GSC Borehole Geophysical Test Site

Bells Corners, Nepean, Ontario
GSC, AECL , Century and IFG Geophysical Logs

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Borehole Geophysical Logs
from the
GSC Borehole Geophysics Test Site
at
Bell's Corners, Nepean, Ontario

G.R. Bernius (1996)

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BELLS CORNERS BOREHOLE GEOPHYSICAL TEST SITE

1. INTRODUCTION AND BACKGROUND

This report presents data collected over the past fifteen years from different borehole geophysical logging systems and probes in an array of test boreholes at the Geological Survey of Canada (GSC) calibration and test facilities. These facilities are located at Bell's Corners, Ontario, 10 km west of Ottawa on the grounds of the CANMET Research complex of the Department of Natural Resources, Canada (Fig. 1).

The Geological Survey of Canada began drilling a series of boreholes in 1981 to test newly developed slimline probes that were being used in the GSC truck-mounted R & D borehole logging system. This natural geological environment includes a variety of rock types and structural conditions, and is particularly suitable for testing new systems that different companies and agencies are using.

The first four holes (BC81-1, BC81-2, BC81-3 and BC81-4) were drilled in March 1981 (Fig. 2). These are all vertical, NQ size (75 mm in diameter), located along a line with BC81-2 10 m from BC81-1, BC81-3 20 m from BC81-2, and BC81-4 70 m from BC81-3. Total distance from 81-1 to 81-4 is 100 m. This pattern provides opportunities for hole-to-hole logging over a variety of hole separations. Hole BC81-1 was drilled to a depth of 300 m and the remaining three holes were drilled to 120 m.

In March 1984, hole BC81-4 was deepened to 300 m and renamed BC84-4, and two additional holes, BC84-5 and BC84-6, were drilled at that time. The former was drilled to 254 m total depth and the latter to 300 m. In order to allow more options for testing hole-to-hole logging techniques, the two new holes were positioned to form two equilateral triangles with sides of 30 m and 100 m, i.e. BC84-5 is 30 m from BC81-1 and BC81-3 while BC84-6 is 100 m from BC81-1 and BC84-4 (see Fig. 2).

In the laboratory, magnetic susceptibility and density (specific gravity) measurements were made on some of the core. A high core recovery made it easy to correlate between the core and down-hole measurements. Thin sections were made in a few selected locations on the core for precise lithological identification.

The site includes a variety of unaltered, flat-lying sedimentary rocks underlain by igneous and metamorphic rocks in various stages of alteration and fracturing as well as having complex structural relationships. In the following section, geological features in the core are related to the responses seen on the geophysical logs. Data from logging systems other than the GSC R & D system are included, with a discussion of the probes used in those systems.

2. GEOLOGY OF THE BOREHOLE GEOPHYSICS TEST SITE

The first scientific geological study and mapping of the Bells Corners area was done by Alice E. Wilson and is documented in GSC Memoir 241 (Wilson, 1946). Since then, there have been a few detailed studies of certain features of the region, notably the Paleozoic sediments (Greggs and Bond, 1972; Bond and Greggs, (1973); Brand and Rust, 1977). Little attention has been paid to the Precambrian metamorphic rocks, mainly because they are extensively covered by Paleozoic sediments at this location and their petrology is often quite variable over a short distance. This is evident from the variety of Precambrian metamorphic rocks found in the cores from these holes.

The Paleozoic sediments intersected by the drill holes are about 65 m thick. The various lithological units in the sediments dip at a low angle (~4 degrees), and thicken slightly to the north-northwest. This is consistent with deposition on the shallow edge of the gradually deepening Ottawa Graben as part of a slowly transgressing epicontinental sea. The sediments represent intertidal and subtidal units (Kumarapeli, 1985). They are upper Cambrian to lower Ordovician (Tremadocian Epoch) in age.

The following geological description begins with the more recent units in the sedimentary sequence and progress down the hole, rather than following chronological order (i.e. oldest to youngest).

2.1 Oxford Formation-

The uppermost unit is the Oxford Formation of lower Ordovician age. It varies in thickness from 11 to 16 m due to surficial weathering and glaciation. It is a grey to reddish-brown, sandy dolomite, as seen in the core, containing calcite-filled cavities 4-5 cm in diameter. Information from the geophysical logs indicates that the physical properties are highly variable due to weathering and fracturing near surface, but the dolomitic composition is indicated by a higher density on the logs. The gradually increasing density towards the top indicates a higher carbonate content and deeper water.

2.2 March Formation-

Immediately below the dolomitic Oxford Formation lies the 4-metre thick transitional March Formation named after the township to the west of the city of Nepean. This unit comprises two facies which include a light grey-coloured dolomitic sandstone at the bottom and a massive quartz arenite at the top. It is considered to be subtidal to intertidal in origin (Bond and Greggs, 1973).

This formation was drilled for its uranium potential by mining companies in the 1970's (Charbonneau, et. al. 1975; Ford, 1978) because the lowermost layer contains thucolite (a carbonaceous material containing thorium and uranium) as well as chalcopyrite. This layer is clearly seen in all but one of the logs as an anomaly in the natural gamma logs (total count, uranium) and in the electrical logs (resistivity, IP, SP). This radioactive unit appears widespread since as it can be easily identified on borehole logs from the Lebreton St. test hole near the G.S.C. headquarters in

Ottawa, 20 km to the east.

2.3 Nepean Formation-

The Nepean Formation consists of a group of sandstones of Upper Cambrian age which was studied in some detail by Greggs and Bond (1972). It is important to note that the GSC boreholes are located only 1 km south of the road cut on the Queensway (Highway 417) which was suggested by Greggs and Bond (1972) as a "principal reference section" for this formation. It would appear that the core from the holes is an ideal "principal reference section" for this formation. The GSC core and logs show that the Nepean Formation consists of two, somewhat different units, separated by a thin and readily identifiable shale unit. In contrast to Greggs and Bond (1972) observation that "the upper beds of the sequence are dominated by bioturbation", the core shows that only the lower units consist of bioturbidites, whereas the upper sequence is clear and rather featureless sandstone. These observations are a direct result of core studies. However, multiparameter borehole logging methods could greatly assist in evaluating lithology by comparing the responses on the different parameters in this section.

A thin (50 cm) layer of reddish-brown shale overlies the intertidal sequence at about 37 metres depth which shows clearly on many of the logs. This is followed by very pure, well sorted, massive, white sandstone about 16 m thick to a depth of about 20 m below surface. The upper contact with the overlying March Formation is a disconformity.

At the base of the Paleozoic sequence is a thin layer (5 cm) of quartz-feldspar orthoconglomerate. Immediately above this layer, with a thickness of approximately 27 metres, is a sequence of cross-bedded sandstones that appear to be intertidal in origin. There are 15 identifiable bioturbidite layers that range in thickness from 2 cm to 10 cm and alternate with the cross-bedding in this section. Each of these zones contains glauconite and no apparent structure. Just below each of these zones there are vertical worm holes of the species skolithos, Diplocraterion and Arenicolites (Fejer, 1986).

2.4 Precambrian

The Paleozoic sequence discussed above is separated from the underlying Precambrian rocks by a sharp unconformity. This lower sequence consists of syenites, granites and gneisses of Grenville age. The top 15-17m of the Precambrian directly under the unconformity, is a highly altered/weathered zone with a very irregular surface that could be called "saprolite". This zone consists of pinkish-red friable clays and altered feldspars derived from syenite and granite. or greenish-grey saprolite derived from more mafic gneisses. The zone is composed mostly of quartz, plagioclase and many alteration minerals such as sericite, clay minerals, chlorite, epidote, hematite and some calcite.

The transition at the unconformity is clearly seen in the core and in the geophysical logs where it forms a reference point which can be used to adjust the logs for depth correction.

Towards the bottom of the alteration zone, the rock gradually appears fresher and less altered. The remainder of the rock types encountered in the holes consist of a mixture of Precambrian igneous and metasedimentary rocks whose structure and mineralogical composition changes within a very short distance. It has, therefore, been impossible to trace any single unit with certainty, between holes. This is true even after a careful examination of the logs and the drill core between boreholes BC81-1 and BC81-2, which are separated by only 10 m.

Most of foliation is dipping steeply (45 deg or more), but the direction is unclear. Based upon the regional trends in the nearest Precambrian outcrop on the geological map of the area, the strike is anywhere between N - S and NE - SW.

3. GEOPHYSICAL INTERPRETATION OF THE HOLES

3.1 Test Borehole BC81-1

Drilling on the first hole in the series began on March 1 and was completed on March 9, 1981. It reached a depth of 299.4 metres and of which 4.9 metres was cased at the top. The hole was blocked at about 65 metres in August 1989 but has since been cleared to the bottom.

The pattern seen on the logs in approximately the upper 65 metres of Paleozoic sediments is almost identical in all six holes except for the radiometric response at the bottom of the March Formation. Consequently the following detailed description of the logs for this sedimentary zone will apply to all holes except where otherwise noted.

PALEOZOIC ROCKS:

Oxford Formation-

From 0 to 16.3 m the hole passes through the Lower Ordovician Oxford Formation. Described by Wilson (1946) as a thick-bedded, rusty weathering dolomite, it is, in the fresher core, more grey-green with some reddish-brown areas. It is actually a sandy dolomite or dolostone (Williams, et al, 1983).

The borehole logs cover only the portion of this formation below the casing. The natural gamma logs are quite variable in this section likely due to the unequal distribution of clay minerals. The gamma-gamma density logs show a slightly higher density than elsewhere in the sedimentary section, decreasing lower in the section. This is almost certainly due to changes in the clay content.

March Formation-

The March Formation lies immediately below the Oxford Formation. It is a 4 m thick section of sandstone and dolomite that is buff to white in colour. The top contact is sandstone and the bottom contact is dolomite and there are two of these sandstone/dolomite sequences in the unit. Near the bottom of the section there is a noticeable increase in radioactivity. In the GSC natural gamma spectral logs the K, U, and Th logs clearly show the presence of a uranium-bearing material that is the cause of this anomaly. A 1 to 2 cm thick zone contains thucolite, a radioactive hydrocarbon containing uranium and thorium. It is a mixture of one or more hydrocarbons and uraninite or pitchblende present as microscopic disseminations (Lang, et al, 1962). It is jet black and commonly resembles high grade coal.

Chalcopyrite is also found in this layer, and in some holes the layer shows distinctive characteristics on the electrical logs. This radioactive layer has been observed in boreholes elsewhere in the Ottawa region (i.e. in the borehole at 401 Lebreton St. and in another at Observatory Crescent near the GSC headquarters) where the March Formation has been logged with natural gamma ray logging equipment. Therefore it would appear to be an important marker horizon that can be identified widely in the region.

Nepean Formation-

At 20.5 m, there is a sharp change in colour and lithology at the top of the first massive white sandstone which constitutes the beginning of the Nepean Formation. Although fairly uniform in colour and texture, there is considerable variation in the logs throughout the formation.

Between 20.5 m and 36.8 m, the geophysical logs indicate the sandstone is uniform with low levels of radioactivity, a lower density than elsewhere, and low resistivity. From 36.8 m to 37.4 m there is a distinctive impure shaley layer. The increase shown in the potassium log in this layer is due to the clay minerals, while the electrical log responses (i.e. lower resistivity and I.P.) also indicate the presence of more conductive materials. The Self-Potential Gradient (SPG) log shows a slight anomaly where contrasting sand-clay interfaces are found. There is an increase in magnetic susceptibility in this shaley layer based on core measurements and limonitic stains indicate the presence of iron-bearing minerals.

The section from 37.4 m to the unconformity at 64.6 m is very irregular, both in the natural gamma log response and in the electrical logs. As mentioned earlier in the section on geology, there is a series of alternating bioturbidite zones that contain glauconite. The gamma ray spectral logs indicate that potassium is the only radioelement that is contributing to the pattern. Some, but not all of the bioturbidite zones correlate with peaks in the natural gamma logs. In this same section the electrical logs show weak response, however, if the electrical logs from the other holes are overlaid on this log, they show an almost identical pattern which indicates that the lithologies are continuous between the holes and that they have distinct electrical characteristics.

PRECAMBRIAN ROCKS:

Immediately below the nearly horizontal sedimentary sequence is a sharp unconformity followed by a zone of highly altered syenitic and gneissic rocks. This zone extends from 64.5 m to about 79 m. An increase in radioactivity is the first notable change from the sediments above, and this is due to potassium in sericite which is present in the alteration zones, and also due to potassium feldspar (orthoclase). Deeper in the hole, potassium log values are generally as high or higher than in the altered zone.

The most definitive logs for the alteration zone are the electrical logs. A low IP response and low resistivity are characteristic of the zone which is very porous, filled with clay minerals and saturated with water. The low magnetic susceptibility values are the result of alteration.

In the remainder of the hole, which intersects mostly syenite and gneiss in various stages of alteration, the most distinctive features are found between about 225 m and 239 m and 255 m and 269 m where the resistivity is extremely high (>30000 ohm-m). In the deeper interval, this is due to the presence of a calc-silicate rock (the mineral scapolite forms the bulk of the unit). An explanation for high resistivity in the upper interval is less clear, but may be a result of the presence of relatively fresh granite and gneiss with little or no fracturing.

3.2 Test Borehole BC81-2

This borehole is the best documented and most frequently logged of all the holes in the test site. The reason for this is that over its 120 metres depth, it contains all the features found in the other holes, as well as a particularly anomalous intersection that shows up on virtually all the geophysical logs. Originally drilled to 120 metres, the Century Geophysics Ltd. deviation log showed that it had a true depth of 117.7 metres and a dip of nearly 89 degrees to the ENE when surveyed in 1982. This latter log is not presented on the plots.

Sedimentary Section:

There is little difference in the sedimentary section in this hole from that in BC81-1 ten metres away except for the gamma ray anomaly at the bottom of the March Formation. In this hole, the peak in the uranium log is just over 3 cps, while in BC81-1 it is barely noticeable at about 1 cps. The logs from all of the other holes show no noticeable differences throughout the rest of the sedimentary section.

Precambrian Section:

This section contains metamorphic rocks with some of the most interesting and varied responses in physical parameters seen in any of the holes at the Bells Corners Test Site. In a highly weathered/altered zone of granite and granitic gneiss about 17 m thick and immediately below the unconformity which is at 65 m depth, there is a 2 m thick segment of the unaltered rock type occurring at 70 m to 72 m. This results in a prominent anomaly in almost all the geophysical logs.

The anomalies caused by the fresh granite are most obvious in the magnetic, resistivity, and density logs as a high and as a low in the radioactivity logs. The reason for the latter is the presence of potassium in sericite in the altered granite or syenite and its absence in the fresher granite. Likewise magnetite found in the fresh granite has been altered to low susceptibility hematite in the altered section.

Below the upper 17 m thick altered section, the rock is more gneissic (hornblende/biotite) and variable in physical properties. Generally it has higher magnetite content than granite and is quite resistive, but also it is denser and has a lower level of natural radioactivity. The cause of IP high anomalies at 108 m and 110 m is probably due to pyrite in the gneiss.

3.3 Test Borehole BC81-3

This was the third hole drilled in 1981. It is located in a line 20 m from BC81-2 and 30 m from BC81-1 (Fig. 2). Orientation measurements done by Century Geophysics indicate that it has a true depth of 118 m, an azimuth of 309.1 degrees at the bottom, and a deviation of 2.6 metres from the collar giving it an apparent dip of approximately 88.74 degrees from the vertical.

Sedimentary Section:

This section is essentially the same as for hole BC81-1 except the unconformity is at 63.6 m. One notable feature is the positive gamma ray anomaly near the bottom of the March formation. It has been determined to have a uranium content over 5 times background.

Precambrian Section:

Immediately beneath the unconformity is a 5 cm layer of clay which resembles that found in a fault zone. It is a highly conductive layer as shown on the electrical logs where the resistivity is zero.

The remaining section of Precambrian rocks intersected by this hole appears to be uniform, based on the logs. The rock type is biotite-hornblende-plagioclase gneiss in varying stages of alteration. The alteration minerals are chiefly chlorite, sericite, and hematite; generally they are more abundant towards the top of the Precambrian section. The gneiss is separated by a few sections of more granitic material, but the contacts appear to be more gradational than those found in many of the other holes.

3.4 Test Borehole BC84-4

This hole was drilled to a depth of 120 m in 1981 and deepened to 300.25 m in 1984. It is located in line with BC81-1,2 and 3, and is 100 m from BC81-1 or 70 m from 3 (Fig. 2). Century Geophysics Ltd. logged the holes before 1984, their deviation logs indicated the hole was 119.6 m deep and deviated 1.85 m at the bottom to the east-southeast of the collar.

Sedimentary Section:

The only feature that differs in the sedimentary section of this hole compared to the other holes is the lack of radioactivity at the bottom of the March formation. This demonstrates the variability of that unit over distances as short as 100 m. The radioactive marker unit is however found in the Lebreton borehole at the GSC buildings 15 kilometres east of Bells Corners.

Precambrian Section:

Most of this section is biotite-hornblende gneiss, although the first unit beneath the unconformity is granitic. The alteration zone is about 16 m thick and roughly corresponds to the granitic unit, although the granitic unit contains a section that is much less altered than the surrounding rock. The entire Precambrian section has a moderate level of magnetic susceptibility, while alteration near fracture zones shows a lower magnetic susceptibility.

At 247 m there is a 2 m thick section which is highly conductive and produces a strong IP anomaly. This appears to be due to a steeply dipping quartz-epidote-hematite-filled fracture zone which is 20 mm thick and runs along the axis of the core.

The pegmatite between 194.6 m and 198 m has a strong potassium anomaly and a narrow spike in the uranium log.

3.5 Test Borehole BC84-5

Drilling on this hole began on March 22 and was completed on March 25, 1984, at a depth of 249 m. Located 30 m from BC81-1 on a line from that hole to BC84-6, it contains some quite different features in the Precambrian section from those found in the nearby holes. No orientation logs were run in this hole.

Sedimentary Section:

The patterns in the logs are very similar to those in the other holes except for the uranium log response at the bottom of the March Formation. This is slightly higher than that found in BC81-2 and slightly less than that found in BC81-3. Since the other 3 holes (81-1, 84-4 and 84-6) do not show any notable gamma ray response when passing through this unit, it is possible that there is a trend relating to depositional depth or a location along an ancient shoreline.

Precambrian Section:

While most of the rock recovered in this hole can be classified as granite/syenite and hornblende-biotite gneiss similar to that found in the other holes, a few notable variations produce strong responses in the physical parameters being measured. Magnetic susceptibility is low throughout most of the hole except for locations at 202, 220.4, 232.3, and 237.5 m where strong magnetic susceptibility peaks are seen in gneiss and granite. This indicates a concentration of magnetite (or pyrrhotite) at these locations.

At 218.5 m and 233.7 m there are occurrences of tourmaline, quartz, epidote and pyrite. The slight resistivity decrease and small, sharp IP anomaly at these locations is probably due to the pyrite.

3.6 Test Borehole BC84-6

This hole was started on March 17 and completed on March 21, 1984 when it reached a depth of 298.7 m. It forms the eastern corner of the triangular array of holes, 100 m from BC84-4 and 100 m from BC81-1. Orientation logs are not available for this hole.

Sedimentary Section:

This section is similar to the other holes except for the absence of any gamma ray anomaly at the bottom of the March formation.

Precambrian Section:

There are at least two notable rock units in this section of the hole that make it different from the otherwise similar assemblage of gneisses and granites. One of these is at 179.6 m where there is a 20 cm thick pegmatite causing a high thorium-log anomaly. The thorium log registers more than double the count rates found in the rest of the hole. The other is a carbonate unit which contains apatite at 258 m.

Special Notes:

In the AECL Sonic Logs there are two different types of units indicated: msecs/ft and msecs/m. The holes were logged in different years and AECL changed to the metric system between these periods.

No attempt was made to convert count rates in the K, U and Th recorded with the GSC equipment, to % and ppm. This is because the count rates are extremely low and, except for the March Formation and the pegmatite in BC84-6, most of the radioactivity appears to be due to potassium based on a qualitative inspection of the unstripped logs.

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APPENDIX I

THE LOGGING SYSTEMS

I. 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, mapping lithology and hole-to-hole stratigraphic correlation. Also possible is in situ assaying of ore, and in situ determination of physical rock properties for 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 CRT monitor to acquire data 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 in diameter, designed to run in BQ holes or larger. The logging speed is usually about 6 m/minute and can be run in air- and/or water-filled holes depending on the sensor. Data sampling rate ranges from 1 to 5 samples per second, providing a measurement every 2 to 10 cm along the hole.

The GSC 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 their Geological Responses

1. GAMMA-RAY SPECTRAL LOGGING

1.1 Geological Interpretation of Gamma-Ray Spectral Logs

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). 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. Gamma-ray logs are important for detecting alteration zones, and for providing information on rock types. 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 sedimentary rocks, potassium is in general the principal source of natural gamma radiation, primarily originating from clay minerals such as illite and montmorillonite. In igneous and metamorphic geologic environments, 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 and gold exploration areas, the principal source of the natural gamma radiation is potassium because alteration, characterized by the development of sericite (sericitization), is prevalent in some of the lithologic units and results in an increase in the element potassium in these units. 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.

1.2 Principle of Gamma-Ray Spectral Logging

A gamma-ray probe's sensor is usually a sodium iodide or cesium iodide scintillation detector. Unlike an ordinary gamma-ray tool which only counts the total 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, and emits gamma rays with energies of 1.46 MeV. 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 radioelements. As each radioelement 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 radioelement. 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 while the probe is moving along the hole, the gamma rays are sorted by energy into an energy spectrum. The number of gamma rays in three pre-selected energy windows centred over ^{40}K, ^{214}Bi and ^{208}Tl peaks in the spectrum is computed, as is the total gamma-ray count. These four numbers represent gamma rays originating from potassium, uranium, thorium and Total Count (TC) detected during that one second of counting time.

These data are recorded along with the depth and are displayed on the chart recorder to produce gamma-ray spectral logs. 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, and 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, logging can be done inside drill rod or casing with a slight decrease in sensitivity.

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 over an energy range of approximately 0.07 to 3.0 MeV are recorded from a scintillation detector in the probe. The storage 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 limestone 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

2.1 Geological Interpretation of Density and SGG Logs

The density/SGG logging tool measures rock density and SGG ratio. The SGG ratio (defined below) is related to the effective atomic number of the rock, which depends on the chemical composition of the rock. The SGG ratio log is particularly useful for detecting base metals since these elements have high atomic numbers compared to most rock forming minerals, and they can occur in high enough concentrations to significantly increase the effective atomic number of the rock. The SGG ratio log may also be useful for lithologic mapping in areas where the iron content differs significantly between different rock types.

The density of 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 tends 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 knowledge of in-situ densities of the rocks may provide valuable information for ore reserve estimations. The density log is also useful for locating fractures since open fractures intersected by the borehole often appear as low density zones on the density log (Wilson et al, 1989).

2.2 The GSC Density/SGG Logging Equipment

The density and SGG ratio (or heavy element indicator) logs are derived from the spectral gamma-gamma probe (Killeen and Mwenifumbo, 1988). The density/SGG 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 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". Because gamma rays can be detected through steel, logging can be done inside drill rod or casing with a slight decrease in sensitivity.

3.0 ELECTRICAL LOGGING

The Induced Polarization (IP) tool consists of an assembly of electrodes which are placed in the borehole, usually including a current electrode and two 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 Electrical Logs

3.1.1 Induced Polarization (IP)

In time domain IP measurements, the ratio of the secondary voltage measured during the current off-time to the primary voltage measured during the current on-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 sulphides 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 (R)

The electrical resistivity of rocks depends on several factors including the presence of conductive minerals such as base metal sulphides 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, degree of fracturing, salinity of the pore water, the degree of saturation of the pore spaces, 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 and hence increase the resistivity of the rock. In igneous and metamorphic rocks, the resistivity log is 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 or Spontaneous Polarization (SP)

SP anomalies are mainly an indication of the presence of graphite and/or high concentrations of base metal sulphides including pyrite. Large self potentials observed within and around sulphide 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/minute according to the chosen pulse length (waveform duration). The sample interval is dependant on the chosen logging speed and chosen waveform period. Typically, a 1 second period with a logging speed of 6 m/minute results in sampling every 10 cm along the borehole. This tool must be run in uncased, water-filled holes.

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 array. The downhole current and potential electrodes are gold-plated brass cylinders, 40 mm in diameter.

3.2.2 Self Potential or Spontaneous Polarization (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 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. Resistivity measurements are made with the same arrays as are used in the IP measurements. Single point resistance measurements can also be made using a single downhole current/potential electrode (Pb) and a return/reference electrode on the surface.

4.0 MAGNETIC SUSCEPTIBILITY LOGGING

4.1 Geologic Interpretation of Magnetic Susceptibility Logs

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.

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 contains little or no magnetic minerals.

4.2 The Magnetic Susceptibility Logging Tool Description

4.2.1 MS Measurement with the Geoinstruments TH-3C Probe

The magnetic susceptibility tool consists of a Geoinstruments model TH-3C probe and uses a signal processing unit developed at the GSC (Bristow and Bernius, 1984; Bristow, 1985). The probe contains a coil, 42 mm in diameter by 0.5 m in length, in an electrical bridge circuit energized at a frequency of 1400 Hz. When the probe passes through magnetically susceptible material, the coil inductance changes causing the bridge to become unbalanced. The bridge is balanced automatically by changing the energizing frequency. This change in frequency is converted to magnetic susceptibility. Since the measurements are made inductively (i.e., with EM coils not contact electrodes), the tool can be used inside plastic casing and in dry holes. Susceptibilities within the range from 0 to 2.0 SI can be measured with this tool. The volume of investigation or `sample volume' is roughly a sphere of 30 cm radius, surrounding the sensing coil in the probe. Logging is normally carried out at 6 m/minute and a measurement is taken every second or each 10 cm along the hole.

4.3 The Conductivity Logging Tool Description

4.3.1 Conductivity Measurement with the Geoinstruments TH-3C probe

The Maxwell-bridge circuit which is used in the TH-3 probe also allows conductivity of material close to the coil to be measured simultaneously with susceptibility. This is possible by resolving the change in complex impedance seen by the bridge into its inductive and resistive vector components. (Resistive material around the coil causes the coil to behave as a transformer with the resistive material acting as a combined and distributed "secondary winding" and "load"). Resistivity measurements using this technique are limited however to a range of 10^{-1} ohm-m to 10^{3} ohm-m. In practice only a few sedimentary formations would normally have resistivities low enough to fall within this range, while in igneous rocks only graphitic conductors or mineralized zones such as massive sulphides would be included (Bristow and Bernius, 1984).

5.0 TEMPERATURE/T-GRADIENT LOGGING

5.1 Geological Interpretation of Temperature Logs

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.

5.2 The Temperature Logging Tool Description

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.

6.0 ACOUSTIC LOGGING

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 300 mm. 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 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.

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).

II. ATOMIC ENERGY OF CANADA LIMITED Logging System

Introduction:

The AECL System had been assembled under the guidance of the GSC from commercially available logging equipment, for the purpose of studying the physical properties of rocks in a project to determine potential sites for disposal of radioactive waste materials. All of the components of the system were manufactured by the Mount Sopris Instrument Company of Delta, Colorado. The probes are powered from the surface, and data are received digitally and displayed in analog format on a chart recorder, and they are processed by computer and stored on magnetic tape. Each probe requires its own up hole module for the different parameters. The probes are described below under the coding system used by Mount Sopris.

