APPENDIX C

DOWNHOLE GEOPHYSICS LOGGING RESULTS

borehole geophysics / hydrophysics

Geophysical Logging Results
Flathead Valley Deeps Well BFF#5
Kalispell, MT

Prepared for
Montana Tech
December 30, 2021

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Table of Contents

List of Acronyms

NMR – Nuclear Magnetic Resonance
FTC – Fluid Temperature Conductivity
ft – feet
ftbtoc – feet below top of casing
ftbgs – feet below ground surface
min. – minute
g/cc – grams per cubic centimeter
cm – centimeter
sec – second
μS – micro Siemens
cps – counts per second

Geophysical Logging Results
Flathead Valley Deeps Well BFF#5

Introduction

In accordance with COLOG's proposal dated December 15rd, 2020, COLOG has applied geophysical logging methods to investigate the borehole BFF#5 in Kalispell, Montana. The objectives of the investigation were to:

1) Obtain geologic characteristics and properties, including lithology and porosity, of the upper alluvium and especially the lower alluvium in the Flathead Valley. The data will be used to characterize and group lithologic layers conveying groundwater.
2) Obtain hydrogeologic characteristics, including water content, horizontal hydraulic conductivity, and effective porosity, of the material penetrated by the borehole with a focus on the saturated zone(s) conveying groundwater.

BFF#5 was drilled to a depth of 1600 feet with a 9.25 inch diameter bit. The well was cased with a 10 inch steel casing to 540 feet. Logging was able to proceed in the open hole as planned in the scope of work, except for flow meter tools, as the borehole fluid was too thick for tools to collect readings properly. A gyro deviation log was not run as client decided data was not needed at that time. With Electric Log, Caliper, NMR, Density, and Neutron measurements potential water-bearing zones were identified.

COLOG's logging of the subject borehole was performed over the period of October 9th through 10th, 2021. All depths reported herein are referenced to ground surface, unless stated otherwise.

Methodologies

Fluid Temperature and Fluid Resistivity

Geothermal gradients in the near surface earth are usually dominated by conduction, and are generally linear increasing with depth due to the relative constancy of the thermal conductivity of earth materials. Convective heat flow within the borehole fluid is caused by formation fluid entering or leaving the borehole at some permeable interval. Therefore, deviations from the linear thermal gradient can be attributed to fluid movement. Both the thermal gradient and fluid resistivity profile of the borehole fluid can be obtained with the same probe. The temperature is measured with a thermistor and the fluid resistivity is measured with a closely spaced Wenner electrical array.

Slope changes in both the temperature and fluid resistivity logs may be indicative of fluid flow between the formation and the borehole. Both responses are affected by drilling method, time since circulation, mud type or additives and well development procedures.

A differential temperature log is a calculated curve that amplifies slight slope changes in the temperature gradient and can assist in the interpretation of the fluid temperature log. As the probe is lowered downhole, small changes in the slope of the temperature curve are identified by a differential curve that is plotted from a center zero line. The differential temperature is constructed by using a temperature point at one depth and subtracting a point at a lower depth throughout the entire logged interval.

$$(\text{temperature value}^{\text{Depth 1}}) - (\text{temperature value}^{\text{Depth 2}}) = \text{differential value}$$

In real time the differential values are calculated across the acquisition digitizing interval (e.g. 0.1 to 0.5 ft). Because of the small digitizing interval the calculated real time differential curve may only identify larger temperature gradient deviations. Another differential temperature can be constructed in post processing over a larger sample interval (sometimes up to 2 ft). This log commonly provides a more diagnostic differential curve and is used frequently in the temperature profile interpretation.

The fluid resistivity in the borehole is controlled primarily by the salinity. Therefore, salinity stratification, or the introduction of a fluid of different water quality into the borehole, can be observed by changes in the fluid resistivity log. Often, the exchange of fluid between the formation and the borehole influences both the temperature and the fluid resistivity so that the response is evident in both logs.

Temperature corrected resistivity can be converted to equivalent NaCl salinity in parts per million (Bateman and Konen, 1977). A salinity profile can then be plotted which indicates the general water quality trend of the borehole fluid. If the assumption is made that the borehole fluid is in equilibrium with the formation fluid, then the borehole salinity profile can be interpreted as a formation fluid salinity profile. Differences between these profiles from well to well, may contain information concerning the extent of hydraulic connectivity in the area.

Natural Gamma

The natural gamma log (also known as gamma or gamma ray log) provides a measurement recorded in counts per second (CPS), that is proportional to the natural radioactivity of the formation. Actual counts depend upon the detector size and efficiency but are often normalized in API units. 200 API units equal the detector response in a specially constructed physical model designed to simulate the typical shale. For most of COLOG's gamma probes, 1 API unit is approximately equal to 1.25 CPS. The depth of investigation for the gamma log is typically 10 to 12 inches. Gamma logs provide formation clay and shale content and general stratigraphic correlation in sedimentary formations. In general, the natural gamma ray activity of clay-bearing sediments is much higher than that of quartz sands and carbonates. Gamma logs are also used in hard rock environments to differentiate between different rock types and in mining applications for assessment of radioactive mineralization such as uranium, potash, etc.

Gamma radiation is measured with scintillation NaI detectors. The gamma-emitting radioisotopes that naturally occur in geologic materials are Potassium40 and nuclides in the Uranium238 and Thorium232 decay series. Potassium40 occurs with all potassium minerals, including potassium feldspars. Uranium238 is typically associated with dark shales and uranium mineralization. Thorium232 is typically associated with biotite, sphene, zircon and other heavy minerals.

The usual interpretation of the gamma log, for hydrogeology applications, is that measured counts are proportional to the quantity of clay minerals present. This assumes that the natural radioisotopes of potassium, uranium, and thorium occur in exchange ions, which are attached to the clay particles. Thus, the correlation is between gamma counts and the cation exchange capacity (CEC). Usually gamma logs show an inverse linear correlation between gamma counts and the average grain size (higher counts indicate smaller grain size, lower counts indicate larger grain size). This relation can become invalid if there are radioisotopes in the mineral grains themselves (immature sandstones or arkose), and if there are differences in the CEC of clay minerals in the different parts of the formation. Both of these situations are possible in many environments. The former situation would most likely occur in basal conglomerates composed of granitic debris, and the latter where clay occurs as a primary sediment in shale and another as an authigenic mineral deposited in pore spaces during diagenesis.

The assumption of a linear relationship between clay mineral fraction in measured gamma activity can be used to produce a shale fraction calibration for a gamma log in the form:

$$Csh = (G-Gss) / (Gsh - Gss)$$

Where Csh is the shale volume fraction, G is the measured gamma activity; Gss is the gamma activity in clean sandstone or limestone; Gsh is the gamma activity measured in shale.

Calibration of the gamma logging tool is usually performed in large physical models such as the API test pits in Houston, or the DOE uranium calibration test pits. In hydrogeology, the gamma measurement is usually a relative log and quantitative calibrations are not routinely performed. However, the stability and repeatability of the natural gamma measurement is routinely checked with a sleeve of known radioactivity. It is also common to routinely check the gamma log by repeat logging a section of a well. Natural radioactive decay follows a Gaussian distribution; that is, approximately 67% of the radioactive response occurs within ± the square root of the count rate. For instance, if a background radiation of 100 CPS is being measured, there is approximately ± 10 CPS variability.

Fundamental assumptions and limitations inherent in these procedures are as follows:

- The natural gamma ray log, as with all nuclear or radiation logs, have a fundamental advantage over most other logs in that they may be recorded in either cased or open holes that are fluid or air filled. Borehole fluid and casing may attenuate the gamma values.

Excessive borehole rugosity, often caused by air drilling, may degrade natural gamma ray log.

Electric Log Methodology

All electrical logs require the presence of the borehole fluid to carry the current from the probe to the formation, and therefore these devices only operate below fluid level. Quantitative formation electrical resistivity, spontaneous potential, and qualitative single point resistance can be measured with a combination tool. The operational features of each measurement are discussed under the measurement heading.

16-inch and 64-inch Normal Resistivities

Formation resistivity is dependent on the fluid salinity, permeability, and connected fracture paths within the depth of investigation of the measurement. Measured resistivity is also controlled by particle surface conduction in clastic environments. The resistivity measurement decreases in larger diameter boreholes and areas in which the borehole has been broken out, and/or highly fractured. The above responses allow interpretation of lithologic types, correlation of beds, estimation of fluid quality and possible fractured zones.

A constant current is supplied to the downhole current electrode and the resulting voltage drop is measured on the return electrodes 16" and 64" away from the current electrode. The resistivity of the surrounding media (which includes the borehole fluid) is derived from Ohm's Law and the geometry of the electrode arrangement. The static electric field which results from the geometric arrangement of electrodes is ideally a sphere 16" or 64" in radius (for the short and long normal functions respectively). The presence of the borehole diameter and mudcake affects the measurement sphere by decreasing the lateral extent, and increasing the vertical extent. Borehole corrections based on the borehole fluid resistivity can be made, but these corrections do not address the effects of vertical averaging. Accurate interpretation of the logs minimizes this averaging effect. The influence of the borehole size becomes less with smaller diameter boreholes. Calibration of the 16" and 64" normals is performed in the field with a resistance box which tests a range of known resistivities from 0.0 ohm-m to 1,000 ohm-m.

Single Point Resistance (SPR)

The SPR measurement is controlled by rock and fluid parameters in much the same way as resistivity logs. SPR is a simple system of two electrodes (the resistivity current electrode) and a surface electrode. Current is passed through the formation and voltage differences are measured between the two electrodes. The measured resistance includes the resistance of the cable, borehole fluid, and the formation around the borehole. The current density is higher near the borehole electrode and surface electrode. Since the current density at the surface electrode is constant, formation variations close to the probe produce the resistance changes visible on the logs. Since there is a single downhole electrode, not an array, the log effectively shows a point measurement. This gives a very "responsive", high vertical resolution measurement. Though the single point resistance cannot be calibrated quantitatively, its instantaneous response is a good boundary indicator, and does show a more well defined response than the 16" or 64" normals.

Spontaneous Potential (SP)

The SP is a measurement of the naturally occurring potential in the borehole. This naturally occurring potential is most often caused by a concentration gradient between the borehole fluid and formation fluid (electro-chemical), and requires the presence of a clay rich/porous media interface to occur. Reduction/oxidation (redox) interfaces and streaming potentials (electro-kenetic) caused by the flow of fluid in or out of the borehole are also causes for the occurrence of spontaneous potential.

In fresh water environments where the drilling fluid is natural or the salinity is near the formation pore fluid salinity the electro-chemical potential is minimized. The absence of sulfide mineralization or fluid movement into or out of the formation may minimize the redox and streaming potentials.

Caliper Measurement

The caliper log represents the average borehole diameter determined by the extension of 1 or 3 spring-loaded arms. The measurement of the borehole diameter is determined by the change in the variable pot resistors in the probe, which are internally connected to the caliper arms.

One important application of the caliper measurement is to identify intervals where rough borehole walls or washouts have introduced large errors into such logs as neutron porosity and other measurements where log response is affected by borehole enlargement or "rugosity".

Caliper logs may show diameter increases in cavities and, depending on drilling techniques used, in weathered zones. An apparent decrease in borehole diameter may result from mud or drill-cutting accumulation along the sides of the borehole (mudcake) or at the bottom of the boring. The caliper log is often a useful indicator of fracturing. The log anomalies do not directly represent the true in-situ fracture size or geometry. Instead, they represent areas of borehole wall breakage associated with the mechanical weakening at the borehole-fracture intersection. Caliper anomalies may represent fractures, bedding planes, or solution openings. Generally, caliper log anomalies indicate the intervals where fractures intersect boreholes.

COLOG records the caliper log with either a single-arm caliper measurement, using the decentralization arm of the density probe, or a separate stand-alone three-arm caliper. Calibrations of the probe are done routinely on the bench and in the field directly before the tool is placed into the borehole. Calibration standards consist of rings of known diameters that are placed over the extended arms, as the tool response at these diameters is recorded. Additionally, as with other geophysical measurements, a repeat section is collected and compared with original logs for consistency and accuracy.

Nuclear: Focused Density and Neutron

Focused Density

The principle behind density logging is the detection of Compton-scattered gamma rays that originate from a small radioactive source housed in the probe Figure D-1. The intensity of the radiation reflected back to the detectors is primarily a function of the bulk density of the media in which the gamma rays are introduced and scattered.

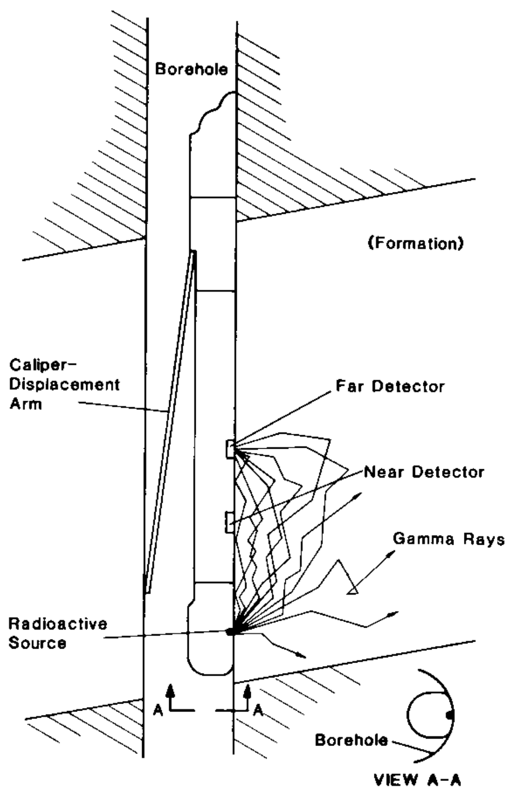

Figure C-1: Probe schematic in the borehole for the dual density (focused) probe.

Compensation is necessary to correct for the condition where the tool is not perfectly flush with the borehole wall (because the borehole is not perfectly smooth.) When calibrated correctly, compensated measurements made with this tool can be accurate to within 1% of the true bulk density. The density compensation algorithm corrects the long-spaced detector measurement for near-borehole effects that are measured by the short-spaced detector. The algorithm COLOG uses was empirically derived specifically for the Mt. Sopris density probe (Scott et al, 1988)[1]. A graph of empirical data that illustrates the compensation is shown in Figure D-2. A caliper log that measures borehole diameter in inches (accurate to 0.01 inch) is always acquired with the density log.

[1] Scott, J. H., Muller, D. C., and Jiajin, L., 1988. A Compensated Density Tool for Mineral Logging: The Log Analyst, v. 29, no. 2.

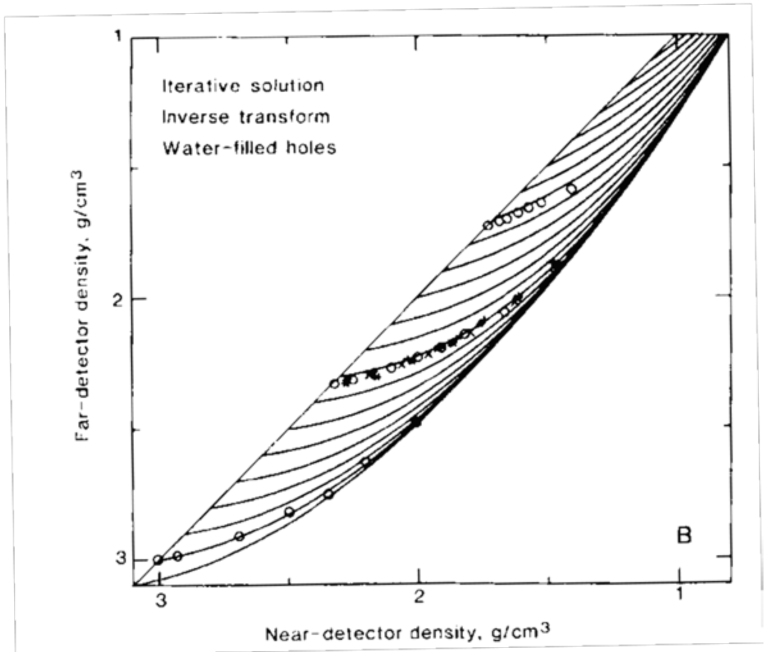

Figure C-2: Compensation curves for the dual-detector density tool. The circles and X's represent actual empirical data from known density calibration test holes measured a various standoffs. A polynomial regression corrects values back to the straight line which represents bulk density measured under perfect borehole conditions.

Calibration of the density tool is accomplished by measuring the reflected gamma radiation from materials of known densities. COLOG routinely performs shop calibrations using lucite and aluminum blocks and periodically checks those calibrations in the USBM calibration test holes at the Denver Federal Center, Colorado (Figure D-3). Further discussion concerning this calibration method can be found in (Keys 1989)[2] and (Hearst and Nelson 1985)[3].

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[2] Keys, W. Scott, 1989, Borehole Geophysics Applied to Ground-Water Investigations: National Water Well Association.

[3] Hearst, J.R., and Nelson, P.H., 1985, Well Logging for Physical Properties: McGraw-Hill Book Company.

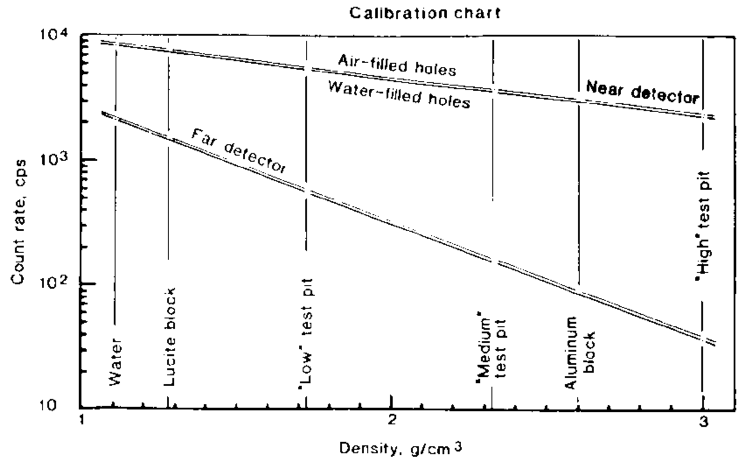


Figure C-3: Calibration chart showing count rate (log scale) from the near and far detectors plotted vs. density (linear scale) for various calibration media (Scott et al, 1988).

Porosity can be derived from compensated bulk densities if the grain density for the rock and a fluid density for the fluid in the pore space is known or assumed (Hearst and Nelson, 1985, p. 389). Fluid density rarely deviates much from 1.00 g/cc, and in the lack of core analysis a grain -density for clastic sedimentary rock of 2.65 g/cc is often assumed (the density of quartz). However, limestone commonly has matrix densities of 2.70 g/cc or higher, causing the calculated porosities based on 2.65 g/cc to often be negative. The present of some cementation minerals such as calcite (density of 2.71 g/cc) and siderite (density of 3.94 g/cc) also result negative porosities. Though deviation of grain densities from the assumed 2.65 g/cc results in calculated porosities that are in error, the occurrence of negative porosities can provide an indication of the presence of these heavier minerals.

Fundamental assumptions and limitations inherent in these procedures are as follows:

- The focused density gamma/gamma log, as with all nuclear or radiation logs, have a fundamental advantage over most other logs in that they may be recorded in either cased or open holes that are fluid or air filled. Borehole fluid and casing may attenuate the gamma values.

- Excessive borehole rugosity, often caused by air drilling, may degrade the focused density gamma/gamma ray log results.

Neutron

High energy neutrons are generated by a 1 or 3 curie Am^{241}-Be radioactive source housed in the probe. These neutrons interact with the media which surrounds the probe including the borehole fluid and formation. The significant aspects of that interaction are the loss of energy due to collisions with hydrogen atoms and the subsequent capture of the neutrons by various nuclei (including hydrogen). The detector in the neutron tool is spaced 14" from source and counts only the low energy (thermal) neutrons which have not been captured. Within a certain range (unspecified) the thermal neutron count rate is inversely proportional to the population of hydrogen atoms surrounding the tool. Therefore, for a constant borehole size the neutron count rate can be related to total water content surrounding the tool, registering higher counts for lower water content. The inverse counts vs. water content relationship can be explained in terms of the degree of neutron capture that occurs. For example, lower water content captures fewer low energy neutrons and results in a higher neutron count rate at the detector.

Total water content in a saturated formation is controlled by the clay content, because clay minerals contain a significant volume of bound water. In view of the inverse relationship described above this means that lower neutron count rates are associated with higher clay content. Repeatability and stability of the neutron tool is routinely checked by measuring the neutron count rate in a barrel of water or federally regulated radioactive pits. No quantitative calibration is performed since the neutron log is a qualitative, relative measurement. A qualitative porosity calibration is performed using tool response in a known borehole size in a known porosity. The data from that calibration is then plotted against the raw data, with the output a porosity value, adjusted for borehole size and standoff.

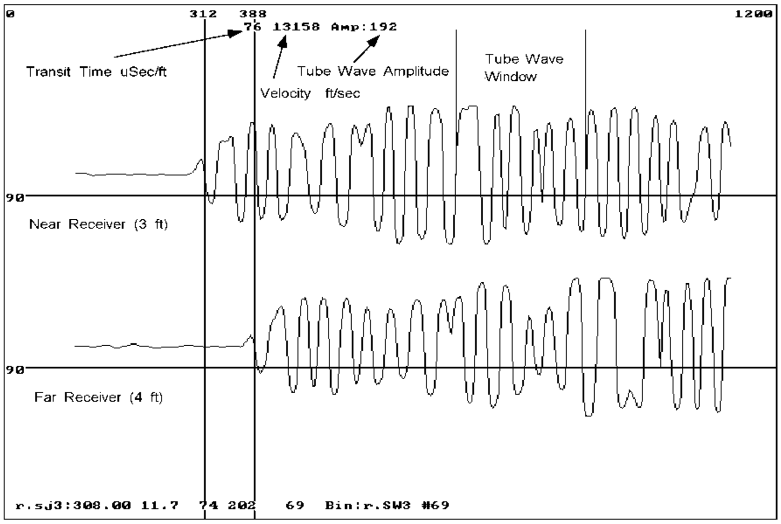
Fundamental assumptions and limitations inherent in these procedures are as follows:

- The focused density gamma/gamma log, as with all nuclear or radiation logs, have a fundamental advantage over most other logs in that they may be recorded in either cased or open holes that are fluid or air filled. Borehole fluid and casing may attenuate the gamma values.

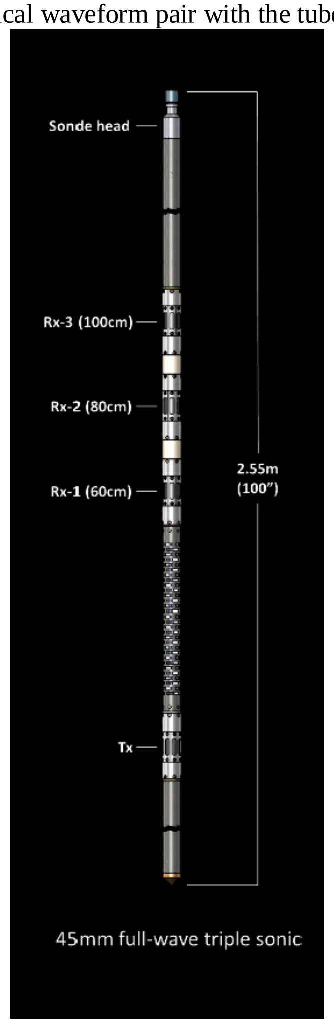
- Excessive borehole rugosity, often caused by air drilling, may degrade neutron count rate and thus the neutron relative porosity log results.

Full Waveform Sonic

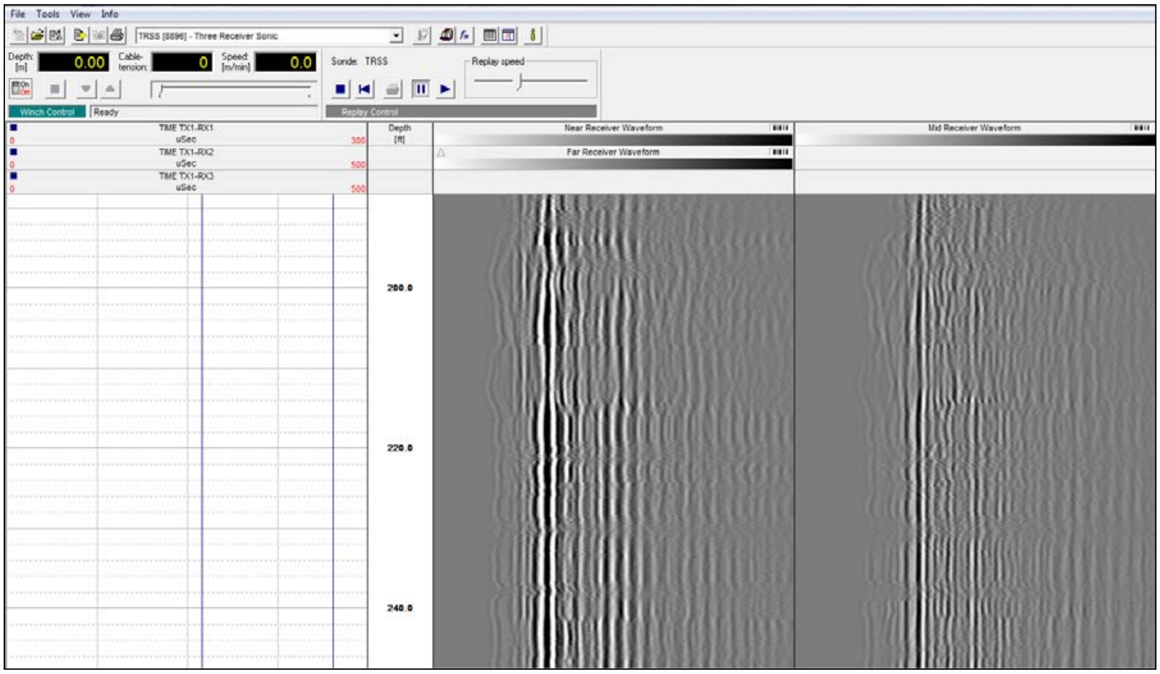
Digital full-waveform sonic (FWS) data is acquired with a Robertson Geologging TRSS Probe, configured with three receivers at fixed separations from the sonic transmitter. In this hole a TRSS Probe was used. The acquisition software allows the real-time viewing of the waveforms as they are written directly to hard disk. The waveforms can also subsequently be viewed and processed for amplitude, frequency, and velocity information. Functionality and repeatability of the probe is monitored by logging in an ungrouted, fluid-filled, steel pipe, and by repeat logging of boreholes at each project.



Example of a typical waveform pair with the tube wave annotated.



Probe schematic for the TRSS sonic probe.



Real-time presentation from the Robertson acquisition software,
illustrating the output of a TRSS configured with three receivers.

The FWS log, recorded in the time domain at two or three downhole receivers, consists of interacting sonic waves generated by a 23 kHz acoustic energy pulse from the downhole transmitter. Sonic logs can only be obtained in the fluid filled portion of the borehole, and the propagation of these waves is controlled by the borehole wall/fluid interface, at which head waves are critically refracted and complicated reflections occur.

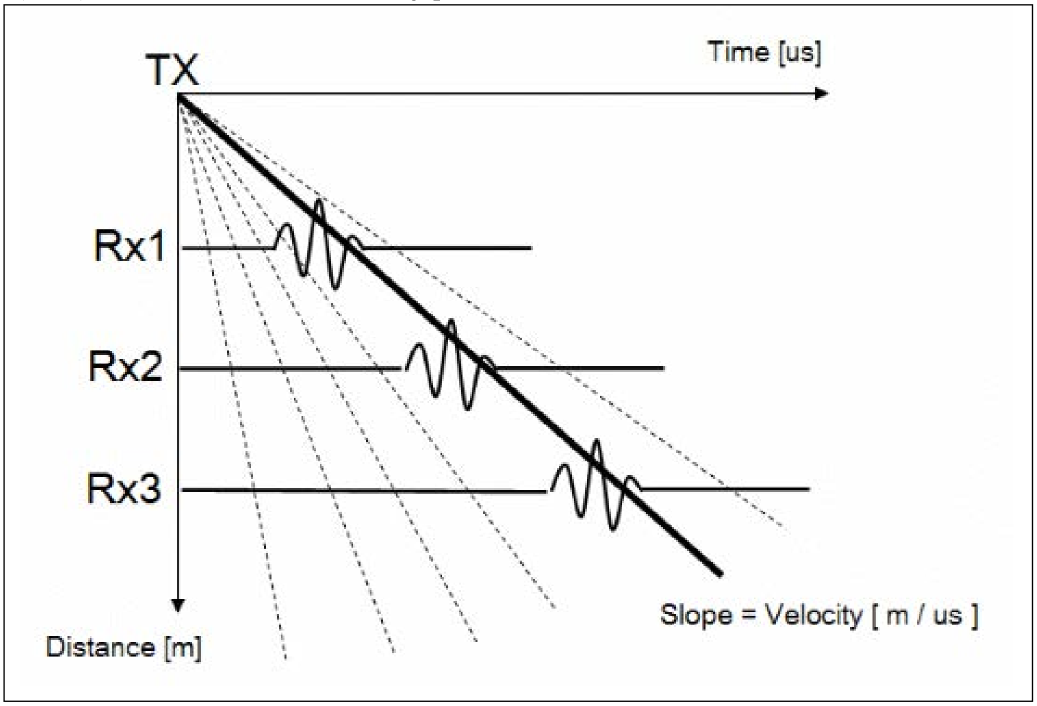
Sonic transit time is the compression-wave travel time, per foot of rock, and represents the inverse of velocity (i.e., greater transit time equals slower velocity). Often referred to as "delta-T" because it is the difference in arrival times between two receivers spaced one foot apart, transit time can be used to characterize rock lithology, consolidation, and presence of discontinuities. These characterizations, however, usually require calibration from core data unless regional relationships are available. Transit times are also used to help in the processing of seismic reflection and refraction data.

The tube wave (Stoneley wave) is a guided fluid wave that travels along the borehole wall/fluid boundary at a velocity slightly slower than the speed of sound in water.

Vertical stacking of the individual waveforms creates the full waveform display, which uses a banded presentation to represent the sinusoidal nature of sonic waves. By convention, black bands represent high amplitude waves above the centerline, dark gray is the low amplitude portion of the positive wave, while light grey is the low amplitude portion of the negative wave below the centerline, and white is the high amplitude portion of the negative wave. The degree of discontinuity of the rock is reflected by the deviation from parallel banding in the FWS Variable Density Log (VDL) display. The velocities and other information obtained from sonic logs are used to determine the lithology, formation porosity, cement bonding, formation weathering, rock strength, and to identify fractures.

Velocity Analysis

The Velocity Analysis process is used to determine the slowness of Compressional (P), Shear (S), and Stoneley (Tube) Waves from the measurements of a multi receiver sonic tool. The Velocity Analysis process computes the semblance to line out coherent events between all receivers. The returned image log type contains the slowness (us/ft) along the abscissa and the semblance (amplitude) for each slowness at each depth. The compressional (P-Wave), shear (S-Wave), and tube (fluid) waves are then interactively picked.

