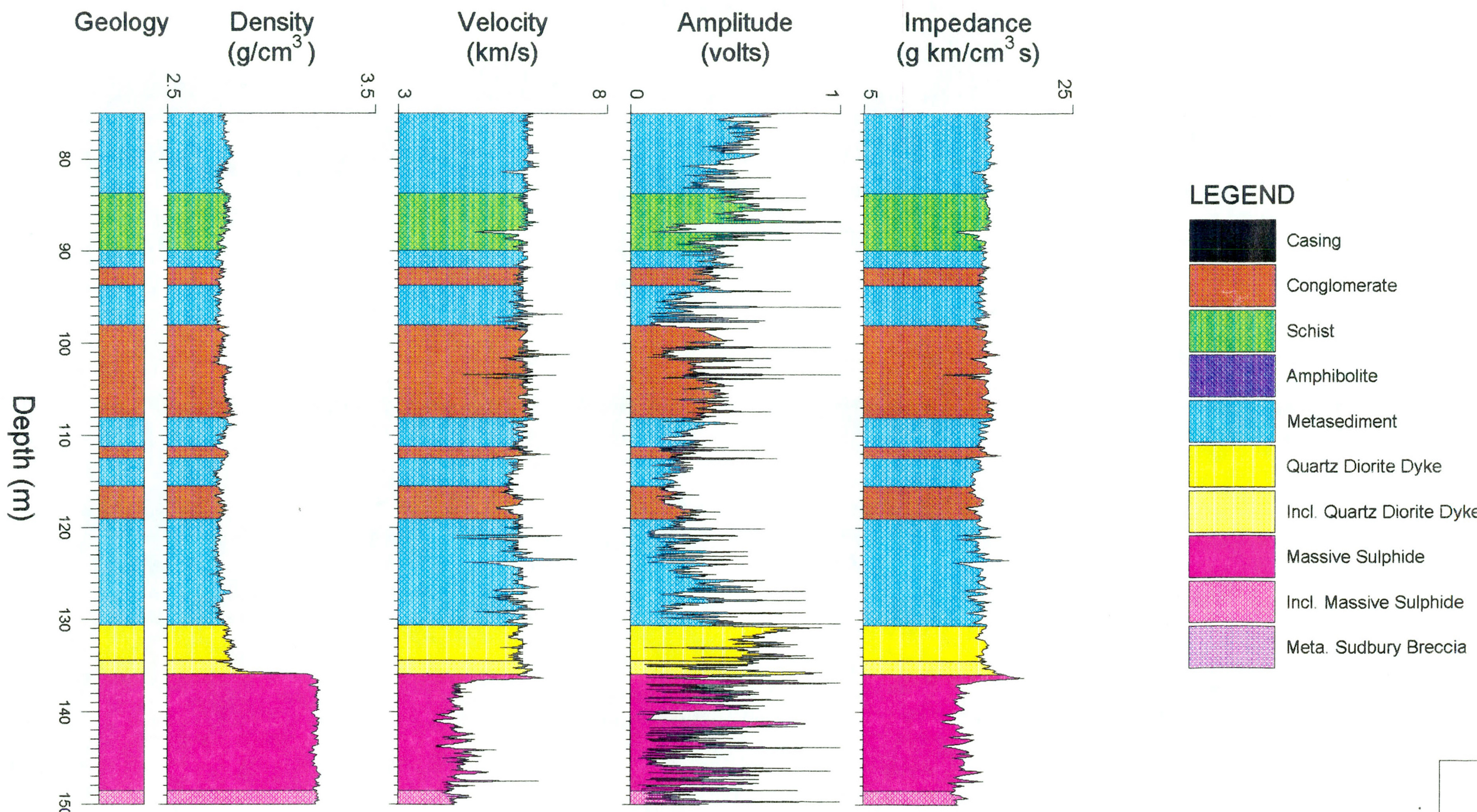
MCCONNELL DEPOSIT (GARSON OFFSET)
(Acoustic and Density Logs)
Latitude (46°33'12"), Longitude (80°52'28")



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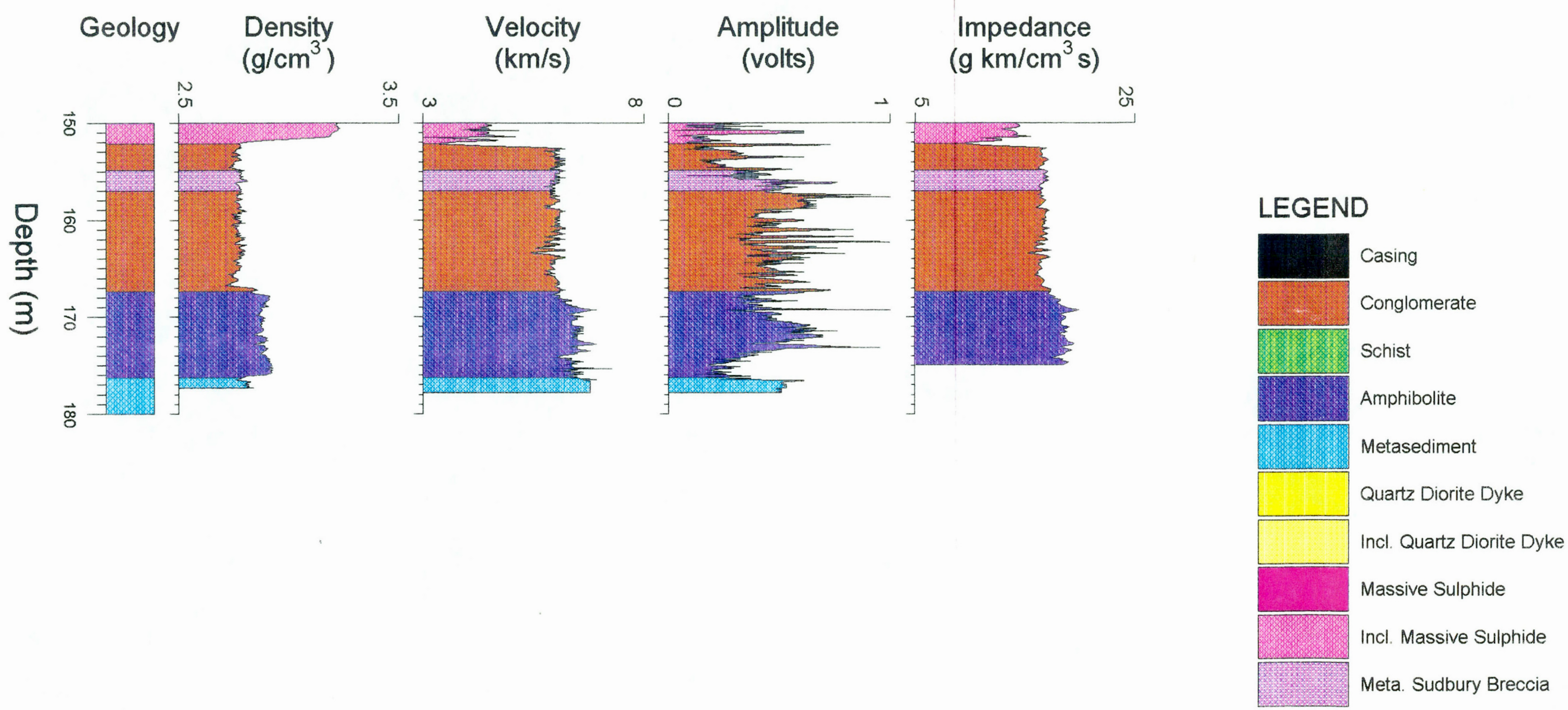

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