The holes at Bells Corners were logged in 1986 and 1987.

The logs are presented from left to right on the plots in the order they are described below.

Probes:

ALP:

This is a combination probe providing a natural gamma log (Total Count) and three electrical parameters including 400 mm (16 in.) normal resistivity, single point resistance, and self-potential gradient. It incorporates a 22 mm X 76.5 mm (7/8 x 3 in.) NaI(Tl) crystal together with two electrodes spaced 40 cm apart. A preamplifier and precision rectifier circuit in the probe amplify the voltage produced between the two electrodes. The signal generated is proportional to the 400 mm normal resistivity. It is transmitted to the surface where it is filtered and scaled prior to recording.

The probe is 38 mm in diameter and 2.14 m long. The data from this probe are shown in the first four logs on the accompanying plots.

GLP:

The fifth log on the plot is produced by the three-arm caliper probe. This probe measures the diameter of the hole by means of three spring-loaded, motor-driven caliper arms, where arm movement is converted to a pulsed frequency that is transmitted to the surface.

The probe is 1.16 m long and 51 mm in diameter; it can measure hole diameters up to 254 mm.

CLP:

The sixth and seventh logs are produced by the digital acoustic velocity probe. The first of these two logs is the acoustic velocity or sonic log, and the second log is the sonic amplitude.

The first three holes at the test site were logged with the original settings from Mount Sopris and data are shown as microseconds per foot. When the last three holes were logged at a later date, the software was modified to show the data in microseconds per metre.

The same data are used to calculate the compressional wave (P-wave) amplitudes.

The tool is the same as that described as the GSC's acoustic logging tool.

FLP:

The 1-arm caliper log and the density data, shown in the eighth and ninth logs. The caliper arm is used to push the probe against the wall of the hole. It is connected to a transducer which senses movement of the arm as the hole diameter changes and the output is then transmitted up the hole.

The gamma-gamma density part of the probe consists of a NaI(Tl) crystal for detection of gamma rays and a 100 mCi ^{137}Cs radioactive source. Source-detector spacing is 250 mm.

This probe is 1.3 m long and 54 mm in diameter.

OLP:

This is a thermal neutron probe in which high energy neutron flux are emitted by a 1 Ci ^{241}Am-Be source. The ^{3}He detector is separated from the neutron source by a shield and a spacing of 35 cm. In this system, the neutrons emitted are absorbed by hydrogen, chiefly in the form of water. A lower count rate at the detector reflects a high water content and hence a higher porosity. This tool is mainly used for determining the porosity of a rock or formation.

The probe is 1.1 m long and 41 mm in diameter.

MLP:

This probe combines fluid resistivity and temperature measurement in a single tool. The fluid resistivity is measured using a miniature Wenner array having a 30 mm spacing. The outside electrodes are excited with an AC current having a fundamental frequency of 271 Hz. A differential receiver measures the voltage between two electrodes. A voltage-to-frequency converter is used to send the signal to the surface.

The temperature is sensed using a two-terminal thermistor with a current output of 1

Microamp/degree Kelvin over the range -55 to 150 deg.C. The accuracy is better than 1 deg.C and has a sensitivity better than .025 ^{0}C over the range -20 to 30 ^{0}C.

The probe is 1.75 m in length and 41 mm in diameter.

III. CENTURY GEOPHYSICS LTD. Logging System

Introduction:

Century Geophysical Corporation Ltd. of Calgary logged the Bells Corners Test Holes in September 1982. They used four slim-line probes which were designed to measure natural gamma rays and other parameters related to coal and uranium exploration. At the time they carried out the work only four holes were completed (i.e. BC81-1 to BC81-4), and BC81-4 stopped at 120m.

Data were recorded in the field on 9-track tape in binary format. They were then converted to ASCII before delivery to the GSC.
This system samples at a high rate (1 cm intervals) resulting in a large amount of data. All data were presented as recorded and received from CENTURY GEOPHYSICS in this report without any editing. It would be preferable to smooth the data, which are about four times more frequently recorded than that of the GSC.

The data, nevertheless, show a close correspondence with that gleaned from other sources, and are useful when comparing different crystal sizes, sources, electronic configurations, logging speeds, etc.

Coal Probe (9030A):

This probe is designed to measure those parameters most often used in coal exploration: Natural Gamma, Gamma-Gamma Density, Resistivity, and Hole Size (caliper). It is 5 cm in diameter and 292 cm long. The first four logs on the plot were obtained from one run up the hole.

The caliper is a single motorized arm that is deployed at the bottom of the hole in order to press the probe against the side of the hole for maximum contact and to minimize hole size effects. This is important in measuring electrical parameters. It is capable of working in hole diameters from 5.1 cm to 35.6 cm.

A 2.8 by 11.4 cm (1 1/8" X 4 1/2") NaI(Tl) crystal detector is used in this probe. Total radioactivity is presented as API units.

The gamma-gamma system utilizes a gamma source of 100 mCi of ^{137}Cs, a 1.3 X 5 cm NaI(Tl) detector, and the adjustable source-detector spacing is set at 20.3 cm. The system is calibrated and the count rate data are converted and presented as g/cm^3.

Resistivity is measured using a focused three electrode guard type array designed to respond symmetrically to thin beds. It has a range of measurement from 2 to 40,000 Ohm-metres with a resistivity contrast ratio of 4000. Data are presented in Ohm-metres.

Uranium Probe (9055):

Six parameters are logged in a single pass with this tool: natural gamma, temperature, neutron-neutron porosity, self potential, deviation and single-point resistance. Only the natural gamma count rate is presented on the logs for comparison with the other probes that have different crystal sizes.

The NaI(Tl) detector is 28 X 102 mm (7/8" X 4"). Logging speed was 18.3 m/min (50 ft/min). The logs are presented in cps.

The probe is 45 mm in diameter and 2.79 m in length.

Uranium Probe (9067):

This probe measures two parameters: natural gamma and neutron-neutron in a single pass. It is 32 mm in diameter and 2.50 m long (1 1/4" X 98 1/2"). Both logs are presented in the compilations.

Since the NaI(Tl) detector in this probe, (13 X 76 mm), is smaller than the detector on the uranium probe 9055 on page 30, the logging speed is reduced to between 6 and 9 m/min to compensate.

The neutron-neutron part of the probe uses a 1 ci ^{241}Am-Be source with a source-detector spacing of 42.5 cm (16 3/4"). Data from both parameters are presented in cps.

Density Probe (9068):

This probe is designed to measure density and natural gamma counts inside casing. It is the same size as probe 9067 (32 mm by 2.5 m).

For the gamma-gamma density measurements, the same size NaI(Tl) detector is used as in 9067, with a 125 mCi ^{137}Cs source separated from the detector by a spacing of 45 cm. The depth of penetration is approximately 22 cm into the borehole wall. Data are presented as received from Century Geophysics. This is a qualitative inverse logarithmic plot in cps (false density) where a high count rate equals a low density.

Natural gamma rays are detected in the NaI(Tl) crystal mentioned above and these data are presented in cps.

Comments on the Century Logs:

Virtually all the logs plotted here are similar in character to those recorded by the GSC and AECL, and show little difference when overlain on each other. The exception is in the Century resistivity logs where the focussing design gives a much higher resolution than the other resistivity logs. This allows for smaller fracture zones and thin beds to be more easily detected.

IV. IFG Corporation Portable Geophysical Logging System

The primary components of the portable logging system are:

1. the borehole probes containing the geophysical sensors;
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. the data acquisition systems which include a PC computer for running the acquisition software and displaying logging information.

IFG's data sampling rate ranges from 0.5 to 2 samples/sec., providing a measurement every 5 to 20 cm along the hole at a logging speed of 10 cm/sec.

The portable system includes the following probes: the natural gamma-ray spectral probe, the spectral gamma-gamma probe, and the multiparameter probe (model BMP-04). The characteristics of the logging tools and their measuring principles are briefly described below.

General Description of IFG Logging Tools and Geological Responses

4.1 The IFG Gamma-Ray Spectral Logging Tool

The 40 mm diameter spectral gamma-ray probe consists of a 25 mm X 76 mm (1 inch X 3 inch) cesium iodide (CsI(Na)) scintillation detector and measures natural gamma radiation in the energy range from approximately 0.1 to 3.0 MeV. The probe is controlled by a microprocessor which transmits data digitally to the surface data acquisition unit. Full gamma-ray spectra are recorded every 2 seconds in 256 or 512 channels (switch selectable) and up to 10 energy windows can be displayed during logging. Five standard windows are usually monitored during data acquisition, and these include two total count windows (TC1: 0.1-3.0 MeV; TC2: 0.4-3.0 MeV), the potassium (K), uranium (U), and thorium (Th) windows.

The gamma probe is temperature-stabilized in the borehole water at a depth of about 30 m for approximately 30 minutes before logging. The temperature of the detector is monitored through a sensor at the detector monitors the detector temperature until it reaches a constant value of the borehole fluid temperatures. The probe is brought to the surface and the detector is then energy-calibrated with cesium and cobalt calibration sources. A spectrum is acquired for approximately 2 minutes during this process and recorded. This energy calibration is repeated after the uphole run.

Logging is generally done at 6 m/minute and the data are sampled at 2 second intervals equivalent to an average sample depth interval of 20 cm along the drillhole.

4.2 The IFG Density/SGG Logging Tool

This tool (developed with technology transferred from the GSC), is 40 mm in diameter and has a 25 mm by 76 mm (1" x 3") CsI(Na) detector. Gamma rays from the source that are backscattered by the rock around the borehole. The probe is controlled by a microprocessor which transmits data digitally uphole along the logging cable to the surface data acquisition unit. Full gamma-ray spectra covering the energy range of approximately 1.17 to 1.33 MeV are recorded in 512 channels every 2 seconds.

Density information is as described in the GSC tool description.

4.3 The IFG Multiparameter Logging Tools

The IFG multiparameter probe (BMP-04) is 45 mm in diameter and measures the following parameters:

A. Borehole magnetometry and orientation
    - 3-orthogonal magnetic field components (Hx, Hy, Hz plus total magnetic field, Ht)
    - 2-orthogonal tilt sensors (Tx, Ty)
B. Magnetic Susceptibility
C. Electrical measurements
    - Single point resistance (SPR)
    - 2 resistivities:
        1) 40-cm normal resistivity
        2) 120-cm (three-electrode) resistivity
    - Self Potential (SP)
    - 2 Self Potential Gradients
        1) 174-cm dipole spacing (SPG1)
        2) 85-cm dipole spacing (SPG2).
D. Temperature

The probe is fully digital, transmitting all measured values along the logging cable at a rate of 2 per second. Logging is generally done at 6 m/minute, providing a sample depth interval of 5 cm.

4.3.1 The Magnetometer and Orientation Logging Component

The 3-component magnetometer/orientation component of the multiparameter probe measures the three components of the earth's magnetic field as well as the orientation (dip and azimuth) of the borehole. The magnetometer measurements are of interest in mineral exploration for detecting the presence of magnetic bodies at some distance from the hole. The borehole orientation measurements are important since drillholes often deviate from the planned path by significant amounts.

The magnetometer/orientation component of the multiparameter probe consists of two sets of sensors: (1) three fluxgate sensors, with a sensitivity of 1 nanoTesla (nT) over a range of +/- 100,000 nT, which measure the magnetic field component (Hz-component) collinear with the probe axis and two orthogonal components (Hx-, Hy-components) in the plane normal to the probe axis, (2) two inclinometers with a sensitivity of 0.1° over a range of +/- 80° aligned orthogonally in the plane normal to the probe axis. Measurements from these five sensors are used to compute the magnetic field components in a geomagnetic frame of reference (the three components being North, East and vertical), as well as the dip and azimuth of the borehole (Balch and Blohm, 1991).

Logging can be done in open or plastic cased boreholes.

4.3.2 The Magnetic Susceptibility Component

The magnetic susceptibility tool consists of a 40-cm long, 38-mm diameter sensor coil in an electrical bridge circuit energized at a frequency of 1400 Hz. When the probe passes through magnetically susceptible material, the coil inductance changes causing the bridge to become unbalanced. The bridge is balanced automatically by changing the energizing frequency. This change in frequency is converted to magnetic susceptibility. Since the measurements are made inductively (i.e., with E.M. fields not electrodes), the tool can be used inside plastic casing and in dry holes. Susceptibilities within the range from about 100 microSI to 1.0 SI can be measured with this tool. The volume of investigation or `sample volume' is roughly a sphere of 30 cm radius, surrounding the sensing coil in the probe.

4.3.3 The Resistivity and SPR Component

Resistivity data are acquired with two electrode arrays; 1) a normal array with a current-potential electrode spacing of 40 cm and 2) a 120 cm three-electrode (pole-dipole) array with the potential dipole spacing equal to 85 cm. The downhole current and potential electrodes are made of brass, 25-mm long and 38-mm in diameter. Both electrode arrays use a surface return current electrode consisting of a 1-m long steel rod that is generally located approximately 100 m from the drillhole collar. The transmitter on this system is a constant current source, capable of supplying currents up to 20 mA. The volume of investigation depends on the array type and the electrode spacings, but it is larger for the three-electrode array than for the normal array.

Single point resistance measurements are made with a downhole current/potential electrode and a surface return/reference electrode. The downhole electrode is the same as the current electrode used in the two resistivity measurements and is connected to the surface measuring electronics via the logging cable through which an analogue signal is transmitted uphole.

Both resistivity and SPR logging must be done in uncased, water-filled holes.

4.3.4 The Self Potential Component

Self potential measurements are made with the same electrodes that are used with the two resistivity arrays and the single point resistance array. No current is transmitted through the electrodes during SP measurements. The measured potentials are natural, caused mainly by electrochemical processes occurring around base metal sulphides. The potentials observed between a mobile downhole potential electrode and a fixed surface electrode are termed SP measurements. Those that are observed between two mobile, downhole electrodes (a potential dipole) are termed SP gradients or SPG. SPG1 log refers to SP gradients measured with a 174-cm dipole spacing and SPG2 to those measured with an 85-cm dipole spacing

Logging must be done in uncased, water-filled holes.

4.3.5 The Temperature Component

The IFG temperature sensor consists of a thermistor bead with a 1 second time constant and an equivalent temperature sensitivity of 0.0001 degrees Celsius. The thermistor is located at the bottom of the multiparameter probe so that it enters undisturbed water as the probe moves down the hole. The multiparameter probe is also the first log run on a given day so that borehole fluid temperatures are undisturbed. All temperature measurements are continuously recorded on a downhole run at logging speeds of 6 m/minute with data sampled approximately every 5 cm. An uphole log is routinely acquired which often serves as a check on the reproducibility of observed temperature anomalies and hence increases the confidence in their interpretation.

Changes in temperature are recorded as changes in the thermistor electrical resistance that is then converted into true temperatures using a calibration equation determined from temperature bath measurements. The temperature gradient data are derived from the temperatures by means of a combined gradient and smoothing operator. Units of temperature gradient are given in SI as mK/m. These units are numerically equal to the cgs system (°C/km).

Temperature logging can be done in cased or uncased, air- or water-filled holes.

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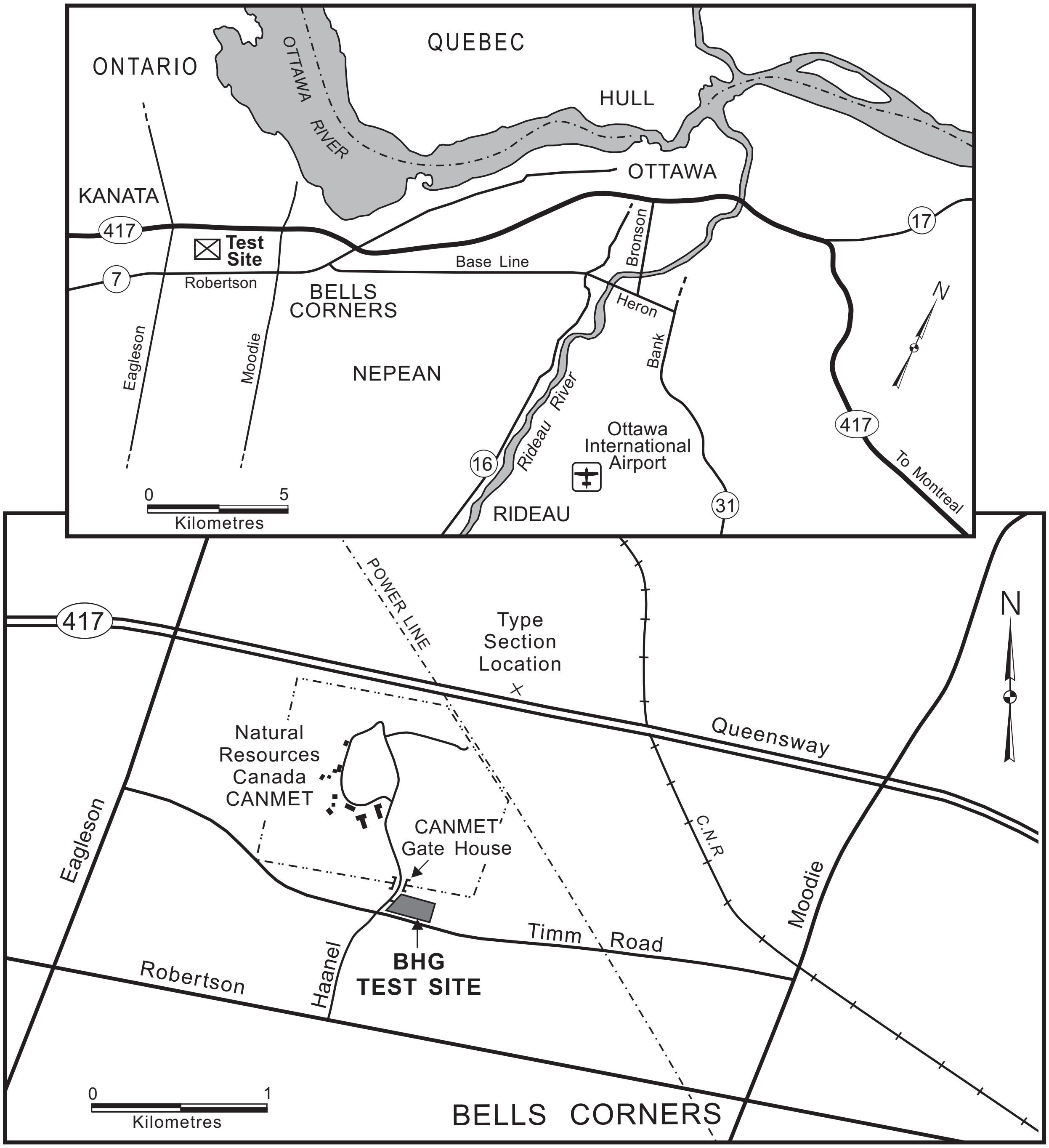
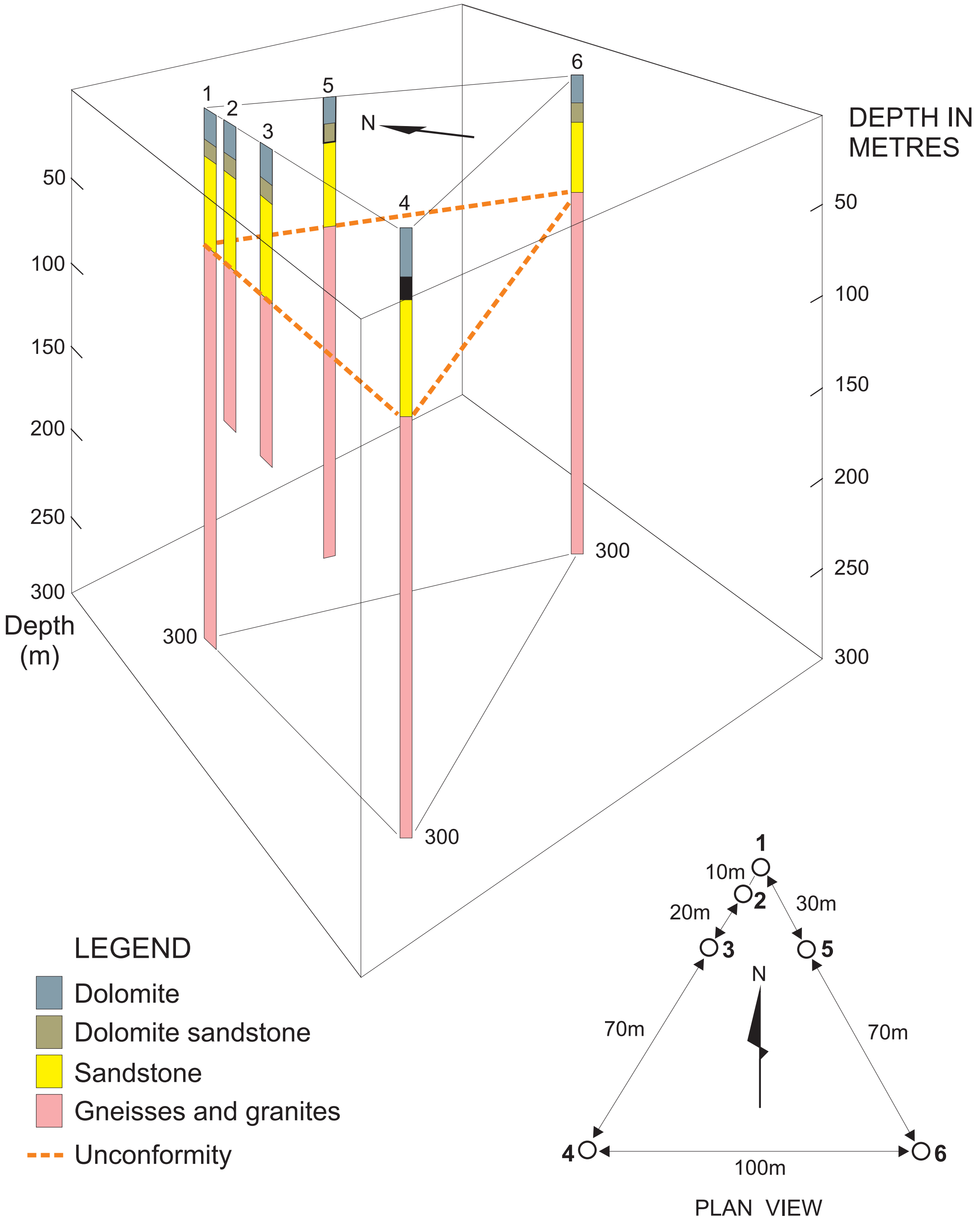


Fig. 1 Location of the Bell's Corners Geophysical Test site west of Ottawa. Note the location of the type section for the Nepean sandstone chosen by Greggs and Bond (1972)

Fig. 2 GSC BOREHOLE GEOPHYSICS TEST SITE,
BELLS CORNERS, NEPEAN, ONTARIO



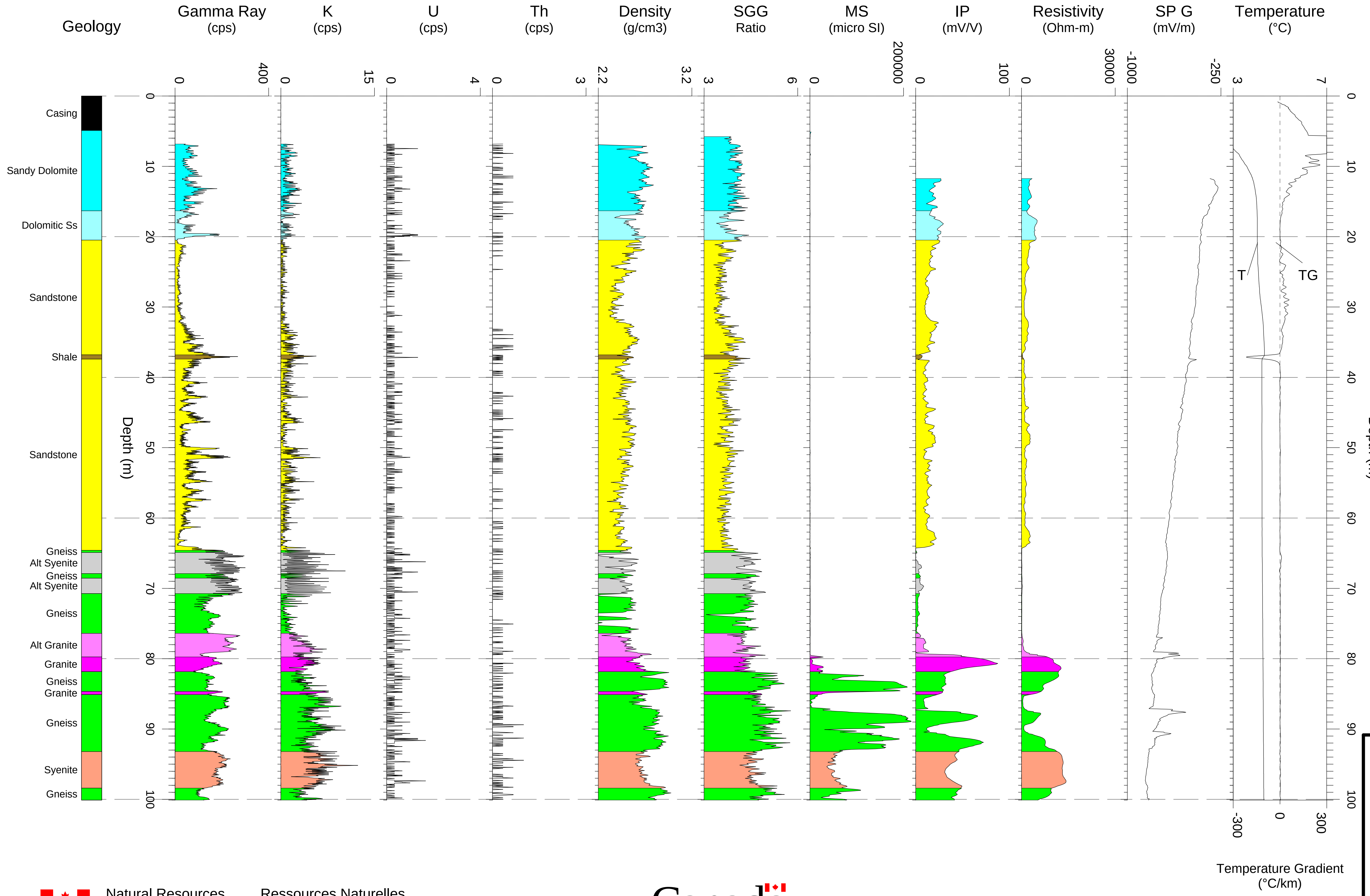
APPENDIX II - THE BOREHOLE GEOPHYSICS TEST SITE LOGS

GSC BOREHOLE GEOPHYSICS TEST SITE

GSC Logs

Bells Corners, Ontario

Borehole
BC81-1
Plot 1 of 3



LEGEND FOR
THIN LAYERS

A	Gneiss
B	Alt Gneiss
C	Granite
D	Pegmatite

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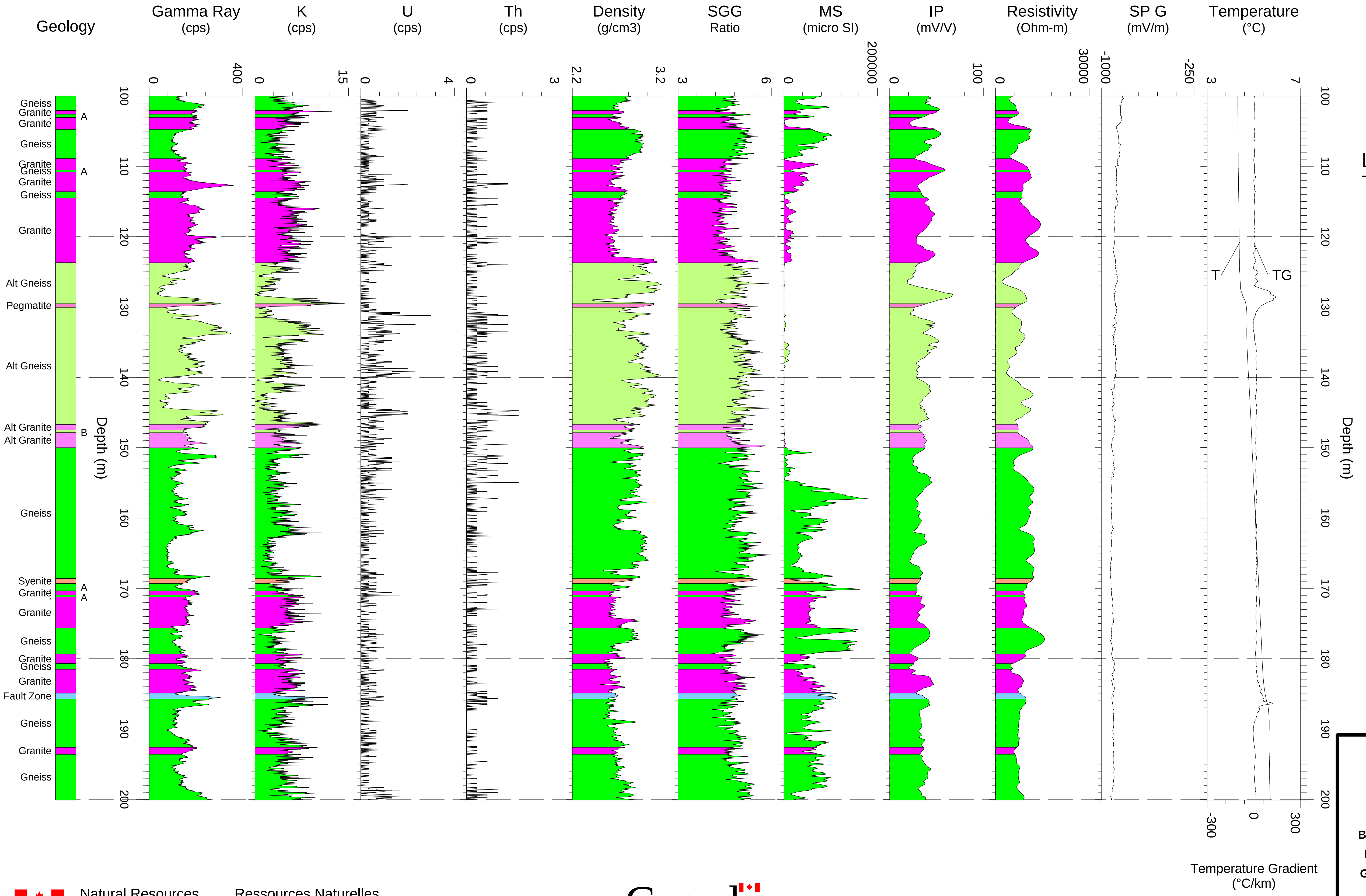
GSC BOREHOLE GEOPHYSICS TEST SITE
GSC Logs
Bells Corners, Ontario