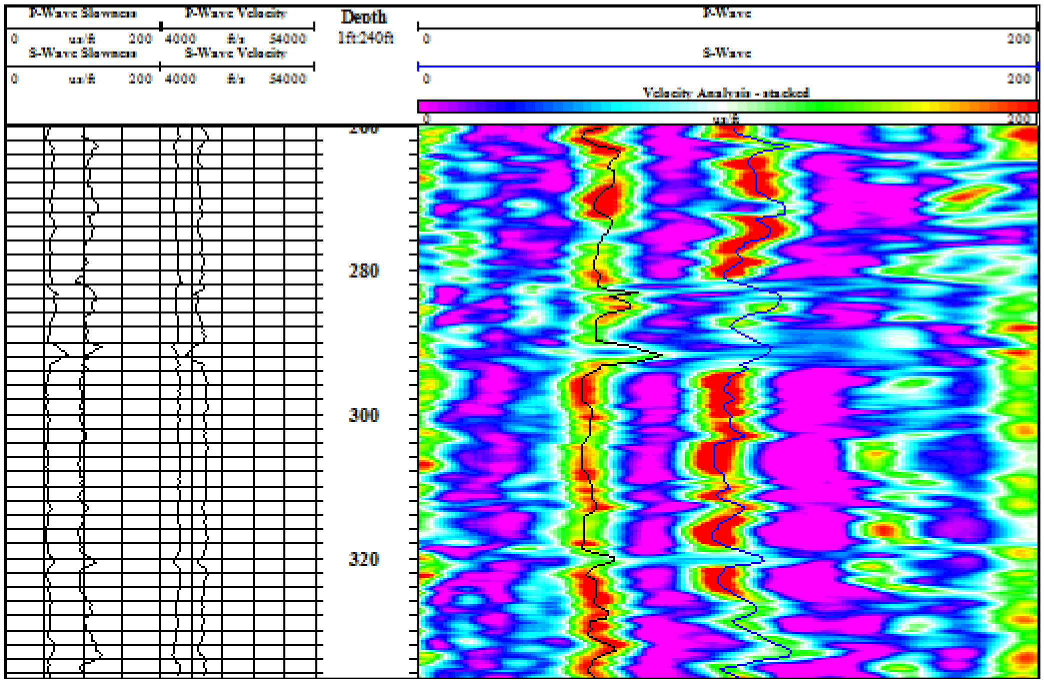


For each depth sample of our Full-Waveform Sonic (FWS) data set we could draw a diagram as shown above, knowing the transmitter to receiver distances and taking the sonic traces from the corresponding FWS Logs. The **Semblance** algorithm creates a fan of lines with different slopes. Each line has its origin at the transmitter position and time zero. The slope of each line is the ratio of time and distance given in (ms/m) and gives the slowness. Along each of these lines a coherence value is calculated using the sonic signal amplitudes found at the intersection of fitted line and data trace. The semblance is computed in order to get a value for the coherence of the signals:

$$S_t = \frac{\sum_{t=t}^{t+j\Delta t} \left(\sum_i x_{ti}\right)^2}{\sum_{t=t}^{t+j\Delta t} \sum_i \left(x_{ti}^2\right)}$$

Semblance is a trace cross-correlation with amplitudes taken into account. It is the ratio of the energy of stacked traces to the sum of the energies of the individual traces within a time window.

The result of this process is an array of semblance values (correlation between Rx1, Rx2, Rx3,… signals) for decreasing slowness (slope of fitted lines) at each depth position. The values are stored in an FWS Log. Remember that the FWS Log is just a data container. Instead of a time sampling rate in ms we have slowness in ms/ft and the signal amplitude corresponds to the semblance value.



Typical output of the semblance processing. Red bands indicate high correlation.

A typical output of the semblance process is shown in the above image. The red bands indicate a high correlation of the signal amplitudes at certain slowness values. As the P-Wave arrives before S-Wave you usually interpret the first high correlation band as the one generated by the P-Wave amplitudes, the second correlation maximum as the one generated from the S-Wave amplitudes. Maximum correlation for Stoneley Wave amplitudes might be seen as well.
The next step would be to pick the "intercepts" of the correlation maxima by roughly drawing a well-log overlaying the semblance image. The output must be corrected using the Adjust Extremum process in order to get the slowness at the maximum correlation value nearest to the rough curve.

The slowness values interactively picked from the output of the semblance analysis must be adjusted to match the maximum semblance value. The Adjust Extremum process adjusts the data in a Well Log to the nearest extremum given in a FWS log. The process returns a new Well Log containing the adjusted slowness picks.

Nuclear Magnetic Resonance

Nuclear magnetic resonance (NMR) is a wireline logging technique used to provide in-situ formation evaluation. NMR responds to both the volumes of fluids present in a rock, and the geometry of the pores in which this fluid resides. As such, it is a powerful addition to any borehole geophysical characterization aimed at evaluating the storage and flow capacity of subsurface formations.

NMR is highly advantageous due to it’s’ ability to provide a lithology independent measurement of formation porosity. A further application of NMR is to estimate the formation permeability.

Semi-empirical models have been developed which quantify the relationship between the pore size distribution captured using NMR and formation permeability. The parameters which are used within these models are formation dependent. Thus the parameters must be calibrated to the geology of interest to ensure that the NMR permeability model is tuned to provide appropriate permeability estimates. The permeability models also assume that formation water is in communication with the borehole. This can lead to overestimations of productivity of a certain zone if not cross checked with other data. For example, a large water filled vug in a limestone will show high free water content on the NMR porosity log, which will lead to high NMR permeability estimates in this zone. However, if this vug is not connected to any other pathways, the actual permeability measured by other testing (packers, pumping, etc.) will be much lower.

Nuclear magnetic resonance (NMR) has been extensively applied to provide measurement of fluid content in geophysical environments. Low-field NMR is renowned in the oil and gas industry for its' application in well logging enabling effective reservoir characterization (Kenyon, 1997). NMR is particularly advantageous as it is able to perform in-situ, non-invasive measurement of geology to provide valuable information on; total porosity, free and bound fluid quantification, permeability and wettability state (Kleinberg and Jackson, 2001, Coates et al., 1999). NMR is not yet widely used in other resource industries, however recent advances in NMR tool design towards mobile, lower cost well-logging tools is allowing measurements to be performed across a variety of geo-resource industries (Hürlimann and Heaton, 2015). For example, NMR has been successfully applied towards determining water content in iron ore (Hopper et al., 2017, Trofimczyk et al., 2018), hydrogeological characterization of groundwater aquifers (Woods et al., 2019) and evaluation of coal seam gas deposits (Hopper et al., 2018).
Nuclear magnetic resonance (NMR) utilizes the renowned technology of NMR to provide quantitative characterization of geo-resources such as iron ore, groundwater and coal seam gas. This section provides a brief introduction to NMR and the aspects fundamental to this work; however for a more detailed description of NMR, the reader is directed towards the extensive literature on the subject (Callaghan, 1993, Levitt et al., 2001). NMR involves the interaction between nuclei of atoms and an external magnetic field. NMR measurements utilize pulse sequences which excite nuclei in the species of interest in order to provide measurable signal decay. One of the most common pulse sequences is the Carr-Purcell-Meiboom-Gill (CPMG) sequence which is used to capture spin-spin relaxation (*T2*) within a material (Carr and Purcell, 1954, Meiboom and Gill, 1958). Spin-spin relaxation (*T2*) quantifies the signal decay in a CPMG measurement and is influenced by three key factors; bulk relaxation (*T2B*), surface relaxation (*T2S*) and diffusive relaxation (*T2D*) (Coates et al., 1999). Bulk relaxation is the intrinsic relaxation of a fluid and is determined by physical fluid properties (e.g. viscosity and molecular size). Surface relaxation is controlled by the interaction between the fluid and the grain surface at the pore wall. Diffusive relaxation is caused by the interaction between excited molecules and a static magnetic field gradient. Molecular diffusion results in molecules moving through an area of changing magnetic field; which results in the molecules experiencing signal dephasing. The contributions of the three relaxation processes to the overall rate of relaxation is quantified by (Brownstein and Tarr, 1979);

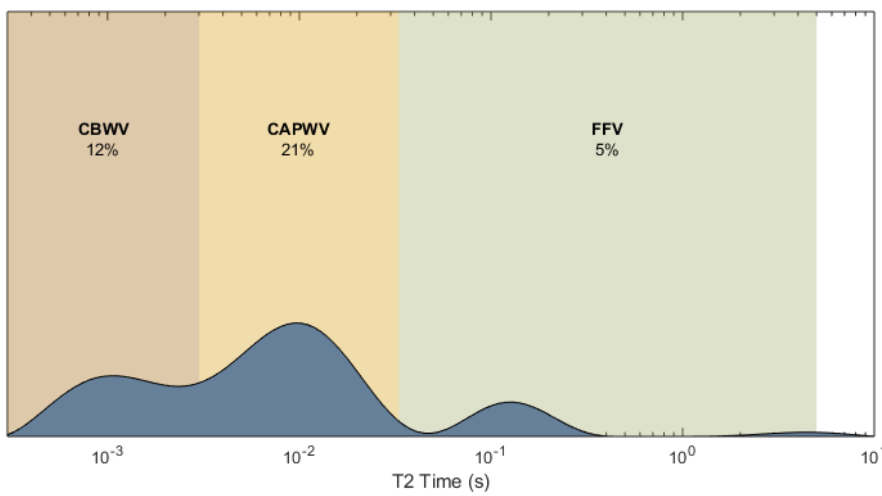
$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \frac{1}{T_{2S}} + \frac{1}{T_{2D}}$$

For NMR measurements of water in porous media; the overall T2 relaxation is dominated by surface relaxation. Surface relaxation is a function of the surface-to-volume ratio (S/V) for the pore space and is often used to infer the pore size distribution of porous geology. Surface relaxation is given by;

$$\frac{1}{T_{2S}} = \rho \frac{S}{V}$$

where ρ is the surface relaxivity of the grain surface. It is this relationship between the relaxation rate and the pore surface-to-volume ratio which enables NMR measurements to be used to estimate permeability (Seevers, 1966). Formations exhibit a distribution of pore sizes; therefore NMR measurements will capture a distribution of relaxation rates, i.e. a *T2* distribution.

NMR measurements are often used to quantify the volumes of free fluid (FFV) and bound fluid (BFV). Free fluid is the fluid which can be extracted from a sample whilst bound fluid is the fluid held within the pore space by capillary tension or clay-bound adsorption. When using NMR *T2* distributions to quantify bound and free fluid volumes; it is assumed that there is a discrete pore size cut-off which exists. Pore bodies which are smaller than this cut-off is considered bound fluid trapped and unable to be extracted due to capillary forces, whilst Pores larger than the cut-off size is free fluid which is producible. Therefore; a corresponding *T2* cut-off will exist which defines the segregation of bound and free fluid. Bound fluid is calculated as the integral of the T2 distribution below the cut-off whilst free fluid is calculated as the integral of fluid above the cut-off. *T2* cut-off values of 33 ms for sandstones and 92 ms for carbonates (but typically range commonly between 80 ms to 120 ms) are commonly used which have been determined from global averages of core plug data (Morriss et al., 1997). The bound fluid region is often further segregated into clay bound water and capillary bound water using a secondary T2 cut-off (e.g. clay bound cut-off of 3 ms). An example of a T2 distribution segregated into the three water volumes is presented in Figure 1.



Example of a T2 distribution with fluid cutoffs indicated. The relevant fluid volumes are clay bound water volume (CBWV), capillary bound water volume (CAPWV) and the free fluid volume (FFV). These volumes are determined by integrating over the relevant regions of the *T2* distribution.

Permeability Relationships

The method of estimating permeability in NMR is derived from the initial work on permeability in porous media by Kozeny and Carman (Kozeny, 1927, Carman, 1956). The Kozeny-Carman equation is used to describe single-phase permeability through a packed bed by (i) modelling fluid flow as laminar flow in tubes crossing the packed bed, and (ii) quantifying the pressure drop using Pouiselle's law for laminar flow. The Kozeny-Carman permeability (*kKC*) is given by;

$$k_{KC} = a\frac{\Phi^2}{\left(\frac{S}{V}\right)^2 (1-\Phi)^2}$$

where *a* is a lithology geometry factor capturing the tortuosity and shape of the pores and ϕ is the porosity.

In geological environments the relationship between permeability and porosity is complicated and depends on the structure and consolidation of a formation. Therefore; NMR permeability models utilise a more generic model which allows flexibility in the permeability dependence on porosity via a porosity exponent (*m*). The generic form of NMR permeability models is;

$$k = a\phi^m \left(\frac{V}{S}\right)^n$$

where *a* is the geometric factor capturing tortuosity and pore shape, *m* is the porosity exponent and *n* is the surface term exponent (where the surface term is the volume-to-surface ratio for the pore space). These three parameters (*a*, *m* and *n*) are lithology dependent permeability coefficients which require calibration.

The three key permeability models used in NMR measurements are the Timur-Coates equation (Timur, 1968, Coates et al., 1991a, Coates et al., 1991b) and the Schlumberger Doll Research (SDR) equation (Kenyon et al., 1988), and the Sum of Echos equation (Sezginer et al., 1999) The Timur-Coates equation uses the ratio free-fluid volume to bound-fluid volume (FFV/BFV) as the surface-term such that the Timur-Coates permeability (kTC) is given by;

$$k_{TC} = a\phi^m \left(\frac{FFV}{BFV}\right)^n$$

For the Timur-Coates equation, typical values for the permeability coefficients in consolidated sandstones are; a = 1×104 mD, m = 4 and n = 2 which have been determined from laboratory studies (Allen et al., 1988). The SDR equation uses the log-mean of the T2 distribution (T2LM) as the surface term, therefore the SDR permeability (kSDR) is given by;

$$k_{SDR} = a\phi^m (T_{2LM})^n$$

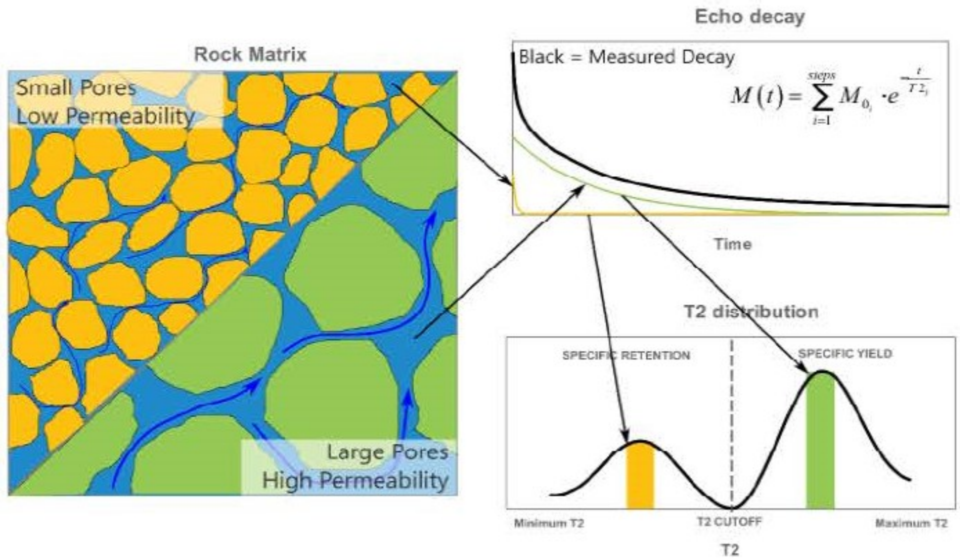
Typical values for the permeability coefficients in consolidated sandstones are; *a* = 4 mD (ms)-2, *m* = 4 and *n* = 2 (Kenyon, 1997). These permeability models assume that a correlation exists between porosity, pore-body, pore-throat size and pore connectivity. The Timur-Coates equation is observed to perform better than the SDR equation in tight sandstones, whilst the SDR equation is more suitable for carbonates.

The Sum of Echoes (SOE) equation is another permeability model used in NMR measurements. The SOE model has an advantage over the models list above where it deals with the raw echoes from the NMR measurement, and does not rely on fitting of the *T2* times or the cutoff between bound and free fluid. The SOE equation is given by;

$$k_{SOE} = (TE * \sum_{n=1}^{N}[echo(n)]^2) * C$$

where *TE* is the echo spacing in seconds, *n* the number of echoes from 1 to N, *echo(n)* is the n-th number echo amplitude, and *C* is a lithological constant. *N* is determined by window (*win)* of NMR receiver over the pulses time of the NMR antenna (typically 1ms). The SOE measurement is better than the other NMR measurements for vertical permeability.

A conceptual illustration has been provided to demonstrate the relationship between the rock matrix, signal decay and resultant *T2* distribution during a NMR measurement. Small pores (containing bound fluid) observe very fast relaxation (due to significant fluid-pore wall interactions) resulting in rapid signal decay and short *T2* times. Large pores (containing free fluid) observe slow signal decay and longer *T2* times.



Conceptual picture illustrating the relationship between pore sizes, measured signal decay and resulting *T2* distribution.

The hydraulic conductivity of water in the geology can be determined by accounting for the physical properties of water (density and viscosity). The average downhole temperature for the slug test measurements is 51.6 oF, giving a water density of 1000 kg/m3 and a water viscosity of 1.26 mPa.s (determined using the Vogel equation (Dortmund Data Bank, 2019)). The hydraulic conductivity (*K*) is determined from permeability using the following equation;

$$K = \frac{k\rho g}{\mu}$$

where k is the permeability (calculated from an NMR model), ρ is water density, μ is the water viscosity and g is the gravitational constant of acceleration (9.81 m/s2).

Discussion

Performing a suite of geophysical logs rather than one or two select geophysical techniques is intended to take advantage of the differences of each of the geophysical logging techniques, to better interpret and correlate anomalies observed in the various logs. At well BFF#5, this is the case. Numerous geophysical logging techniques were chosen and performed at the site to take advantage of the size of some of the probes, the environment that some probes can log in, the depth of investigation of others, and most importantly, what each can measure. The Methodology section above covers in-depth discussion of the suite of geophysical logs chosen for this project. Below is a brief summary of each of the geophysical logging techniques, what they measure in general terms, and very briefly how to interpret their log-response follows, in order to provide context for discussion of the logs:

Fluid Temperature and Conductivity – measures conductivity and temperature of fluid in borehole. Spikes and changes may show fluid coming in to borehole from formations, but also could be the result of differentiation of borehole fluid.

Natural Gamma – measure natural, passive gamma radiation given off by elements in the formation. Higher natural gamma counts per second (cps) typically suggest higher clay content in a sand/silt/clay environment.

1-arm and 3-arm Caliper – measure borehole diameter. Denser more consolidated formations tend to be in gauge with borehole bit size while looser unconsolidated formations tend to have more borehole washouts. Enlarged borehole diameter has effects on other probes, so it is good to refer to caliper log when evaluating significant response from other logs.

Electric Log – Formation resistivity is dependent on the fluid salinity, permeability, and connected fracture paths within the depth of investigation of the measurement. Measured resistivity is also controlled by particle surface conduction in clastic environments. The resistivity measurement decreases in larger diameter boreholes and areas in which the borehole has been broken out, and/or highly fractured. The above responses allow interpretation of lithologic types, correlation of beds, estimation of fluid quality and possible fractured zones.

Focused Density – measures density of the formation. Higher g/cc indicates that more dense material is encountered. Density porosity is calculated from the compensated density as described in the methodology. The measurement is affected by borehole washouts as the pad on the tool loses contact with the borehole wall. A standard matrix density of 2.71 g/cc was used to calculate porosity.

Full Waveform Sonic – measures soundwaves through formation and formation fluid. A lower slowness value indicates a faster formation, and usually harder material. A higher slowness is indicated a slower formation, and usually softer material. Slowness is the inverse of velocity. Porosity was determined from the P-Wave slowness using a formation factor of 75 us/ft adjusted for unconsolidated formations using other logs, as unconsolidated material has a wide range of slowness values. Sonic measurements are affected by borehole washouts and generally have poor returns in less consolidated formations

Dual Neutron– measures water content in the formation. Higher raw cps suggest less water was encountered. Neutron Porosity can differ from Density Porosity due to higher clay content (higher Neutron Porosity), gas in formation (higher Density Porosity) or formation change from Density Porosity constant (depends on formation change). Neutron can be sensitive to mud cake buildup on walls and borehole washouts.

Nuclear Magnetic Resonance – The NMR probe essentially measures bulk porosity, then calculates effective porosity and bound water. The NMR was processed with only the outer two shells (12.5 and 15 inches), as the inner diameter of investigation was over estimating water content. The NMR porosity measurement is less affected by formation changes or mudcake, as it only measure the hydrogen atoms in its shells of investigation. Where there are large borehole washouts the NMR overestimates porosity and hydraulic conductivity. Unconsolidated and semi-consolidated parameters were used to process NMR hydraulic conductivity, with semi-consolidated parameters used on the composite logs.

Correlating Geophysical Logs at BFF#5

It is important to note that the typical log responses mentioned in the brief summaries are broad generalizations and do not necessarily reflect or predict how a geophysical technique should respond in every sedimentary environment. In some cases one or more geophysical logs may correlate with each other while another may contradict them for a myriad of possible reasons. One example is the NMR probe obtains its measurement approximately 12.5 and 15 inches from the center of the probe *without* being influenced by the material between those theoretical shells and the probe. Every other geophysical logging probe used on this project measures, and is affected by, all of the material between the probe and its maximum depth of investigation. When conducting a suite of several geophysical logs it is common for a particular anomaly observed on two or more logs to be off depth from each other slightly. Different geophysical logging techniques respond differently to the formation due to factors such as the differing depths of investigations, different spacing between various detectors and sources, and varying methods of acquiring data between the probes. As such, it is not uncommon to identify an anomaly on one log but observed that anomaly approximately 1 foot deeper or shallower on another log.

The Electric, Sonic, Neutron, Density, and NMR logs all show strong correlations in a formation change from 1200-1210 feet. The resistivity values fell significantly below this zone, suggesting higher conductivity for the formation fluid than the zone above. Slowness values from the sonic log were higher, indicating a softer formation. NMR showed a large amount of mobile fluid in this part of the hole, making up most of the portion of the total fluid volume. Porosities from the Sonic, Neutron, NMR, and Density also shift across this interval. Neutron and Density porosity units average across this interval, 15.24, and 13.52% respectively. Sonic Porosity and NMR effective porosity (all porosity that isn't bound in clay) average twice as high at 29.38 and 30.00%. The reason for this discrepancy is a product of the relatively small diameter of investigation of the Neutron, and Density tool relative to the NMR. These tools are also affected by borehole conditions such as mud cake, while the NMR is uninfluenced by material not included in its specific shell of investigation. The sonic porosity was adjusted to the NMR porosity, as the sonic porosity equations read low in unconsolidated formations. The Caliper shows the hole to be in gauge through this interval, so the NMR reading should not have any extra fluid in the readings caused by an expanded borehole. Hydraulic Conductivity measurements from the NMR show an increase as well across this zone. However, resistivity curves in this zone are very close together, especially compared to the upper zone, suggesting lower permeability. These readings conflict with the higher NMR permeability measurements in this zone. Pump testing in this zone after geophysical logging was preformed also showed low permeability, with aquifer test showing only 0.5 gpm in the lower zone. The reason for this difference, as explained in the methodology, is the NMR permeability models assume all free water has communication with the borehole. The NMR cannot differentiate between pore space that is interconnected or pore space that has no connectivity with other pore space or the borehole. This particular formation, even though natural gamma and NMR readings indicate low clay content, behaves more like a shale, likely due to the organic material present in the sand. Carbon dating of the organic material at 1280' came back carbon dead, indicating an age of more than 43,500 year old. The unit appears mostly homogenous, with the exception of the one spot at 1420 ft with the highest hydraulic conductivity reading, which also correlates to a small change in Natural Gamma, FTC, and Electric Log readings. The change in these other logs is relatively small however, so it might not be significant in the larger picture.

The upper zone is more affected by enlarged borehole as per the caliper readings. NMR, Sonic, and Density Reading are especially affected in the zone from 780 ft up to casing. The upper zone is denser than the zone below however, with an average reading of 2.54 g/cc to 2.49 g/cc, excluding wash outs. The NMR indicates a lot of capillary bound fluid water in this interval, indicating lots of silt size particles, which could be causing the higher density but greater borehole washouts. There is an anomaly in the neutron porosity log in this zone from 700 to 880 ft that does not show up on any other porosity logs. This could be due to a slight change in formation or mud properties in this interval that only affects the neutron, causing more neutrons to reach the detector and thus lower counts.

Special Circumstances and Problems Encountered

1. Natural Gamma counts were unusually low for an unconsolidated alluvium formation. They also did not change much though the entire log, averaging 43 cps. The NMR also indicates very little clay bound water. It could be that most of the material in the hole, including any clay present, does not have good cation exchange capacity and thus poorly bonds to water or natural radioactive material.

2. The hole was significantly mudded up so flow tools, like the CDFM EM Flow meter and Spinner, were not run. Both these tool require very light mud or water to work effectively, as mud will clog up the spinner impeller and the flow tube on the EM Flowmeter.

3. Shear Waves were processed in the preliminary full waveform sonic plots. However, upon further review, the arrival times were in the same window as the expected tube wave arrival times for this particular tool. It is therefore impossible to determine the shear wave arrivals from this data set. This is common in formations with unconsolidated materials, as velocity can vary quite a bit based on compaction. A sonic probe with a larger transmitter sources or larger distances between receivers, such as a suspension logger might be able to pick up the shear wave in this kind of environment at a much slower logging speed.

COLOG
borehole geophysics / hydrophysics

Geophysical Summary Plot

COMPANY: Montana Tech | **PROJECT:** FV Deep

DATE LOGGED: 9-10 October 2021 | **WELL:** BFF#5

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Phone: (303) 279-0171, Fax: (303) 278-0135
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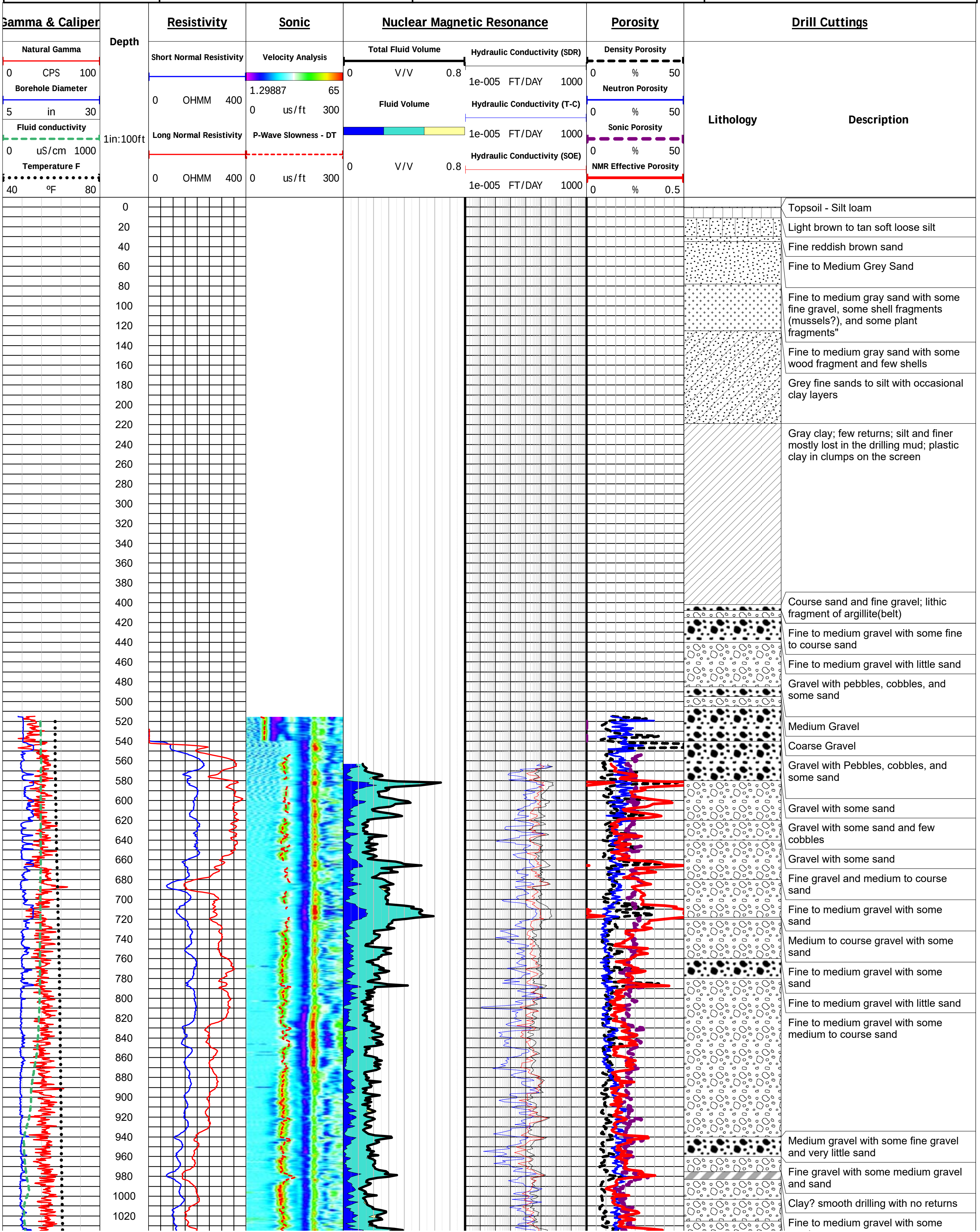

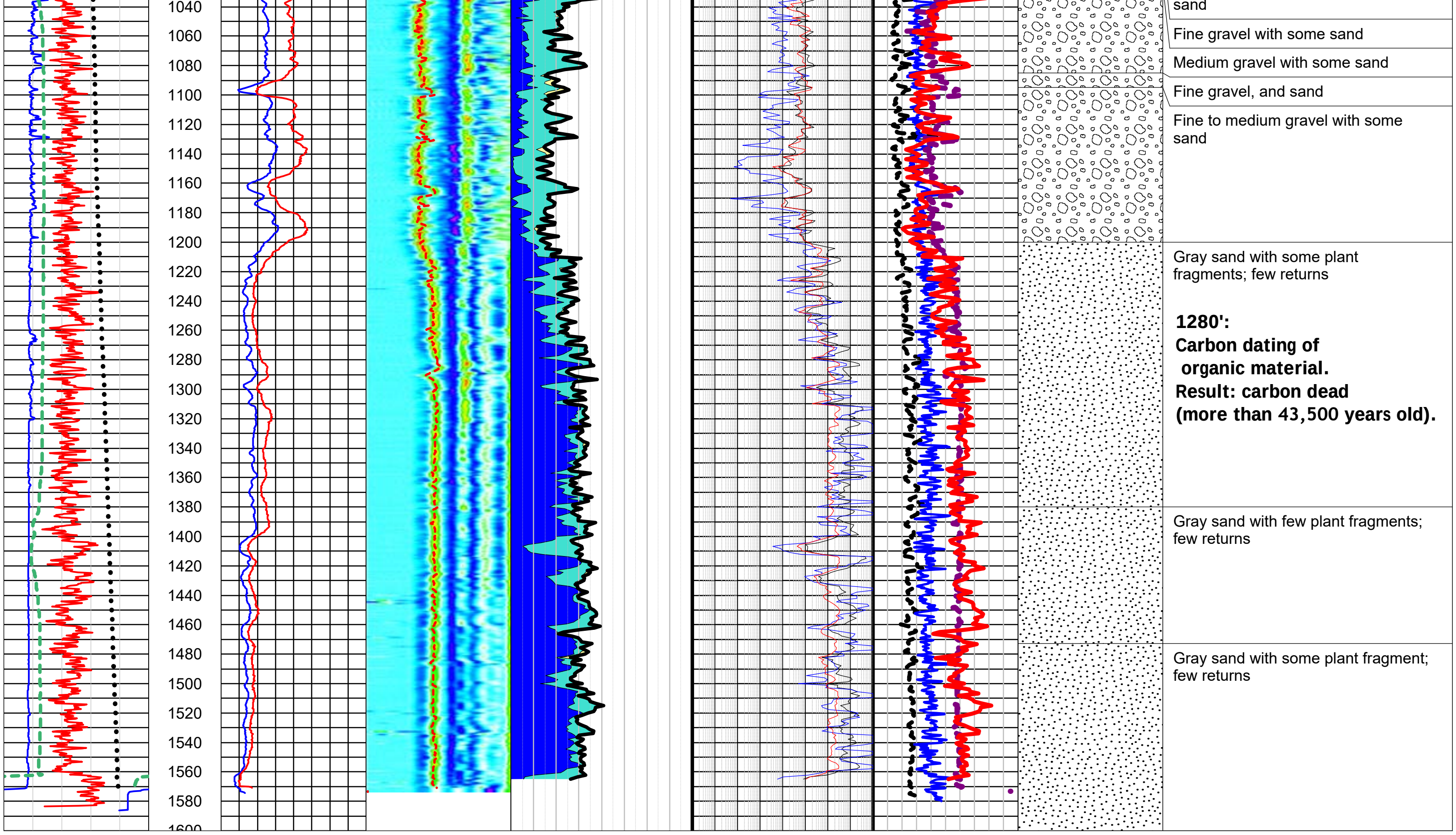
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1400
1420
1440
1460
1480
1500
1520
1540
1560
1580
1600
sand
Fine gravel with some sand
Medium gravel with some sand
Fine gravel, and sand
Fine to medium gravel with some sand
Gray sand with some plant fragments; few returns
1280':
Carbon dating of
organic material.
Result: carbon dead
(more than 43,500 years old).
Gray sand with few plant fragments; few returns
Gray sand with some plant fragment; few returns

Geophysical Summary Plot

COLOG
borehole geophysics / hydrophysics

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COMPANY: Montana Tech	PROJECT: FV Deep
DATE LOGGED: 9-10 October 2021	WELL: BFF#5

Gamma & Caliper
Natural Gamma: 0 CPS 100
Borehole Diameter: 5 in 30
Fluid conductivity: 0 uS/cm 1000
Temperature F: 40 ºF 80