Borehole
BC81-1
Plot 2 of 3



LEGEND FOR THIN LAYERS

A Gneiss
B Alt Gneiss
C Granite
D Pegmatite

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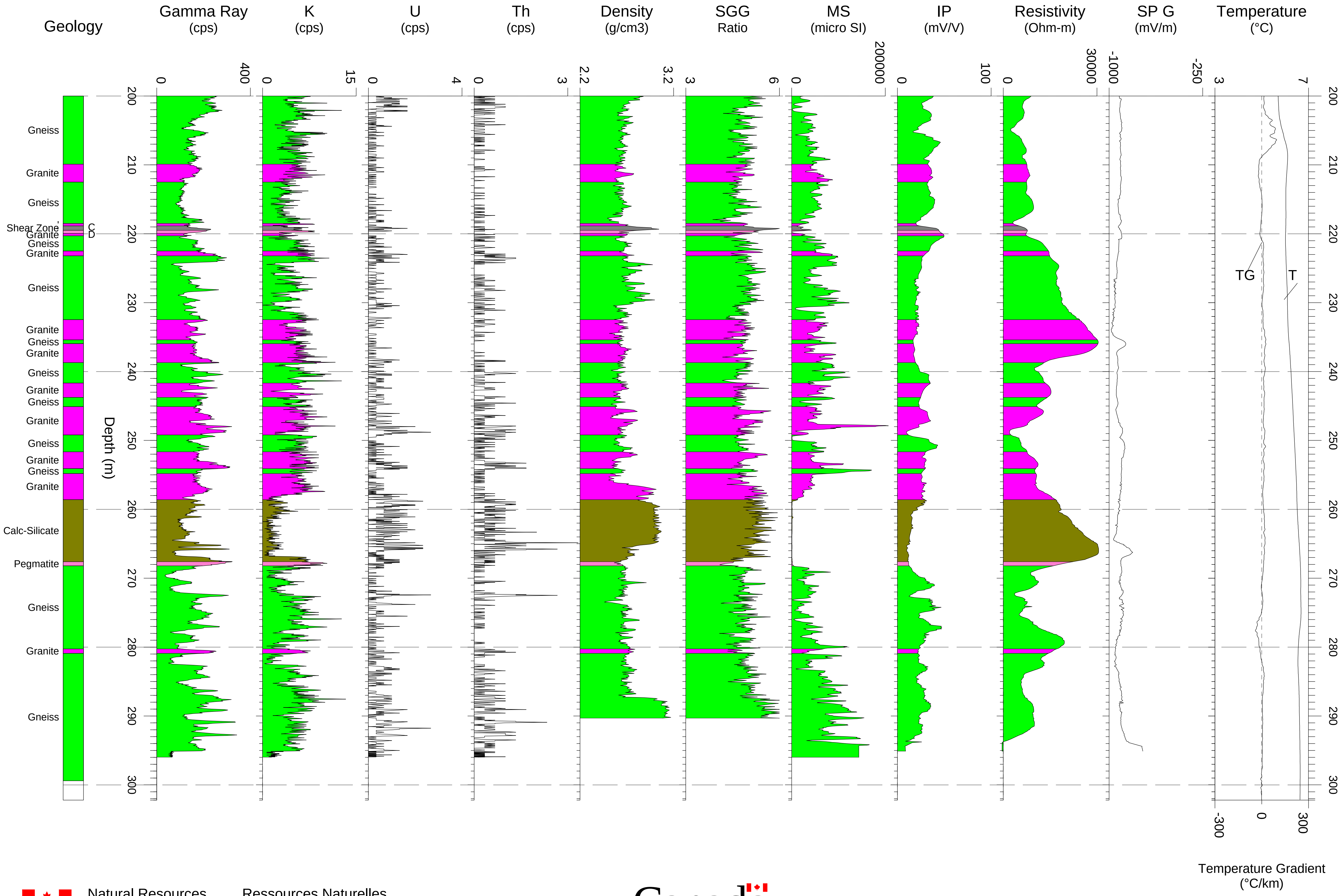
GSC Logs
Bells Corners, Ontario

Borehole
BC81-1
Plot 3 of 3



LEGEND FOR THIN LAYERS

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B	Alt Gneiss
C	Granite
D	Pegmatite

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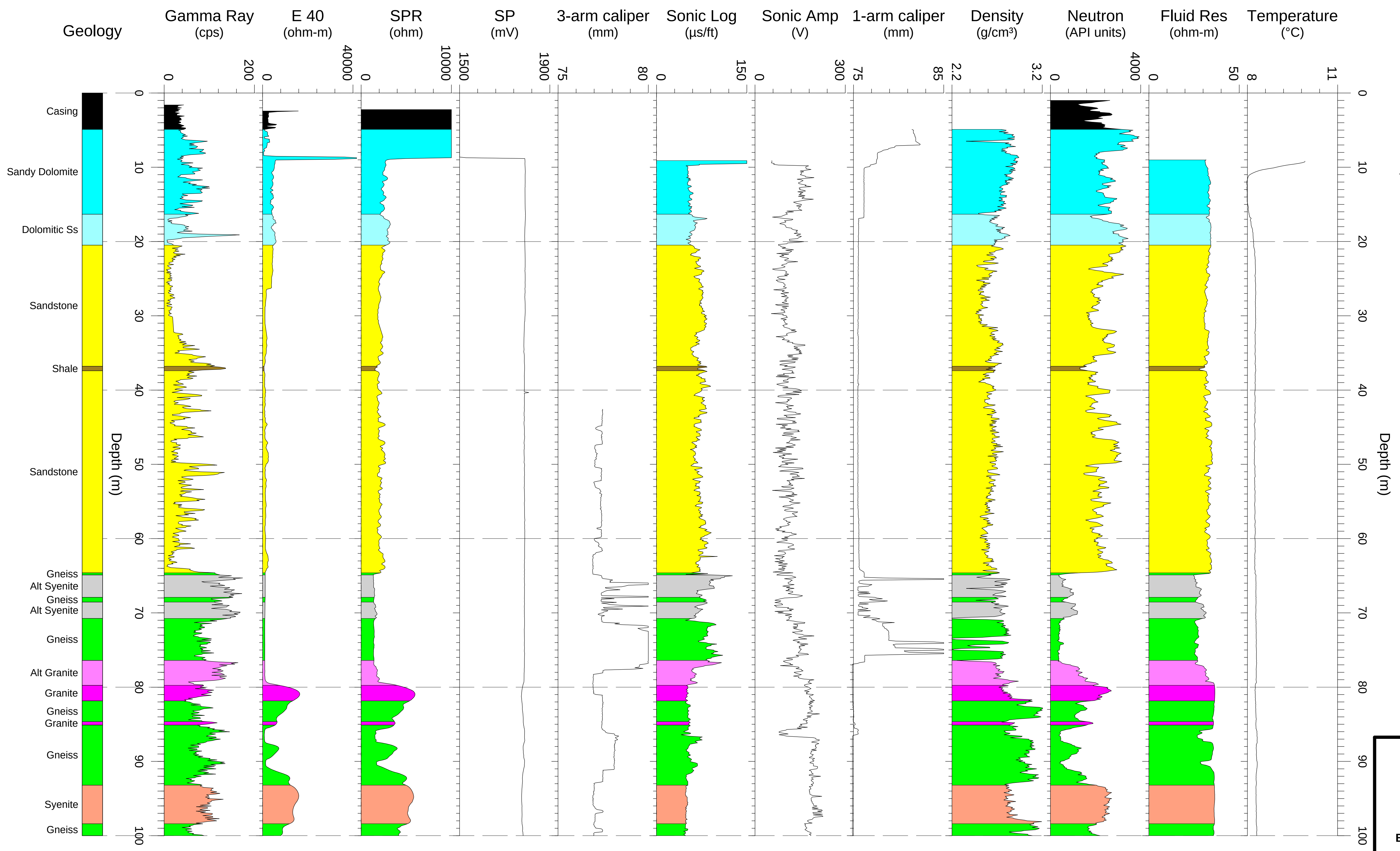
AECL Logs
Bells Corners, Ontario

Borehole
BC81-1
Plot 1 of 3



LEGEND FOR THIN LAYERS

A	Gneiss
B	Alt Gneiss
C	Granite
D	Pegmatite

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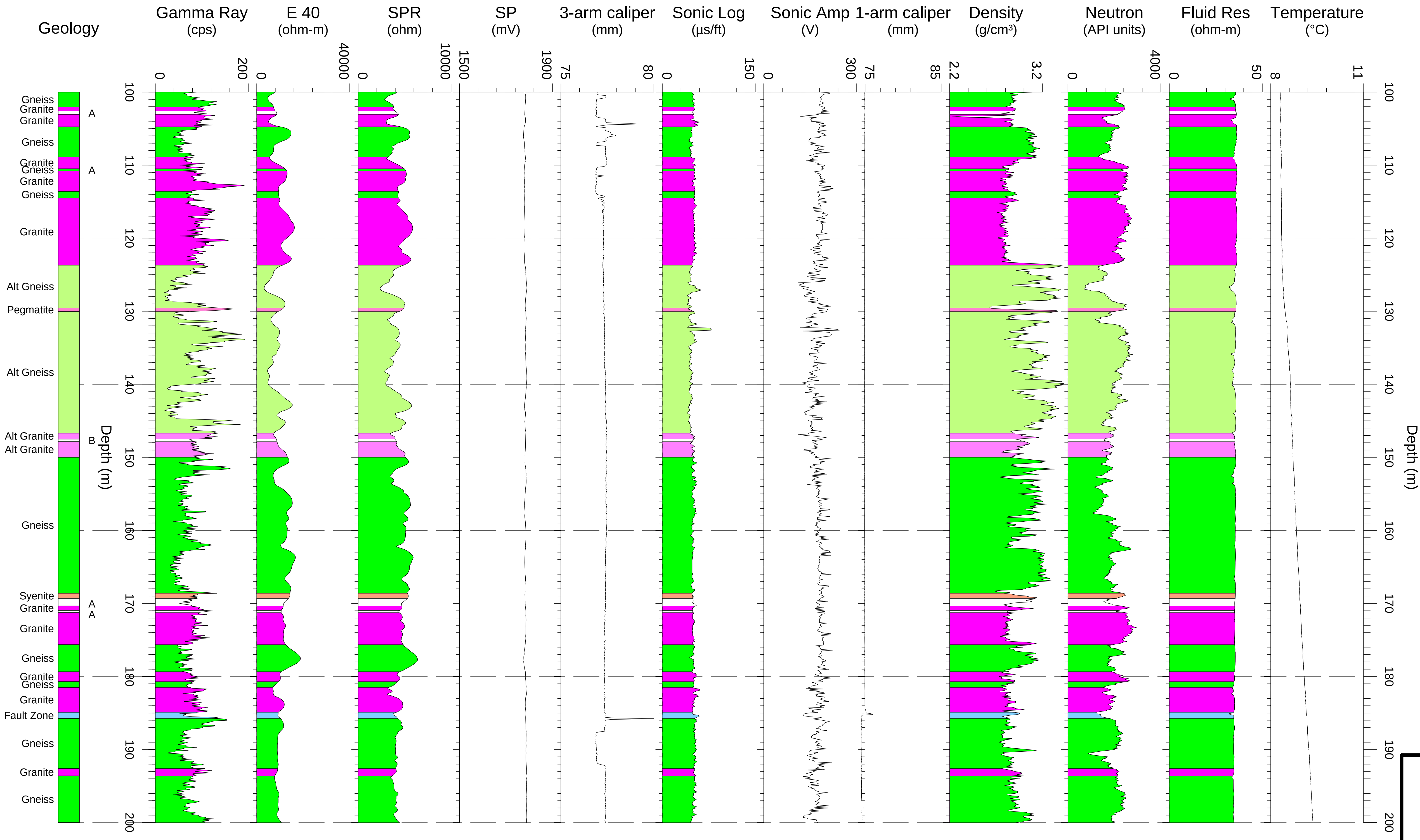
AECL Logs
Bells Corners, Ontario

Borehole
BC81-1
Plot 2 of 3



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B	Alt Gneiss
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D	Pegmatite

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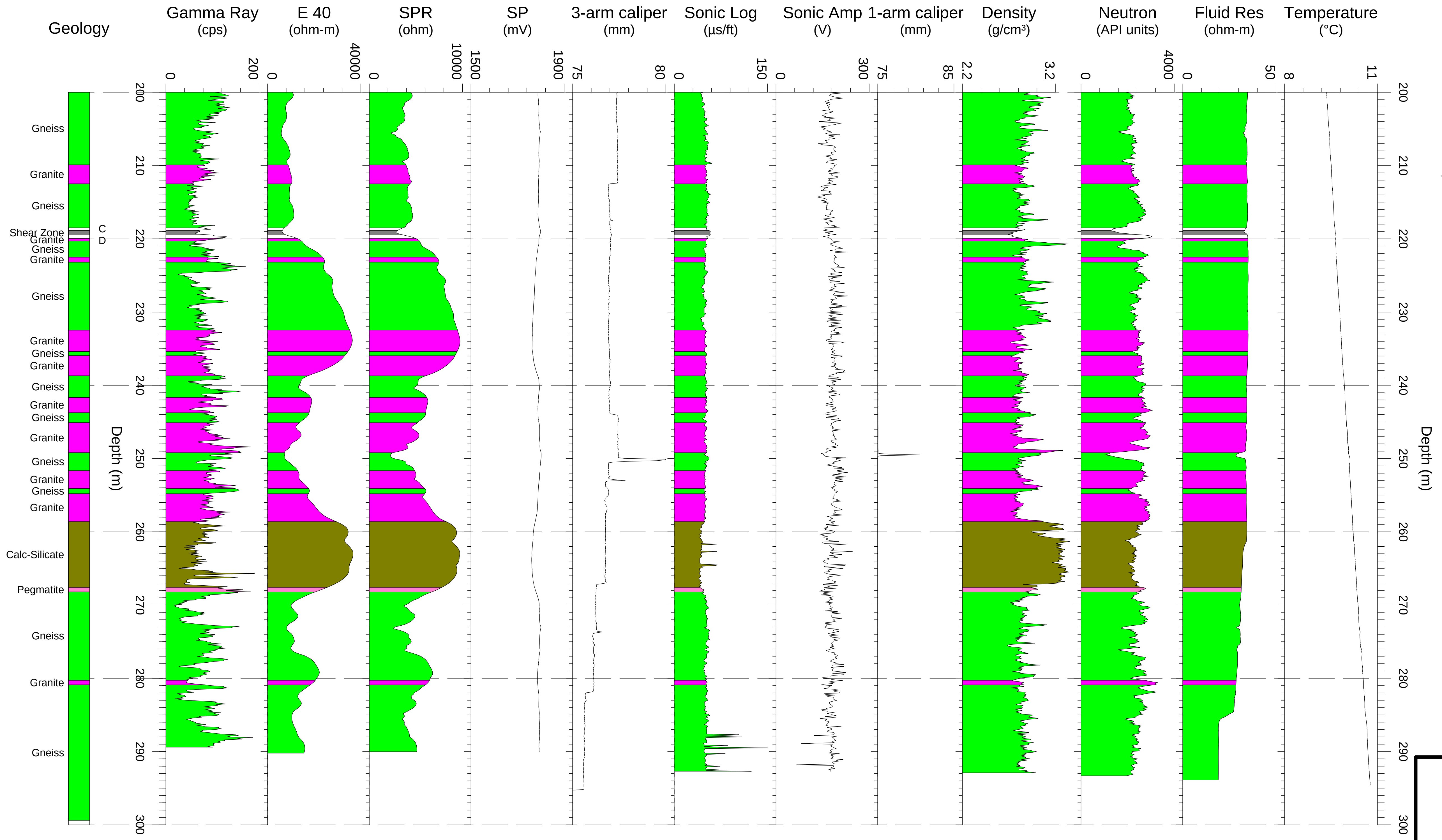
AECL Logs
Bells Corners, Ontario

Borehole
BC81-1
Plot 3 of 3



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C	Granite
D	Pegmatite

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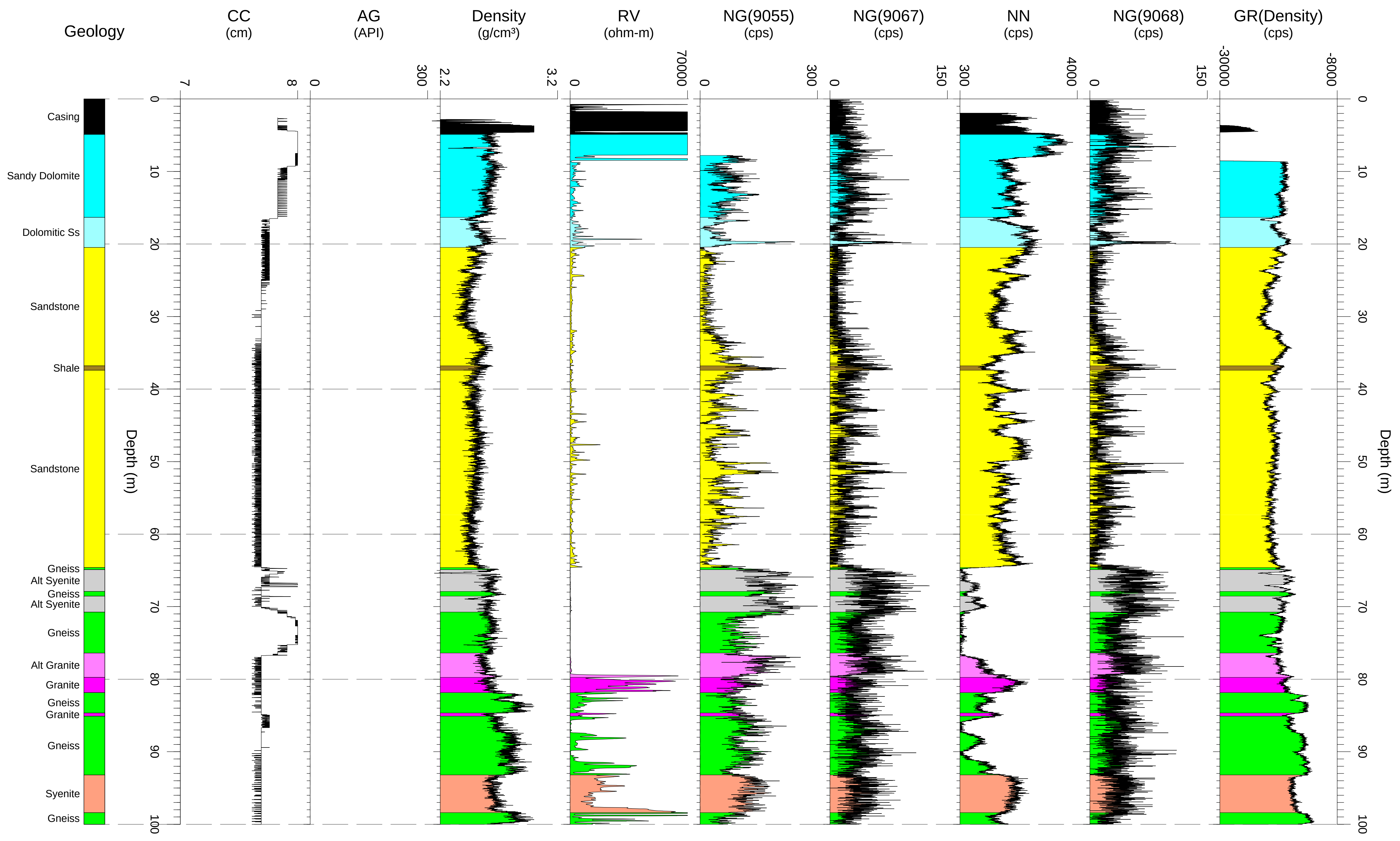
Century Geophysics Logs
Bells Corners, Ontario

Borehole
BC81-1
Plot 1 of 3



LEGEND FOR THIN LAYERS

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D	Pegmatite

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Bells Corners, Ontario

Borehole
BC81-1
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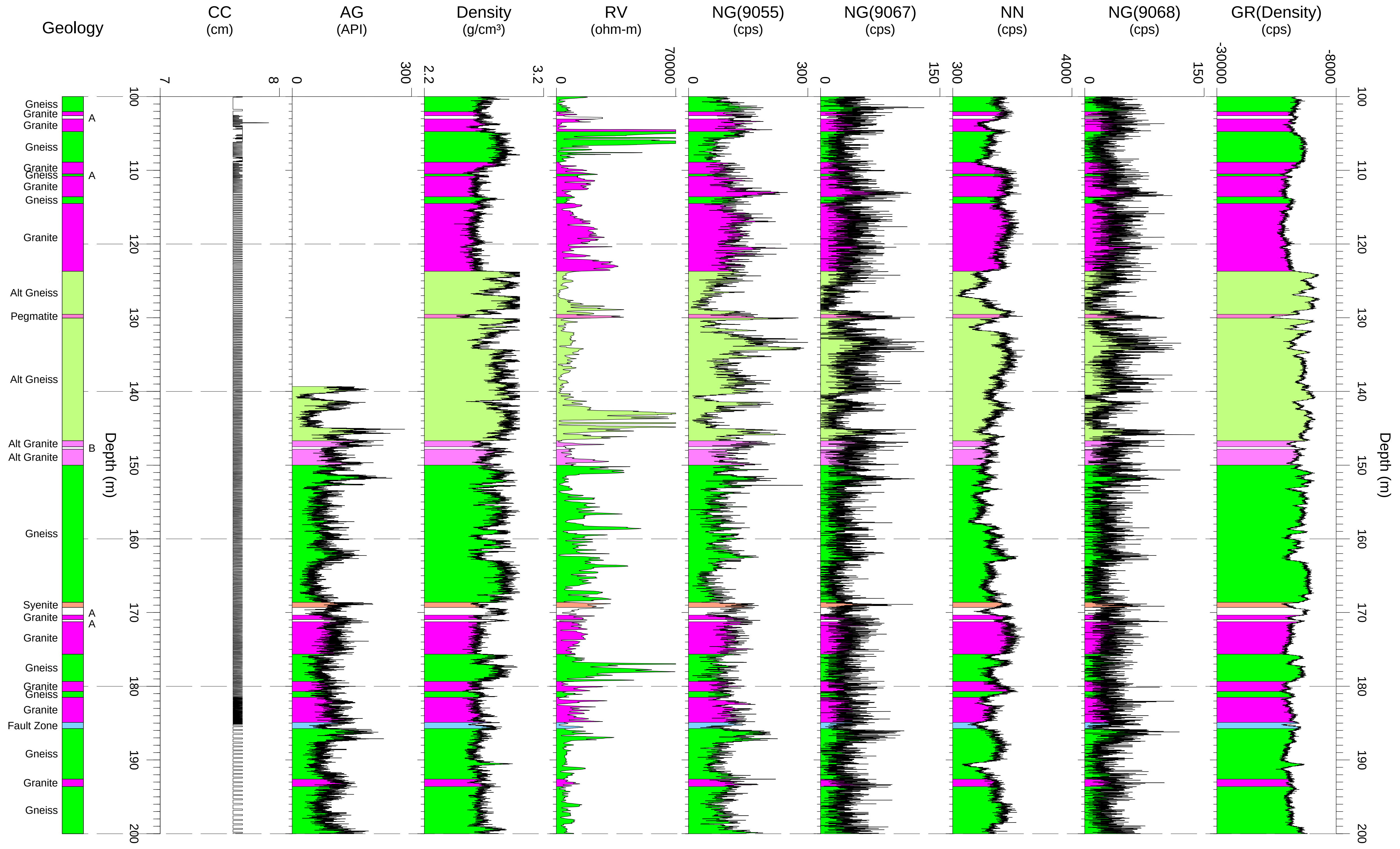