Depth
1in:20ft

Resistivity
Short Normal Resistivity: 0 OHMM 400
Long Normal Resistivity: 0 OHMM 400

Sonic
Velocity Analysis: 1.29887 65
0 us/ft 300
P-Wave Slowness - DT: 0 us/ft 300

Nuclear Magnetic Resonance
Total Fluid Volume: 0 V/V 0.8
Fluid Volume: 0 V/V 0.8
Hydraulic Conductivity (SDR): 1e-005 FT/DAY 1000
Hydraulic Conductivity (T-C): 1e-005 FT/DAY 1000
Hydraulic Conductivity (SOE): 1e-005 FT/DAY 1000

Porosity
Density Porosity: 0 % 50
Neutron Porosity: 0 % 50
Sonic Porosity: 0 % 50
NMR Effective Porosity: 0 % 0.5

Drill Cuttings
Lithology | Description

Depth: 0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200

Description
Topsoil - Silt loam
Light brown to tan soft loose silt
Fine reddish brown sand
Fine to Medium Grey Sand
Fine to medium gray sand with some fine gravel, some shell fragments (mussels?), and some plant fragments"
Fine to medium gray sand with some wood fragment and few shells
Grey fine sands to silt with occasional clay layers

220

240

260

280

300

320

340

360

380

400

420

440

460

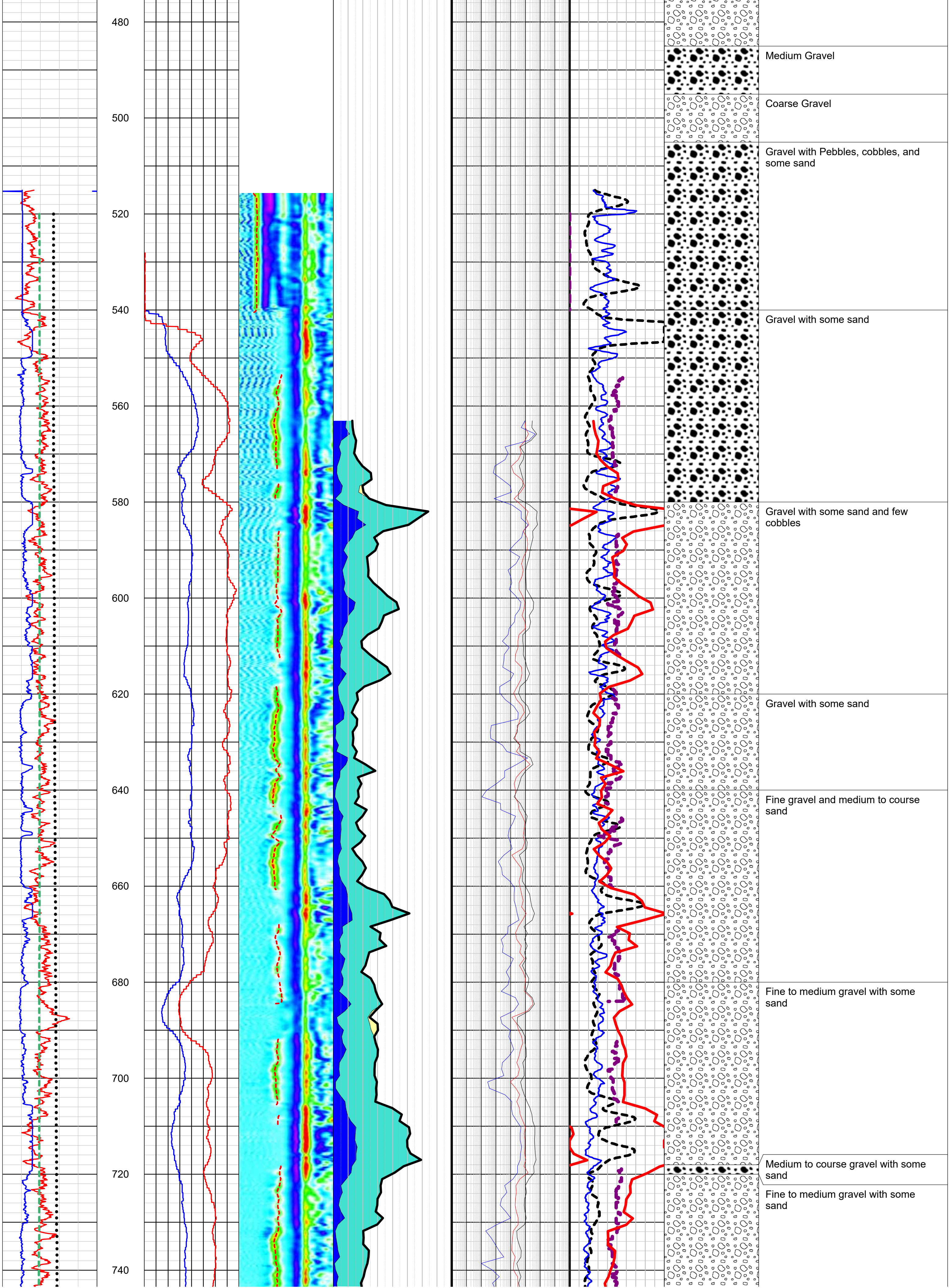
Gray clay; few returns; silt and finer mostly lost in the drilling mud; plastic clay in clumps on the screen

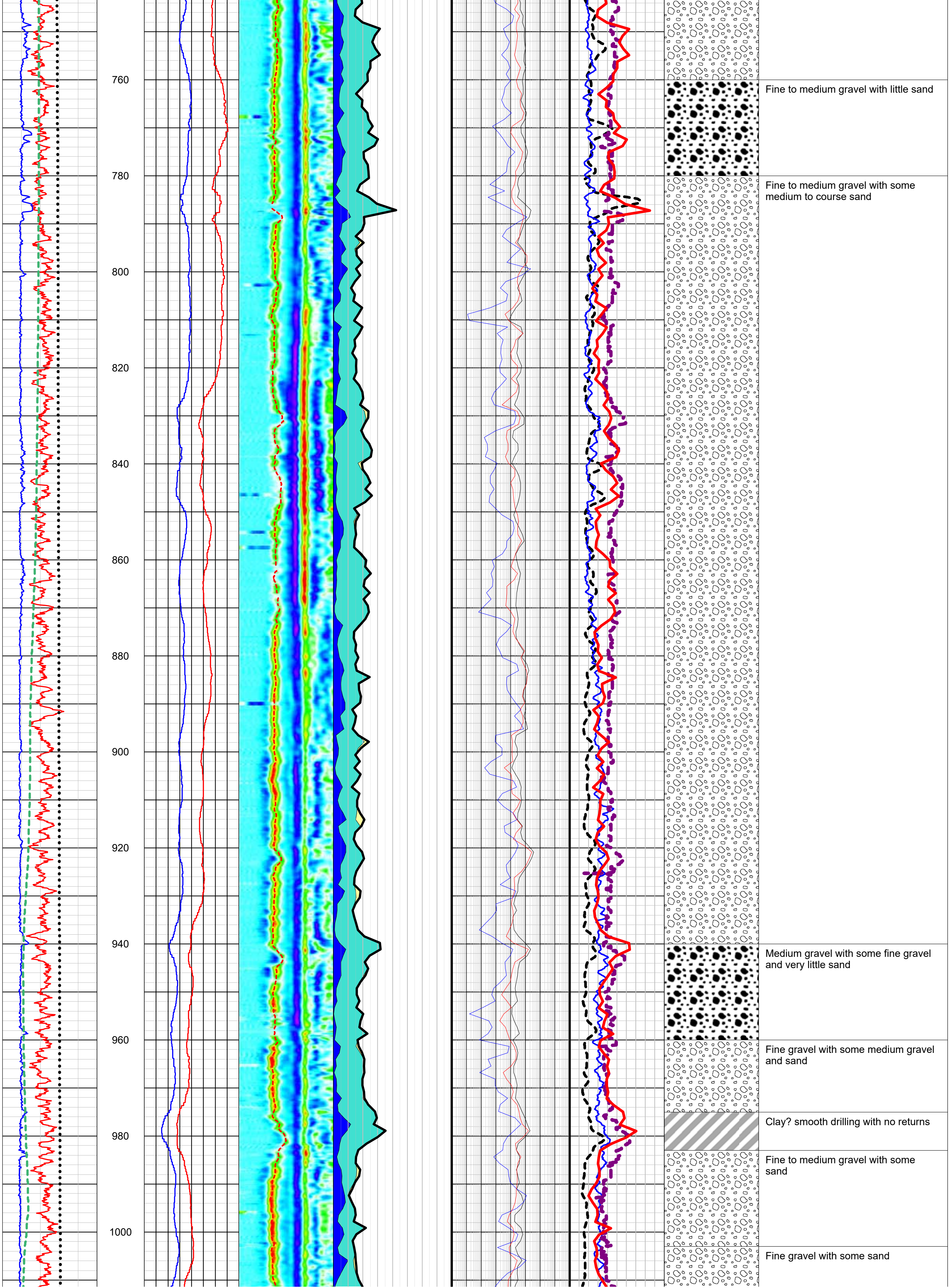
Course sand and fine gravel; lithic fragment of argillite(belt)

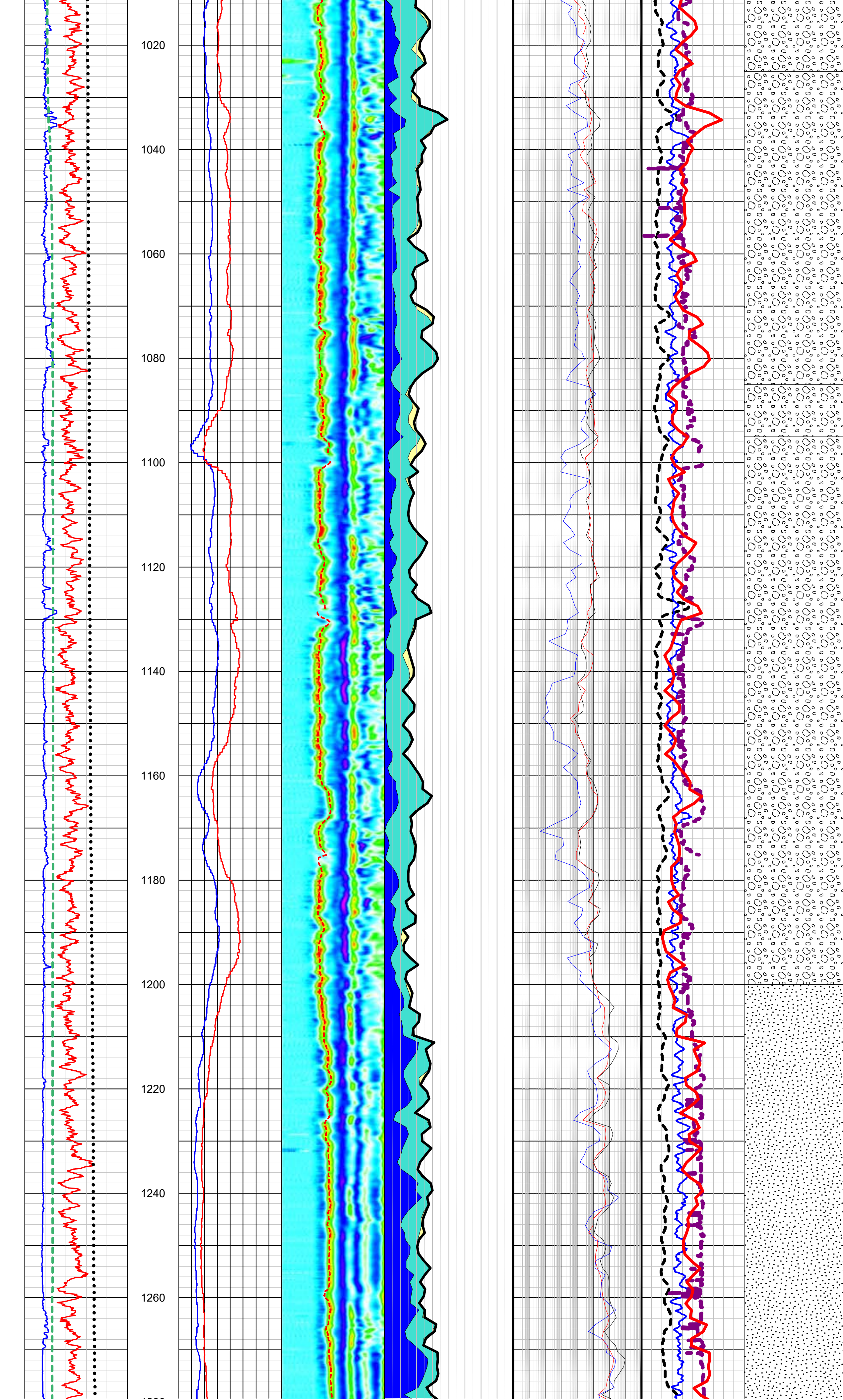
Fine to medium gravel with some fine to course sand

Fine to medium gravel with little sand

Gravel with pebbles, cobbles, and some sand


480
500
520
540
560
580
600
620
640
660
680
700
720
740
Medium Gravel
Coarse Gravel
Gravel with Pebbles, cobbles, and some sand
Gravel with some sand
Gravel with some sand and few cobbles
Gravel with some sand
Fine gravel and medium to course sand
Fine to medium gravel with some sand
Medium to course gravel with some sand
Fine to medium gravel with some sand


760
780
800
820
840
860
880
900
920
940
960
980
1000
Fine to medium gravel with little sand
Fine to medium gravel with some medium to course sand
Medium gravel with some fine gravel and very little sand
Fine gravel with some medium gravel and sand
Clay? smooth drilling with no returns
Fine to medium gravel with some sand
Fine gravel with some sand



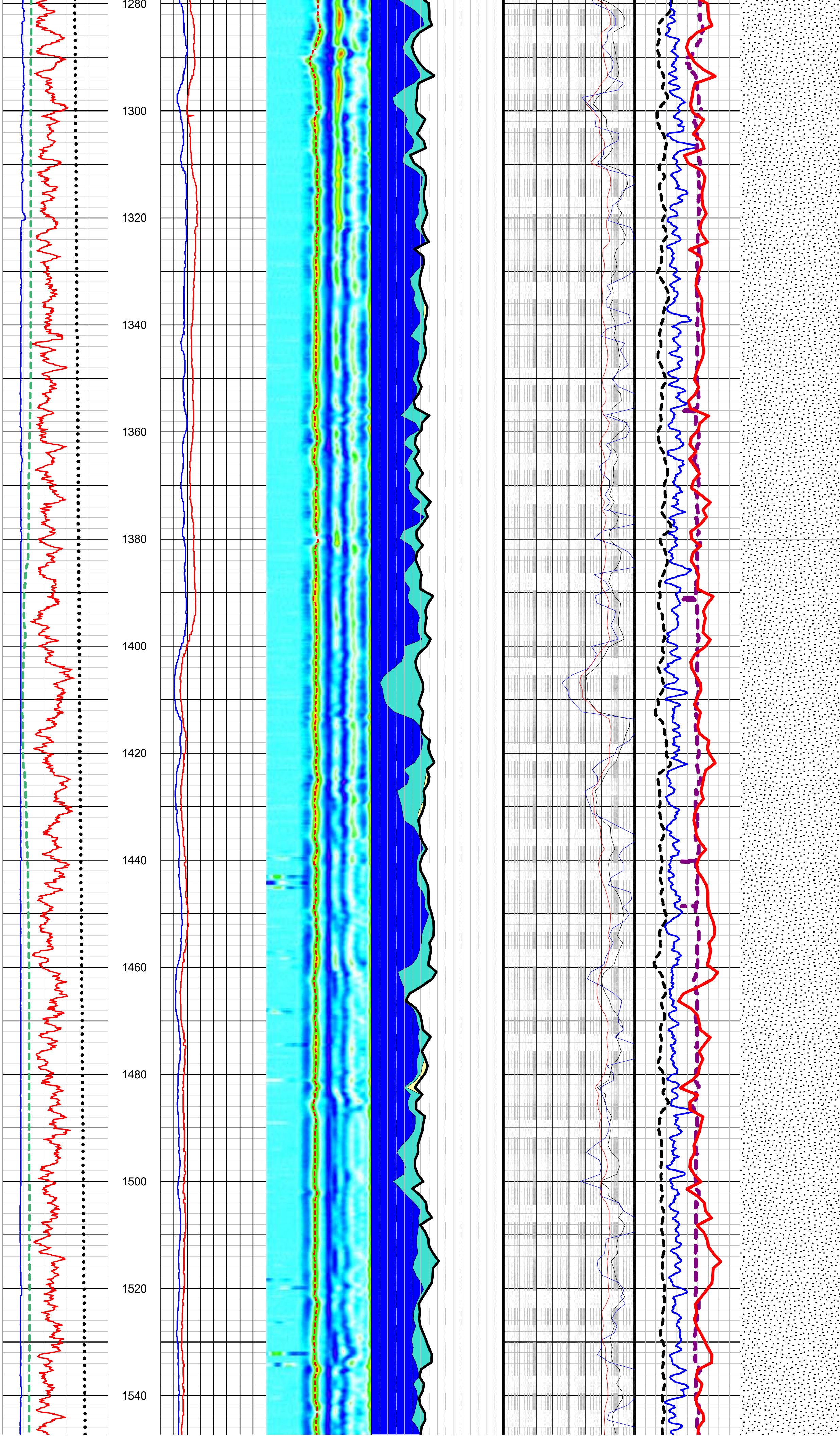
Medium gravel with some sand

Fine gravel, and sand

Fine to medium gravel with some sand

Gray sand with some plant fragments; few returns

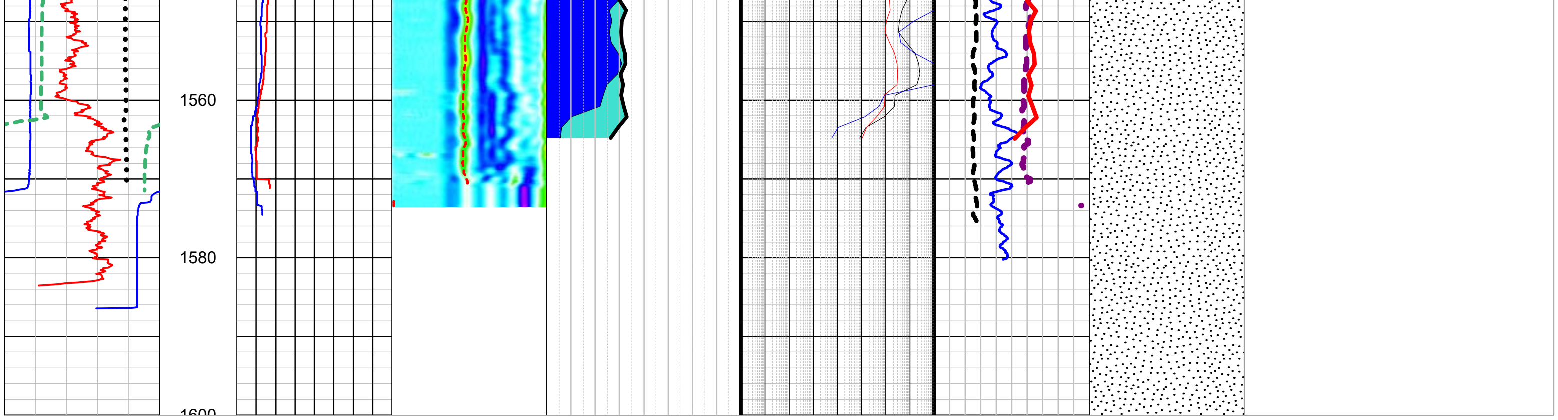
1280':



1280':
Carbon dating of organic material.
Result: carbon dead (more than 43,500 years old).

Gray sand with few plant fragments; few returns

Gray sand with some plant fragment; few returns


1560
1580
1600

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Fluid Temperature & Conductivity

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State Montana

COMPANY Montana Tech
WELL BFF#5
PROJECT FVDeep
COUNTY Flathead **STATE** MT

LOCATION
Lat: 48.10353 Long: -114.18193

QTR SE1/4SE1/4 **SEC** 18 **TWP** 27N **RGE** 20W

OTHER SERVICES
Normal Resistivity
Full Waveform Sonic
Magnetic Resonance
Neutron
Density
Three Arm Caliper
Natural Gamma

PERMANENT DATUM NA **ELEVATION** 2907.64
LOG MEAS. FROM Ground Surface NA **ABOVE PERMANENT DATUM**
DRILLING MEAS. FROM Ground Surface

DATE ACQUIRED	10 Oct 2021			
RUN NUMBER	Five			
LOG TYPE	FTC			
DEPTH-DRILLER	1600.0'			
DEPTH-LOGGER	1575.0'			
BTM LOG INTERVAL	1575.0			
TOP LOG INTERVAL	11.0'			
RECORDED BY	N. Welsh, M. Culig			
WITNESSED BY	A. Bobst			
PROBE TYPE, S/N	2PFA 5969			
LOGGING SPEED	20 ft/min			
A.S.D.E./Sample Interval	1.75' / .1'			
Fluid Level/Fluid Type	60 / WBM			

BOREHOLE RECORD				CASING RECORD			
RUN No.	**BIT**	**FROM**	**TO**	**SIZE**	**WGT.**	**FROM**	**TO**
One	9.25"	540.0'	1600.0'	10"	Steel	0.0'	540.0'
				12"	Steel	0.0'	380.0'

COMMENTS

NA - Not Available, N/A - Not Applicable

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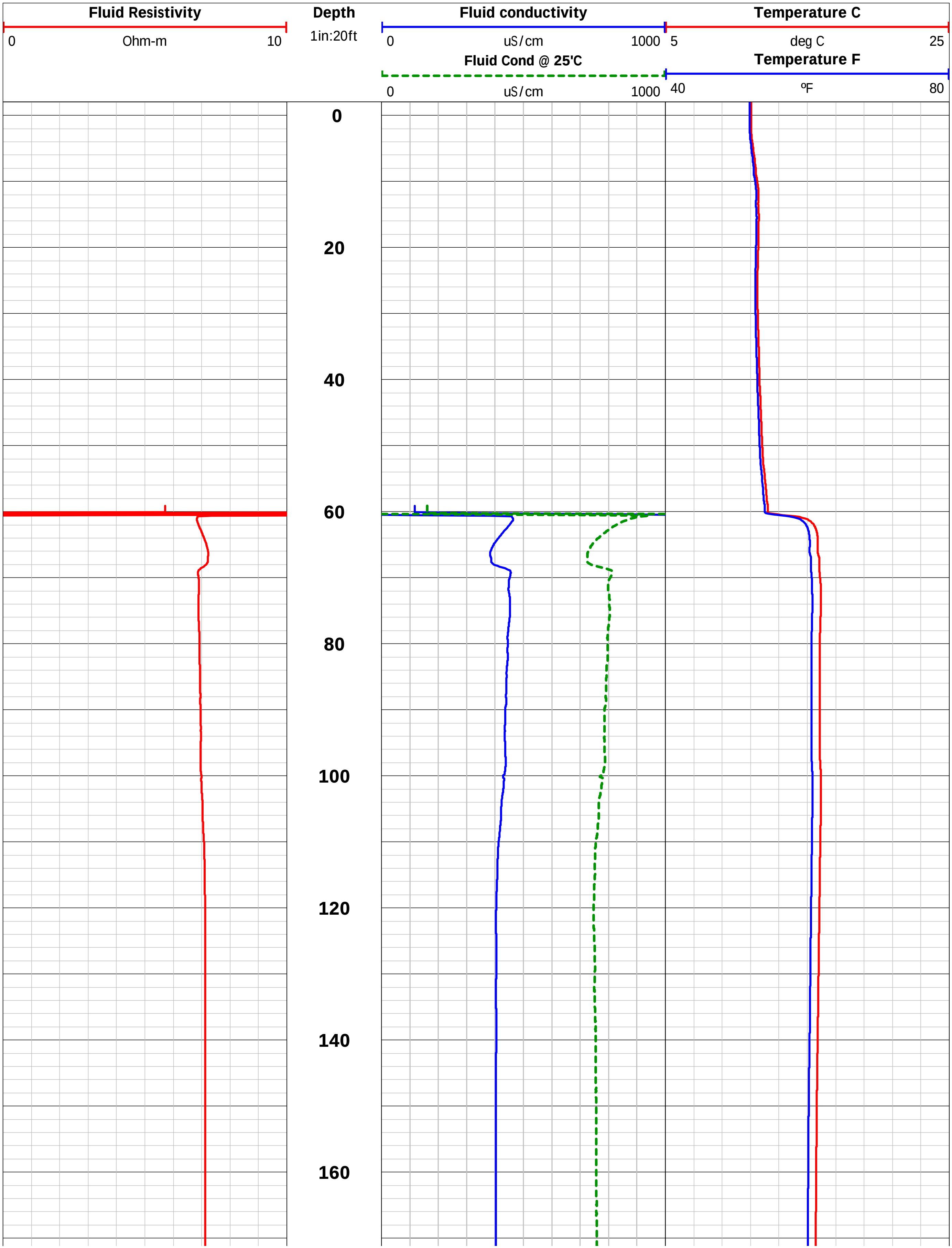
Fluid Resistivity
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Ohm-m
10
Depth
1in:20ft
Fluid conductivity
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uS/cm
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Fluid Cond @ 25'C
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uS/cm
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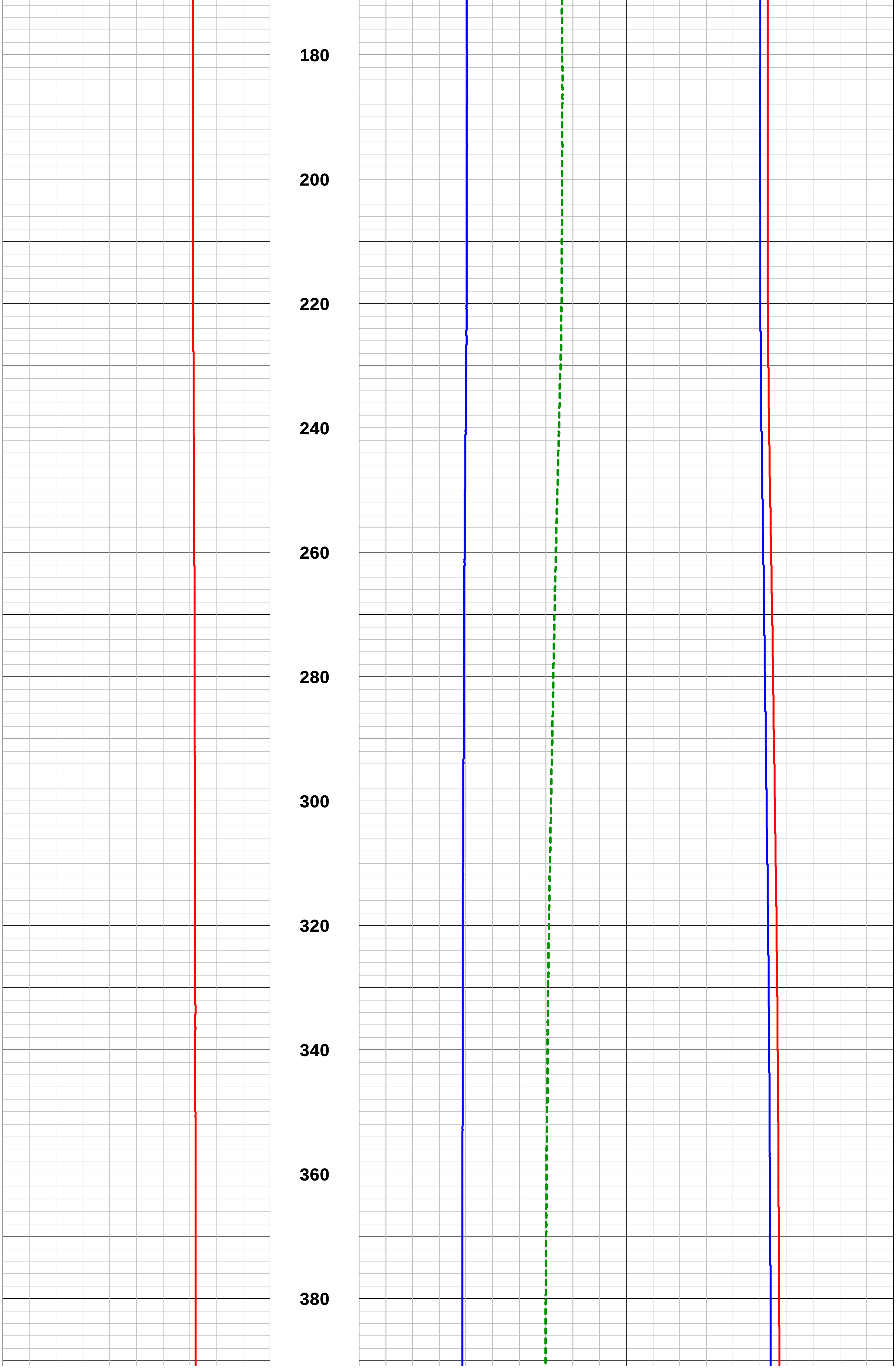
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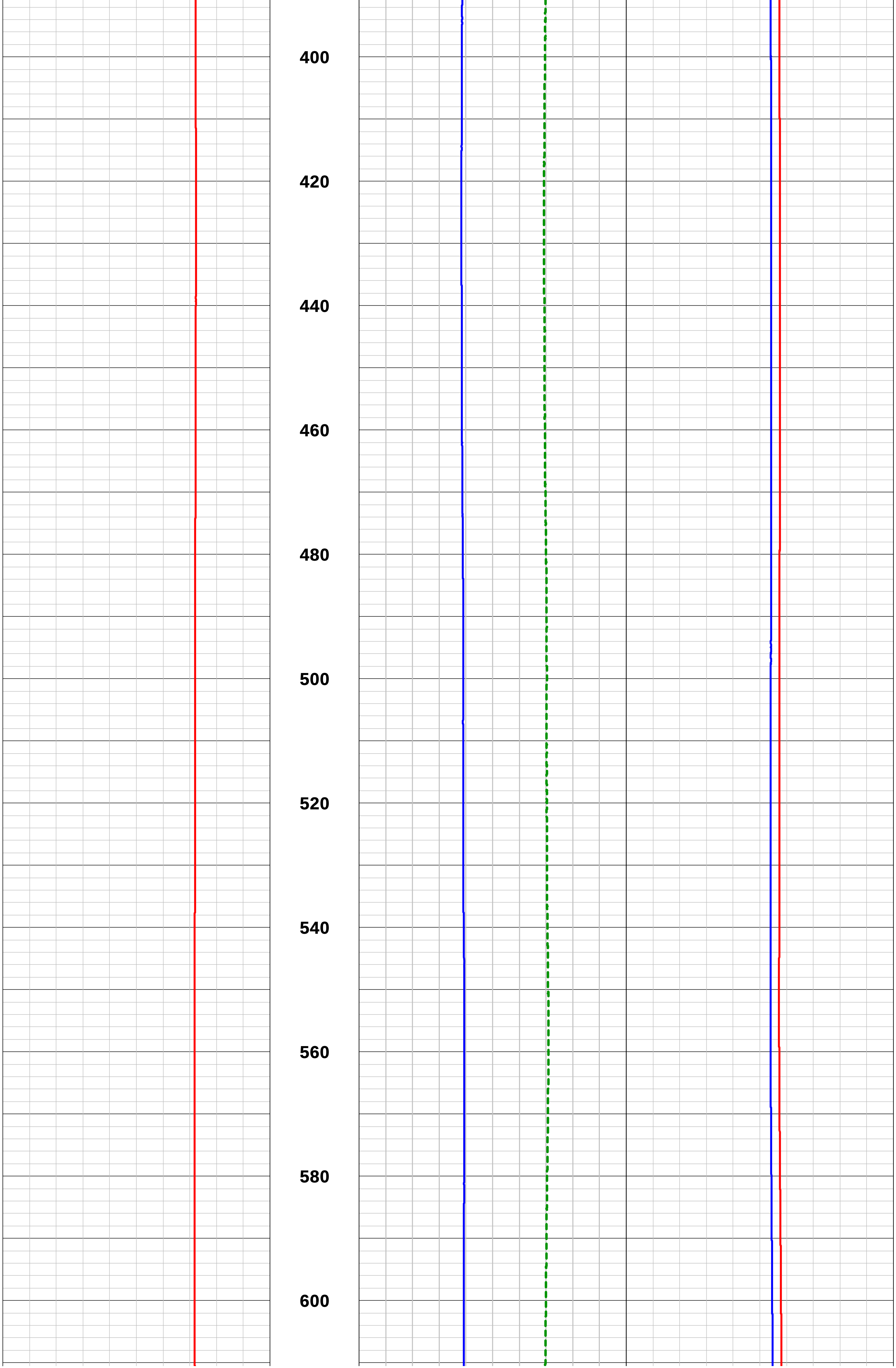