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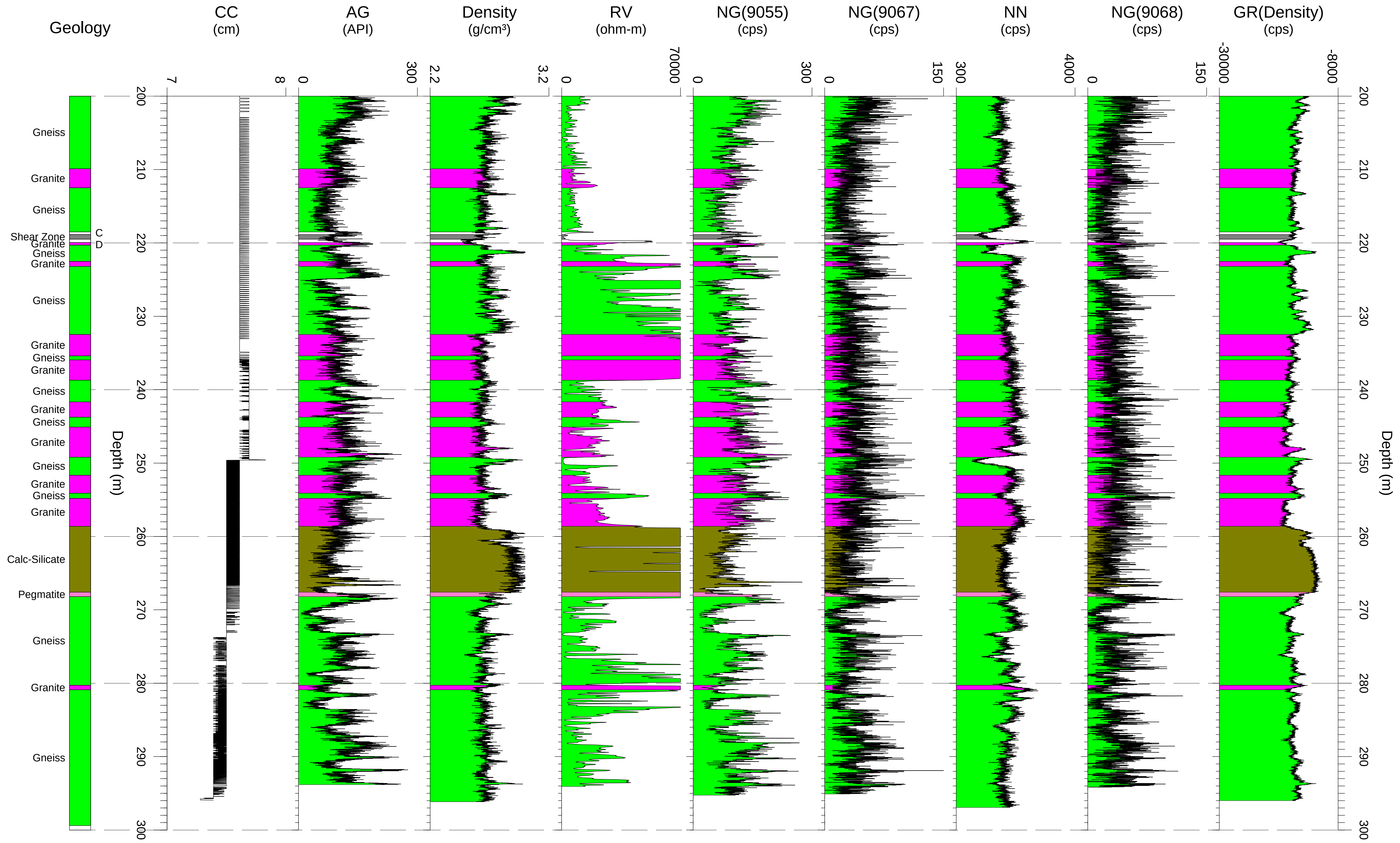
Bells Corners, Ontario

Borehole
BC81-1
Plot 3 of 3



LEGEND FOR THIN LAYERS

A	Gneiss
B	Alt Gneiss
C	Granite
D	Pegmatite

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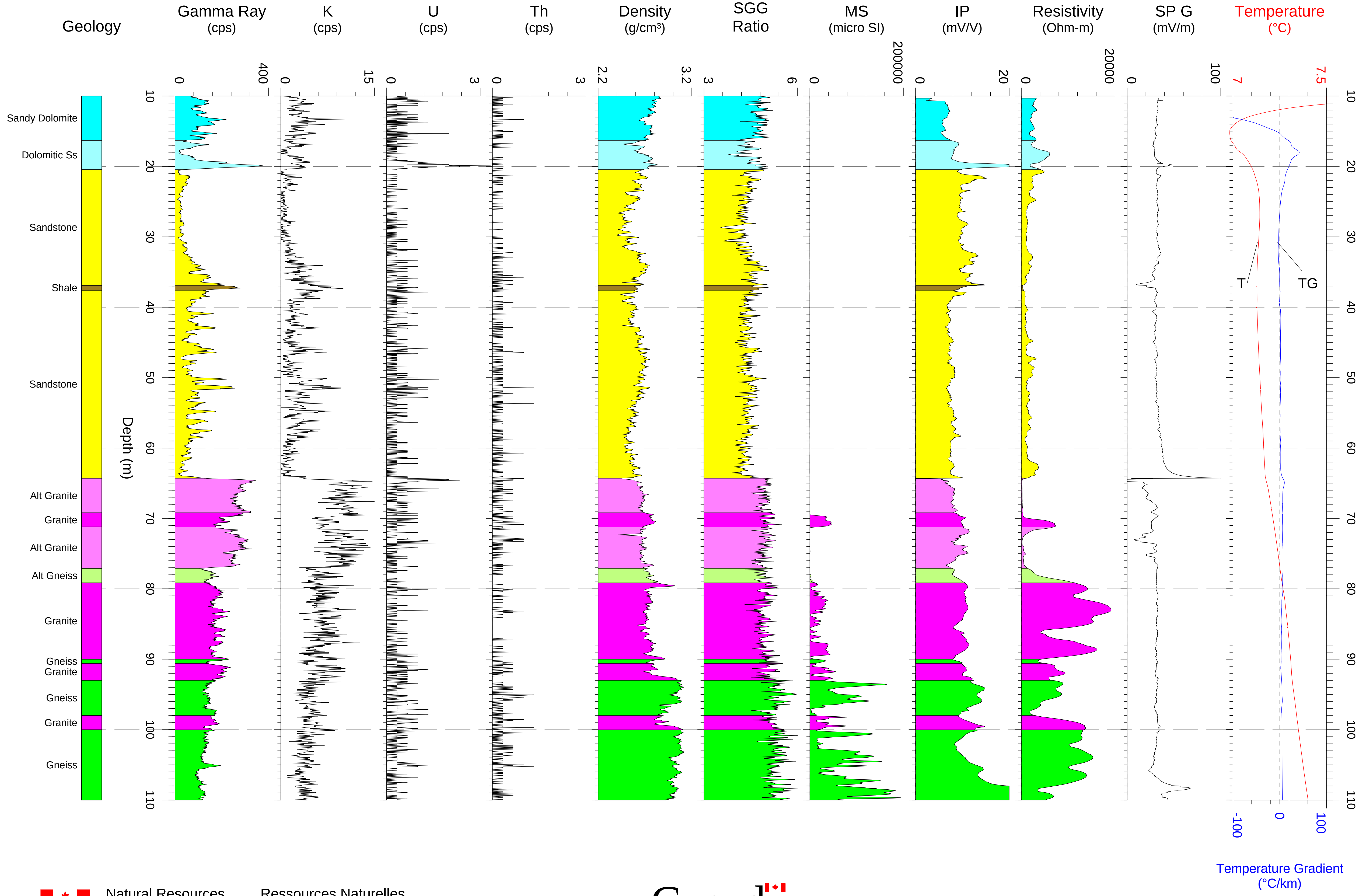
GSC Logs

Bells Corners, Ontario

Borehole
BC81-2



Note:
Additional parameters can be found on a following page.

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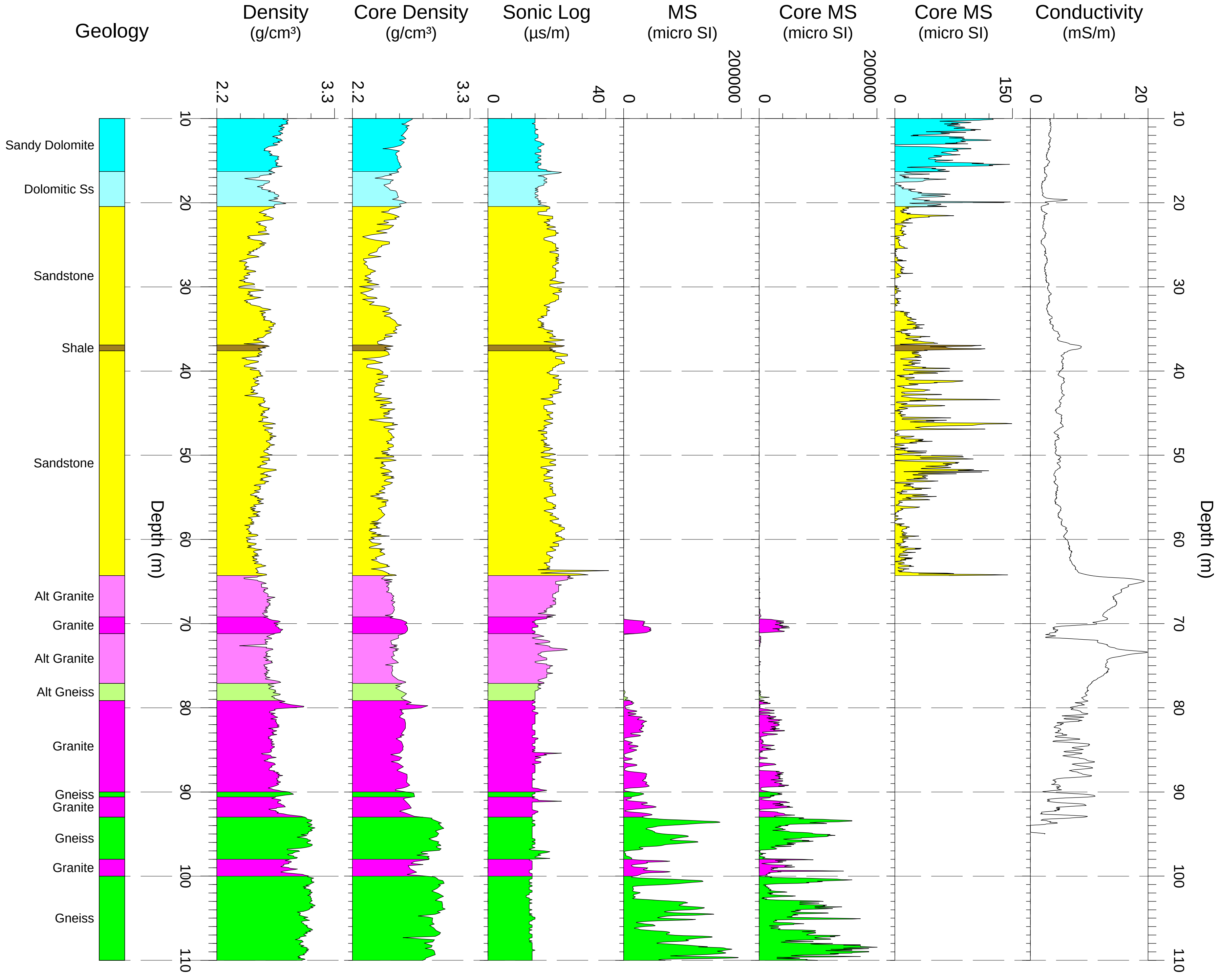
GSC Auxiliary Logs
Bells Corners, Ontario

Supplement to
Borehole
BC81-2



Note:

These logs are supplemental to the logs of the previous page. The auxiliary parameters included here are core density, core magnetic susceptibility, sonic log, and conductivity. Duplicated from the previous page, for reference, are down-hole density and down-hole magnetic susceptibilty.

It should be noted that on both colour plots the depth viewing range is from 10m to 110m.

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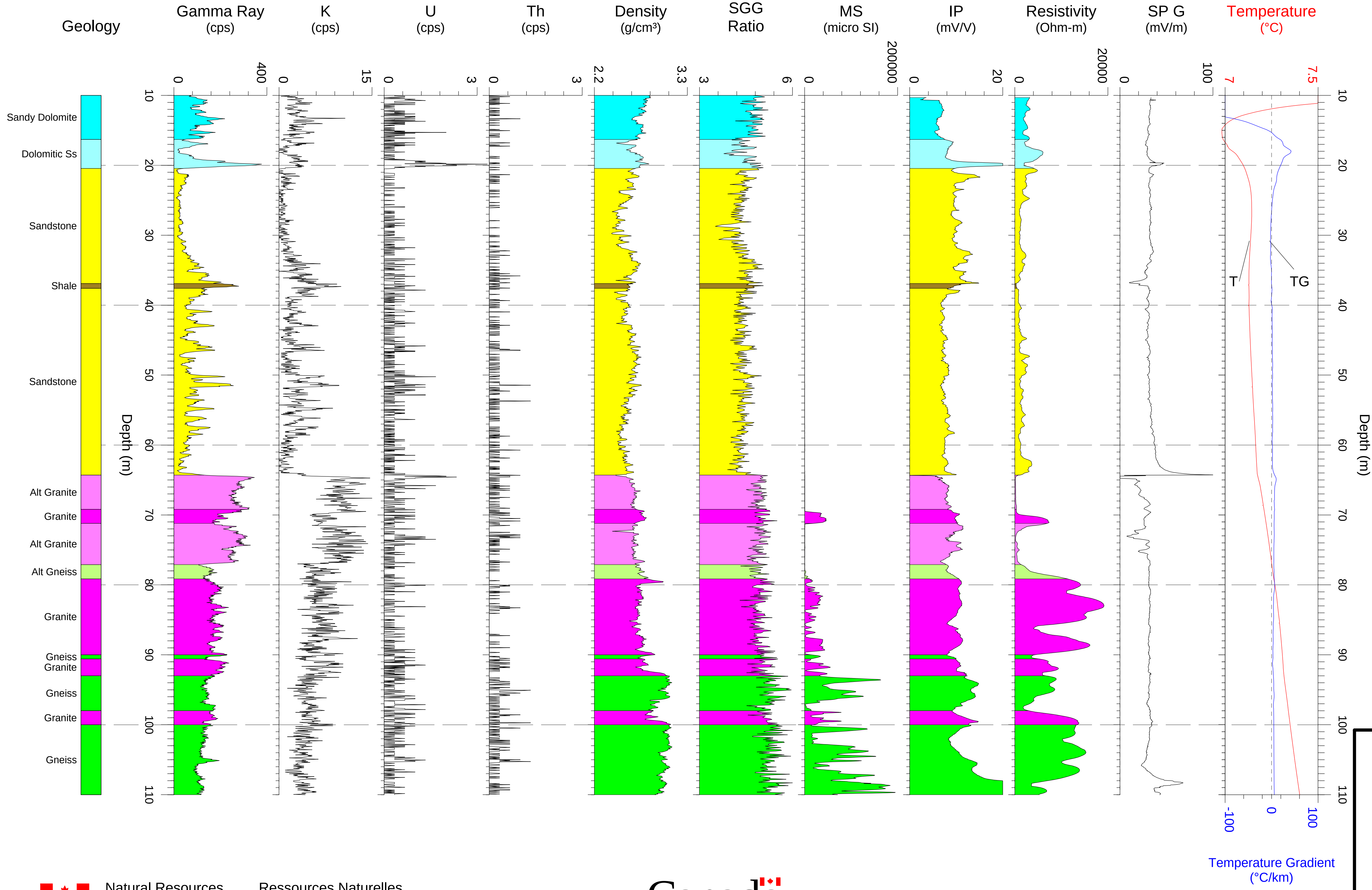
GSC Logs

Bells Corners, Ontario

Borehole
BC81-2
Colour Plot



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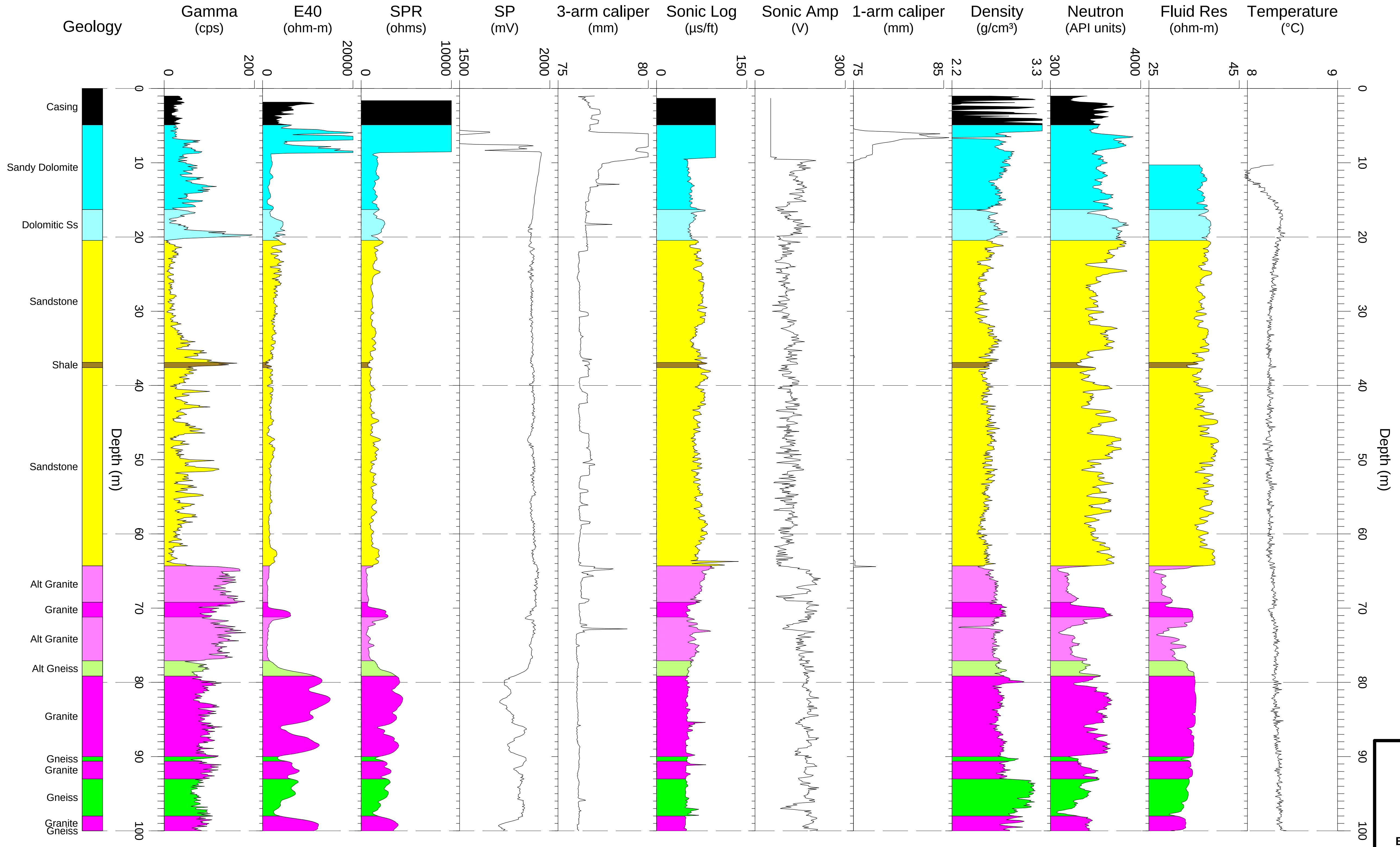
AECL Logs
Bells Corners, Ontario

Borehole
BC81-2
Plot 1 of 2



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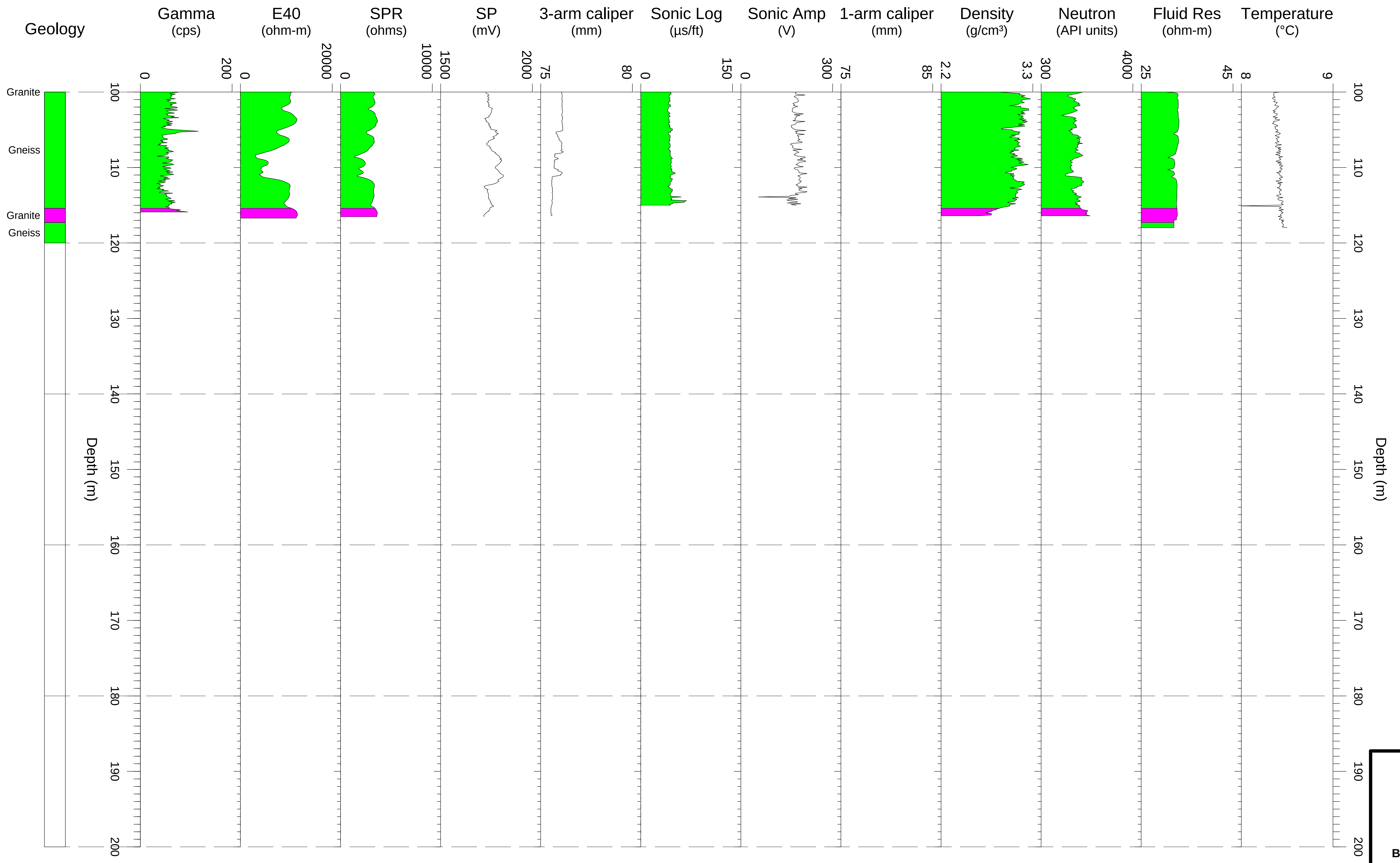
AECL Logs
Bells Corners, Ontario

Borehole
BC81-2
Plot 2 of 2



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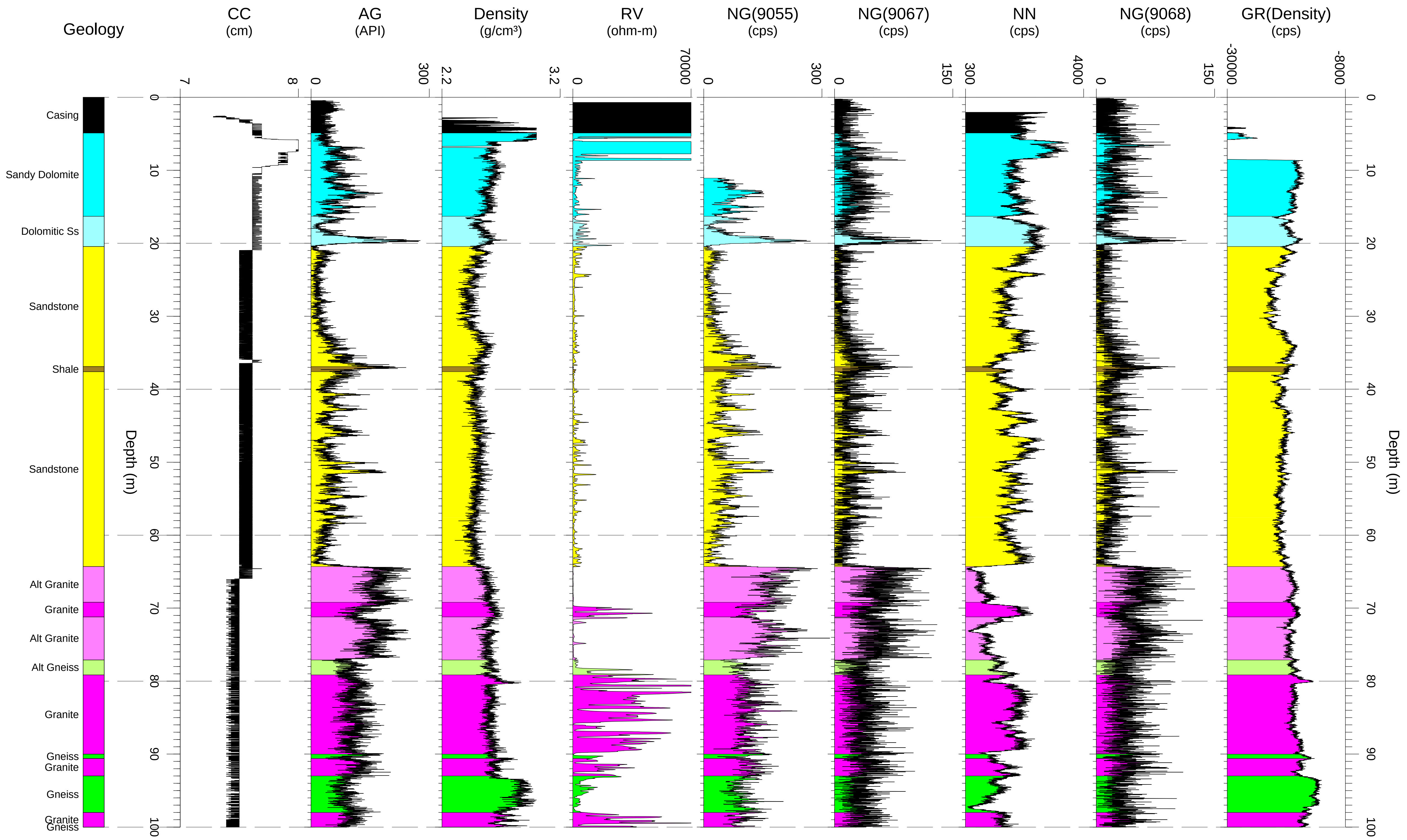
Century Geophysics Logs

Bells Corners, Ontario

Borehole
BC81-2
Plot 1 of 2



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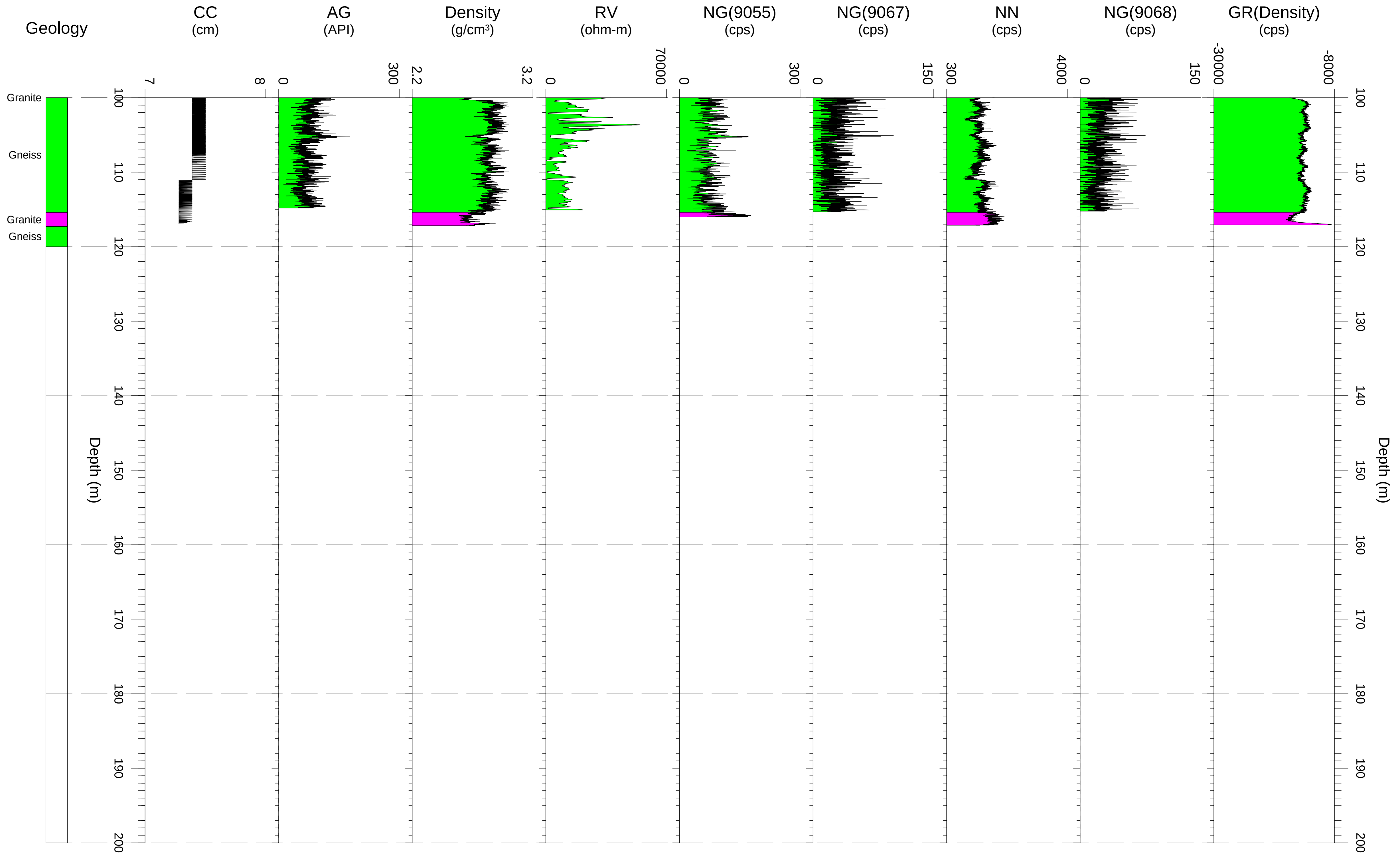
Century Geophysics Logs
Bells Corners, Ontario

Borehole
BC81-2
Plot 2 of 2



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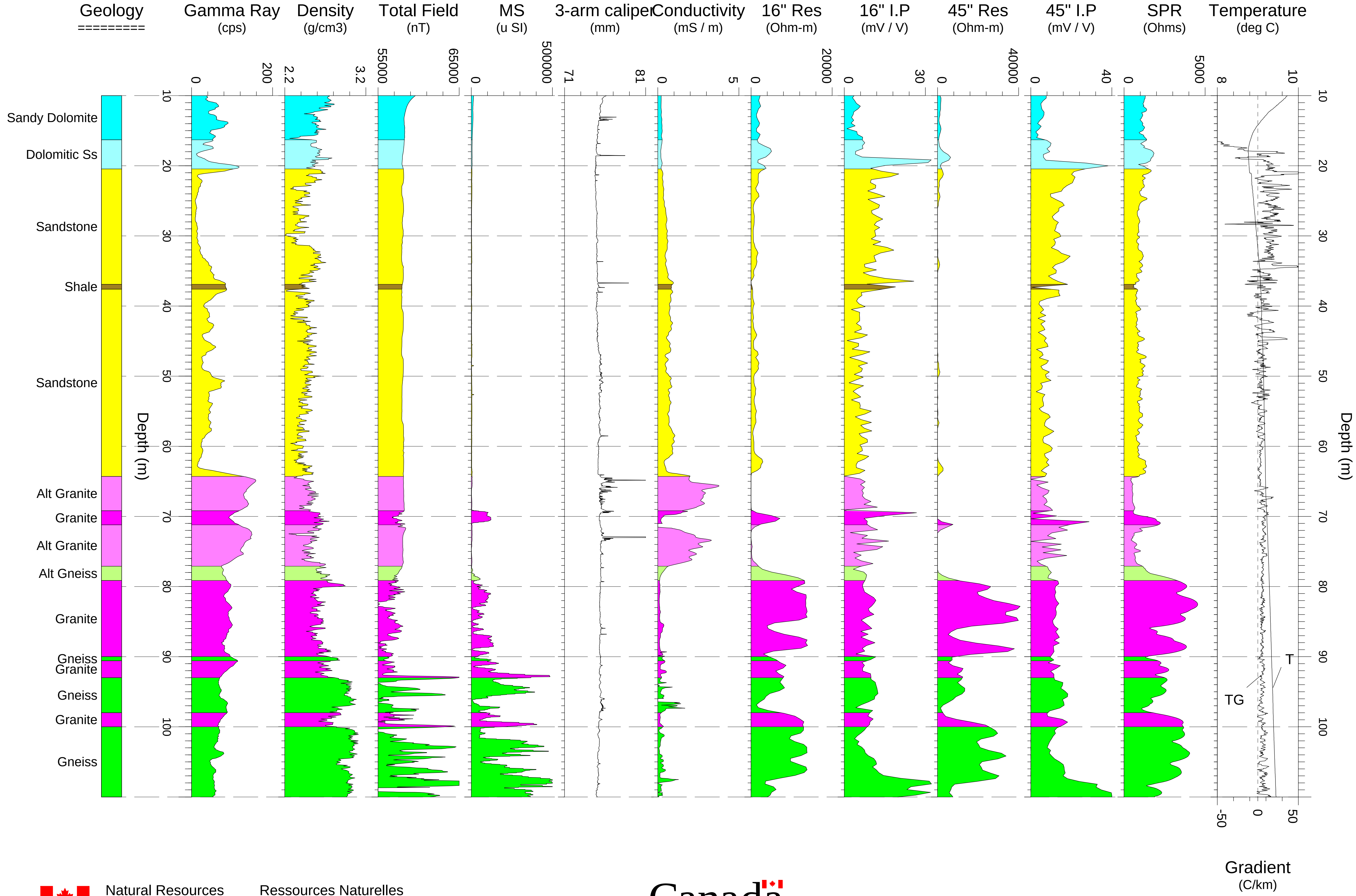
IFG Logs
Bells Corners, Ontario

Borehole
BC81-2



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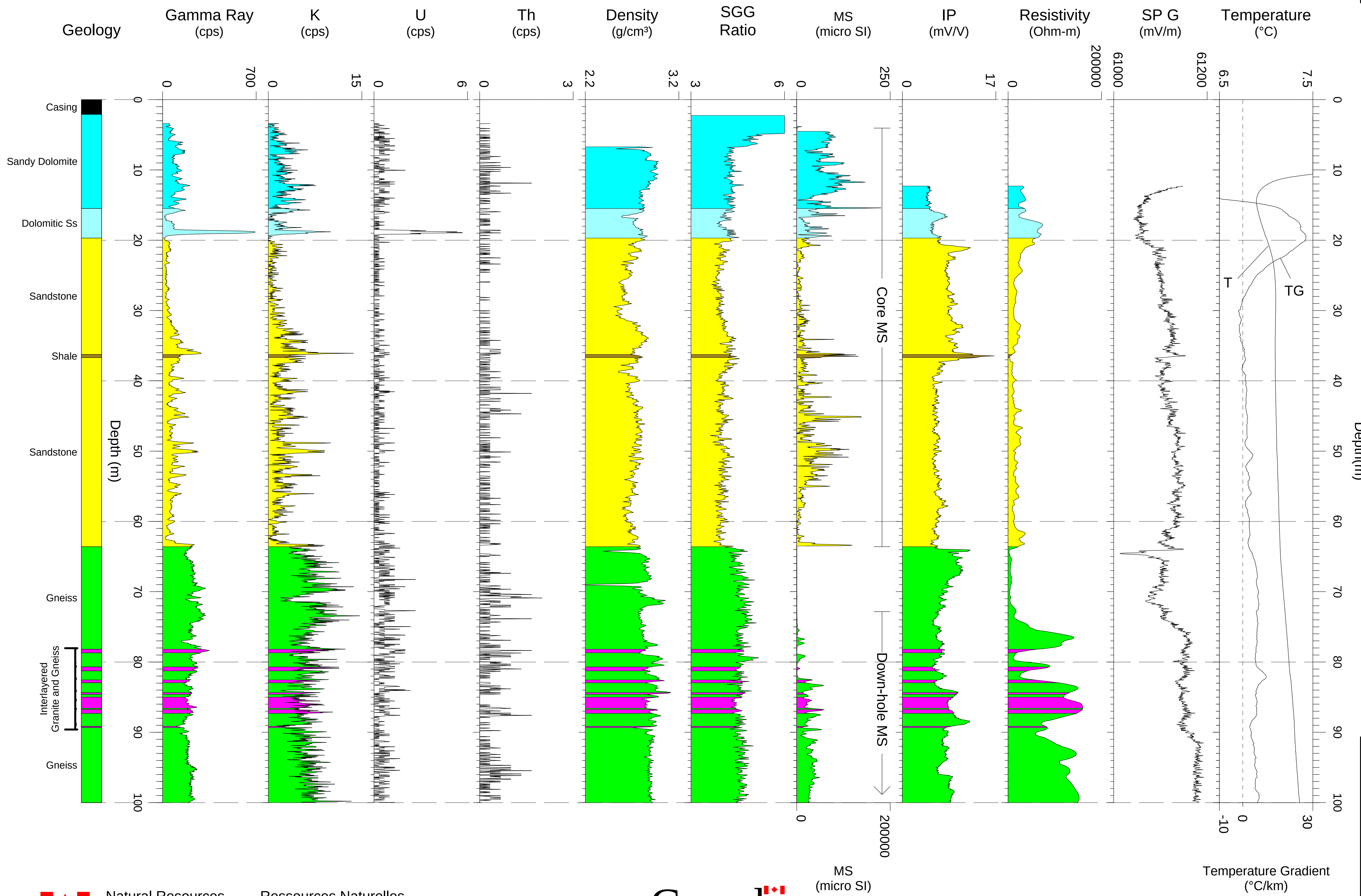
GSC Logs

Bells Corners, Ontario

Borehole
BC81-3
Plot 1 of 2



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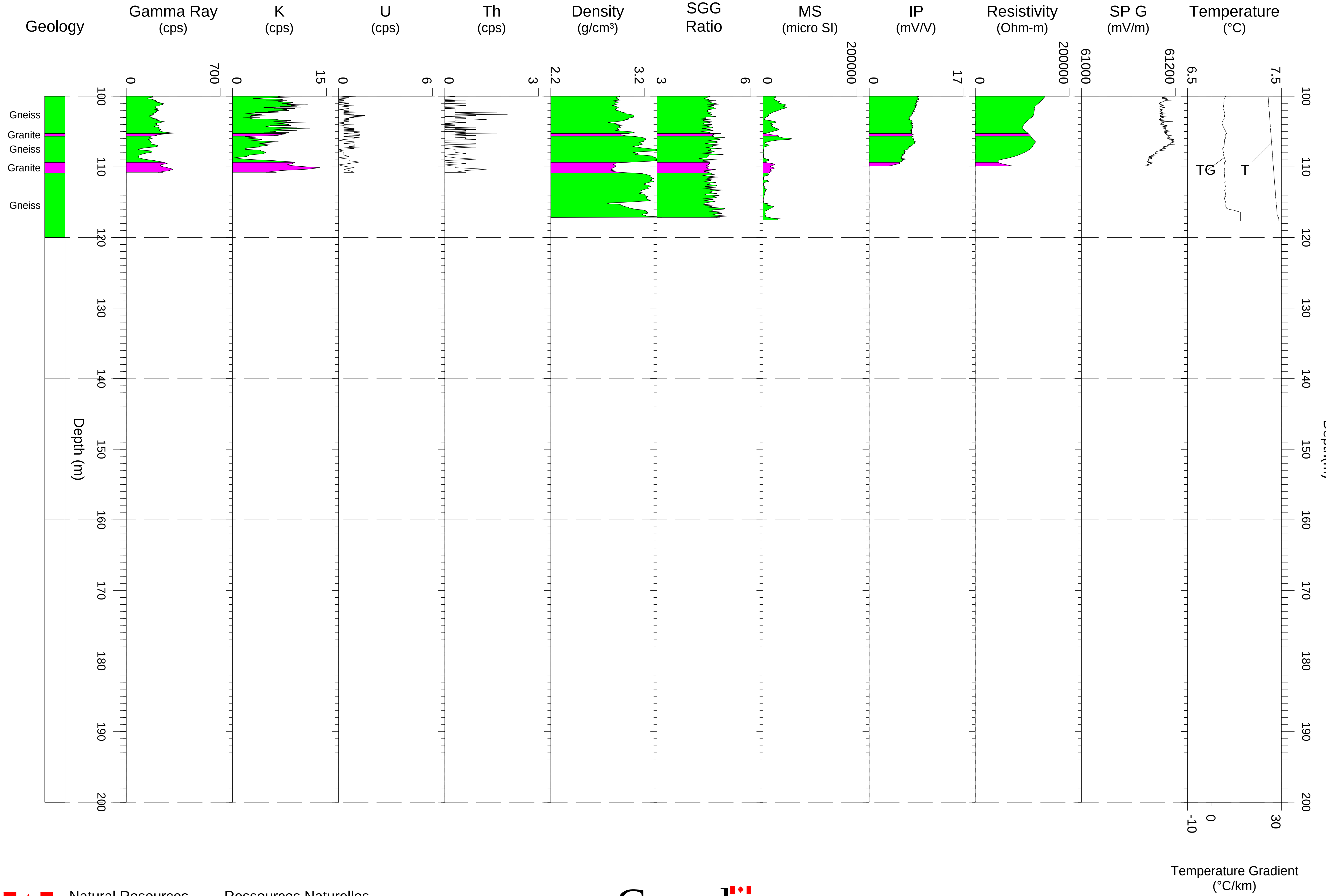
GSC Logs
Bells Corners, Ontario

Borehole
BC81-3
Plot 2 of 2



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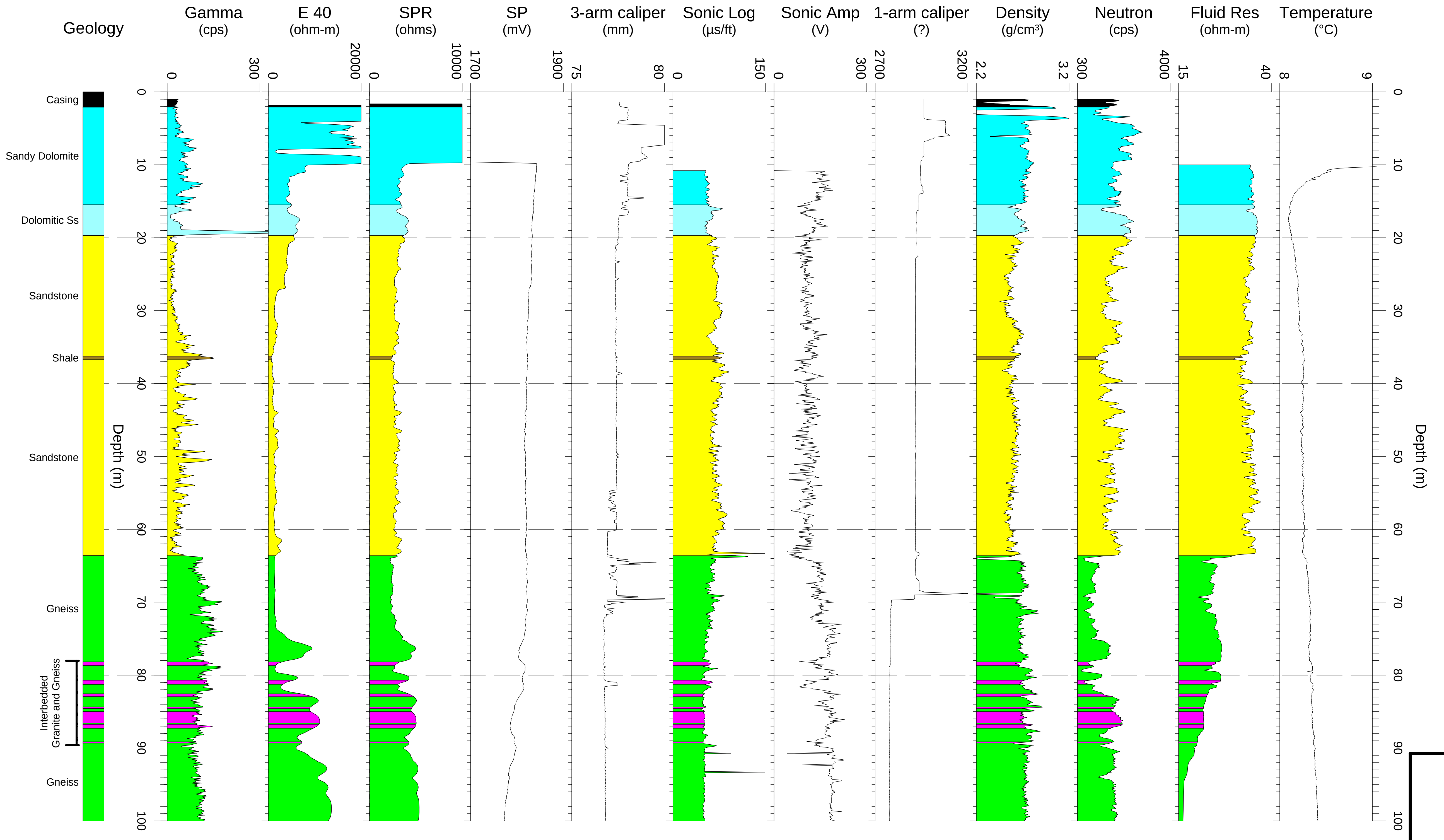
AECL Logs

Bells Corners, Ontario

Borehole
BC81-3
Plot 1 of 2



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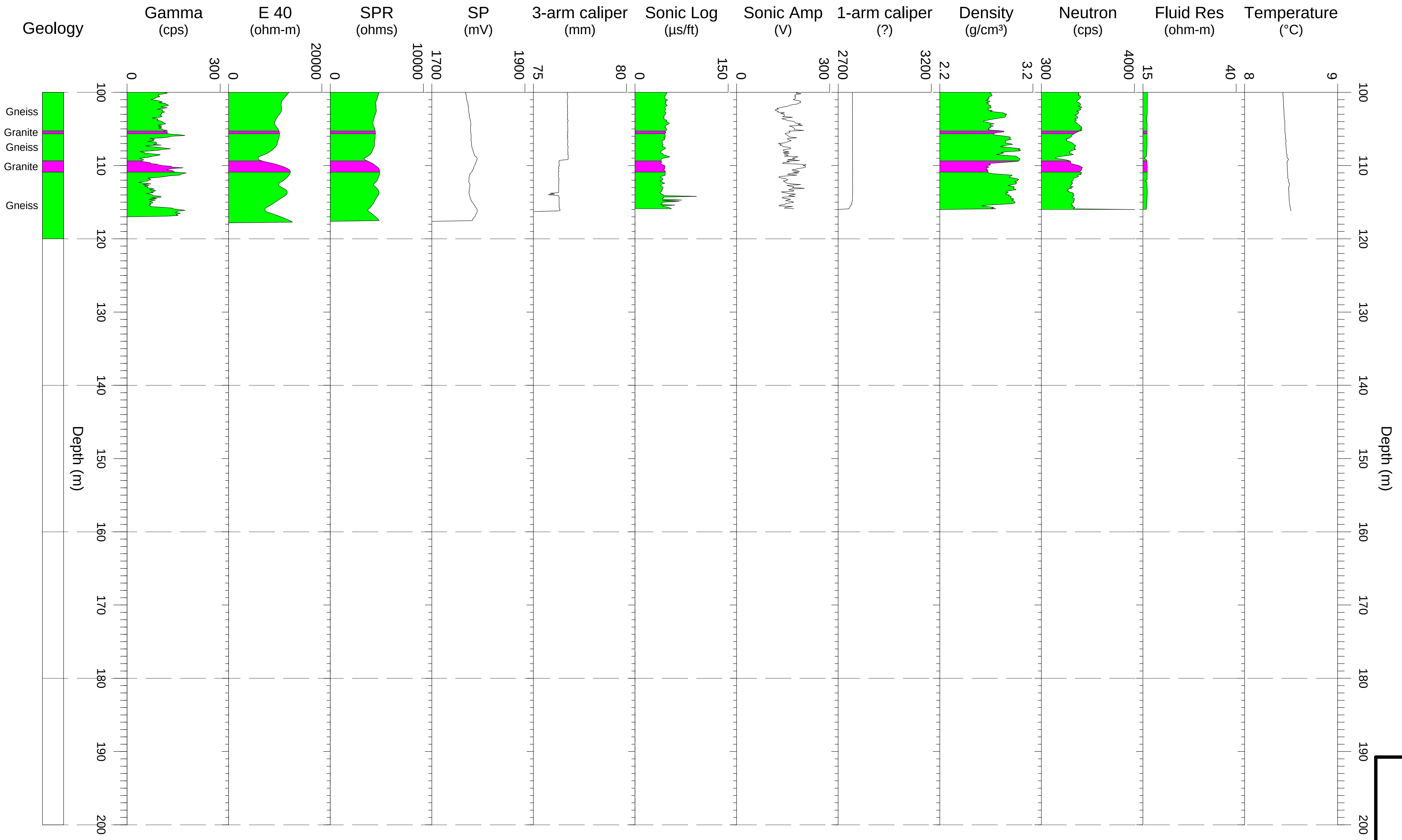
AECL Logs
Bells Corners, Ontario

Borehole
BC81-3
Plot 2 of 2



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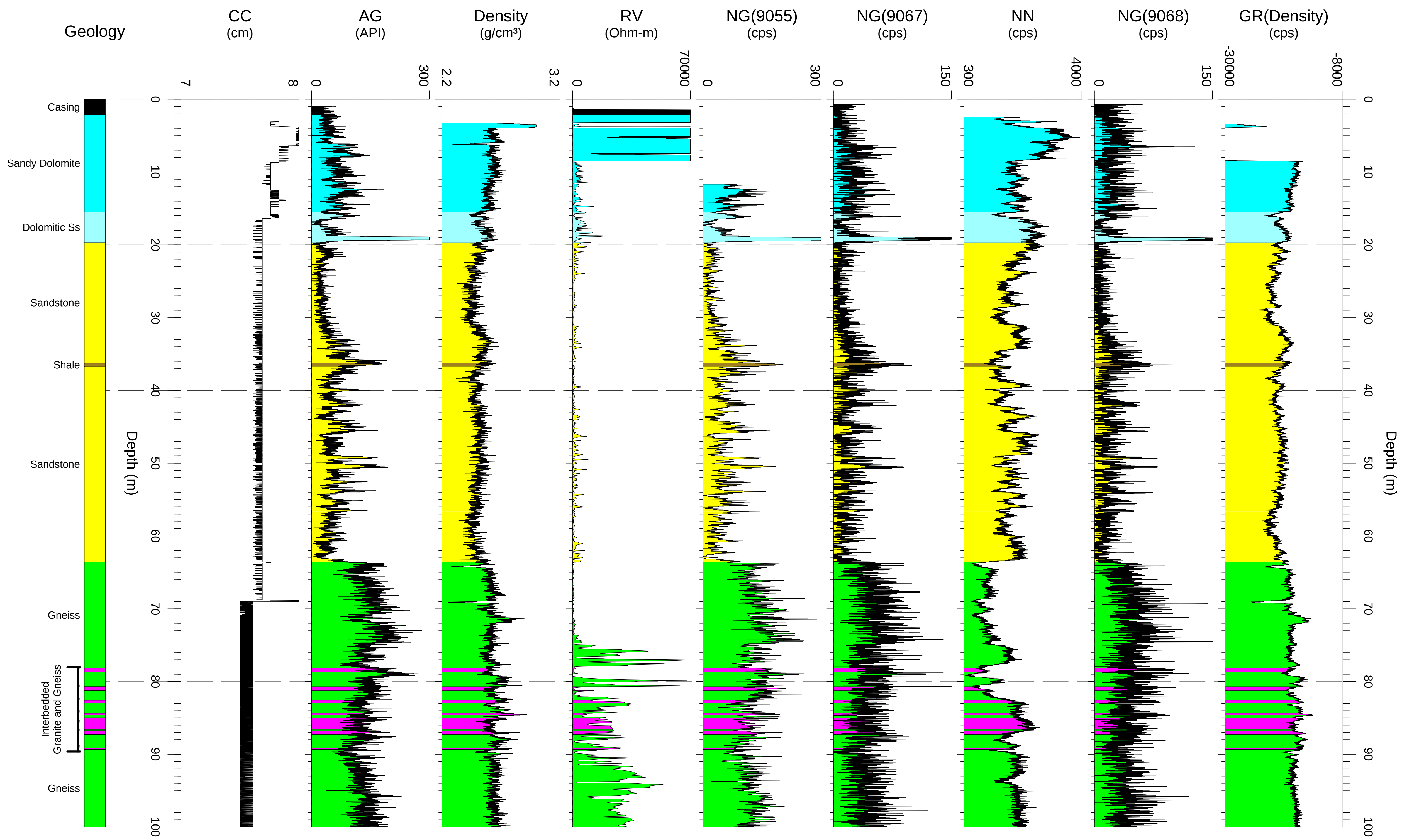
Century Geophysics Logs