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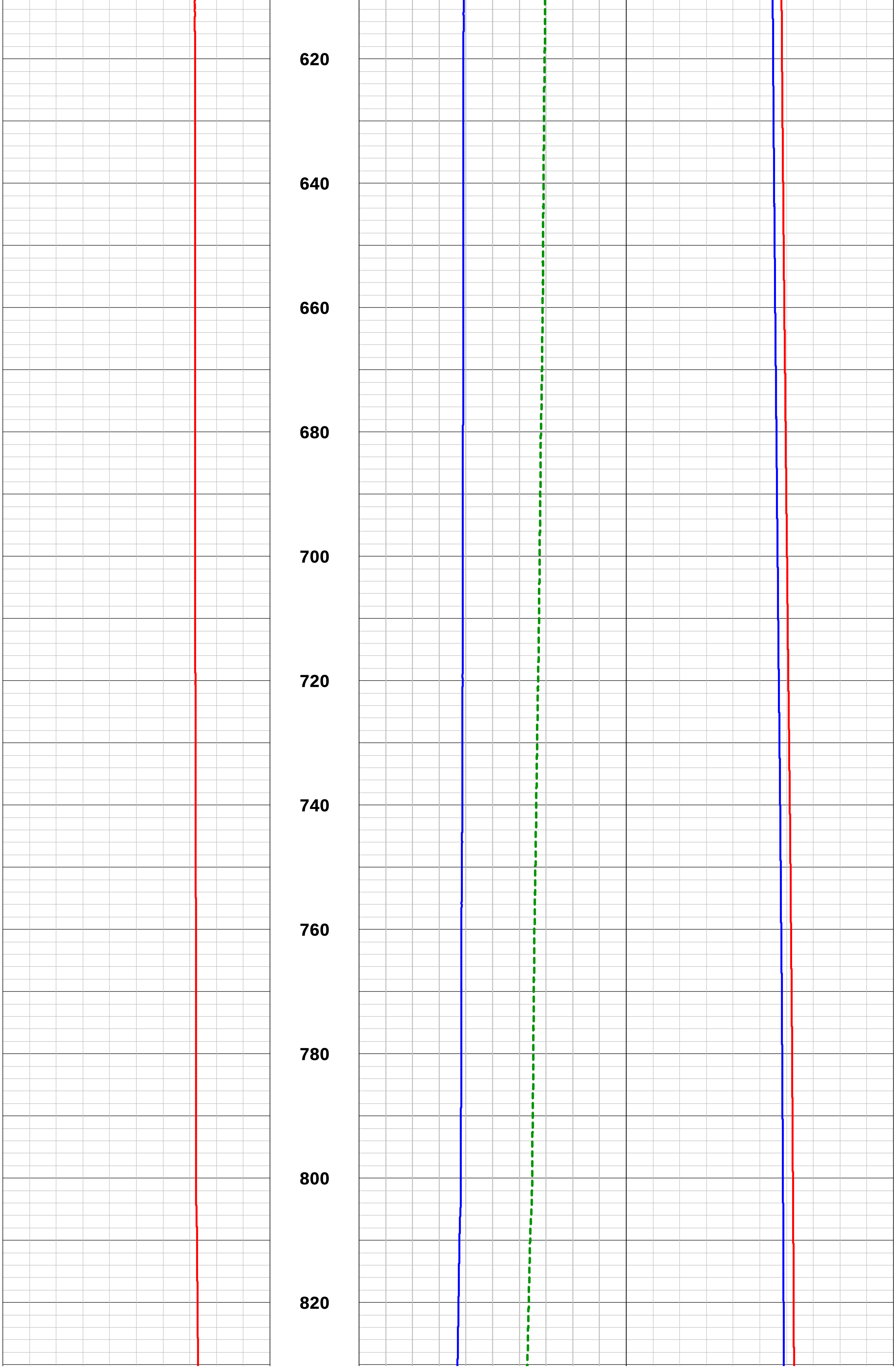
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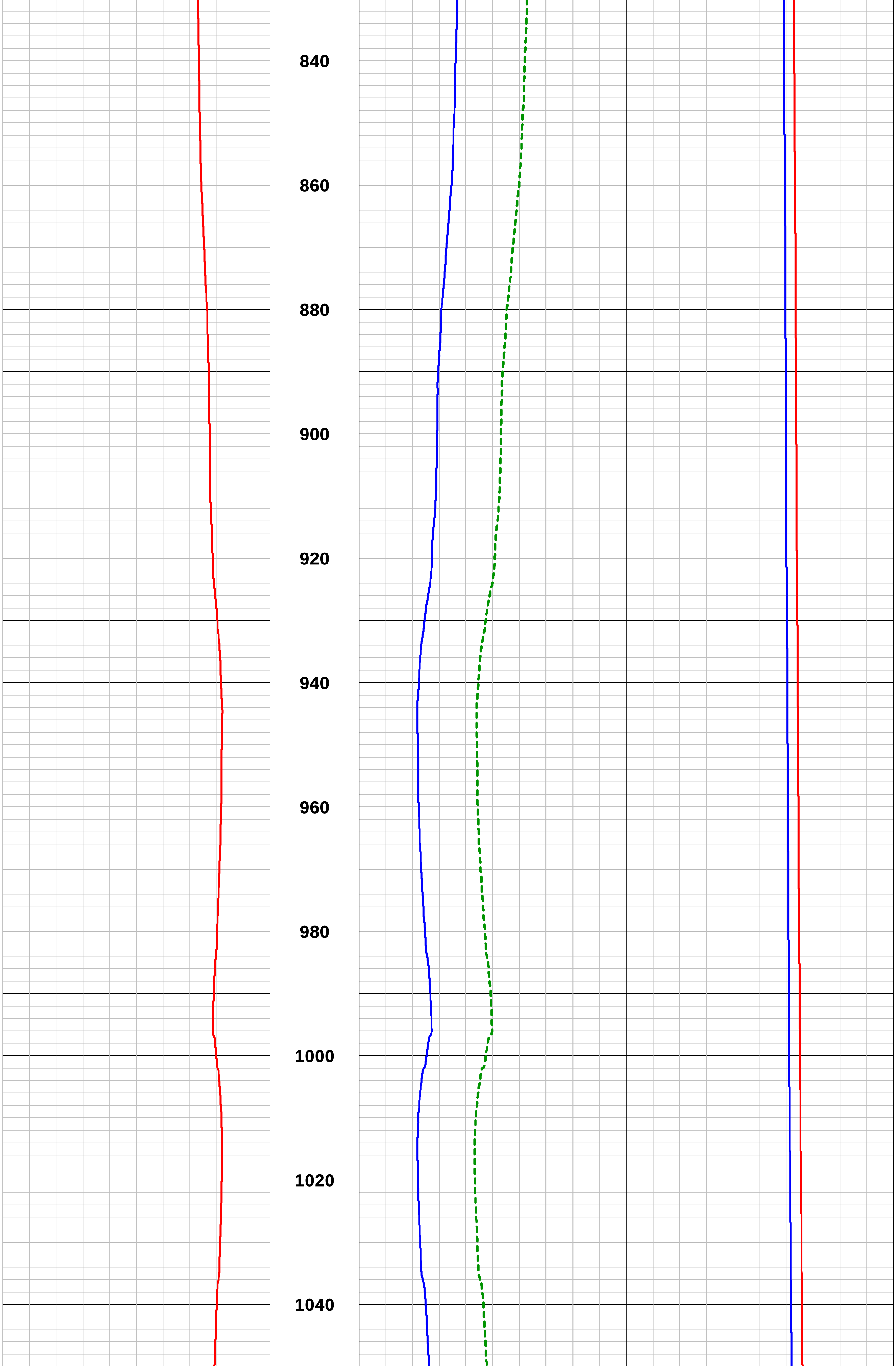
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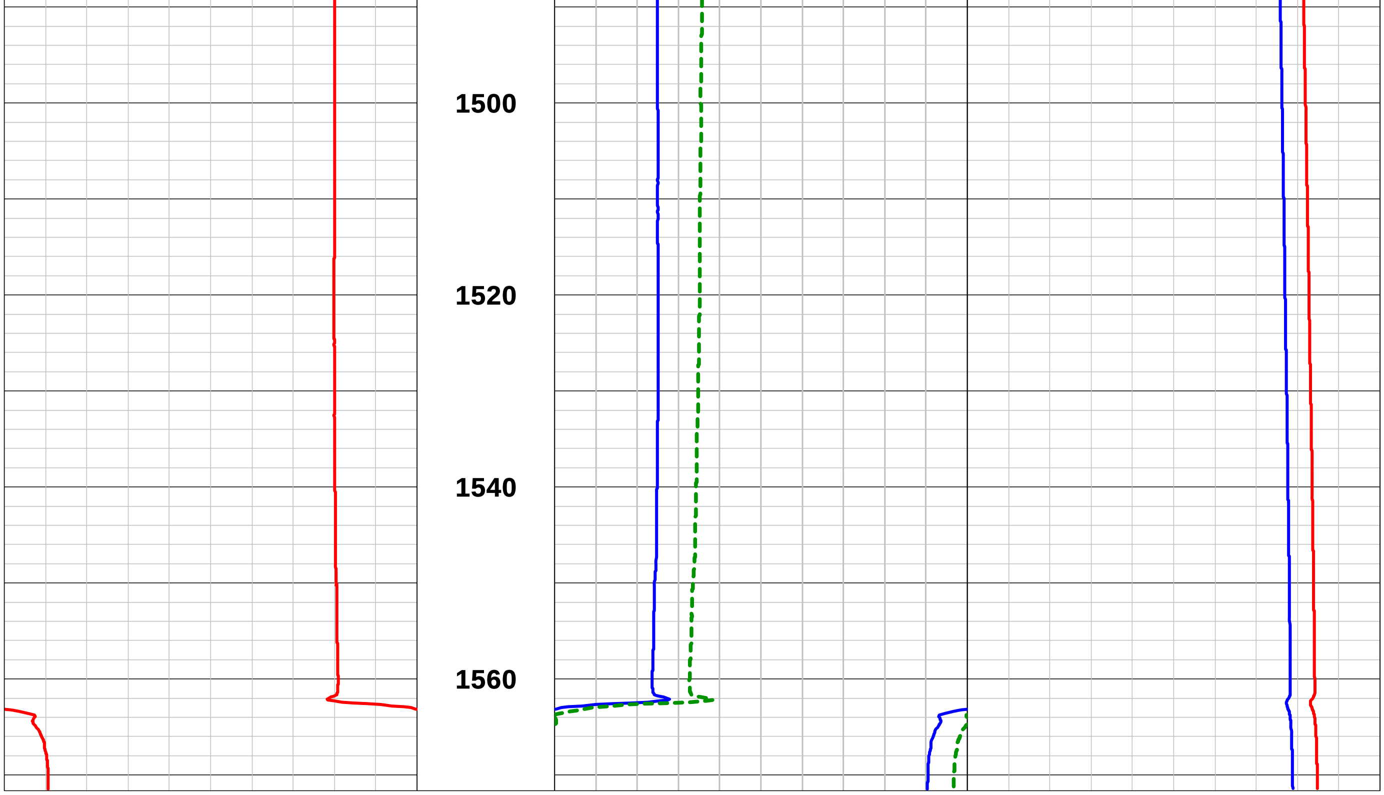
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1520
1540
1560

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Normal Resistivity
Natural Gamma
Spontaneous Potential

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Lat: 48.10353 Long: -114.18193

QTR SE1/4SE1/4 **SEC** 18 **TWP** 27N **RGE** 20W

OTHER SERVICES
3 Arm Caliper
Full Waveform Sonic
Magnetic Resonance
Fluid Temperature &
Conductivity
Neutron
Density

PERMANENT DATUM NA **ELEVATION** 2907.64
LOG MEAS. FROM Ground Surface NA **ABOVE PERMANENT DATUM**
DRILLING MEAS. FROM Ground Surface

DATE ACQUIRED	8 Oct 2021			
RUN NUMBER	Two			
LOG TYPE	Caliper			
DEPTH-DRILLER	1600.0'			
DEPTH-LOGGER	1575.0'			
BTM LOG INTERVAL	1575.0			
TOP LOG INTERVAL	540.0			
RECORDED BY	N. Welsh, M. Culig			
WITNESSED BY	A. Bobst			
PROBE TYPE, S/N	ELTG 5875			
LOGGING SPEED	40 ft/min			
A.S.D.E./Sample Interval	2.89' / .1'			
Fluid Level/Fluid Type	10' / WBM			

BOREHOLE RECORD				CASING RECORD			
RUN No.	**BIT**	**FROM**	**TO**	**SIZE**	**WGT.**	**FROM**	**TO**
One	9.25"	540.0'	1600.0'	10"	Steel	0.0'	540.0'
				12"	Steel	0.0'	380.0'

COMMENTS

NA - Not Available, N/A - Not Applicable

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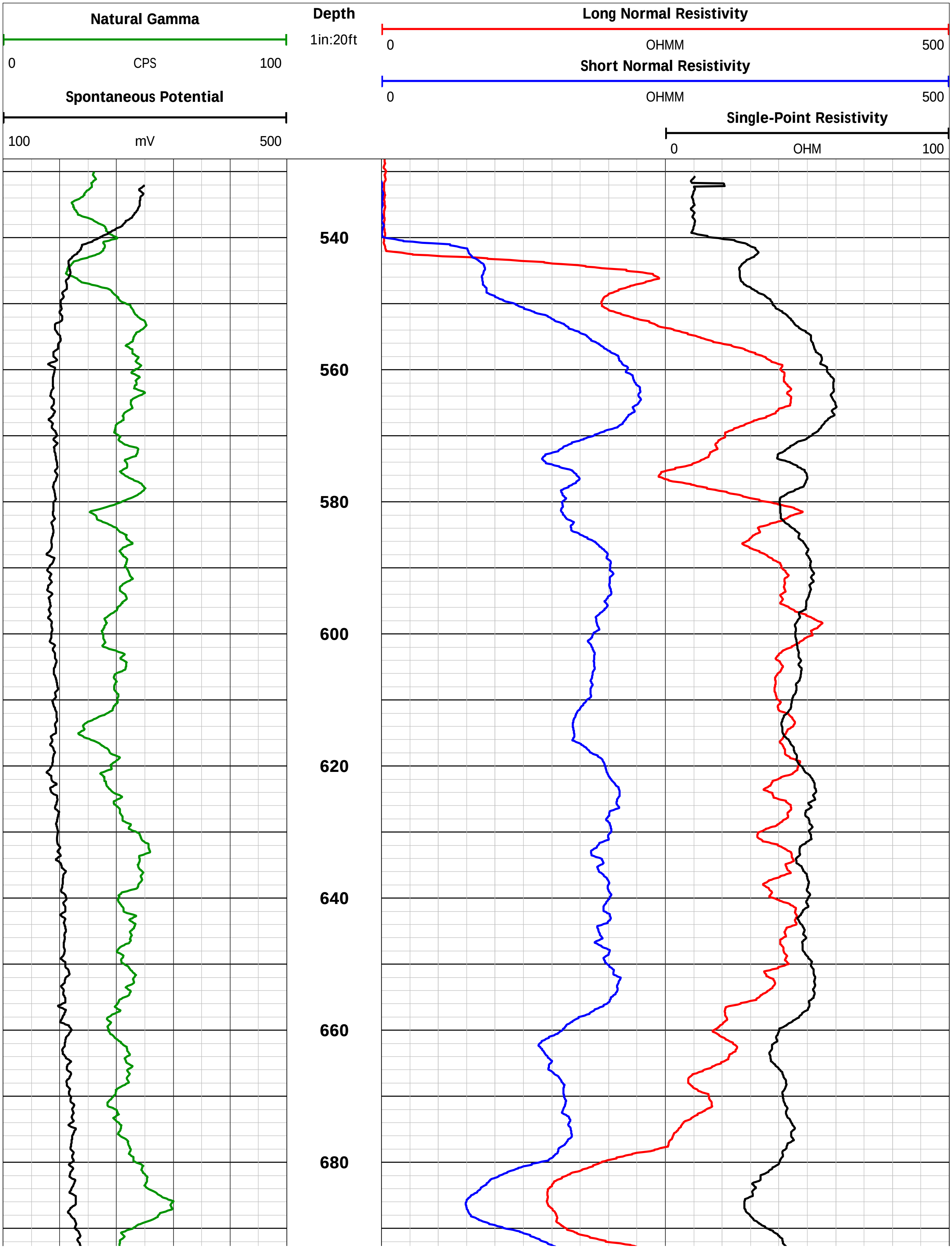
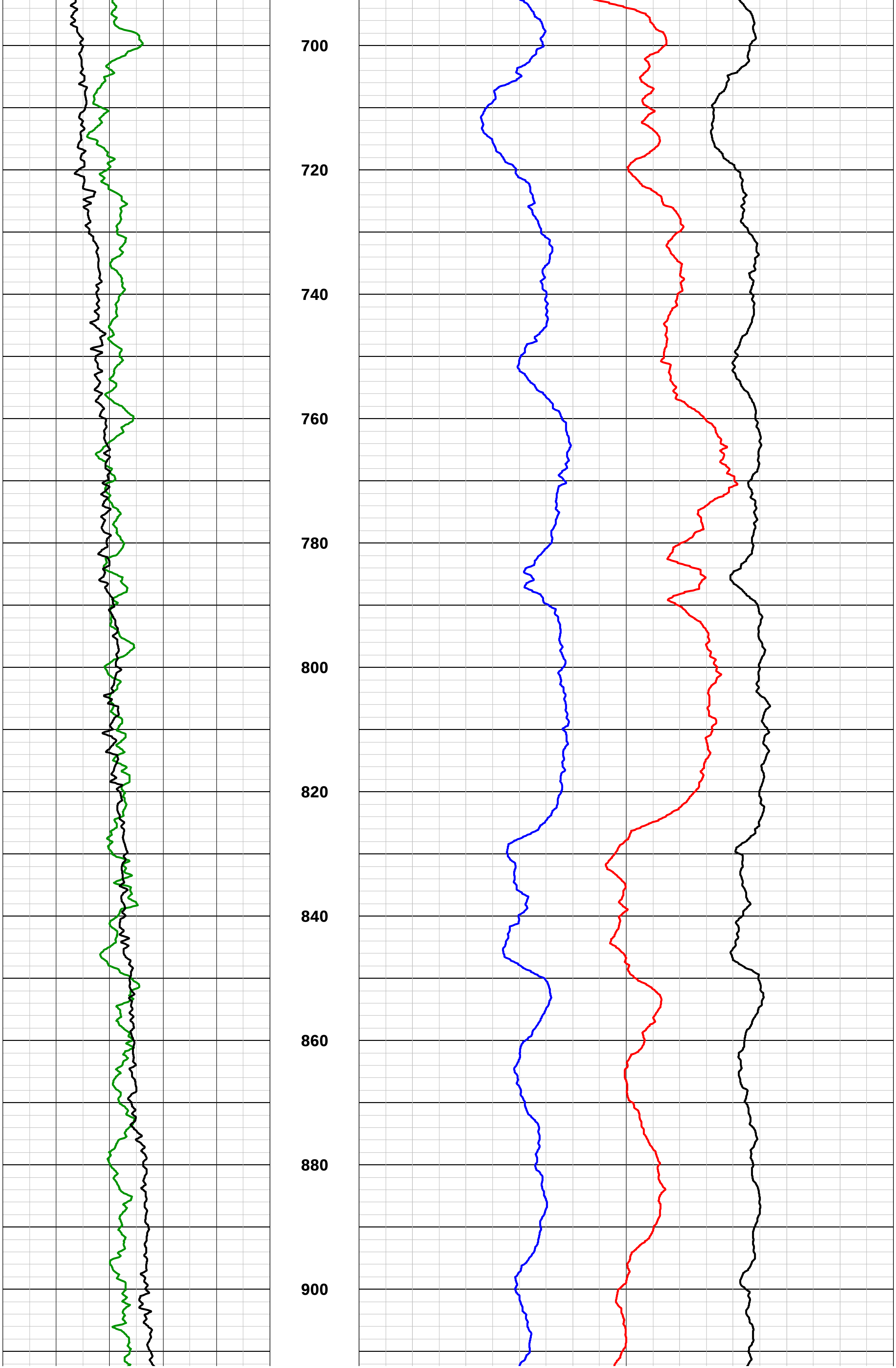
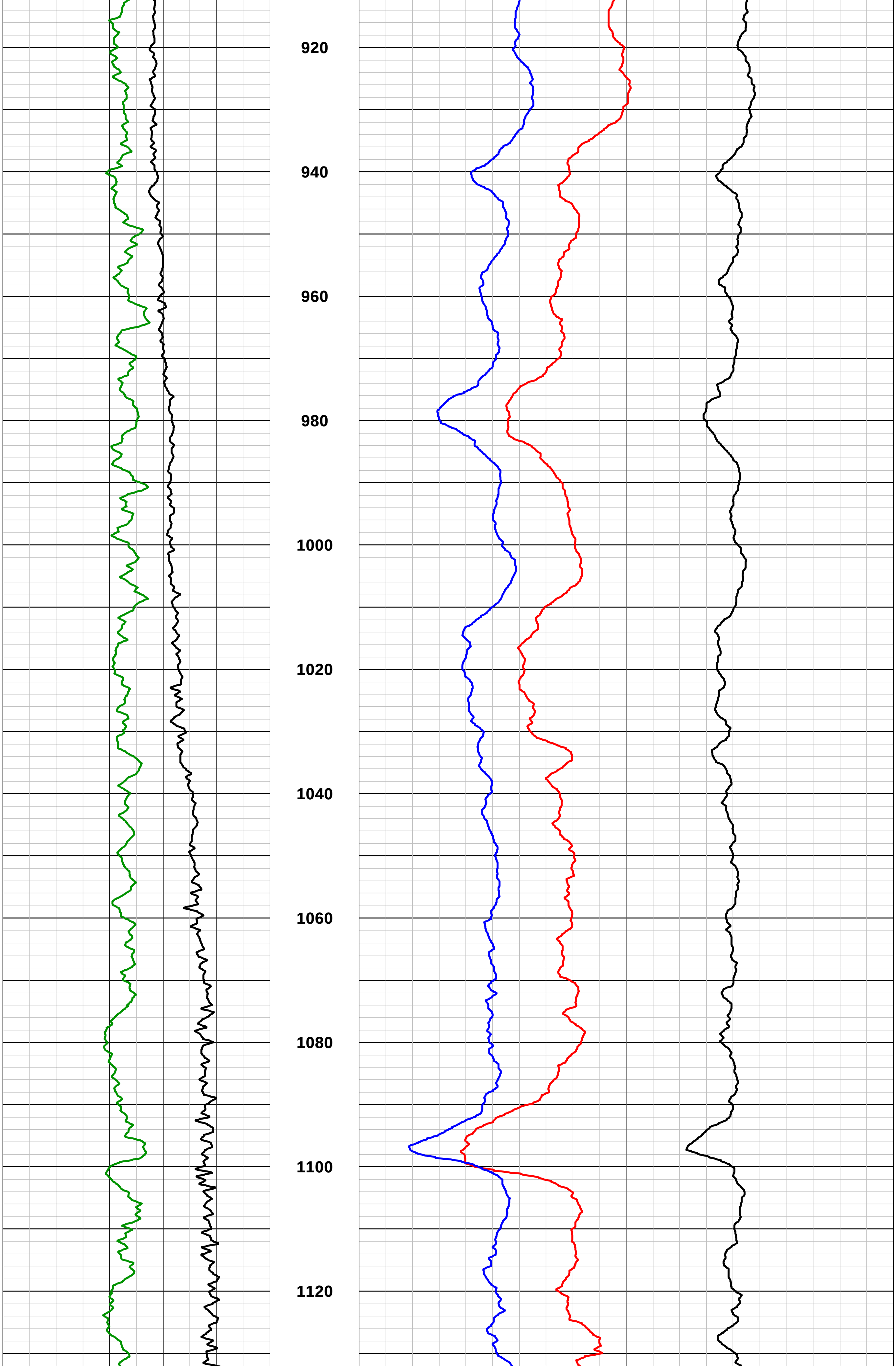
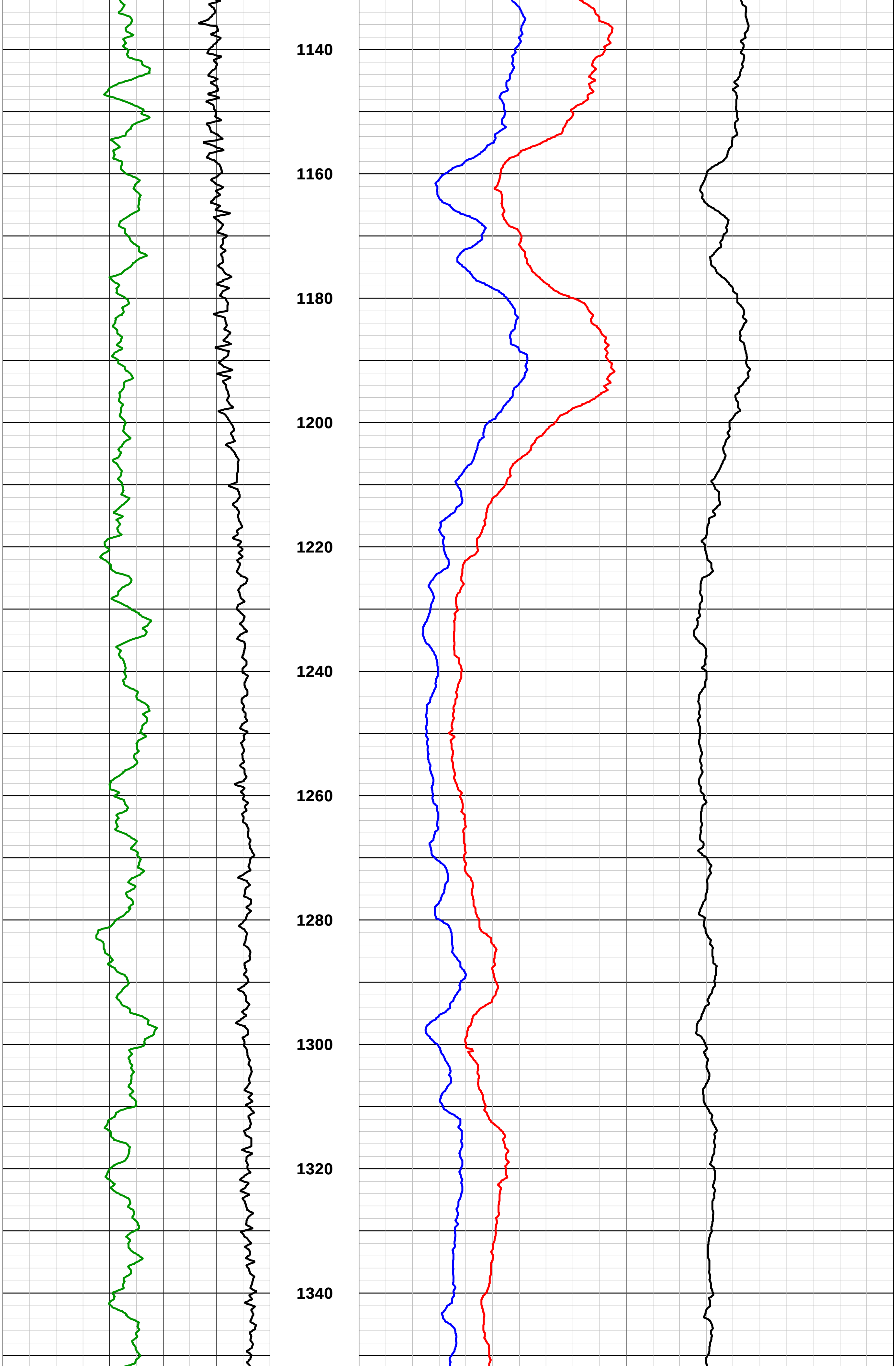
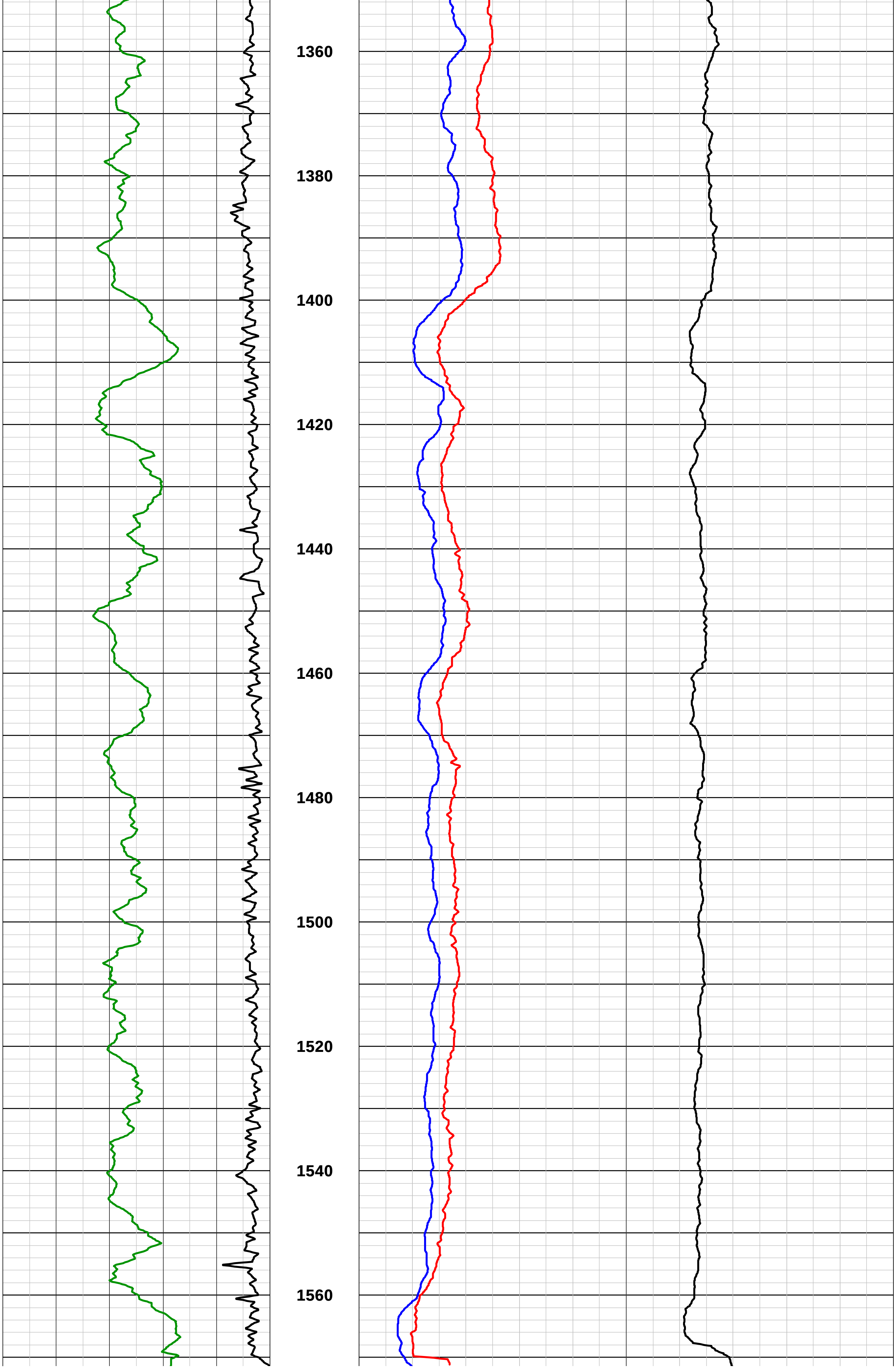
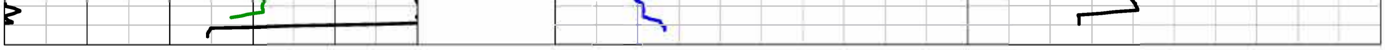

Natural Gamma
0
CPS
100
Spontaneous Potential
100
mV
500
Depth
1in:20ft
Long Normal Resistivity
0
OHMM
500
Short Normal Resistivity
0
OHMM
500
Single-Point Resistivity
0
OHM
100
540
560
580
600
620
640
660
680