Bells Corners, Ontario

Borehole
BC81-3
Plot 1 of 2



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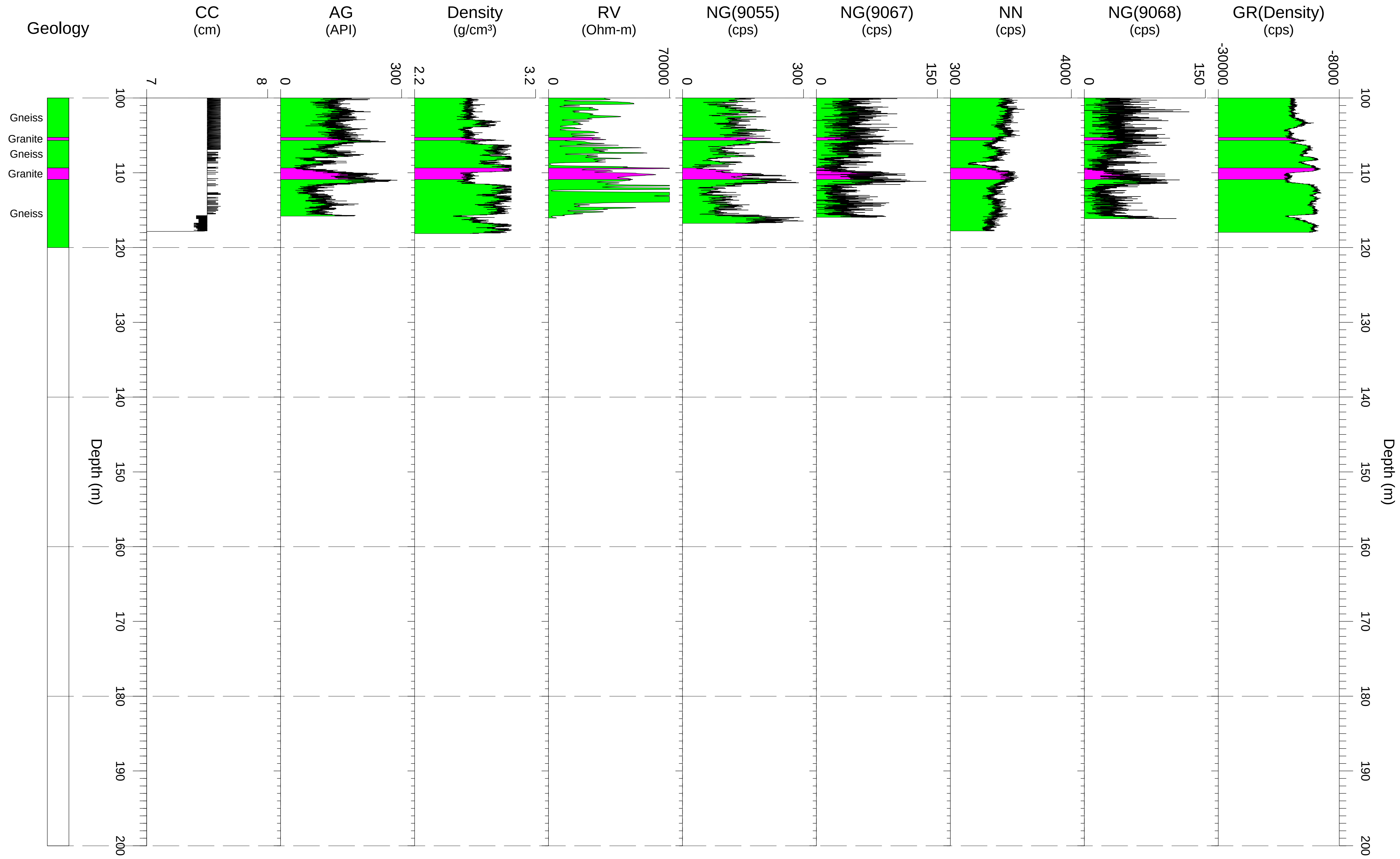
Borehole
BC81-3
Plot 2 of 2



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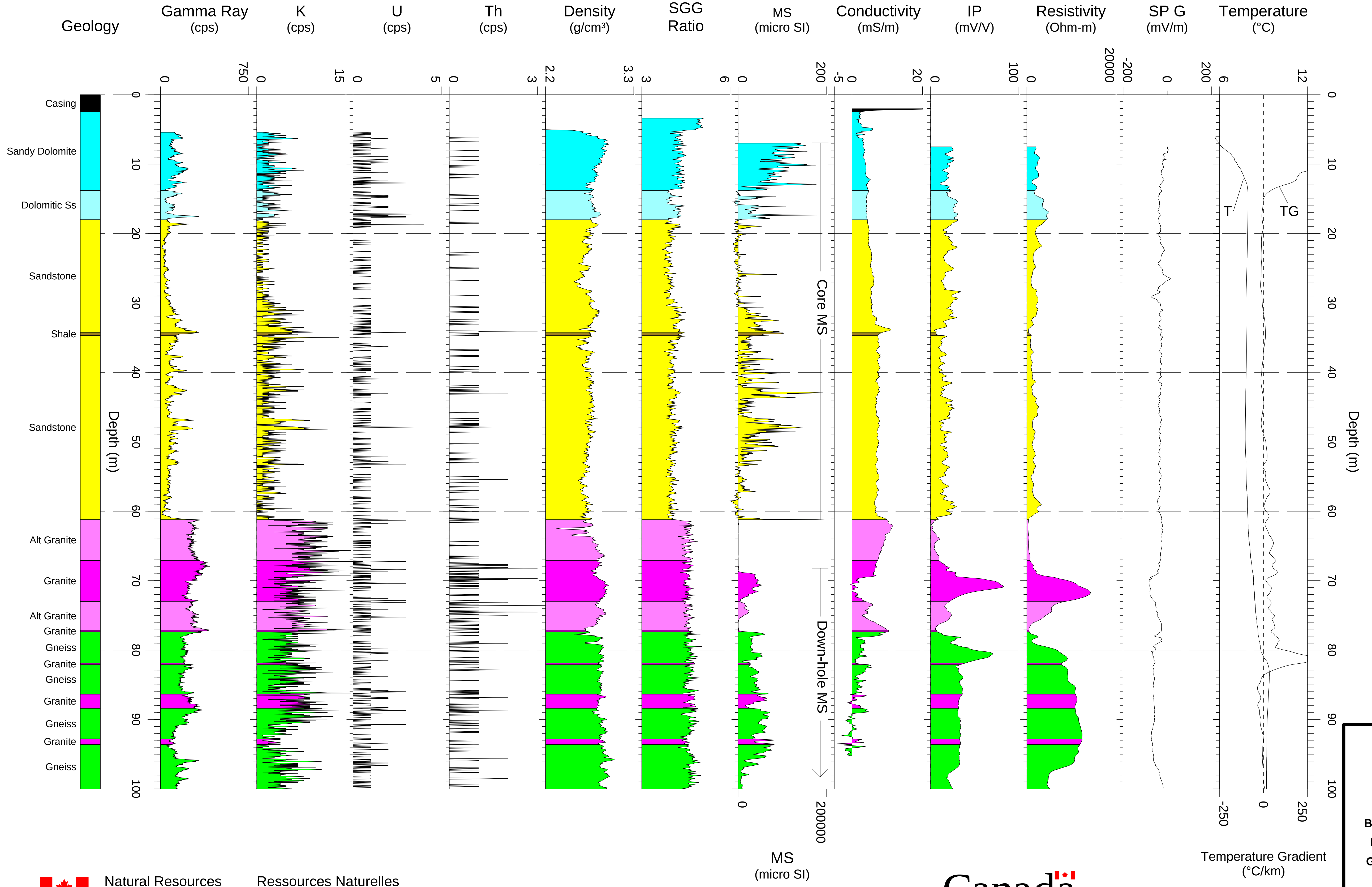
GSC Logs

Bells Corners, Ontario

Borehole
BC84-4
Plot 1 of 3



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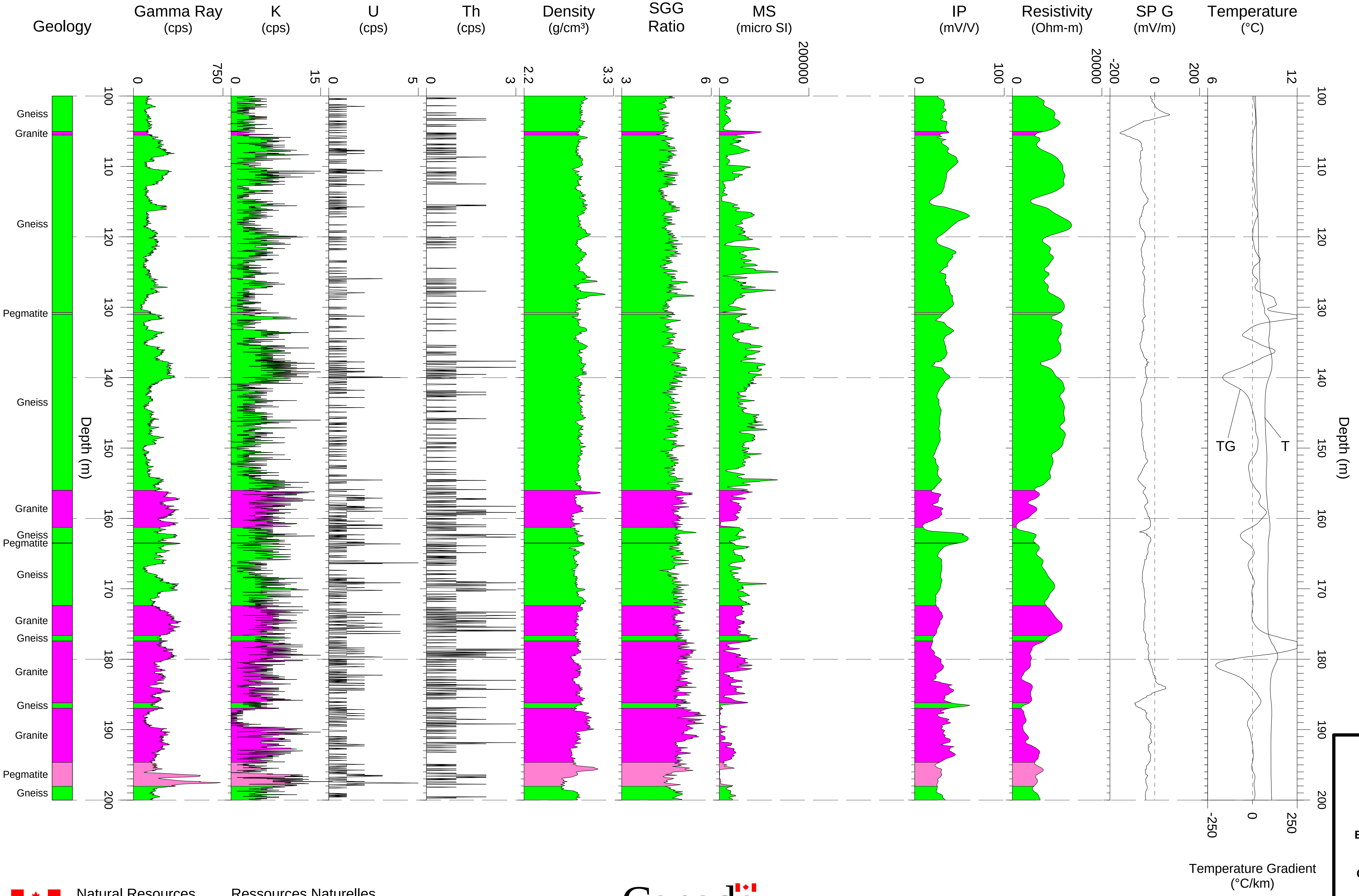
GSC Logs

Bells Corners, Ontario

Borehole
BC84-4
Plot 2 of 3



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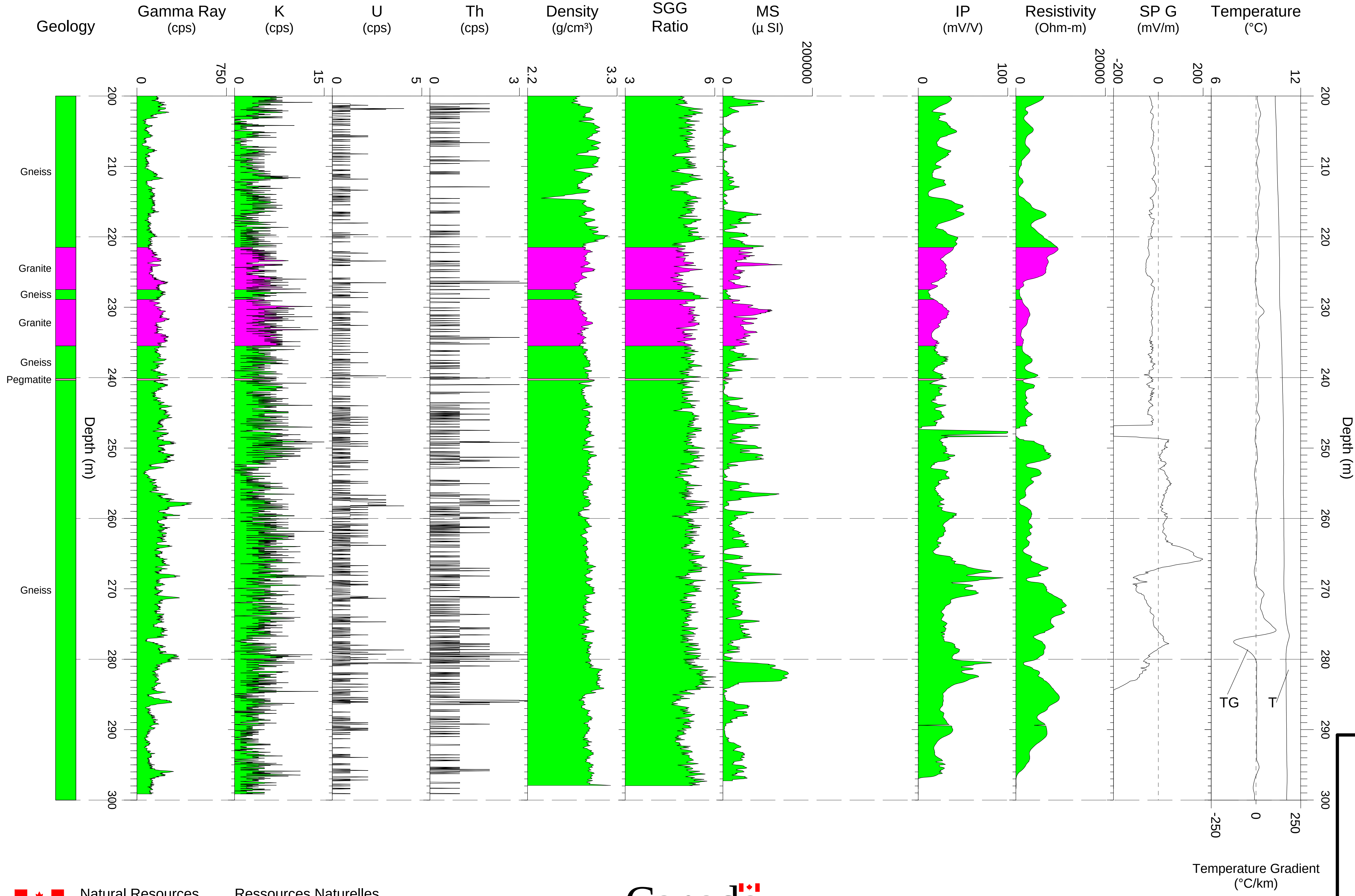
GSC Logs

Bells Corners, Ontario

Borehole
BC84-4
Plot 3 of 3



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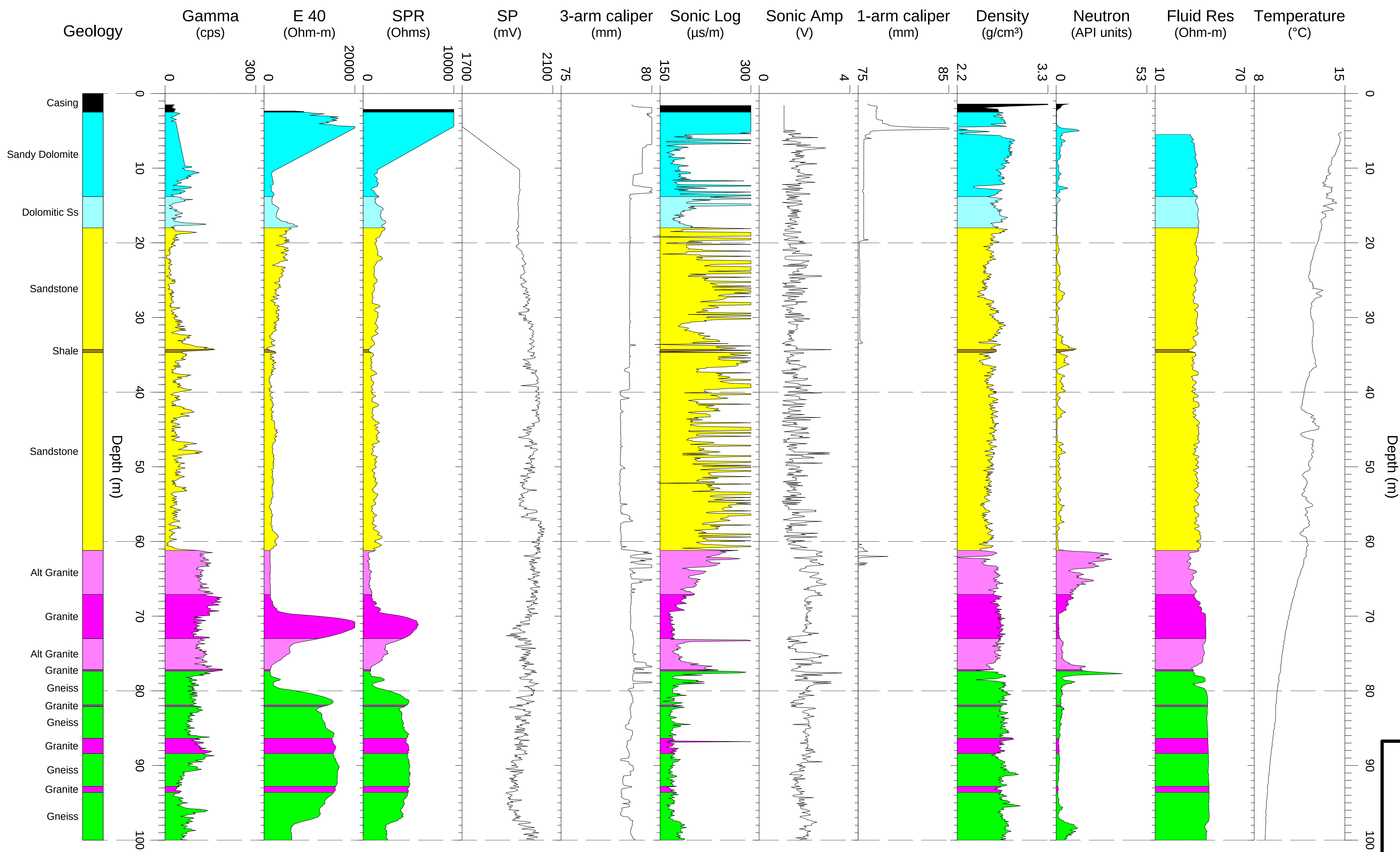
AECL Logs
Bells Corners, Ontario

Borehole
BC84-4
Plot 1 of 3



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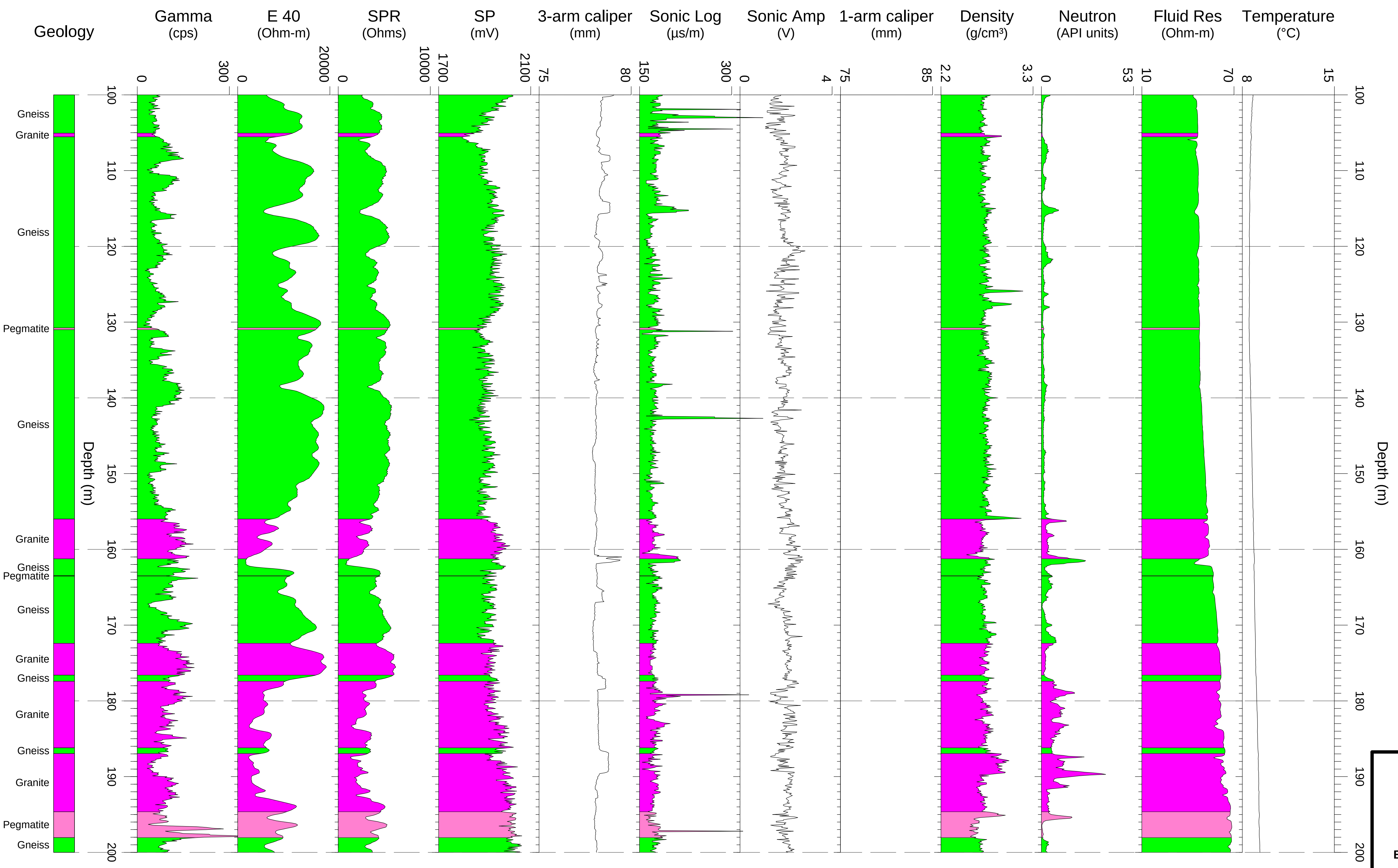
AECL Logs
Bells Corners, Ontario

Borehole
BC84-4
Plot 2 of 3



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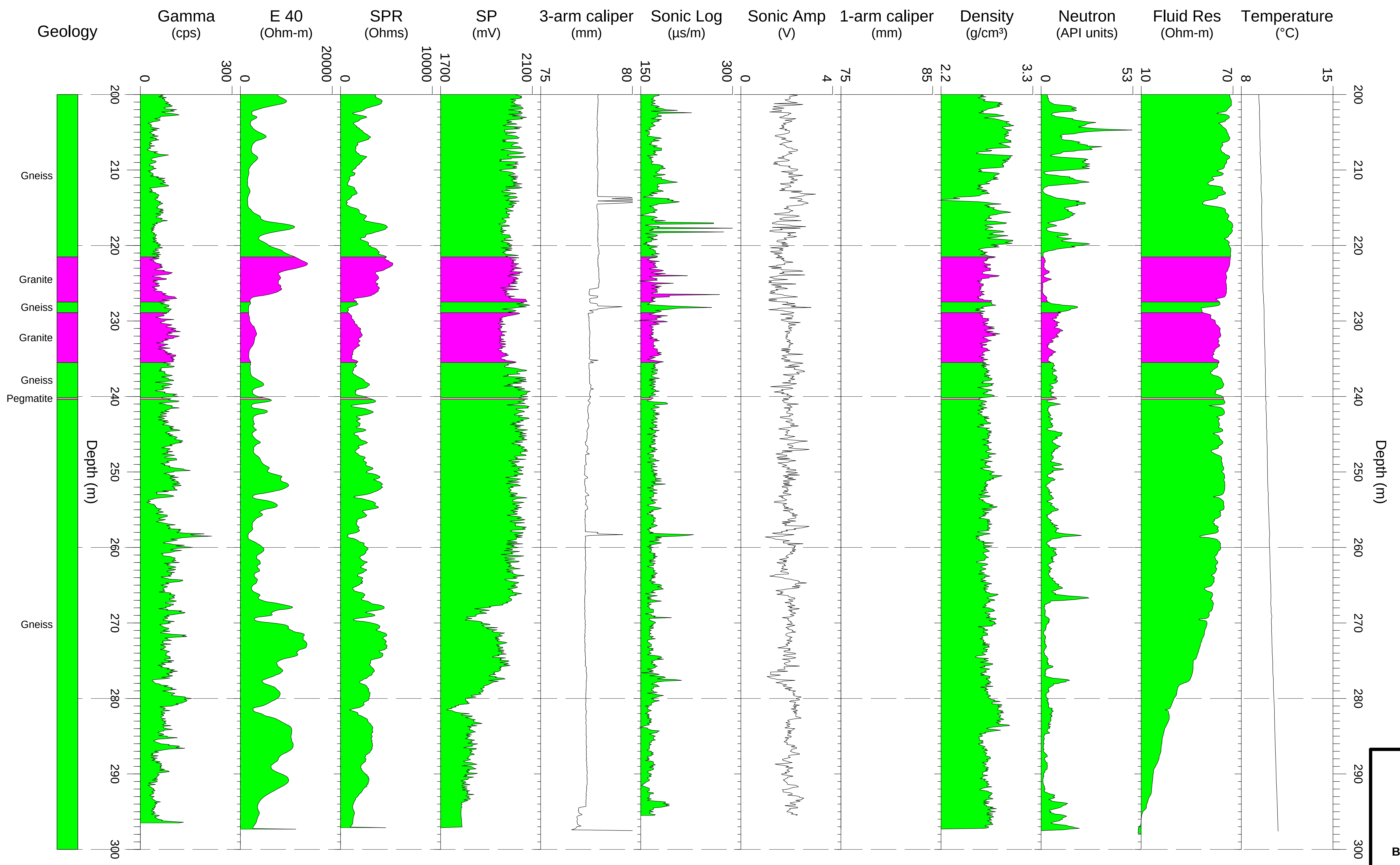
AECL Logs
Bells Corners, Ontario