700
720
740
760
780
800
820
840
860
880
900


920
940
960
980
1000
1020
1040
1060
1080
1100
1120


1140
1160
1180
1200
1220
1240
1260
1280
1300
1320
1340


1360
1380
1400
1420
1440
1460
1480
1500
1520
1540
1560



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Three Arm Caliper

Natural Gamma

w/Volume Print

Company Montana Tech
Well BFF#5
Project FVDeep
County Flathead
State Montana

COMPANY	Montana Tech
WELL	BFF#5
PROJECT	FVDeep
COUNTY	Flathead
STATE	MT

LOCATION
Lat: 48.10353 Long: -114.18193

QTR SE1/4SE1/4 **SEC** 18 **TWP** 27N **RGE** 20W

OTHER SERVICES
Normal Resistivity
Full Waveform Sonic
Magnetic Resonance
Fluid Temperature & Conductivity
Neutron
Density
Gyro

PERMANENT DATUM NA **ELEVATION** 2907.64

LOG MEAS. FROM Ground Surface NA **ABOVE PERMANENT DATUM**

DRILLING MEAS. FROM Ground Surface

DATE ACQUIRED	8 Oct 2021			
RUN NUMBER	One			
LOG TYPE	Caliper			
DEPTH-DRILLER	1600.0'			
DEPTH-LOGGER	1575.0'			
BTM LOG INTERVAL	1575.0			
TOP LOG INTERVAL	11.0'			
RECORDED BY	N. Welsh, M. Culig			
WITNESSED BY	A. Bobst			
PROBE TYPE, S/N	3ACS 117333			
LOGGING SPEED	40 ft/min			
A.S.D.E./Sample Interval	3.86' / .1'			
Fluid Level/Fluid Type	10' / WBM			

BOREHOLE RECORD				CASING RECORD			
RUN No.	**BIT**	**FROM**	**TO**	**SIZE**	**WGT.**	**FROM**	**TO**
One	9.25"	540.0'	1600.0'	10"	Steel	0.0'	540.0'
				12"	Steel	0.0'	380.0'

COMMENTS

NA - Not Available, N/A - Not Applicable

Source File: MontanaTech_FVDeep_BFF#5_Cal-1UL.LOG

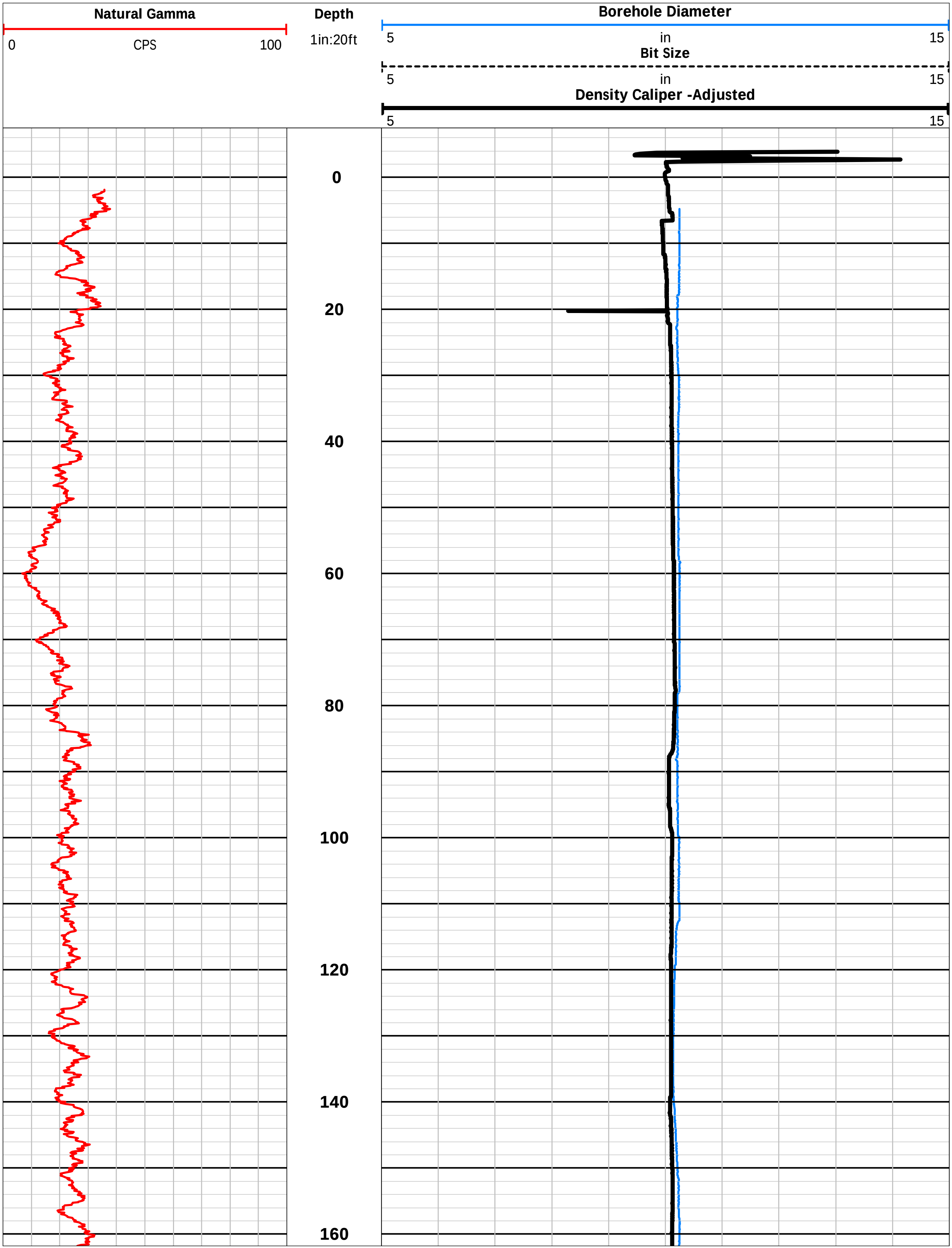
Future Casing of 6" used in volume calculation.

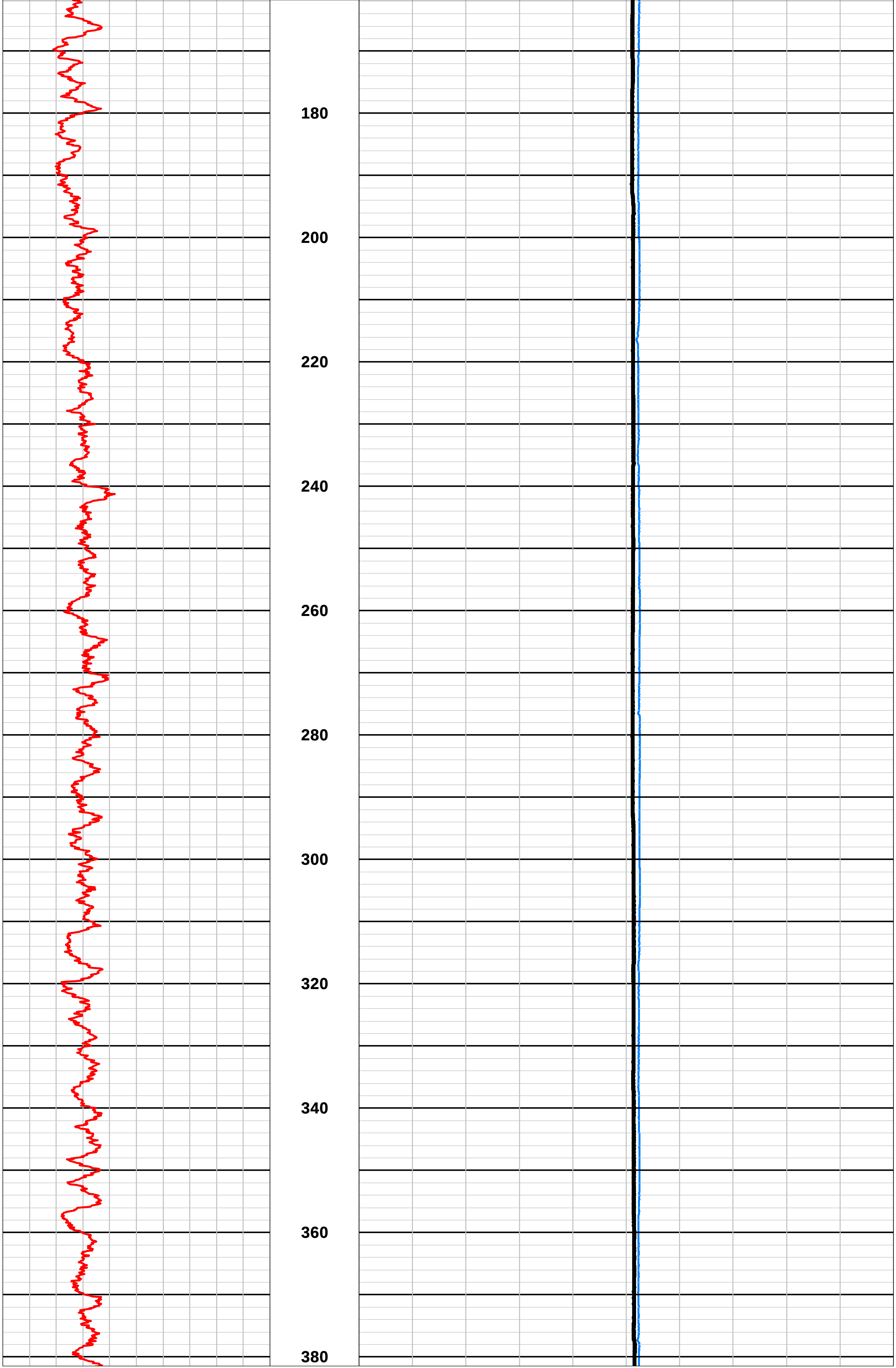
Natural Gamma logged to surface.

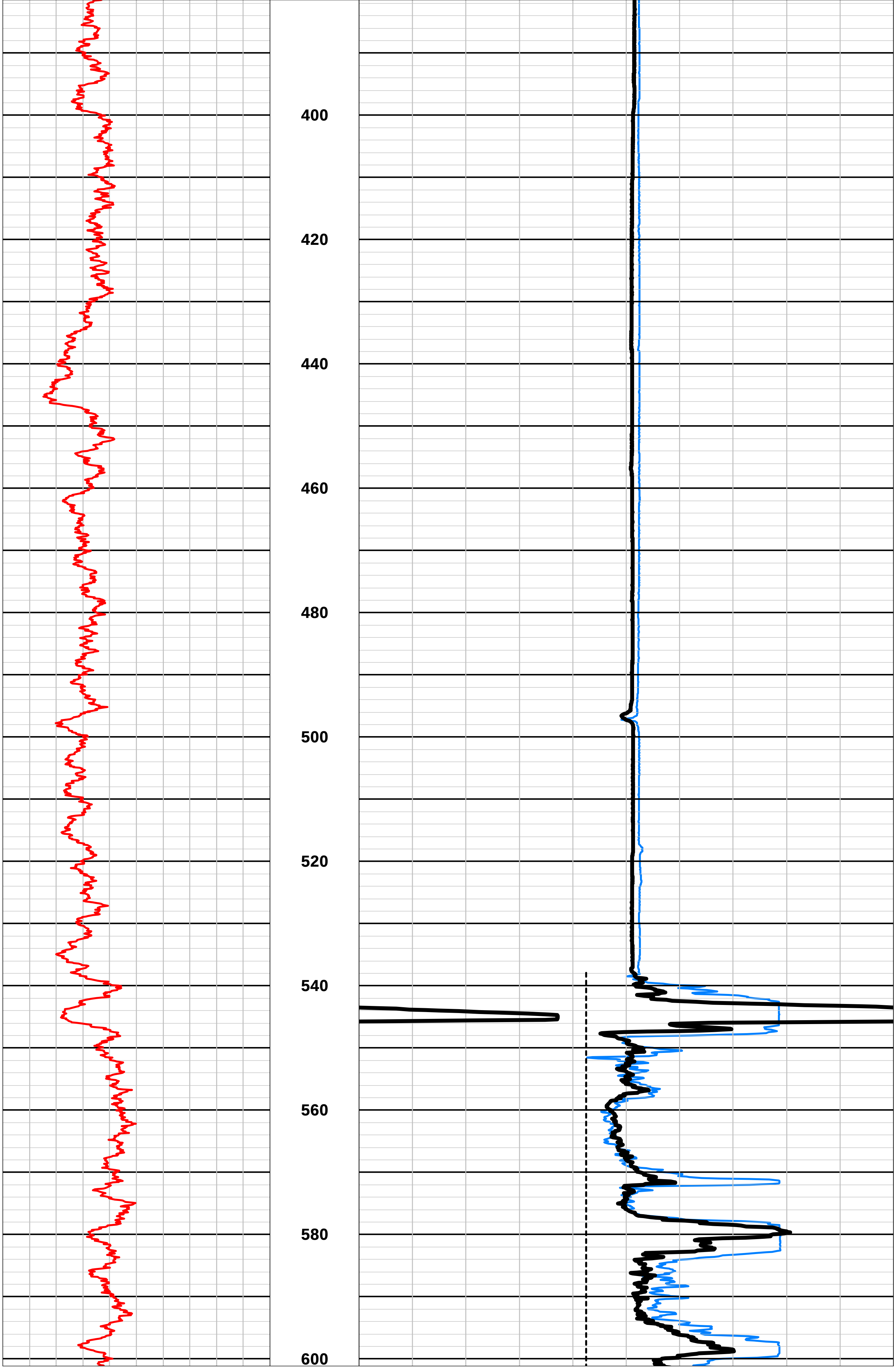
Total Annular Volume: 13.1167 cu. yd. , 354.086 cu. ft.

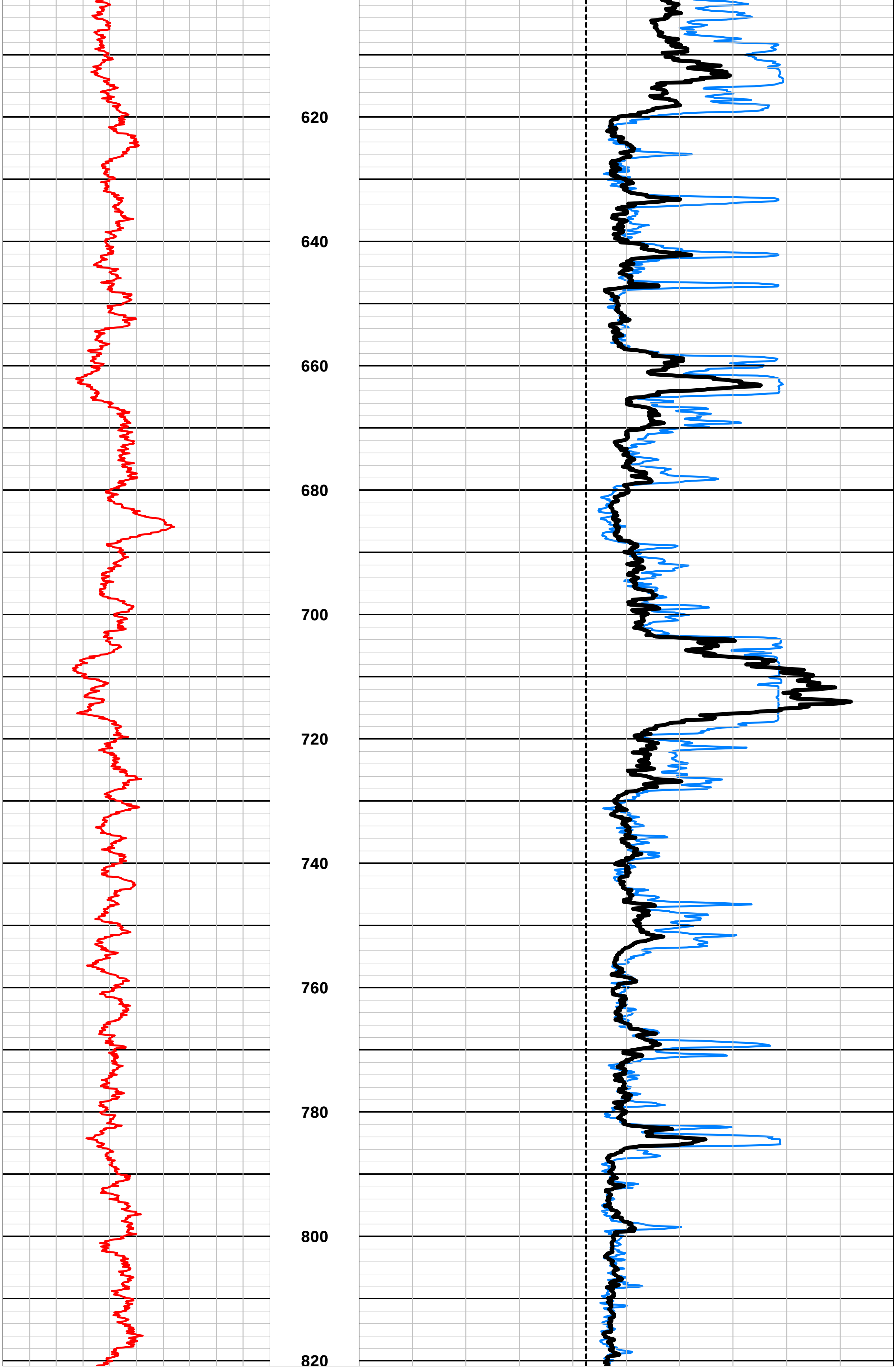
Small Ticks every 1 cu. ft. , Medium Ticks every 10 cu. ft, Large ticks every 100 cu. ft.

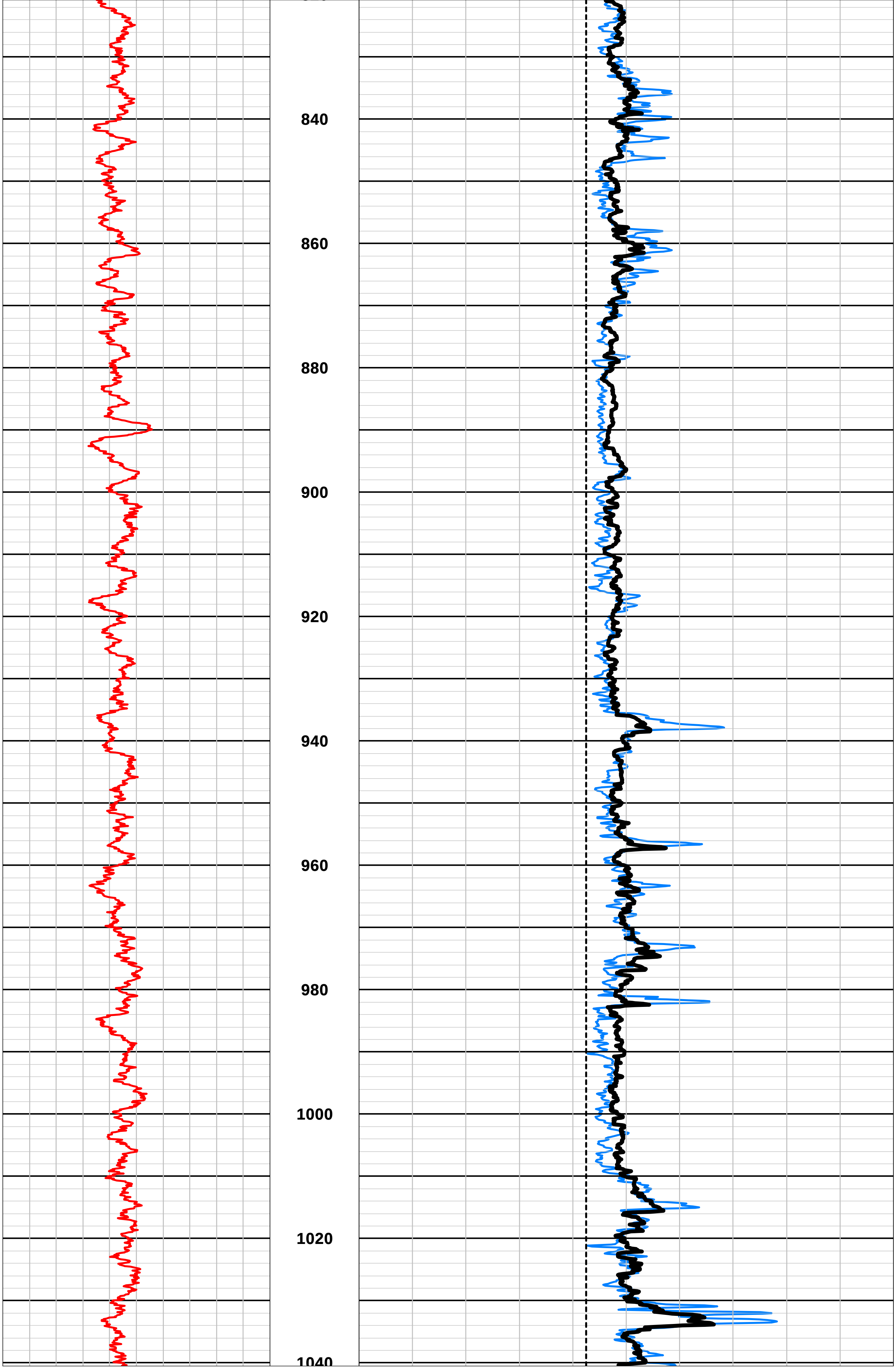
1 Arm Borehole Diameter from Density run last to see any changes in borehole shape.

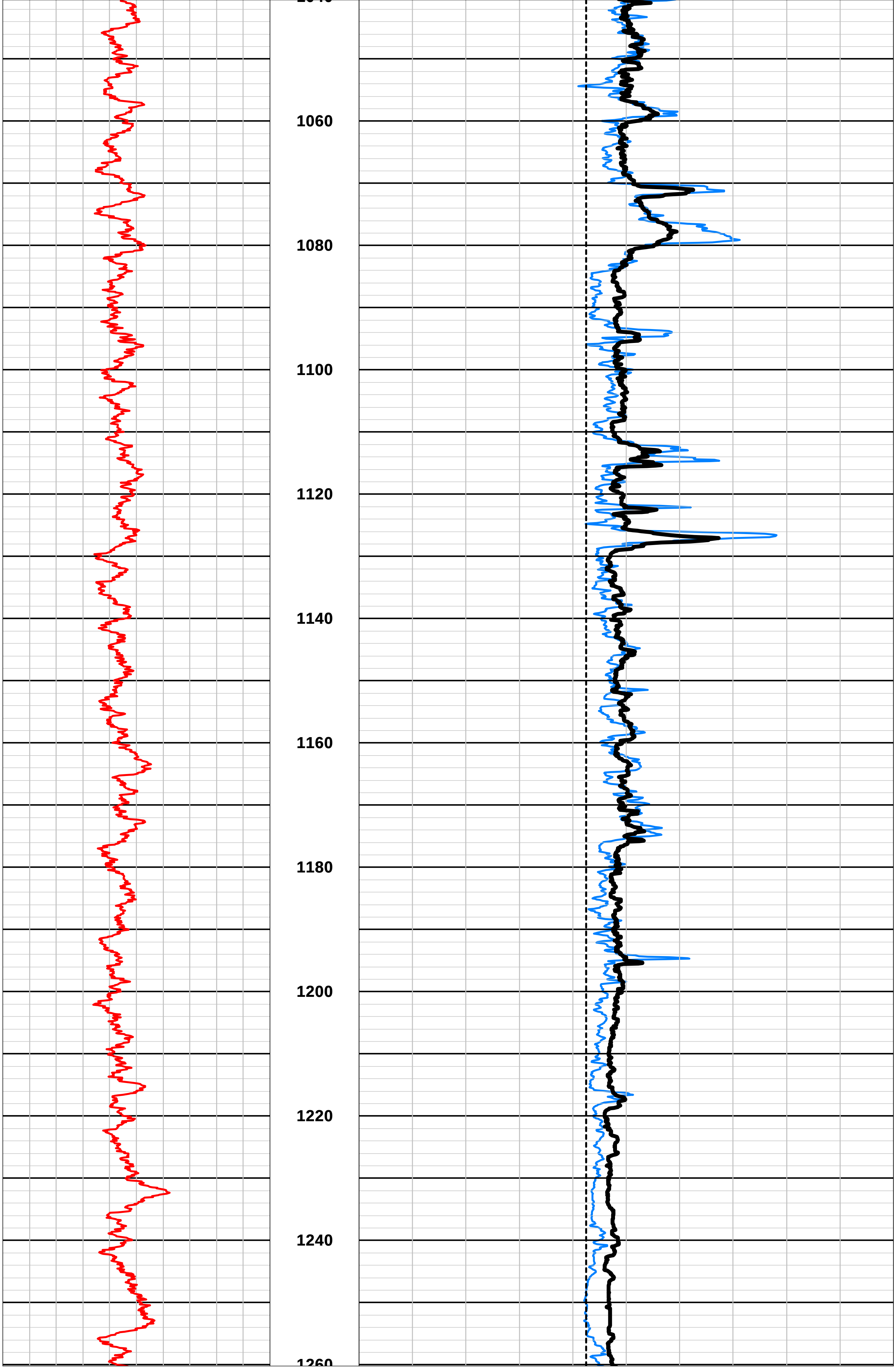

Natural Gamma
0
CPS
100
Depth
1in:20ft
Borehole Diameter
5
in
15
Bit Size
5
in
15
Density Caliper -Adjusted
5
15
0
20
40
60
80
100
120
140
160

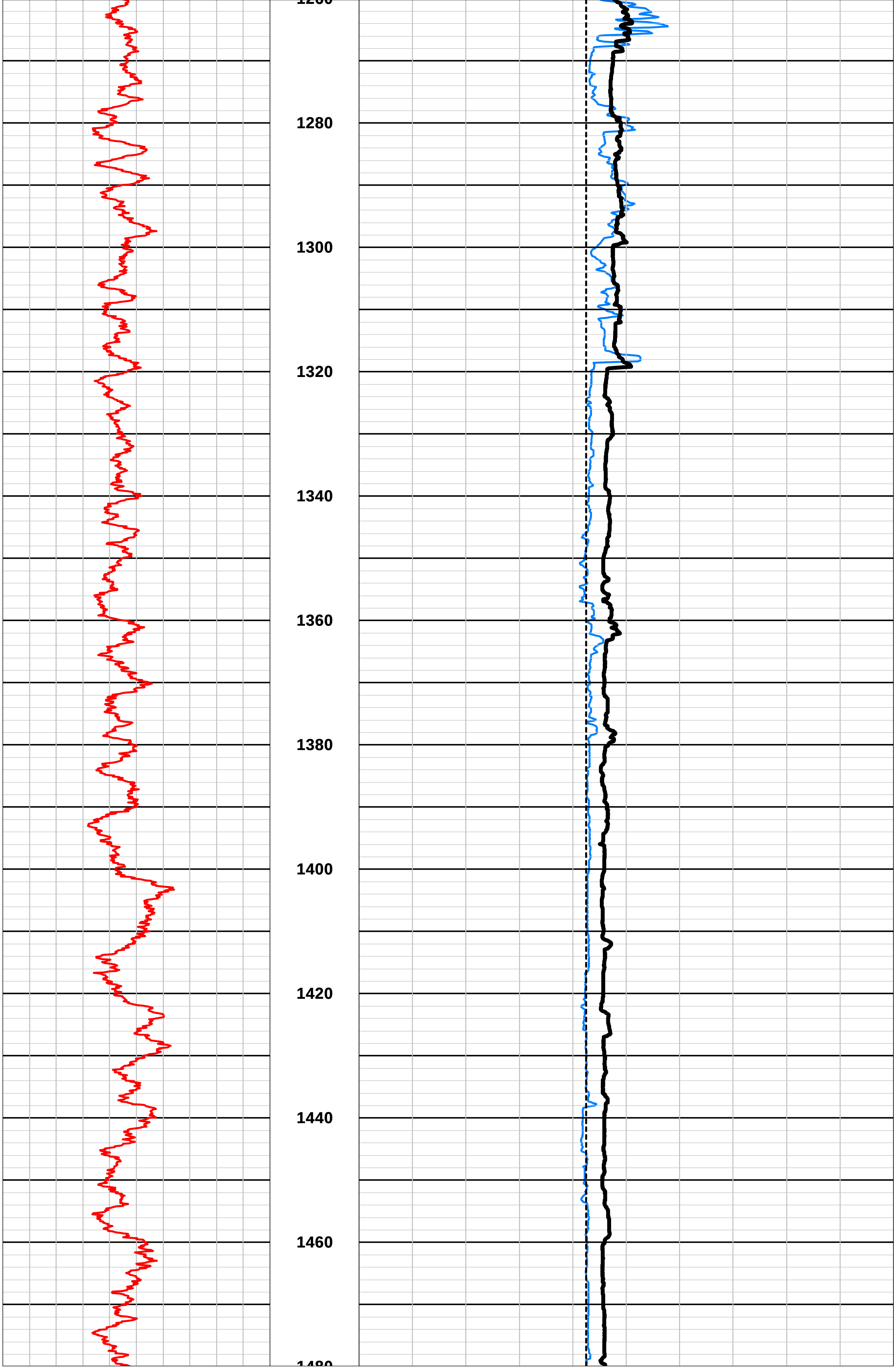

180
200
220
240
260
280
300
320
340
360
380

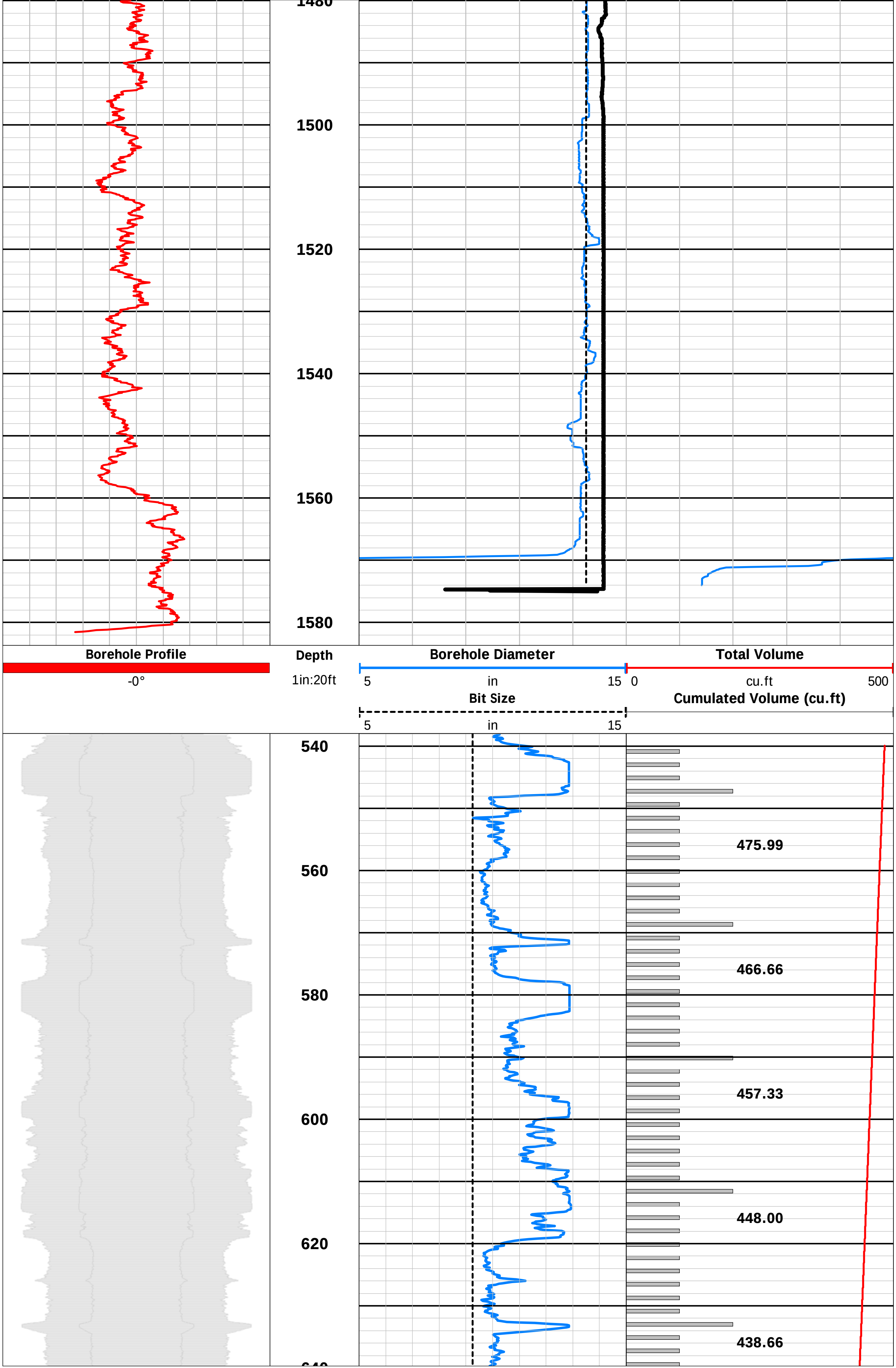

400
420
440
460
480
500
520
540
560
580
600

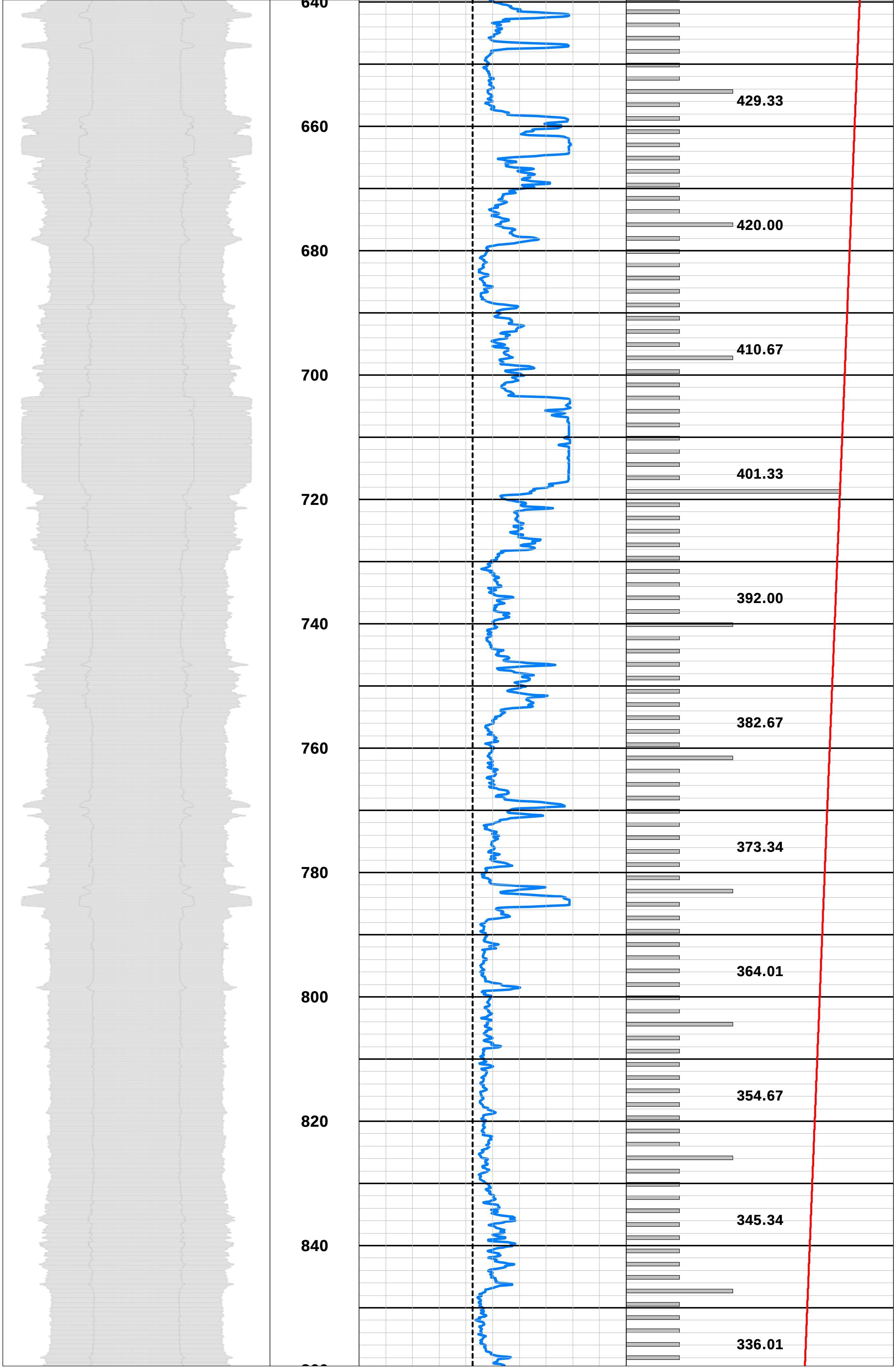

620
640
660
680
700
720
740
760
780
800
820

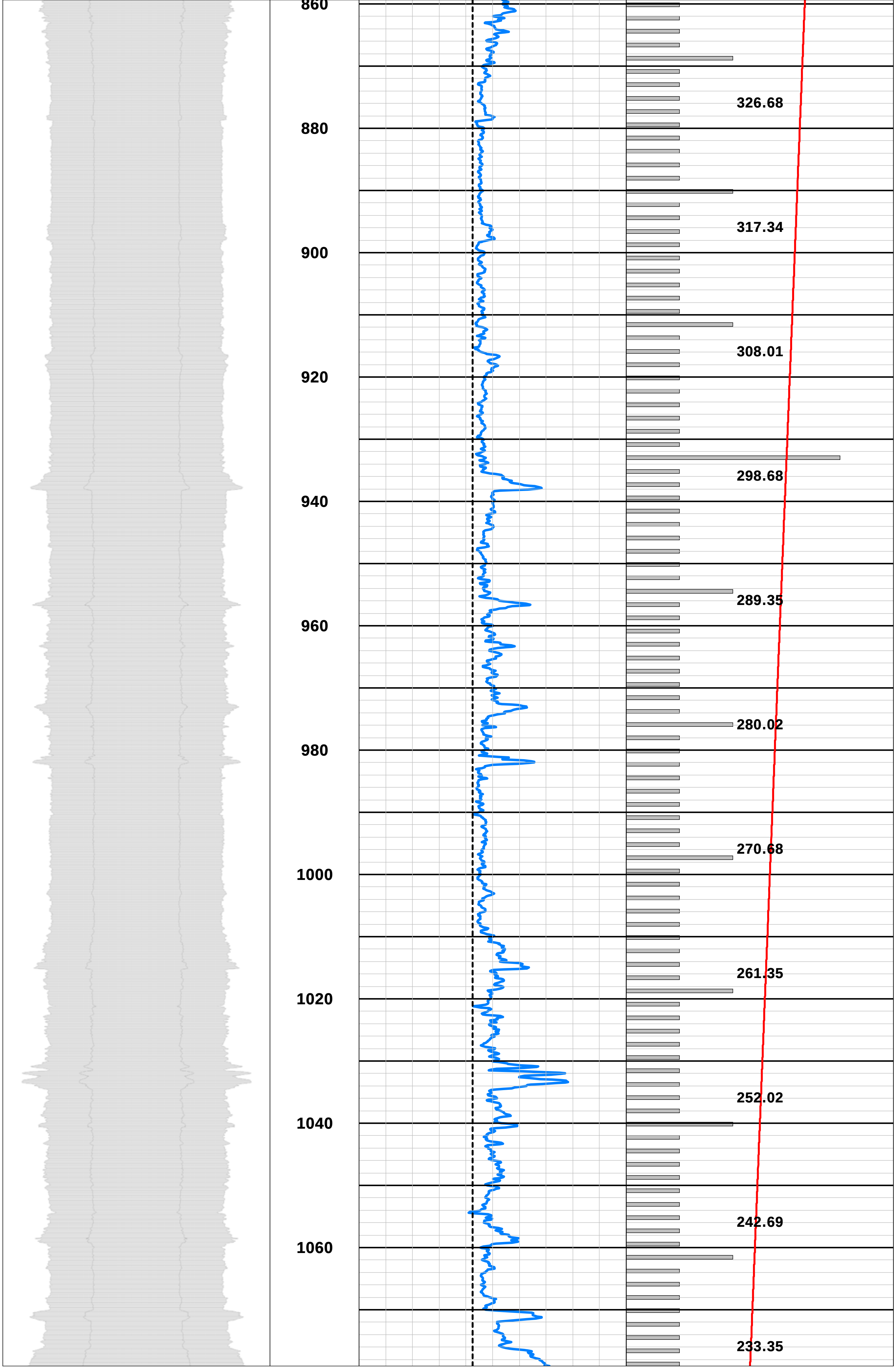

840
860
880
900
920
940
960
980
1000
1020
1040


1060
1080
1100
1120
1140
1160
1180
1200
1220
1240

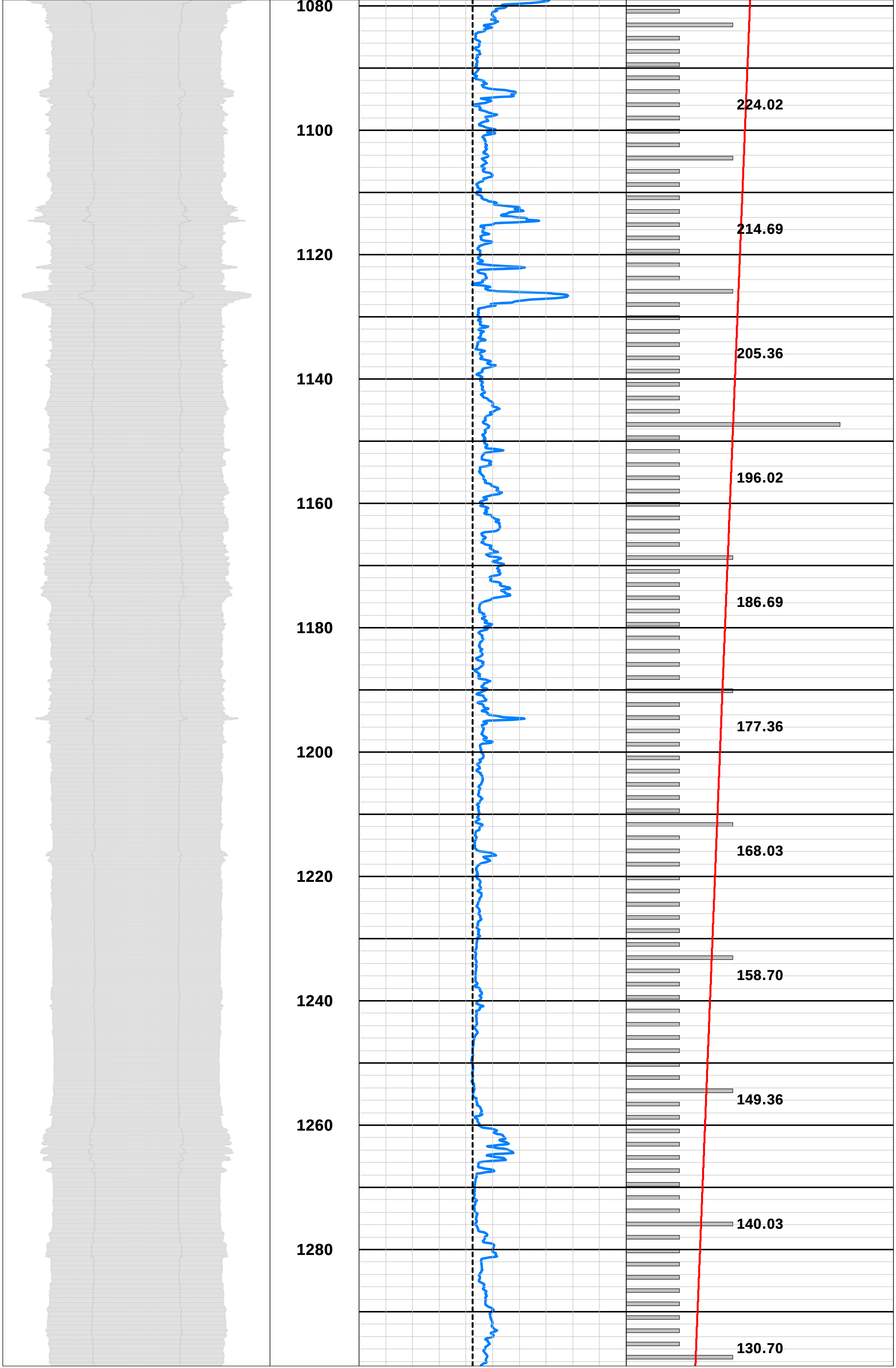

1280
1300
1320
1340
1360
1380
1400
1420
1440
1460

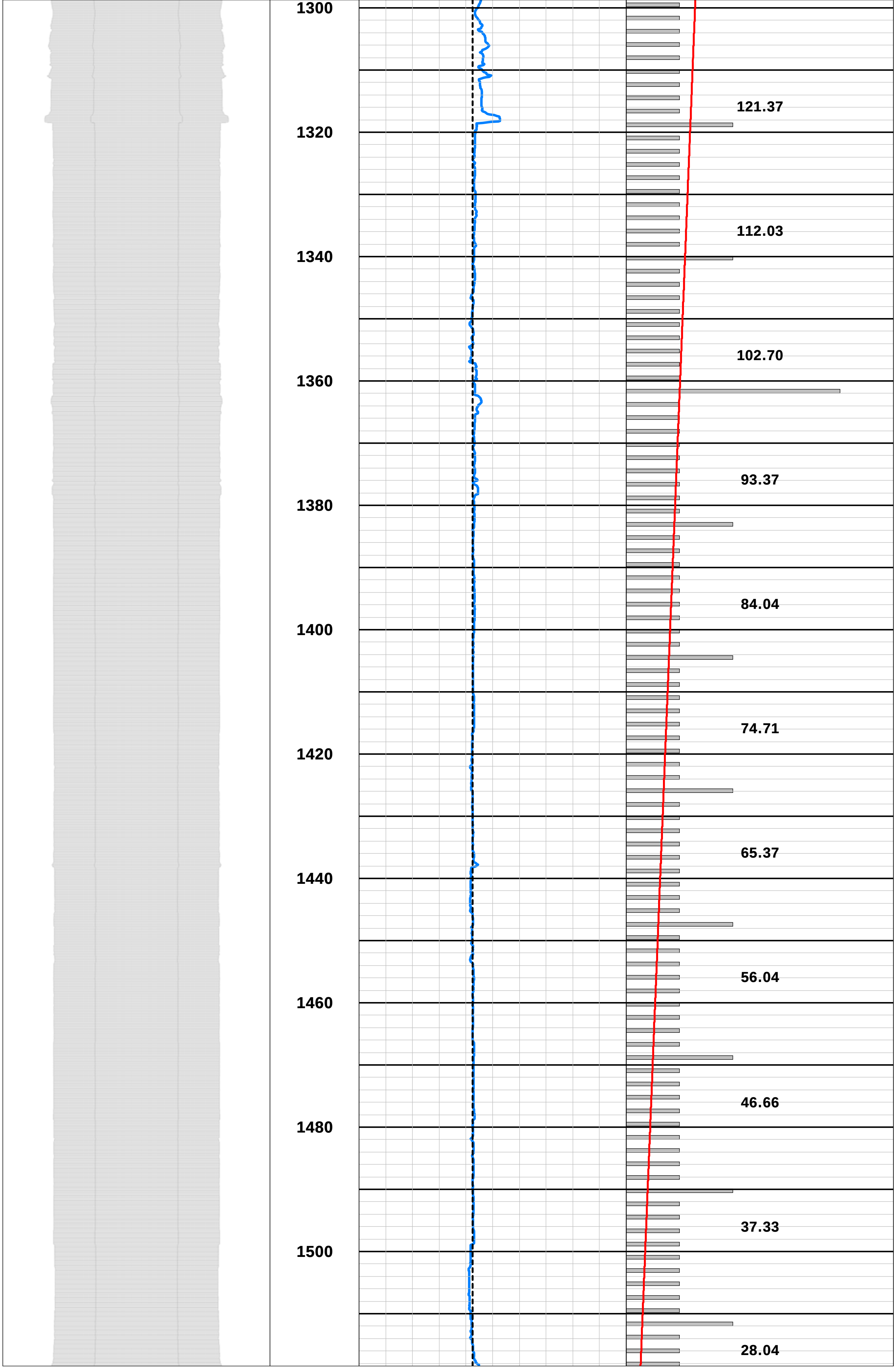

1500
1520
1540
1560
1580
Borehole Profile
-0°
Depth
1in:20ft
Borehole Diameter
5
in
15
Bit Size
5
in
15
Total Volume
0
cu.ft
500
Cumulated Volume (cu.ft)
540
560
580
600
620
475.99
466.66
457.33
448.00
438.66


660
680
700
720
740
760
780
800
820
840
429.33
420.00
410.67
401.33
392.00
382.67
373.34
364.01
354.67
345.34
336.01

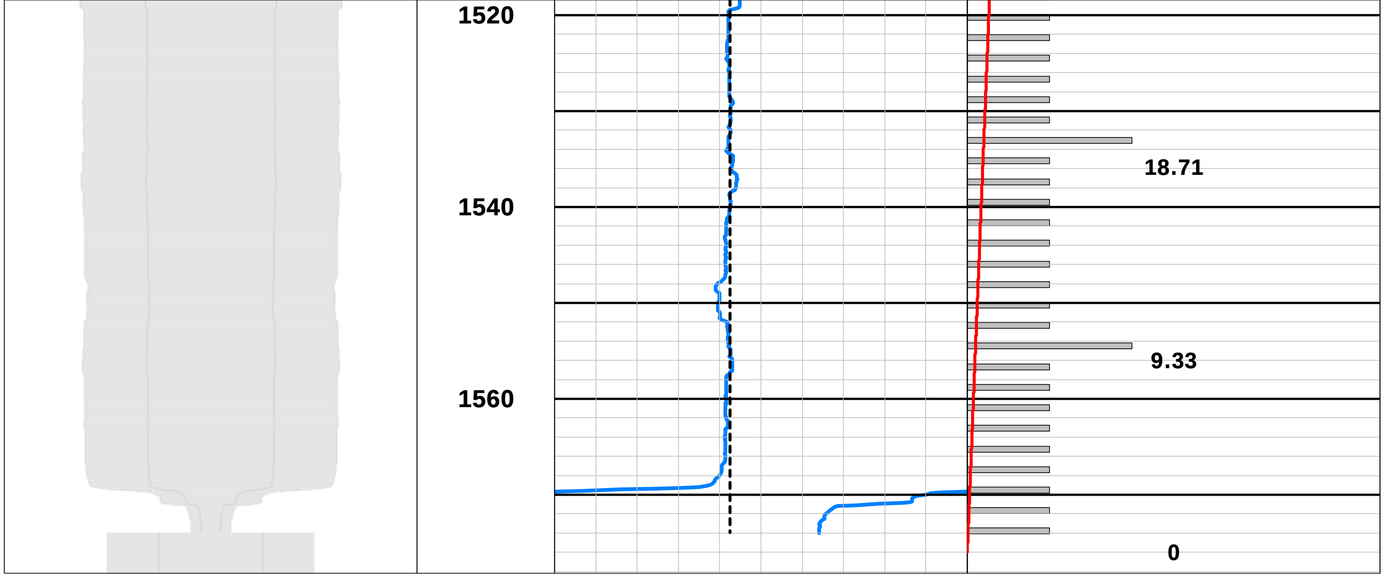


860
880
900
920
940
960
980
1000
1020
1040
1060
326.68
317.34
308.01
298.68
289.35
280.02
270.68
261.35
252.02
242.69
233.35


1080
224.02
1100
214.69
1120
205.36
1140
196.02
1160
186.69
1180
177.36
1200
168.03
1220
158.70
1240
149.36
1260
140.03
1280
130.70



1300
1320
1340
1360
1380
1400
1420
1440
1460
1480
1500
121.37
112.03
102.70
93.37
84.04
74.71
65.37
56.04
46.66
37.33
28.04


1520
1540
1560
18.71
9.33
0

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Neutron & Density

Company	Montana Tech
Well	BFF#5
Project	FVDeep
County	Flathead
State	Montana

COMPANY Montana Tech
WELL BFF#5
PROJECT FVDeep
COUNTY Flathead **STATE** MT

LOCATION
Lat: 48.10353 Long: -114.18193

QTR SE1/4SE1/4 **SEC** 18 **TWP** 27N **RGE** 20W

OTHER SERVICES
Normal Resistivity
Full Waveform Sonic
Magnetic Resonance
Fluid Temperature &
Conductivity
Neutron
Density
Three Arm Caliper
Natural Gamma

PERMANENT DATUM NA **ELEVATION** 2907.64

LOG MEAS. FROM Ground Surface NA **ABOVE PERMANENT DATUM**

DRILLING MEAS. FROM Ground Surface

DATE ACQUIRED	10 Oct 2021	10 Oct 2021		
RUN NUMBER	Six	Seven		
LOG TYPE	Neutron	Density		
DEPTH-DRILLER	1600.0'	1600.0'		
DEPTH-LOGGER	1575.0'	1575.0'		
BTM LOG INTERVAL	1575.0	1575.0		
TOP LOG INTERVAL	11.0'	11.0'		
RECORDED BY	N. Welsh, M. Culig	N. Welsh, M. Culig		
WITNESSED BY	A. Bobst	A. Bobst		
PROBE TYPE, S/N	Comprobe Slim, NSN	FDGS 5002		
LOGGING SPEED	40 ft/min	40 ft/min		
A.S.D.E./Sample Interval	3.1' / .1'	2.0/ .1'		
Fluid Level/Fluid Type	60" / WBM	60" / WBM		

BOREHOLE RECORD				**CASING RECORD**			
RUN No.	**BIT**	**FROM**	**TO**	**SIZE**	**WGT.**	**FROM**	**TO**
One	9.25"	540.0'	1600.0'	10"	Steel	0.0'	540.0'
				12"	Steel	0.0'	380.0'

COMMENTS

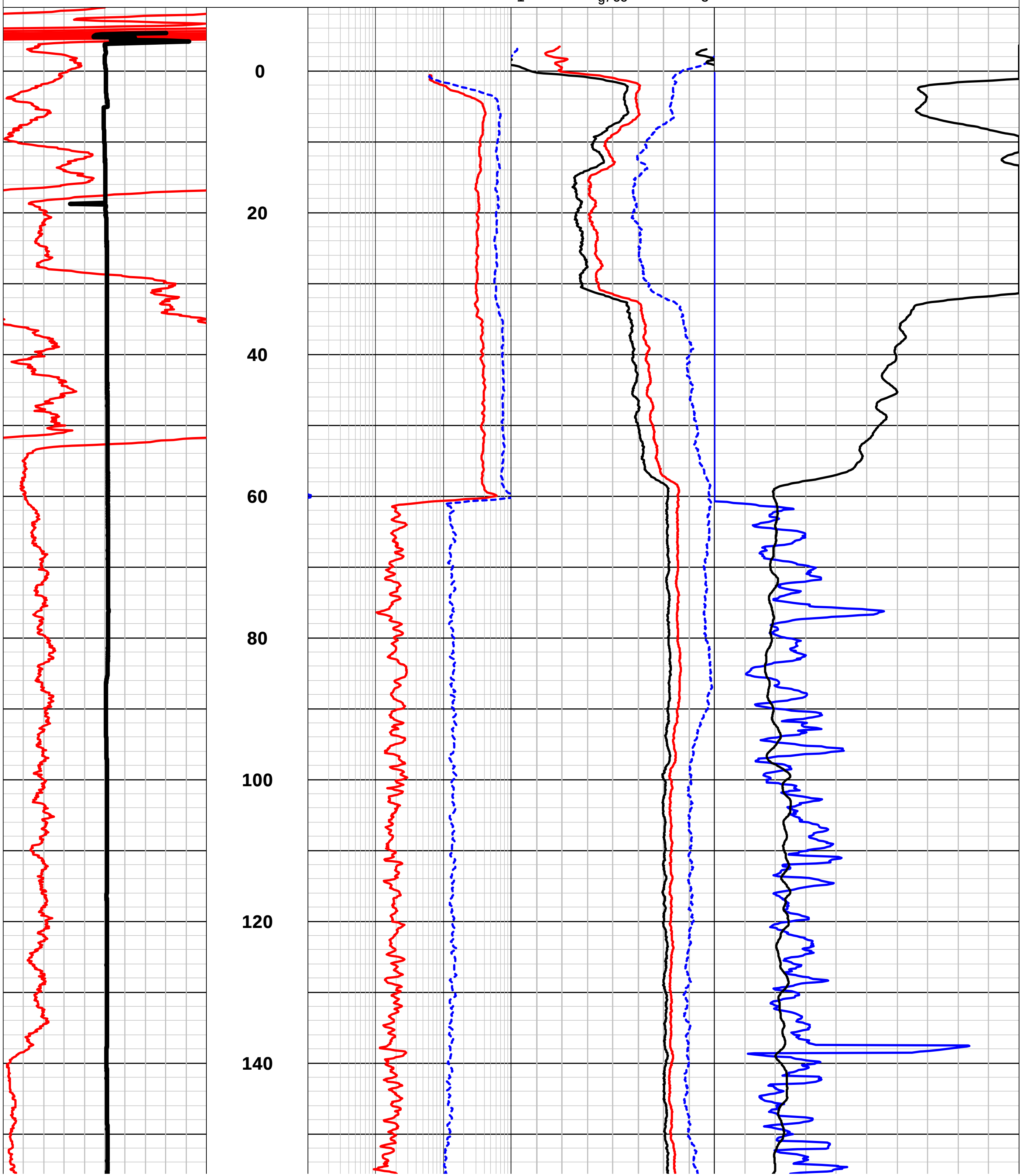
NA - Not Available, N/A - Not Applicable

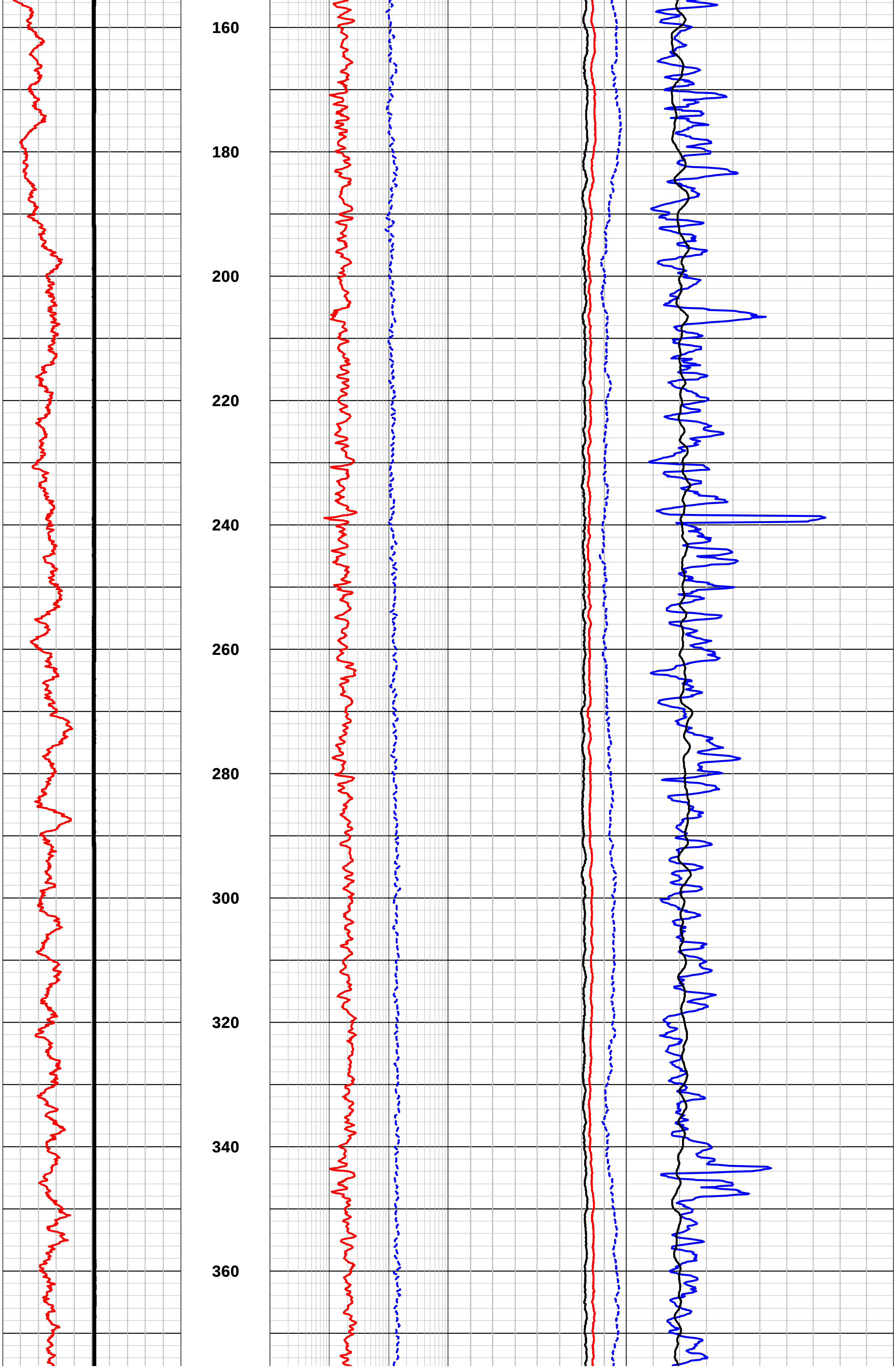
Source File: MontanaTech_FVDeep_BFF#5_Den-1UL.log, MontanaTech_FVDeep_BFF#5_Neu-Near-1UL.tdf, MontanaTech_FVDeep_BFF#5_Neu-Far-1UL.tdf,

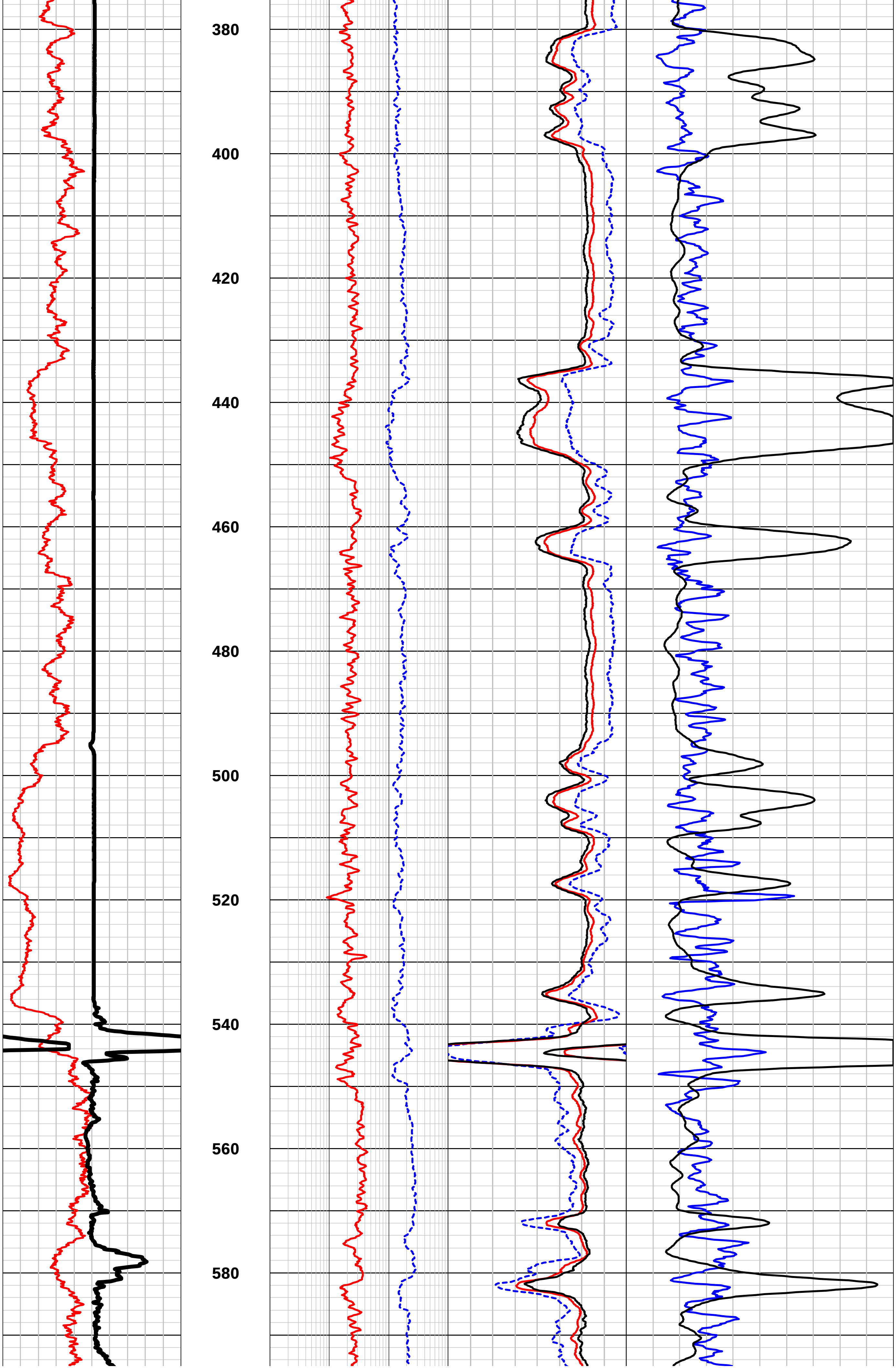
Formation matrix value of 2.71 used in porosity calculations.