Borehole
BC84-4
Plot 3 of 3



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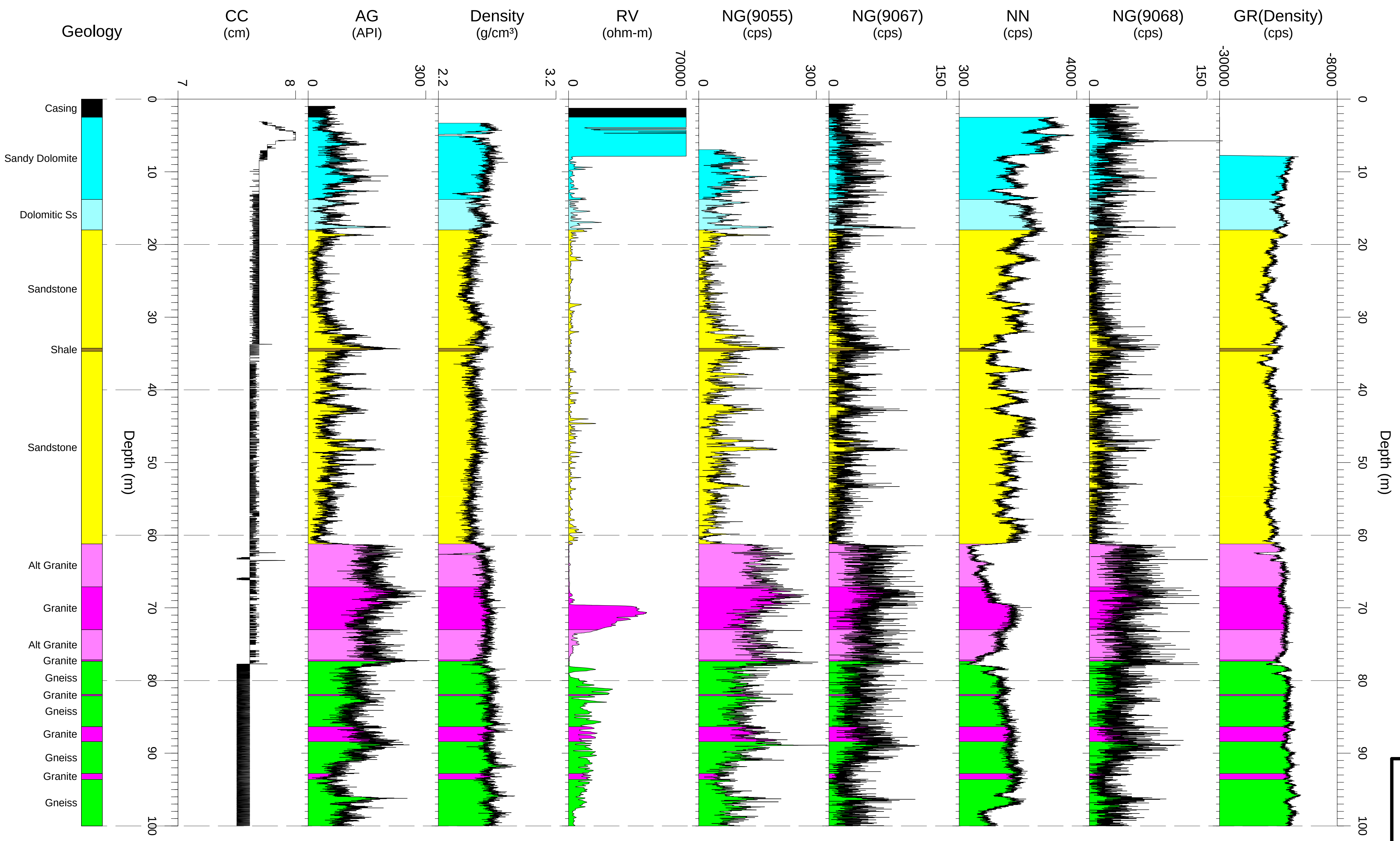
GSC BOREHOLE GEOPHYSICS TEST SITE
Century Geophysics Logs
Bells Corners, Ontario

Borehole
BC81-4
Plot 1 of 2



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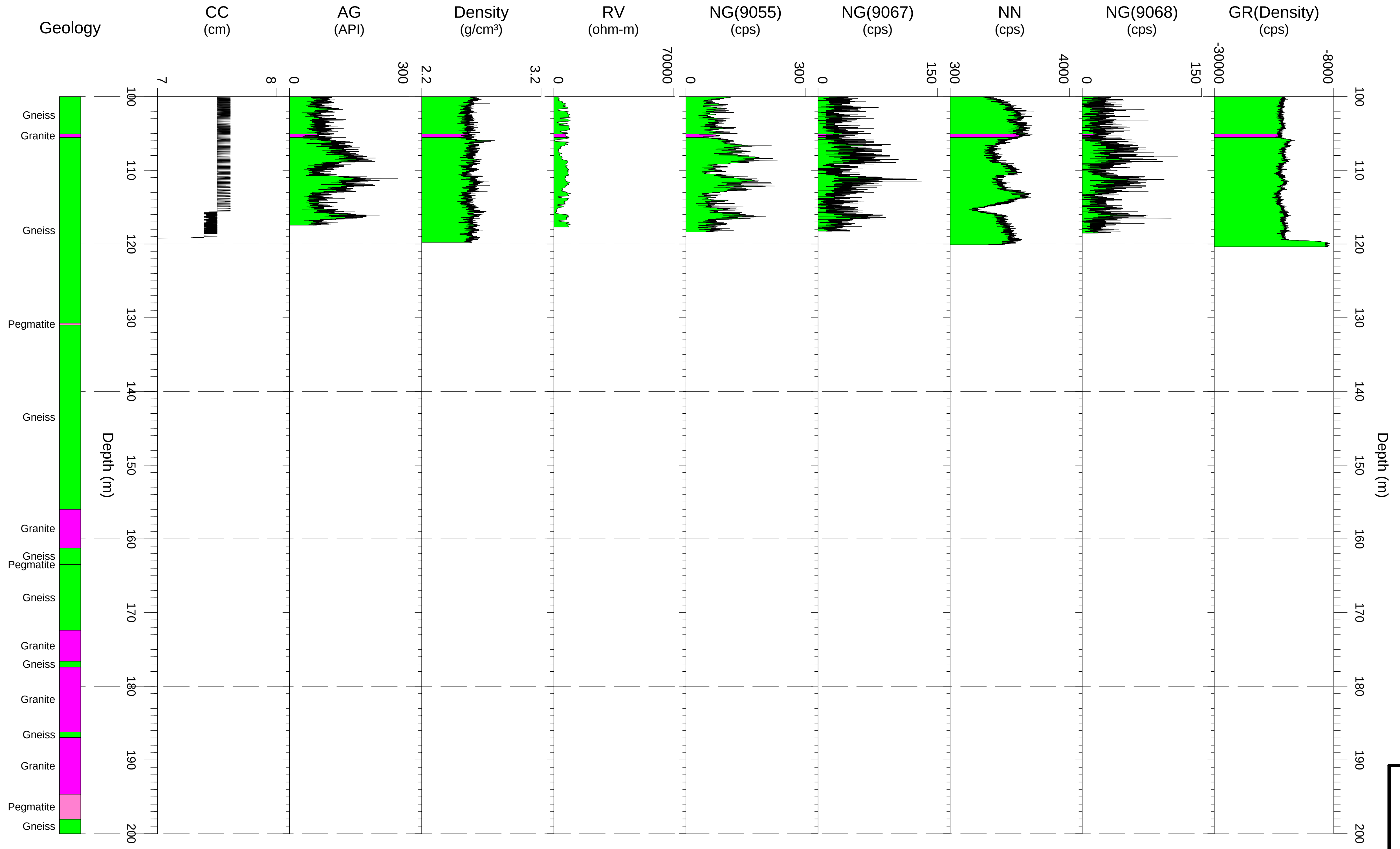
Bells Corners, Ontario

Borehole
BC81-4
Plot 2 of 2



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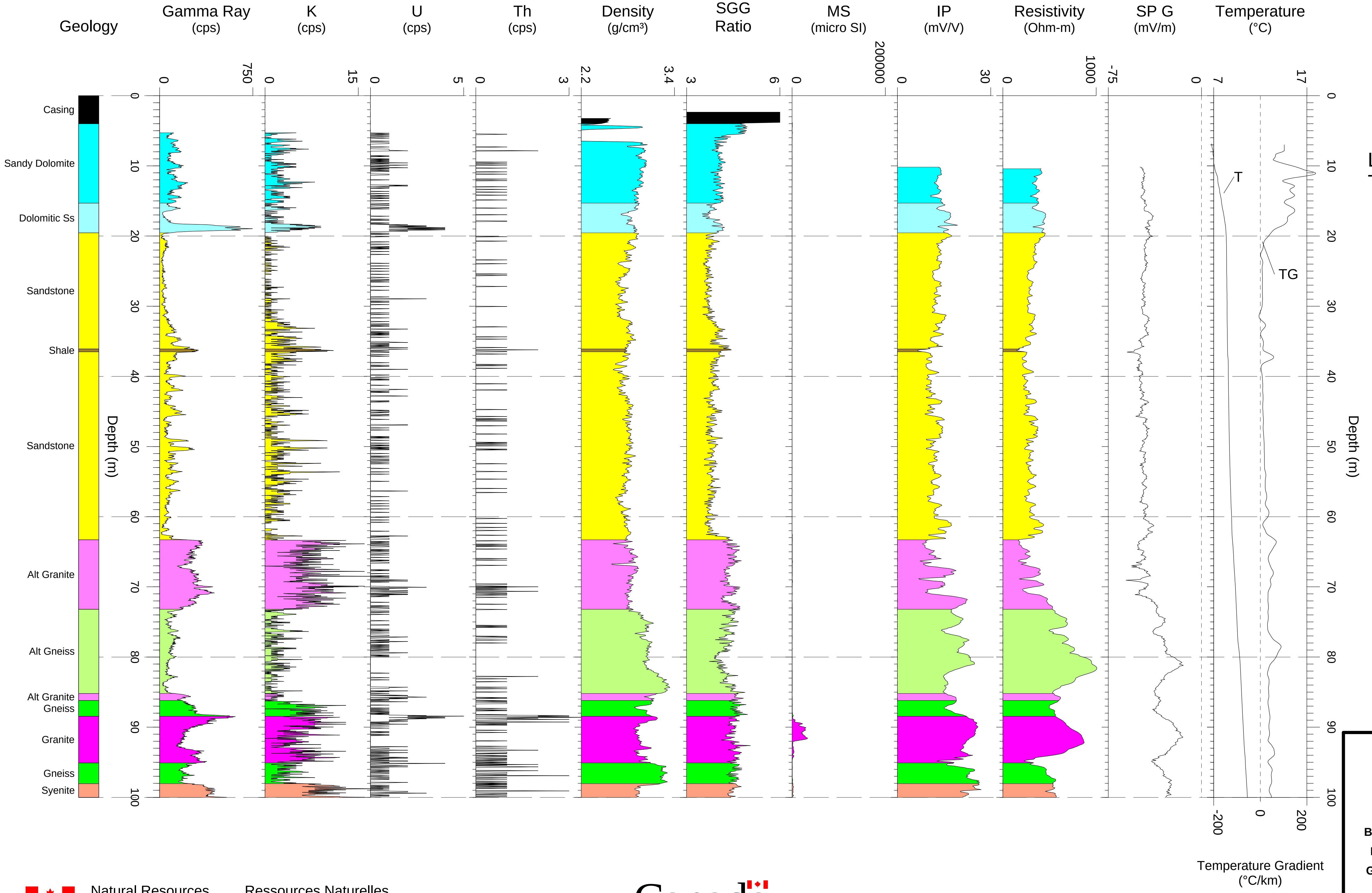
BC84-5
Plot 1 of 3



LEGEND FOR THIN LAYERS

A Gneiss

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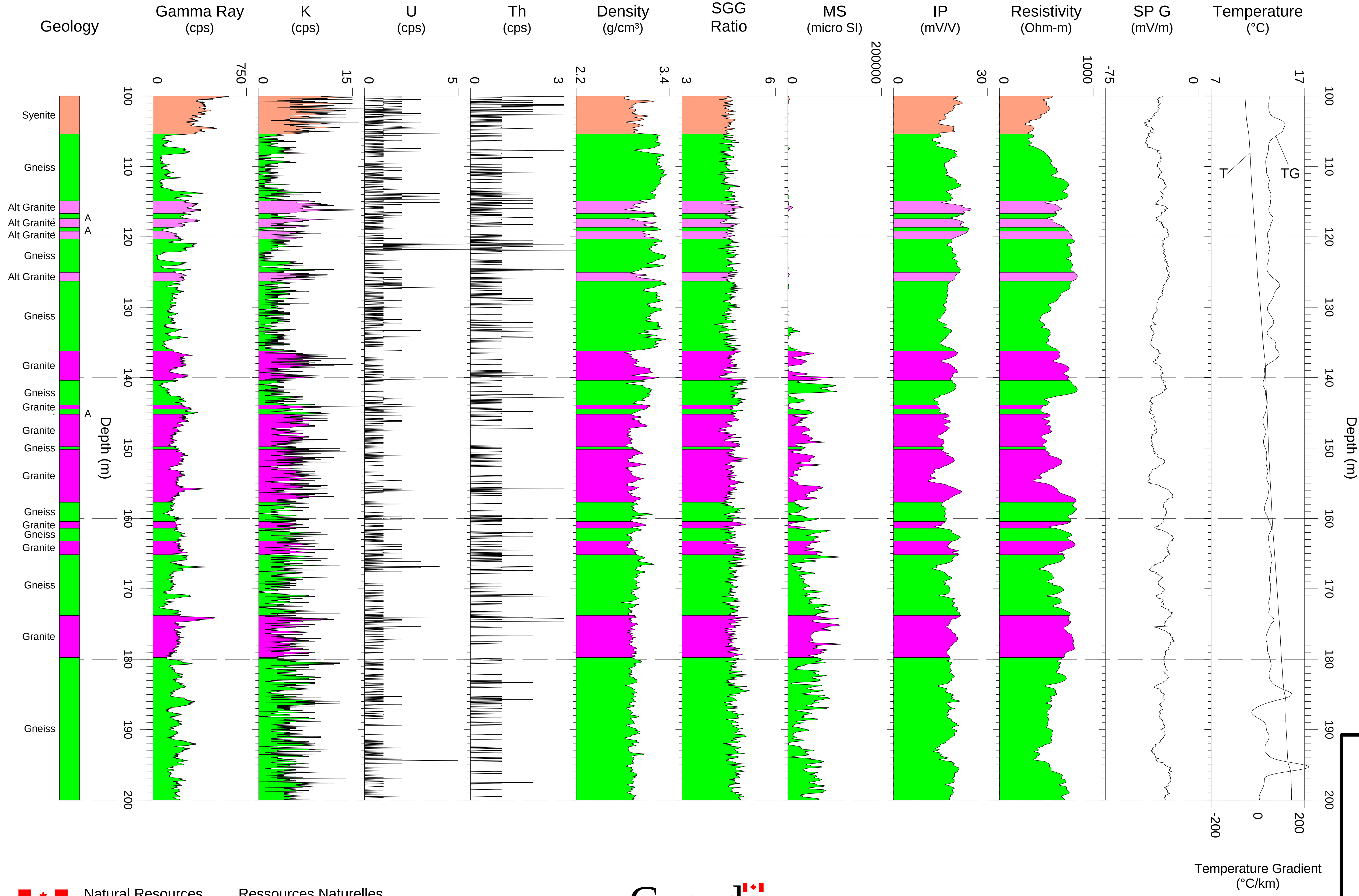
Bells Corners, Ontario

Borehole
BC84-5
Plot 2 of 3



LEGEND FOR THIN LAYERS

A Gneiss

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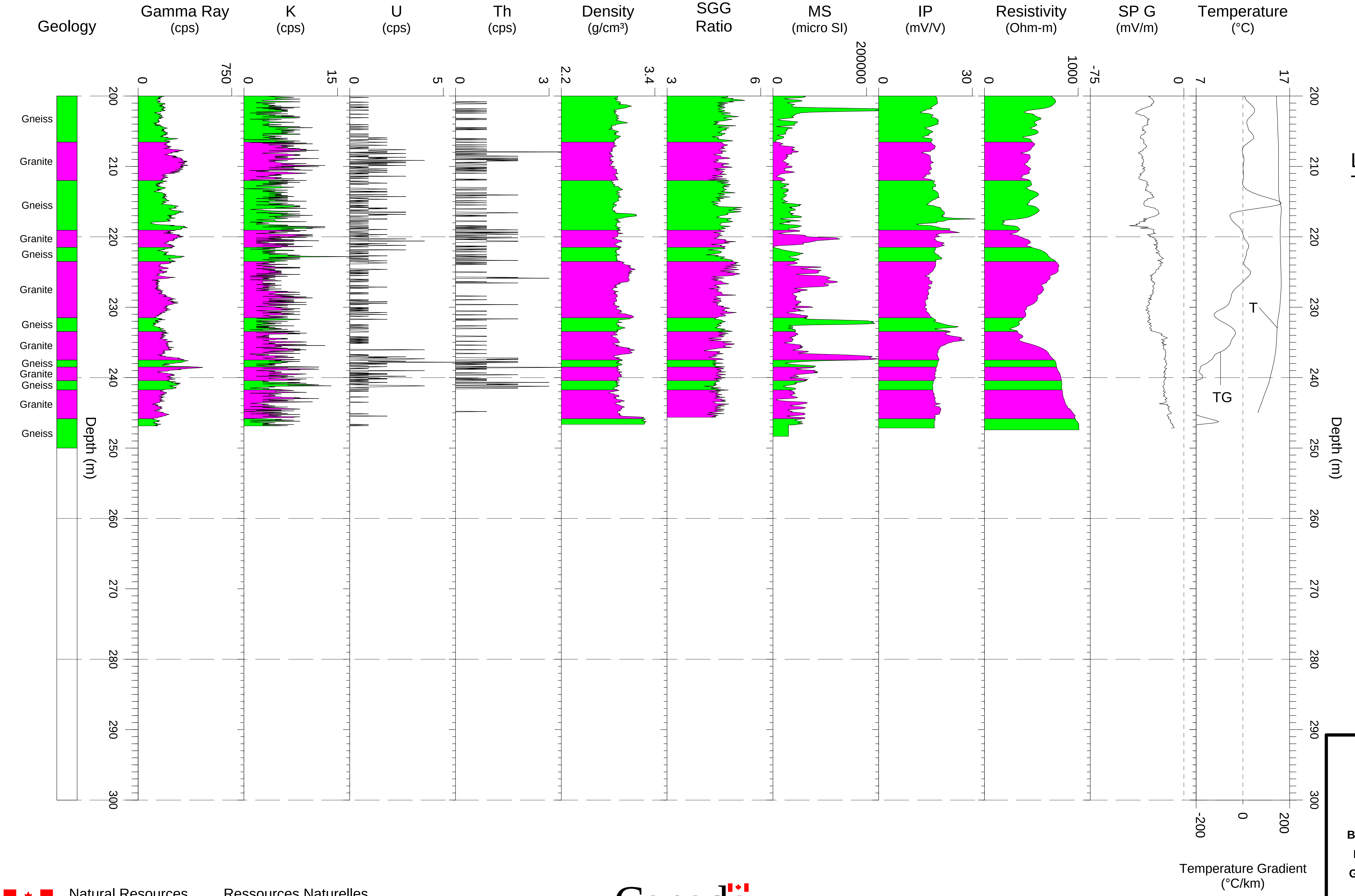
GSC Logs

Bells Corners, Ontario

Borehole
BC84-5
Plot 3 of 3



LEGEND FOR THIN LAYERS

A Gneiss

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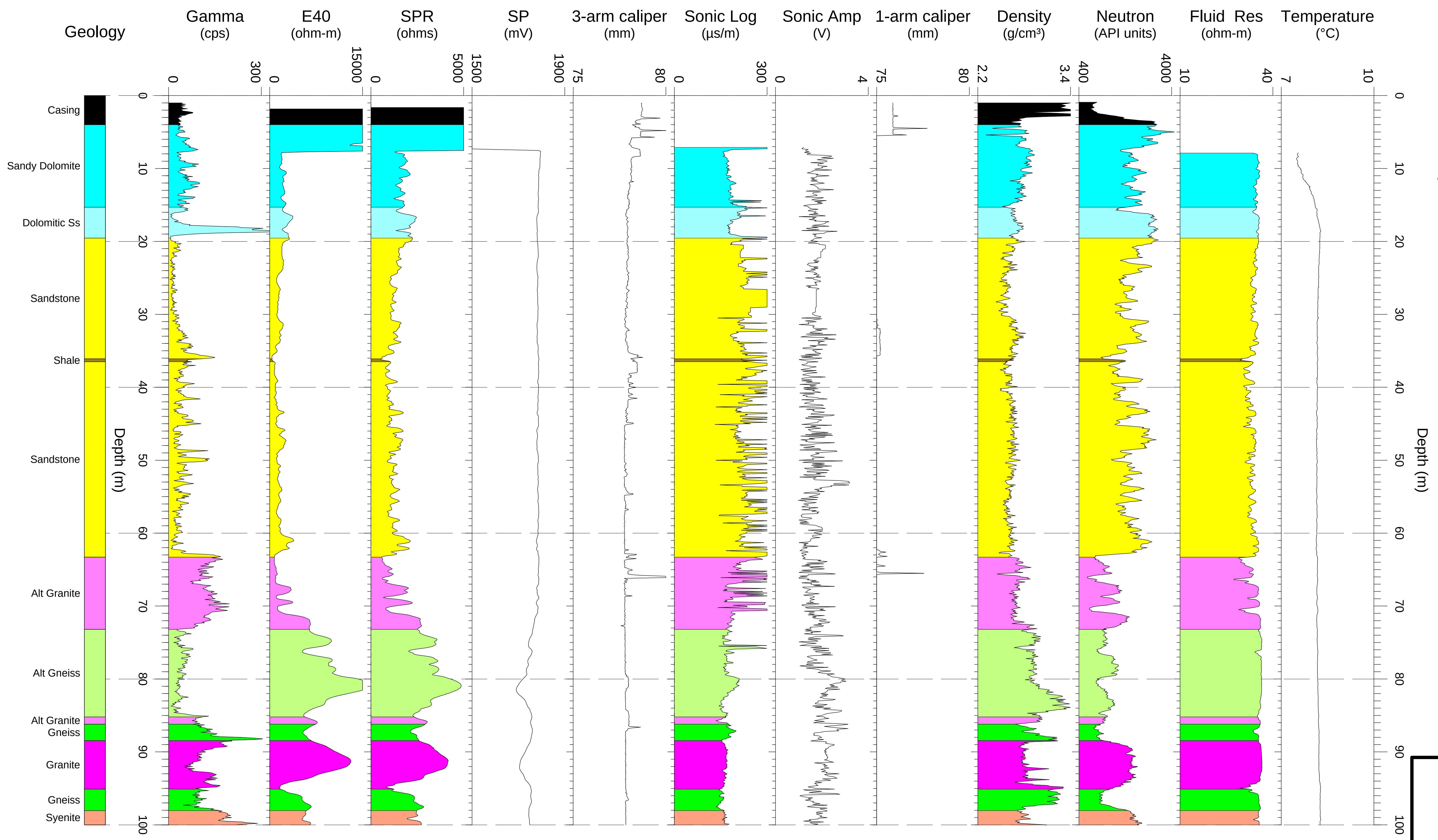
AECL Logs

Bells Corners, Ontario

Borehole
BC84-5
Plot 1 of 3



LEGEND FOR
THIN LAYERS

A Gneiss

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AECL Logs
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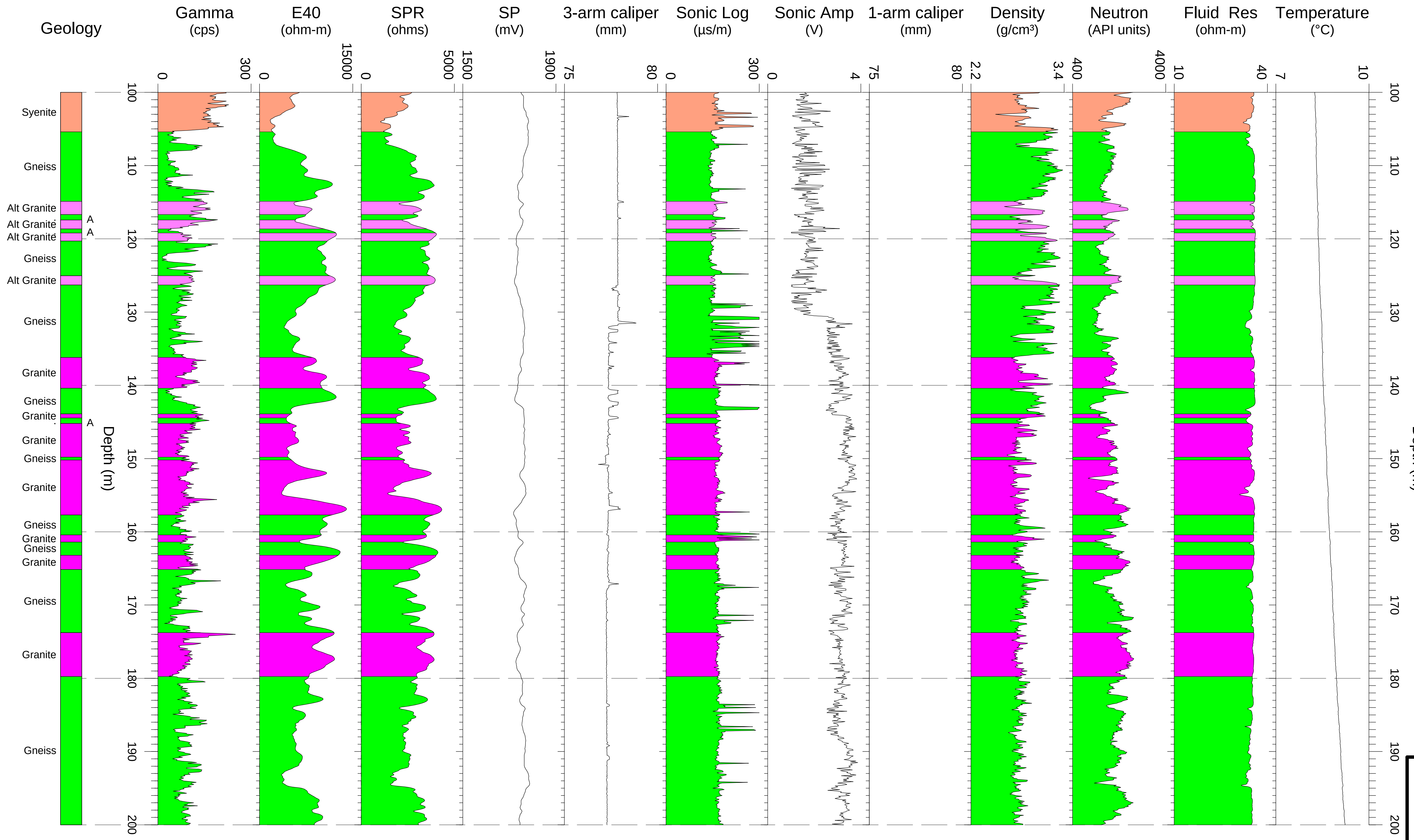
BC84-5
Plot 2 of 3



LEGEND FOR
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A	Gneiss

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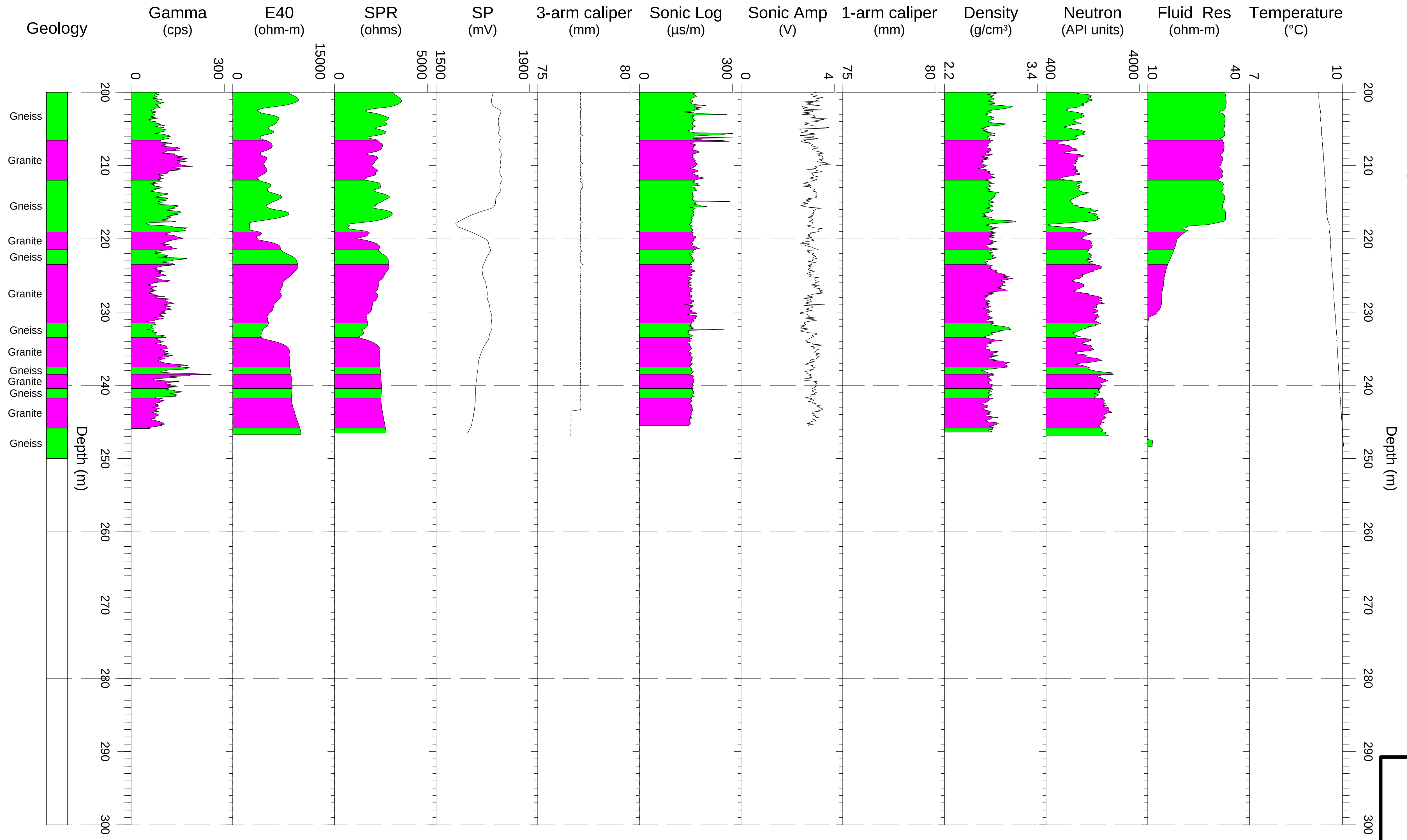
Plot 3 of 3



LEGEND FOR THIN LAYERS

A Gneiss

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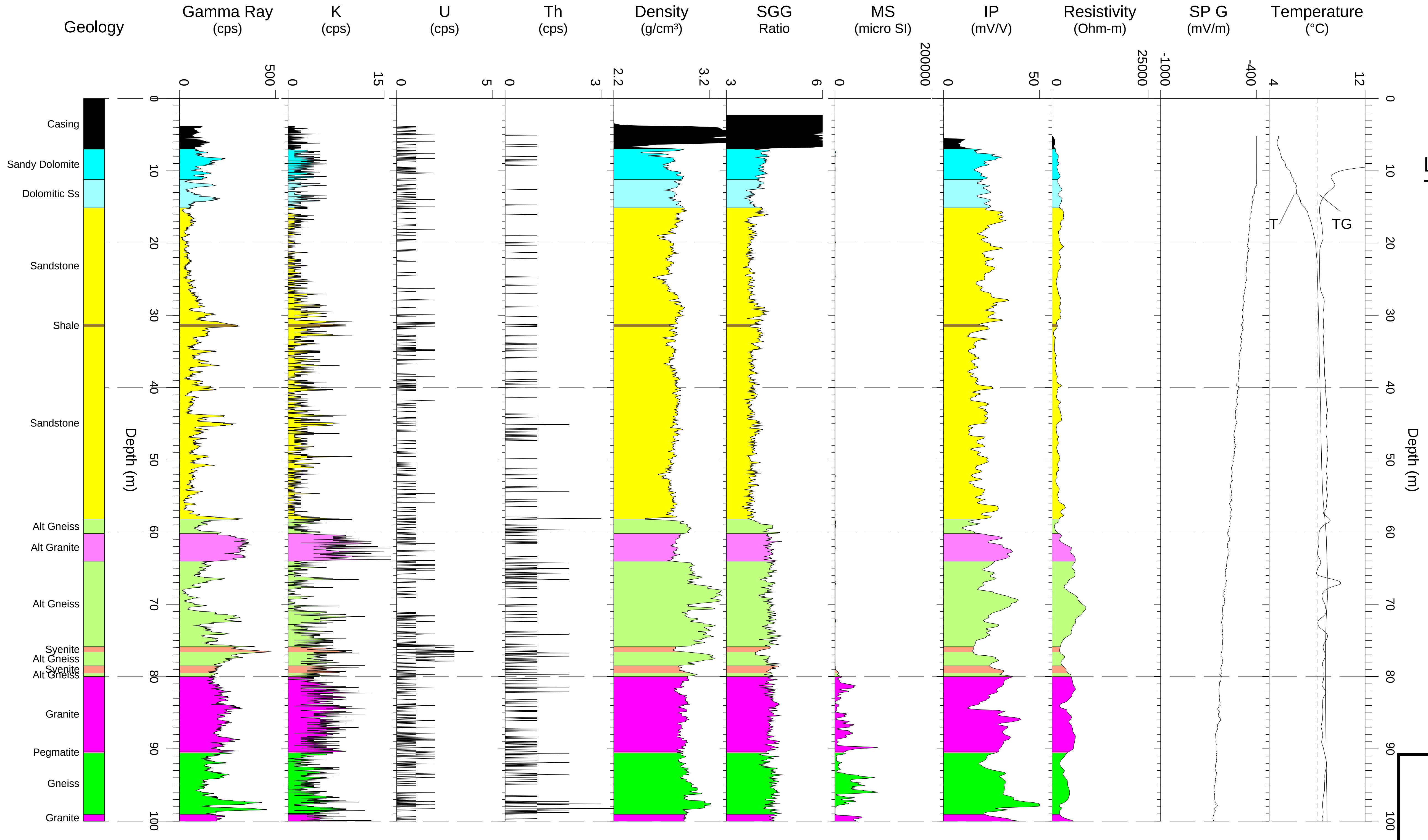
GSC BOREHOLE GEOPHYSICS TEST SITE
GSC Logs
Bells Corners, Ontario

Borehole
BC84-6
Plot 1 of 3



LEGEND FOR THIN LAYERS

A	Gneiss
B	Alt Gneiss
C	Granite
D	Pegmatite
E	Amphibolite

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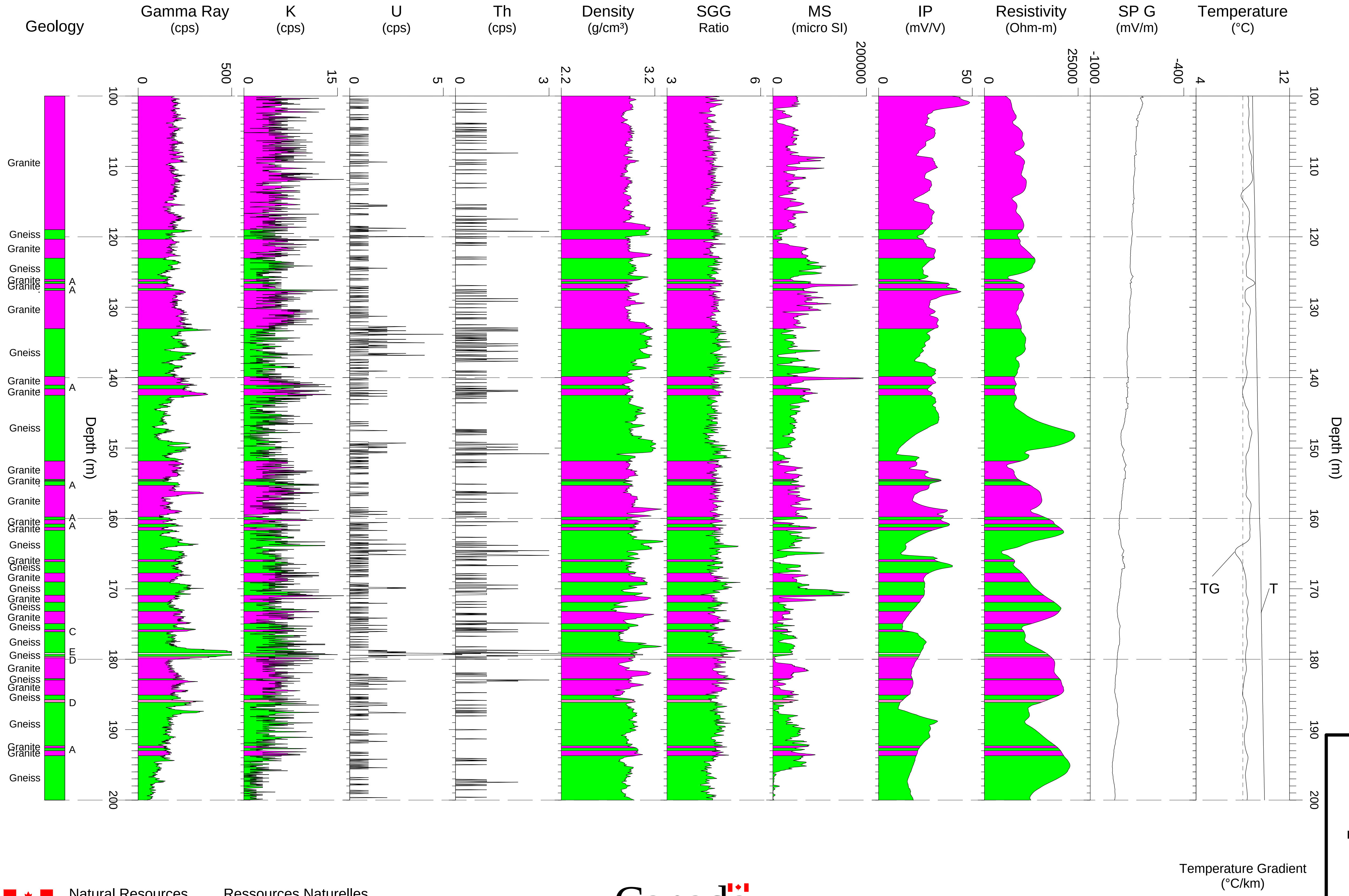
Borehole
BC84-6
Plot 2 of 3



LEGEND FOR THIN LAYERS

A	Gneiss
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D	Pegmatite
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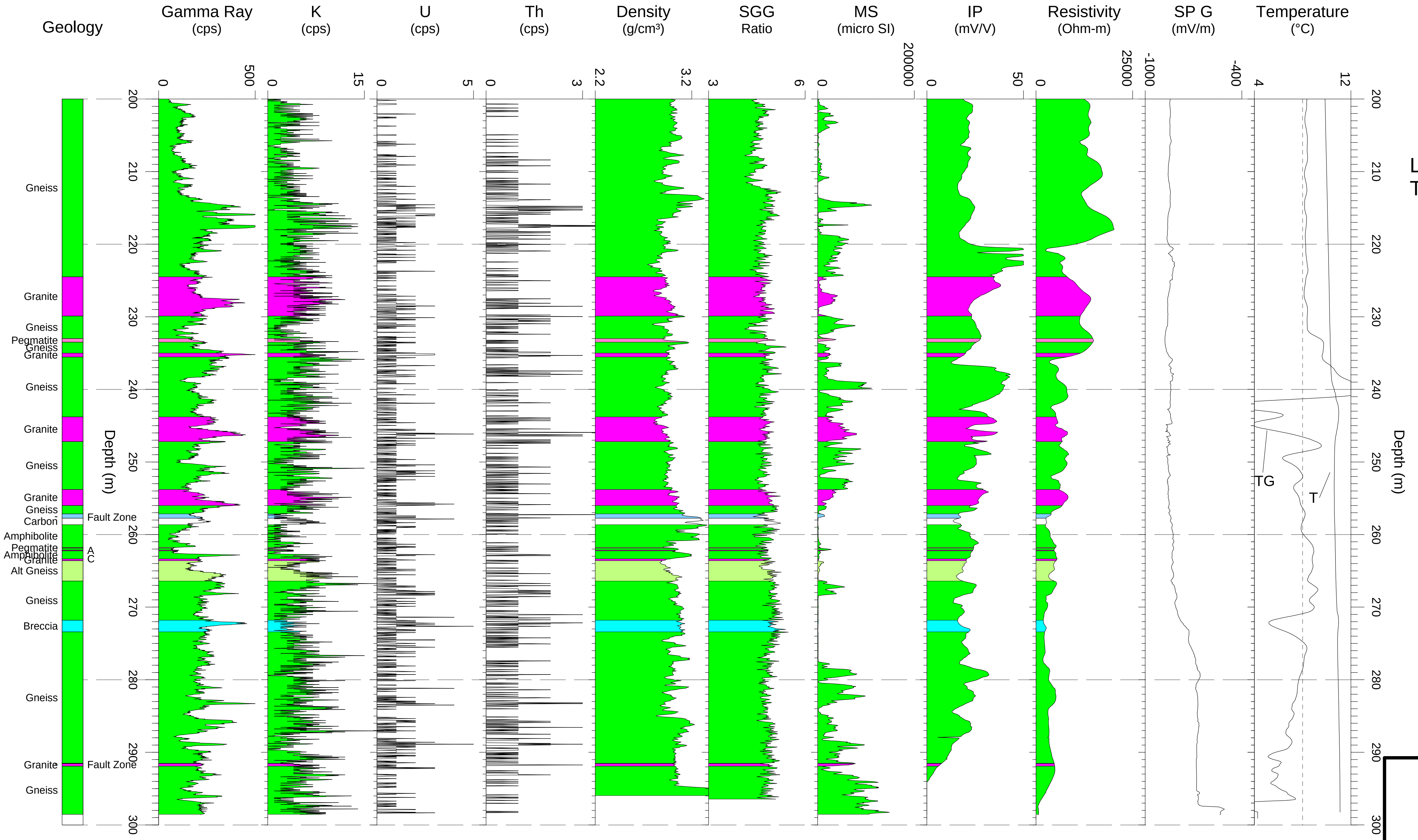
Plot 3 of 3



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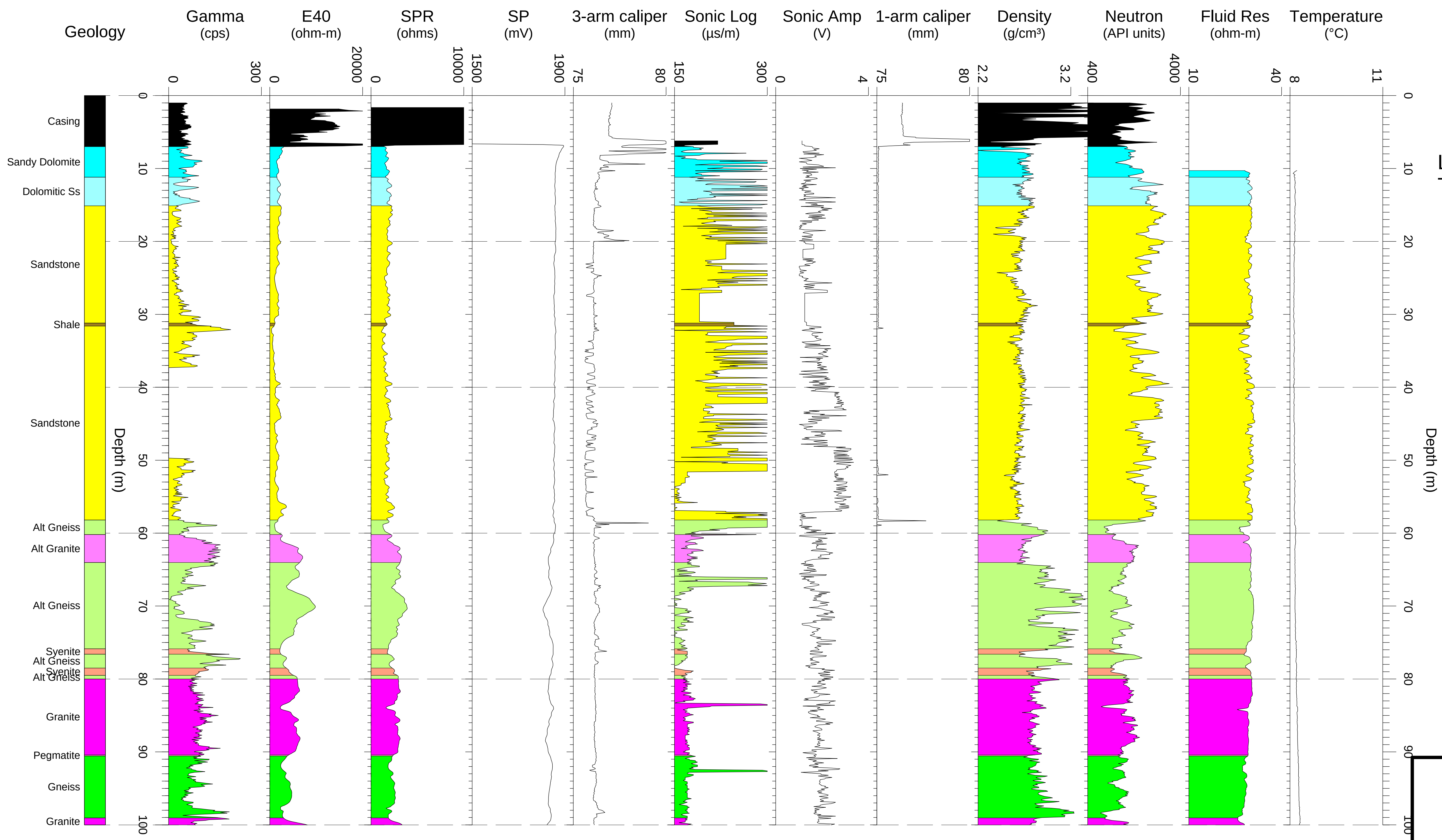

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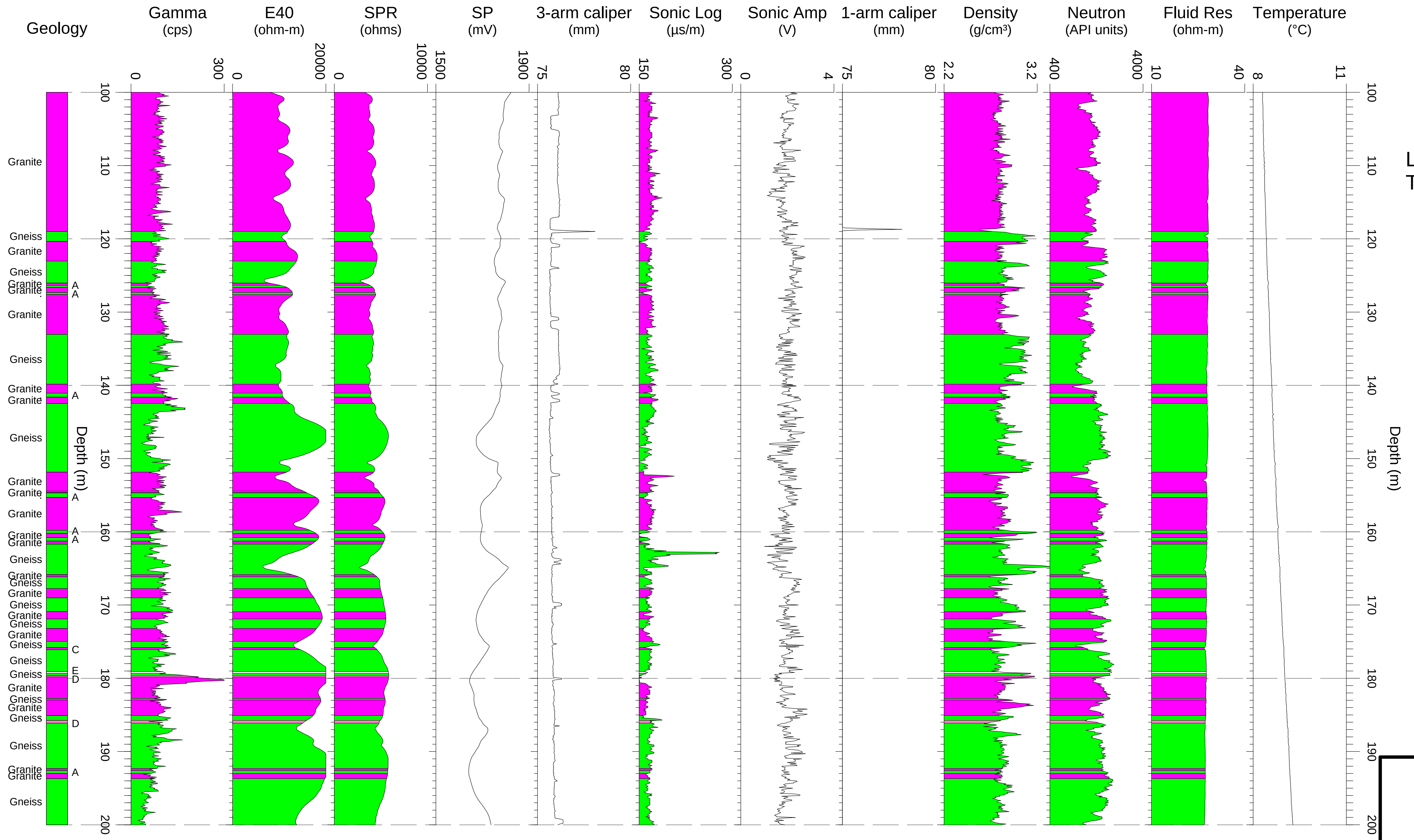
Plot 2 of 3



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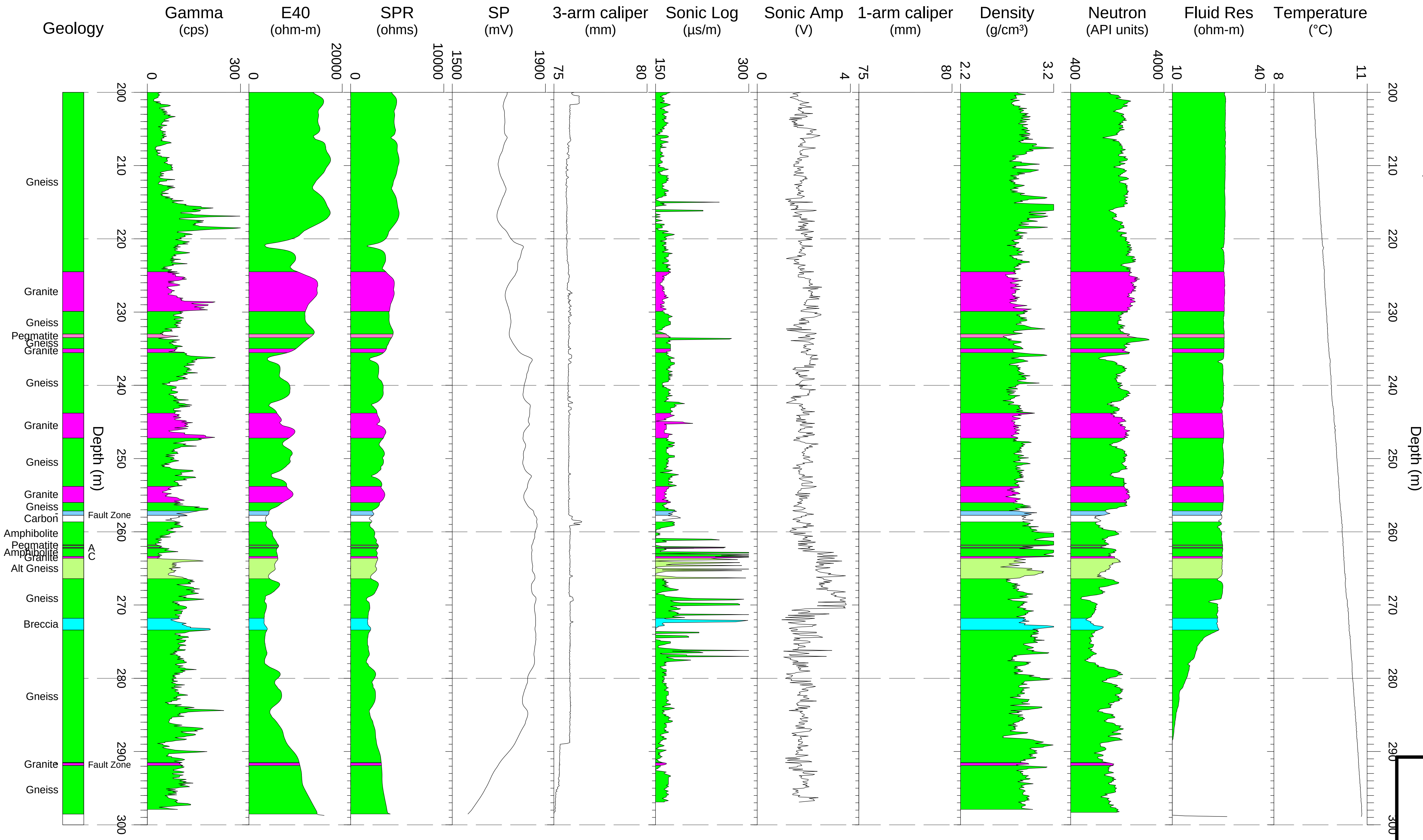

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