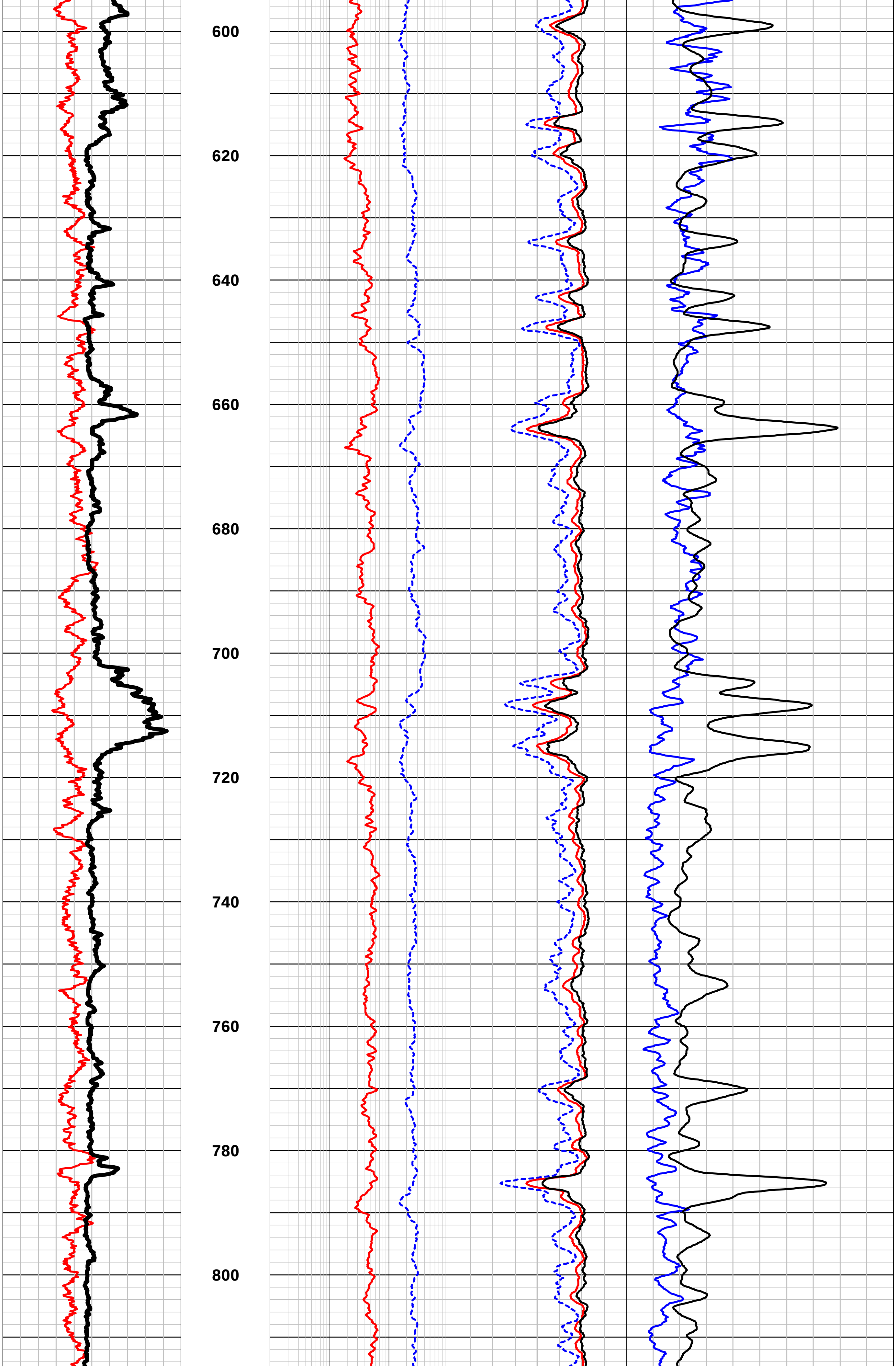
Neutron Porosity corrected -4% for standoff effect.

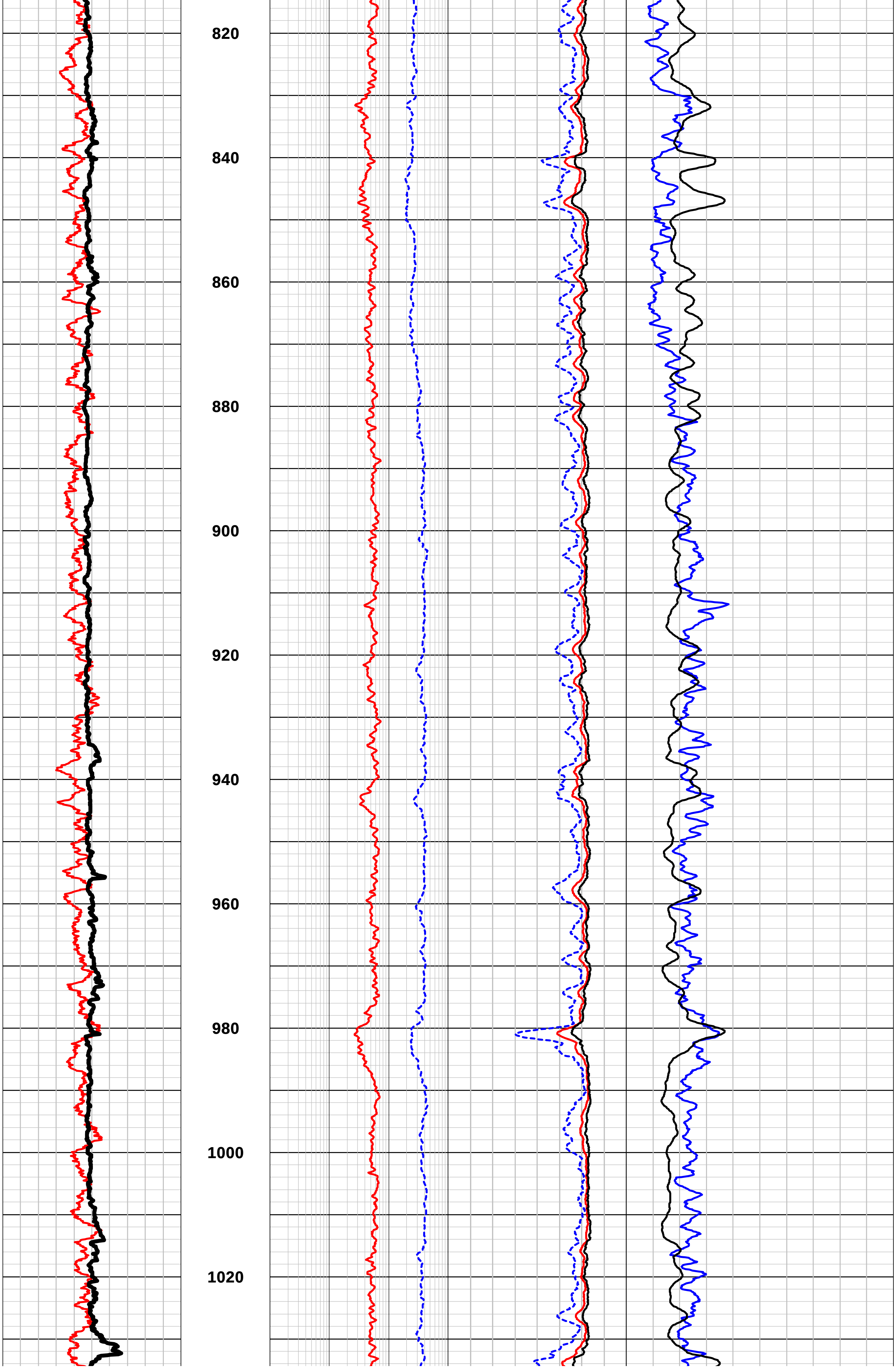
Natural Gamma Density Tool	Depth	Neutron Far	Short Spaced Density	Density Porosity
0 CPS 100		10 CPS 10000	1 g/cc 3	0 % 50
			Long Spaced Density	
			1 g/cc 3	
Density Caliper -Adjusted	1in:20ft	Neutron Near	Compensated Density	Neutron Porosity
5 15		10 CPS 10000	1 g/cc 3	0 % 50

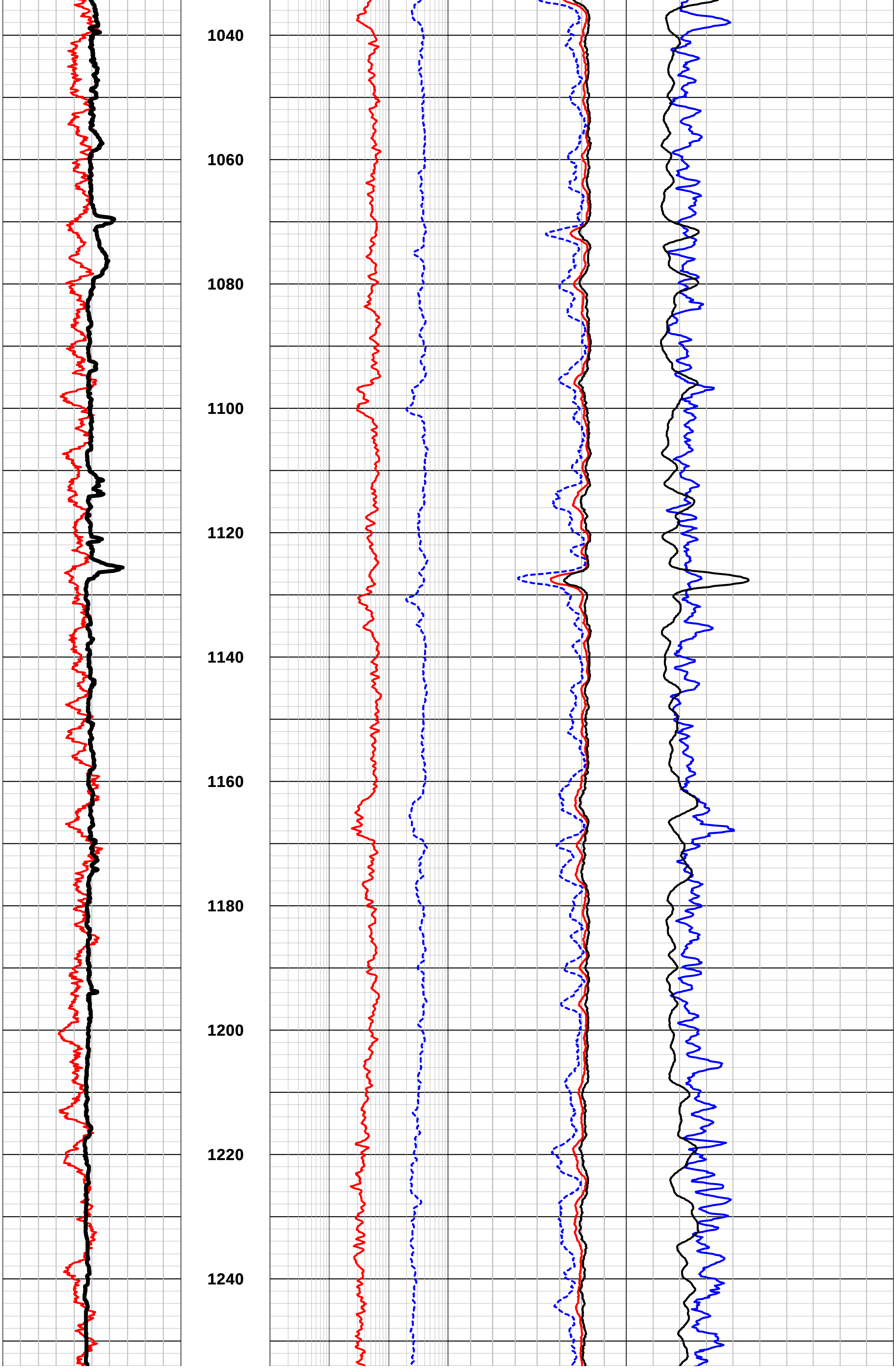


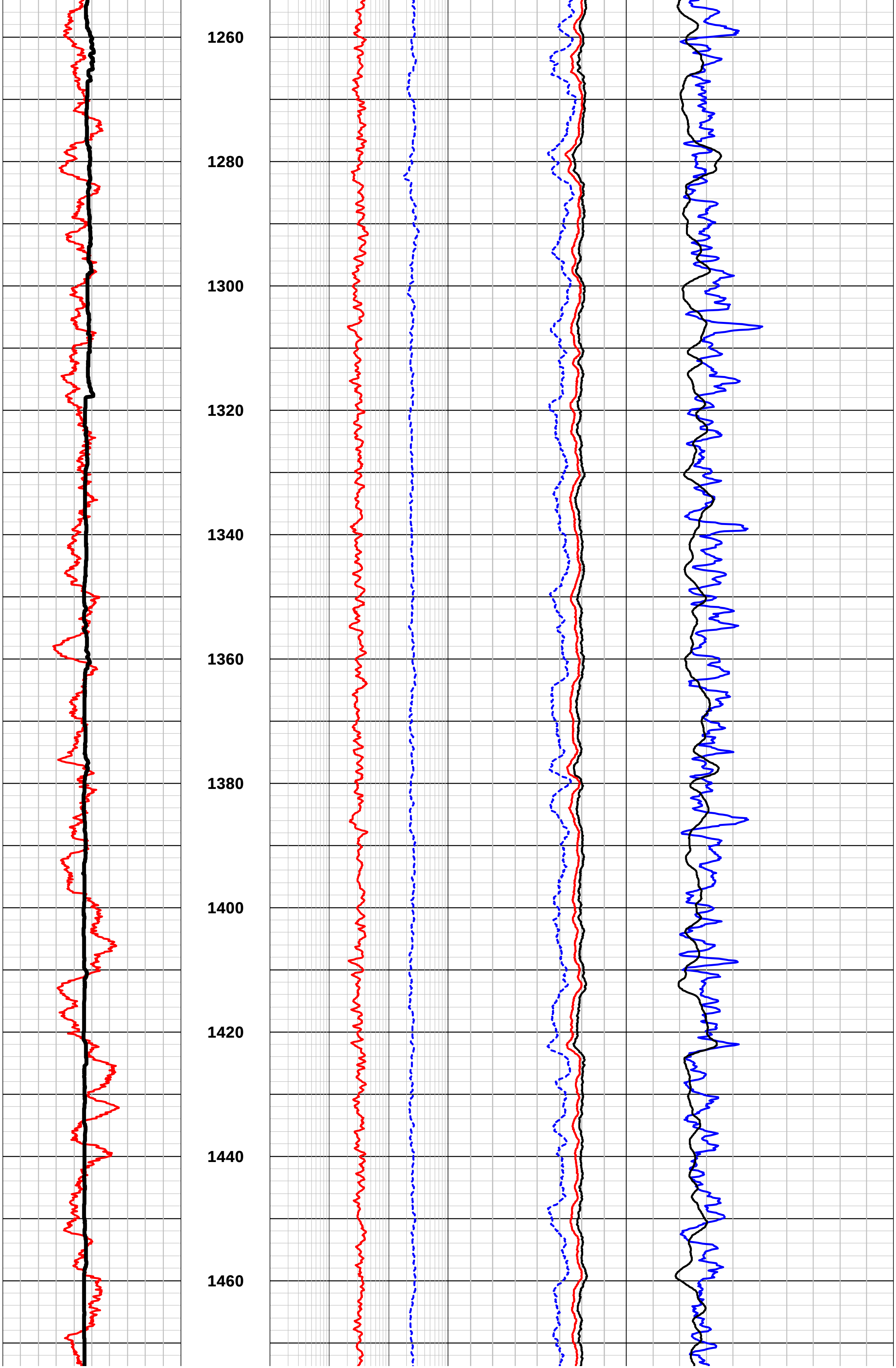

160
180
200
220
240
260
280
300
320
340
360

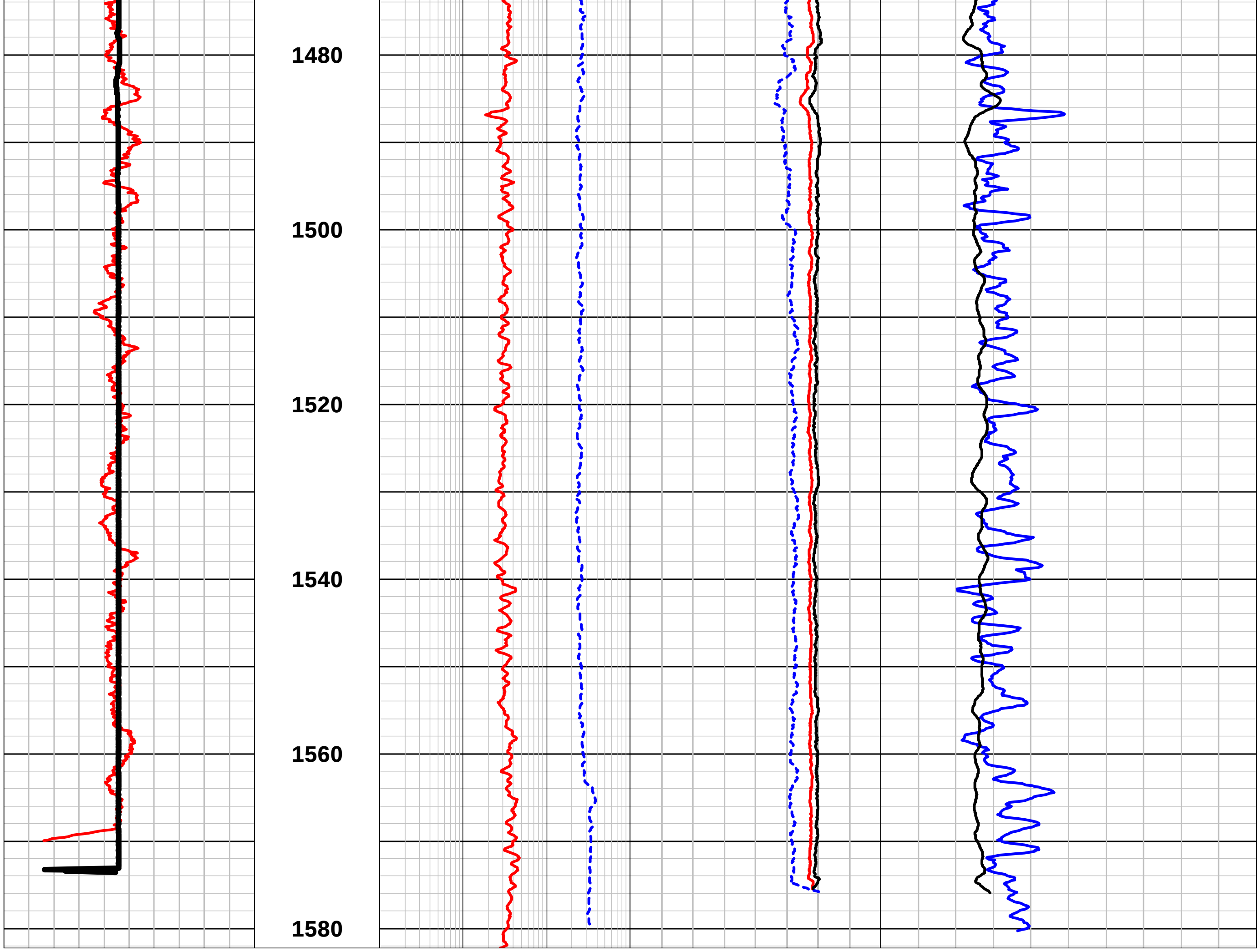

380
400
420
440
460
480
500
520
540
560
580


600
620
640
660
680
700
720
740
760
780
800


820
840
860
880
900
920
940
960
980
1000
1020


1040
1060
1080
1100
1120
1140
1160
1180
1200
1220
1240


1260
1280
1300
1320
1340
1360
1380
1400
1420
1440
1460


1480
1500
1520
1540
1560
1580

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Full Waveform Sonic

Company Montana Tech
Well BFF#5
Project FVDeep
County Flathead
State Montana

COMPANY	Montana Tech		
WELL	BFF#5		
PROJECT	FVDeep		
COUNTY	Flathead	**STATE**	MT

LOCATION
Lat: 48.10353 Long: -114.18193

QTR SE1/4SE1/4 **SEC** 18 **TWP** 27N **RGE** 20W

OTHER SERVICES
Normal Resistivity
Magnetic Resonance
Fluid Temperature & Conductivity
Neutron
Density
Three Arm Caliper
Natural Gamma

PERMANENT DATUM NA **ELEVATION** 2907.64
LOG MEAS. FROM Ground Surface NA **ABOVE PERMANENT DATUM**
DRILLING MEAS. FROM Ground Surface

DATE ACQUIRED	9 Oct 2021			
RUN NUMBER	One			
LOG TYPE	Full Waveform Sonic			
DEPTH-DRILLER	1600.0'			
DEPTH-LOGGER	1575.0'			
BTM LOG INTERVAL	1575.0			
TOP LOG INTERVAL	540.0'			
RECORDED BY	N. Welsh, M. Culig			
WITNESSED BY	A. Bobst			
PROBE TYPE, S/N	TRSS 9210			
LOGGING SPEED	12 ft/min			
A.S.D.E./Sample Interval	3.51' / .1'			
Fluid Level/Fluid Type	6' / WBM			

BOREHOLE RECORD				CASING RECORD			
RUN No.	**BIT**	**FROM**	**TO**	**SIZE**	**WGT.**	**FROM**	**TO**
One	9.25"	540.0'	1600.0'	10"	Steel	0.0'	540.0'
				12"	Steel	0.0'	380.0'

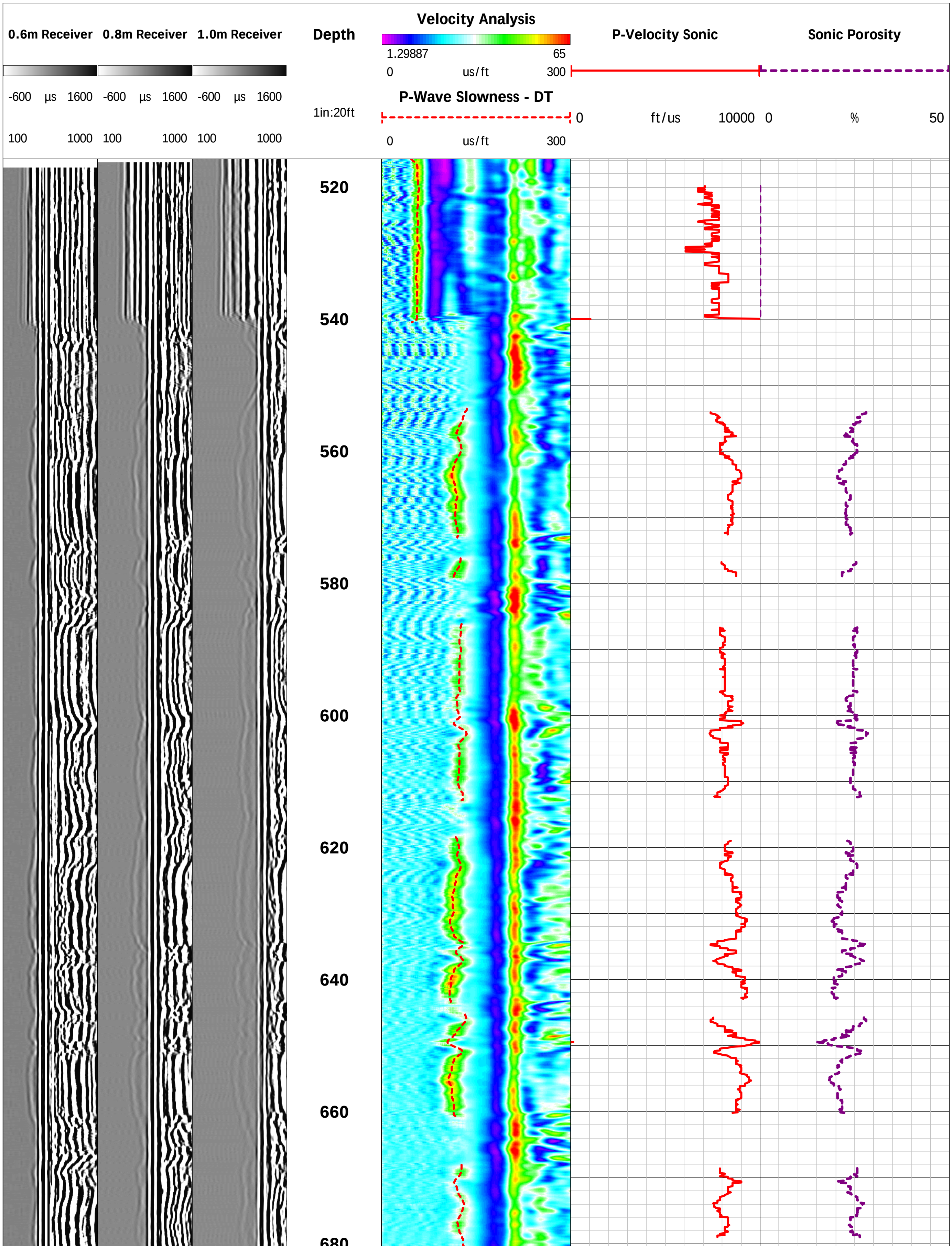
COMMENTS

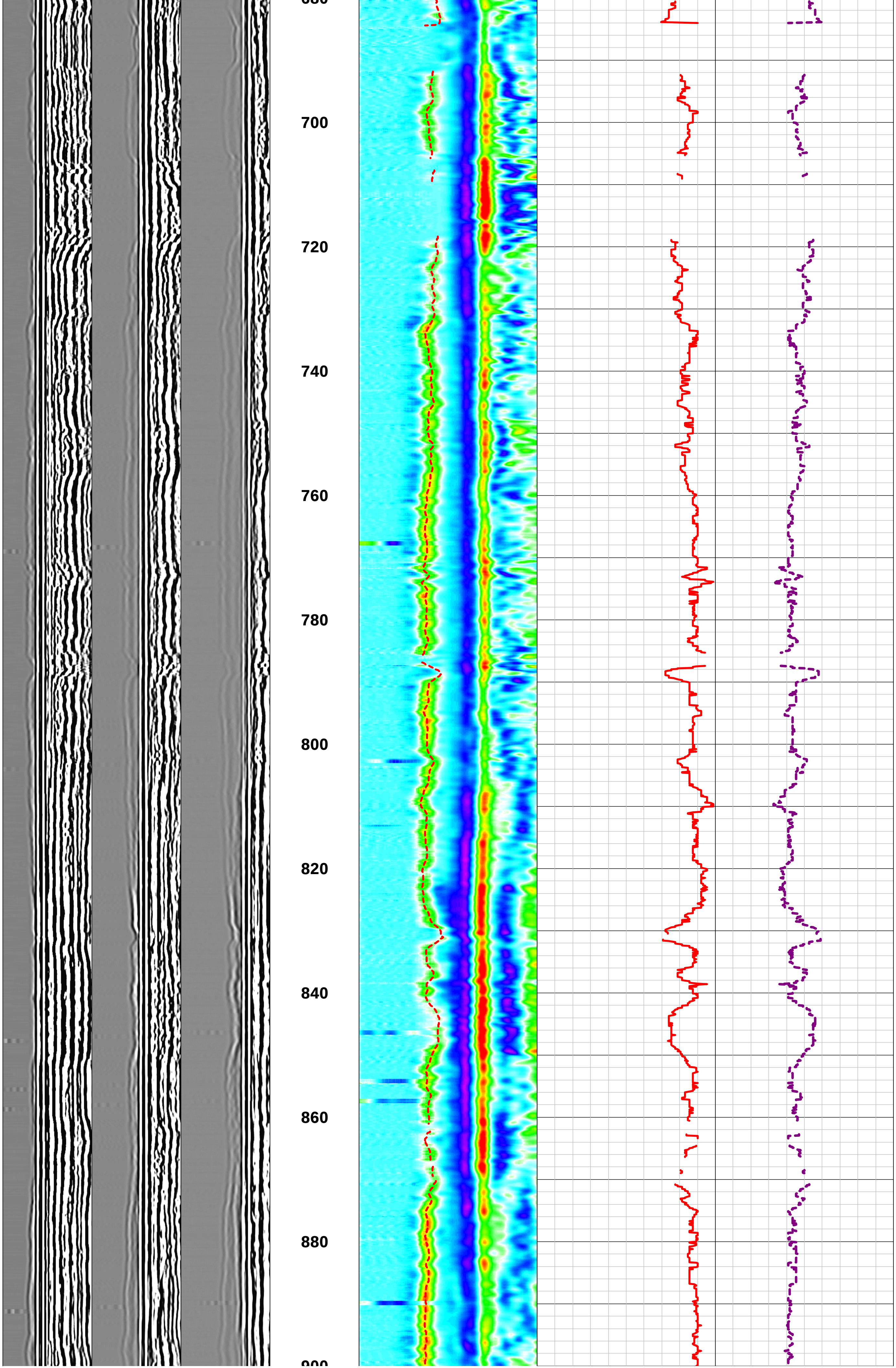
NA - Not Available, N/A - Not Applicable

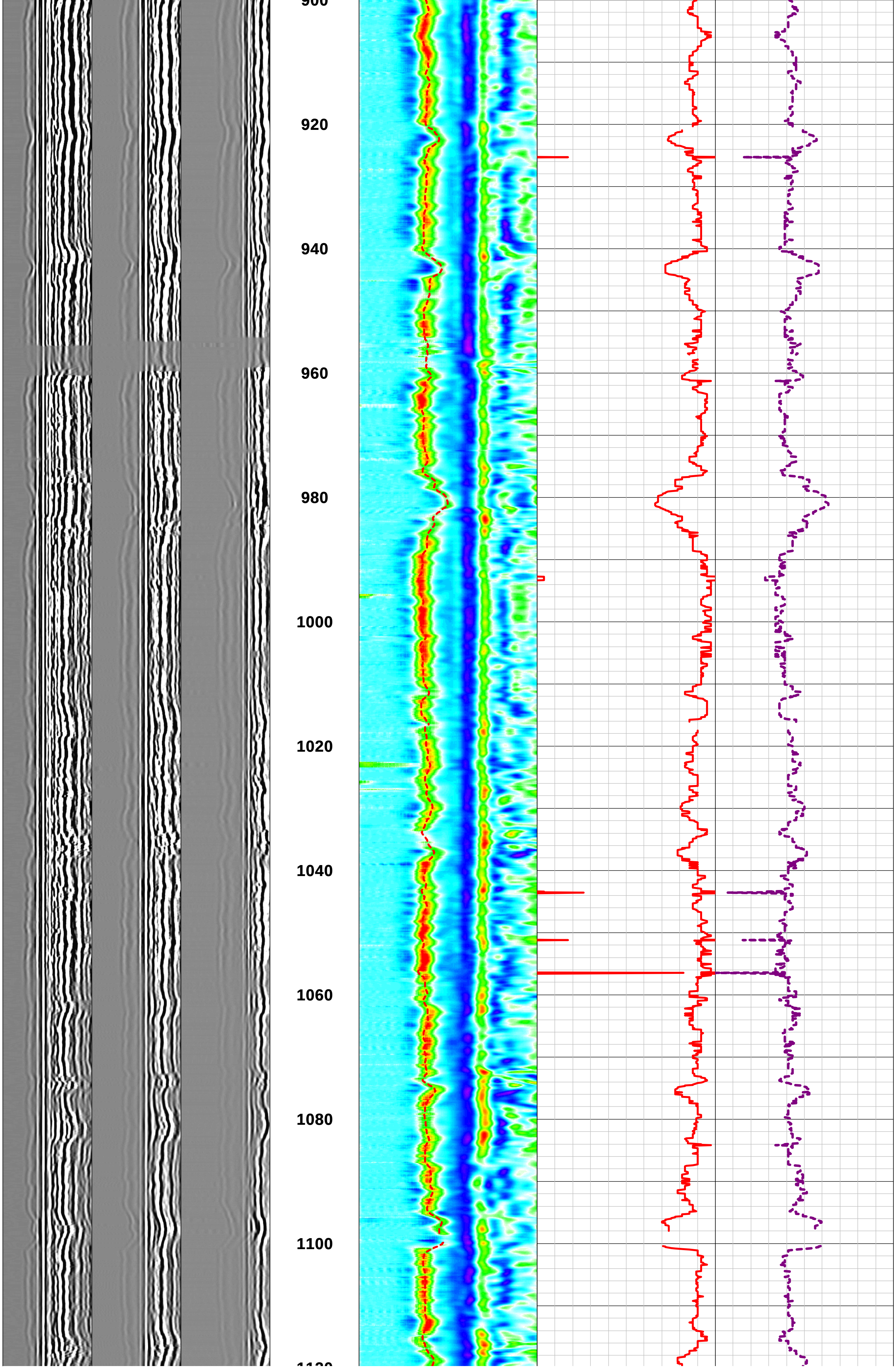
Source File: MontanaTech_FVDeep_BFF#5_FWS-1UL.LOG

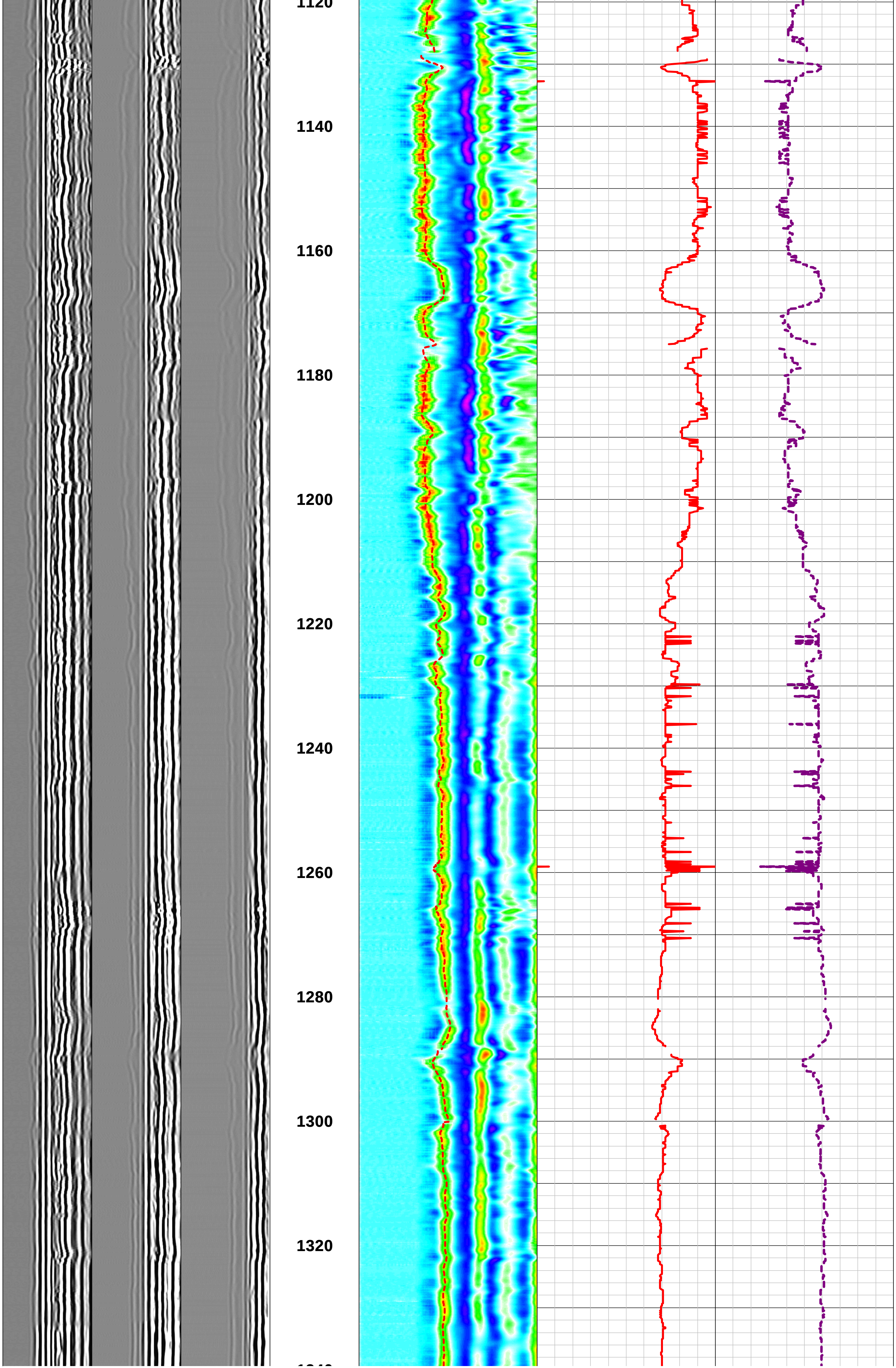
Sonic Porosity calculated using Raymer-Hunt-Gardner equation with formation factor of 75 usec/ft, which fit the Sonic Porosity best with other porosity measurements. Equation is given below:

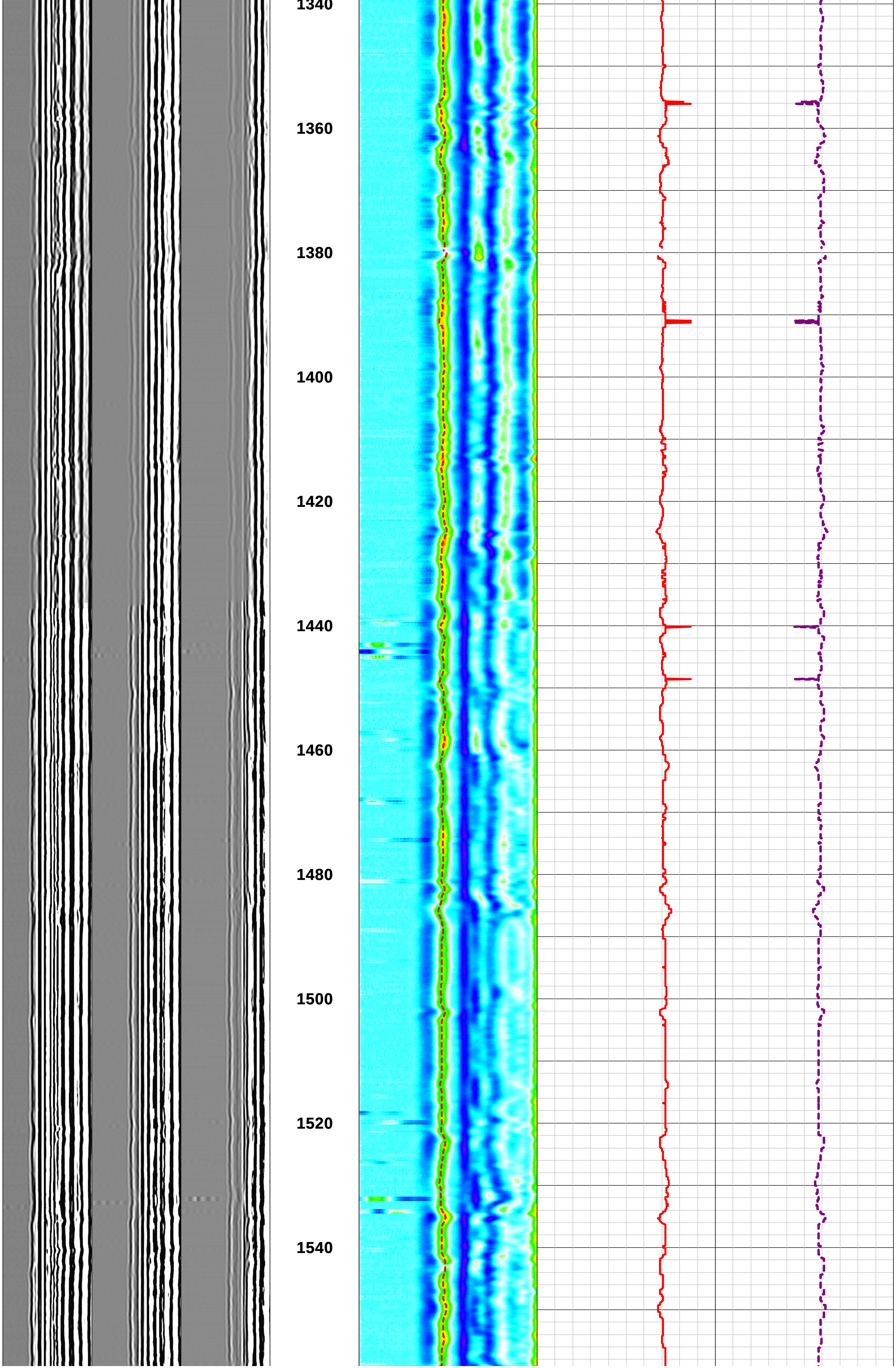
((1-(75/({P-Wave Slowness - DT})))*.63)*100

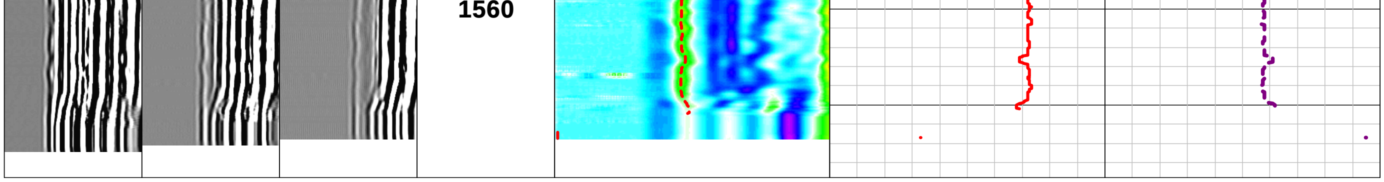

0.6m Receiver
0.8m Receiver
1.0m Receiver
-600 µs 1600
100 1000
-600 µs 1600
100 1000
-600 µs 1600
100 1000
Depth
1in:20ft
Velocity Analysis
1.29887 65
0 us/ft 300
P-Wave Slowness - DT
0 us/ft 300
P-Velocity Sonic
0 ft/us 10000
Sonic Porosity
0 % 50
520
540
560
580
600
620
640
660
680


700
720
740
760
780
800
820
840
860
880


920
940
960
980
1000
1020
1040
1060
1080
1100


1120
1140
1160
1180
1200
1220
1240
1260
1280
1300
1320


1340
1360
1380
1400
1420
1440
1460
1480
1500
1520
1540


1560

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Magnetic Resonance

Water Volume &

Hydraulic Conductivity

Company Montana Tech
Well BFF#5
Project FVDeep
County Flathead
State Montana

COMPANY	Montana Tech		
WELL	BFF#5		
PROJECT	FVDeep		
COUNTY	Flathead	**STATE**	MT

LOCATION
Lat: 48.10353 Long: -114.18193

QTR SE1/4SE1/4 **SEC** 18 **TWP** 27N **RGE** 20W

OTHER SERVICES
Normal Resistivity
Full Waveform Sonic
Magnetic Resonance
Fluid Temperature &
Conductivity
Neutron
Density
Three Arm Caliper
Natural Gamma

PERMANENT DATUM NA **ELEVATION** 2907.64

LOG MEAS. FROM Ground Surface NA **ABOVE PERMANENT DATUM**

DRILLING MEAS. FROM Ground Surface

DATE ACQUIRED	9-10 Oct 2021			
RUN NUMBER	Four			
LOG TYPE	Caliper			
DEPTH-DRILLER	1600.0'			
DEPTH-LOGGER	1575.0'			
BTM LOG INTERVAL	1575.0			
TOP LOG INTERVAL	550.0'			
RECORDED BY	N. Welsh, M. Culig			
WITNESSED BY	A. Bobst			
PROBE TYPE, S/N	JPX350 004			
LOGGING SPEED	2.0 ft/min			
A.S.D.E./Sample Interval	3.30' / .1'			
Fluid Level/Fluid Type	60' / WBM			

BOREHOLE RECORD				**CASING RECORD**			
RUN No.	**BIT**	**FROM**	**TO**	**SIZE**	**WGT.**	**FROM**	**TO**
One	9.25"	540.0'	1600.0'	10"	Steel	0.0'	540.0'
				12"	Steel	0.0'	380.0'

COMMENTS

NA - Not Available, N/A - Not Applicable

Source Folder: BFF#5_Outer2shellonly_10-Oct-2021

Only outer 2 shells (13.5" & 15.0") Processed. Inner shell (12.0") affected by borehole conditions.

NMR Processed Parameters

Processing Parameters used to generate the results in this folder.
This file was auto-generated during data export

Date of Export: 10-Oct-2021 09:32:46
Version of Javelin Pro Plus used: 4.6.1

ACQUISITION METADATA
=====================

	Tr1	Tr2
Averages (#):	4	24
Tr Recovery Time (sec):	5.00	0.20

PROCESSING OPTIONS
==================

Frequency indices included in stack: 2 3
Stacking method: Noise-weighted
Q-scaling: Applied

Depth averaging method: none

Manual depth offset: 0.00
T2 Regularization: 30

PHASE ROTATION
===============
Phase rotation method used: AUTO

F1: -1.3 [-1.3]
F2: 0.3 [0.3]
F3: 0.9 [0.9]

NOTE: First value is the phase rotation applied to data (in degrees). The value in brackets is the auto-calculated phase rotation.

HYDROLOGY ESTIMATORS
===================

Clay cutoff (ms): 3
Cap. cutoff (ms): 33

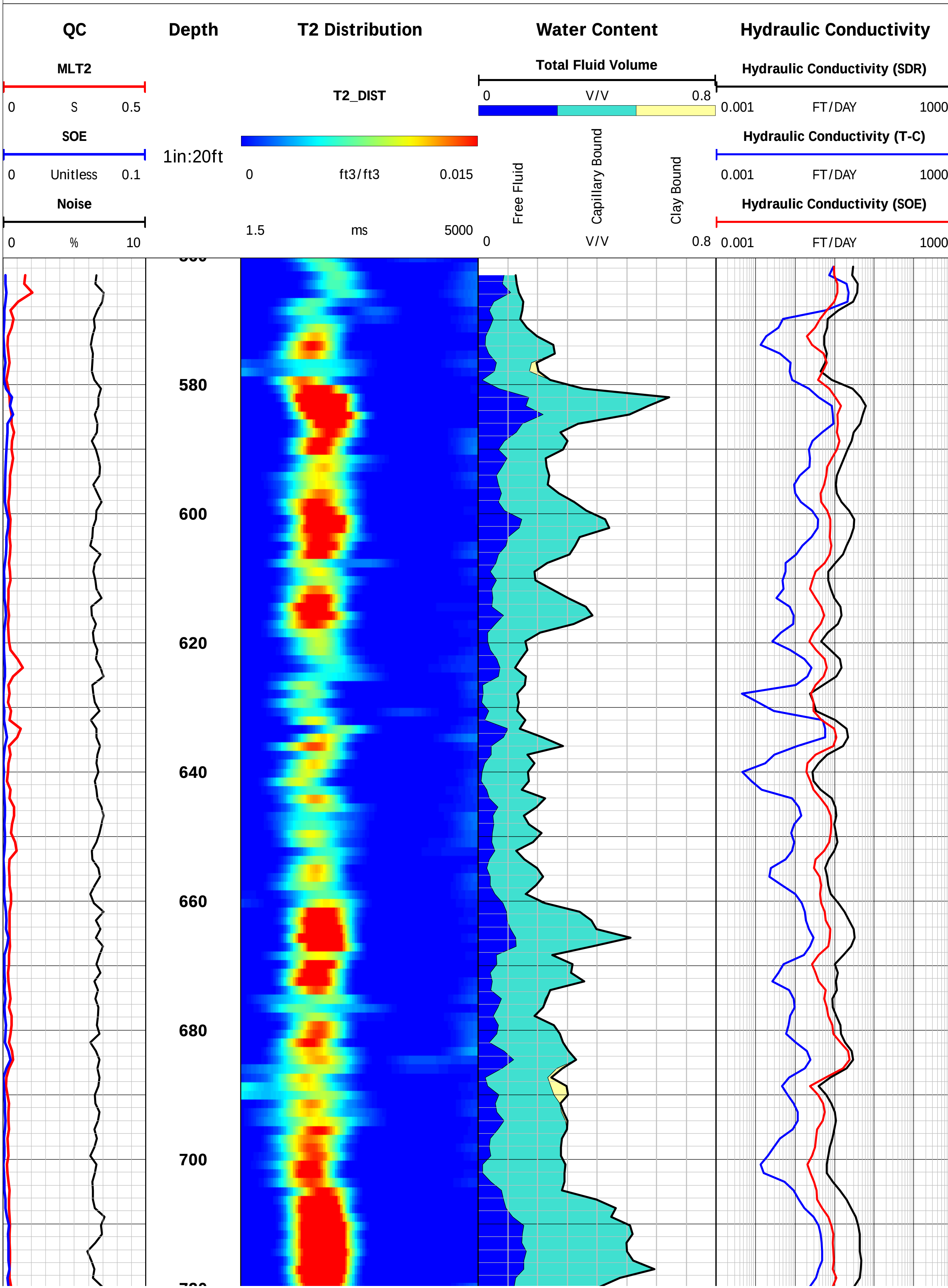
C_SDR: 8900
N_SDR: 2.0

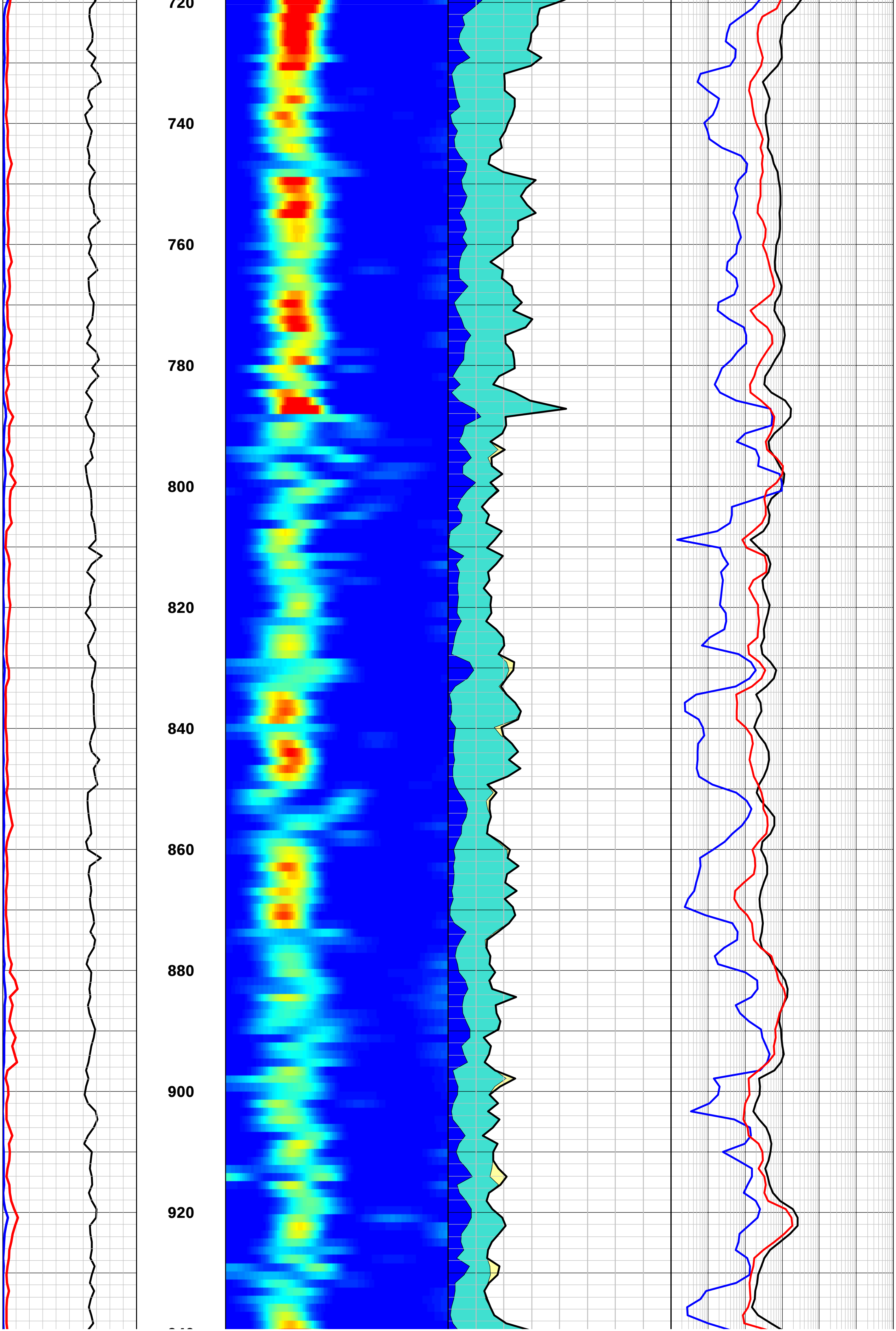
C_SOE: 420
SOE_win: 500

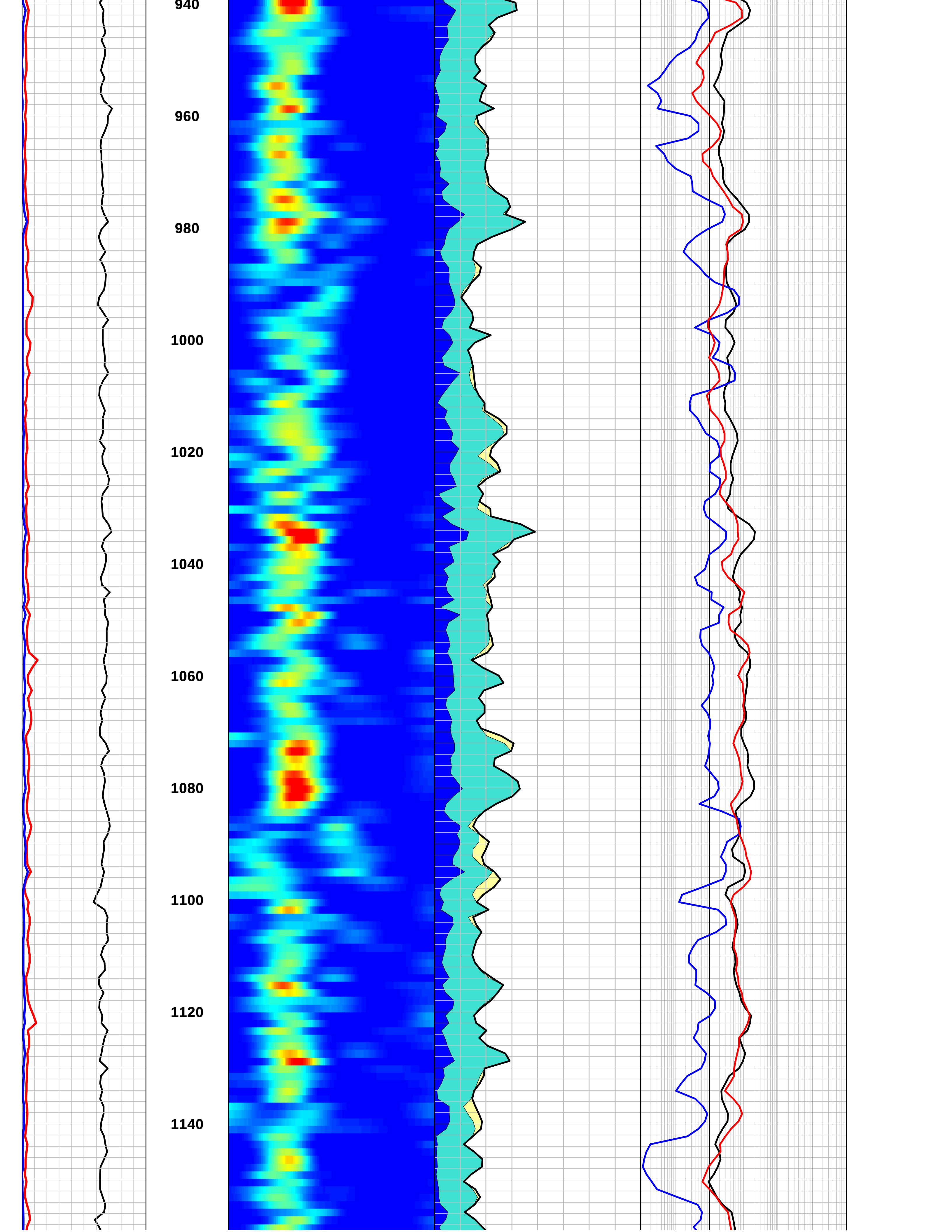
C_TC: 3.0
N_TC: 2.0

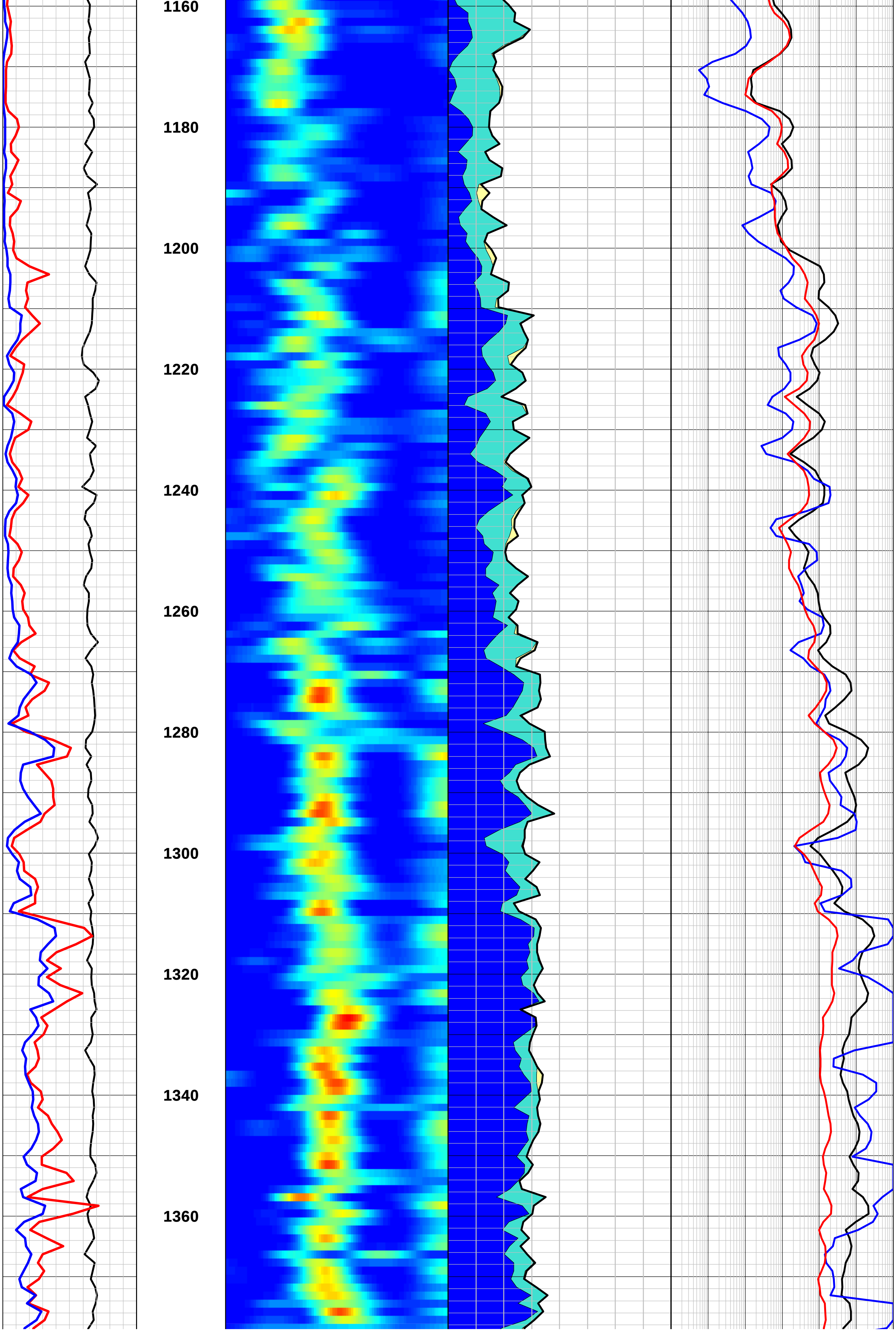
SOURCE FILE INFORMATION
======================

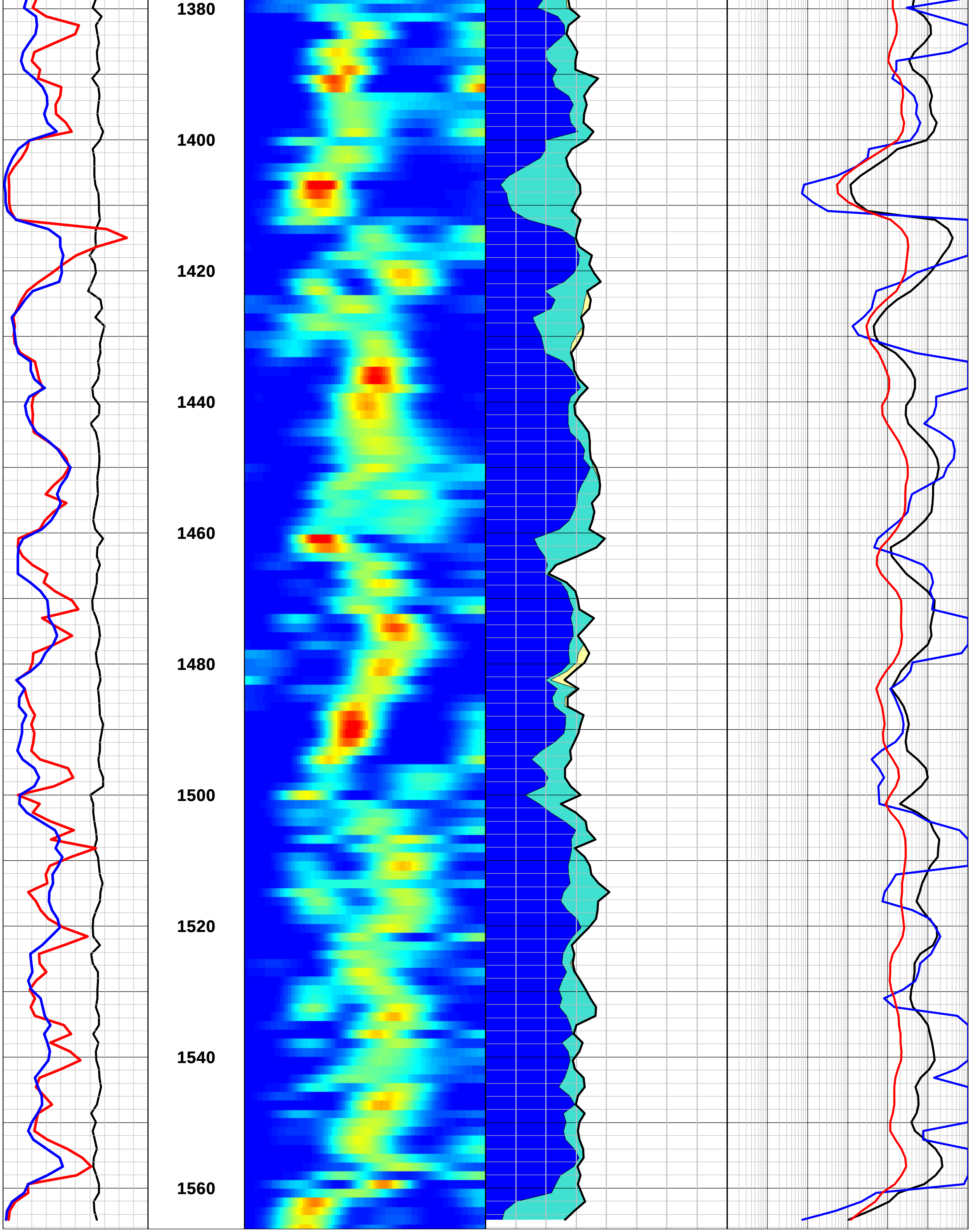
Seed file:
C:\VC_NMR_DATA\Javelin_Wireline\MontanaTech\FVDeeps\BFF#5\MAIN\COMBO\MAIN_1.jrd


QC
Depth
T2 Distribution
Water Content
Hydraulic Conductivity
MLT2
0 S 0.5
SOE
0 Unitless 0.1
Noise
0 % 10
1in:20ft
T2_DIST
0 ft3/ft3 0.015
1.5 ms 5000
Total Fluid Volume
0 V/V 0.8
Free Fluid
Capillary Bound
Clay Bound
0 V/V 0.8
Hydraulic Conductivity (SDR)
0.001 FT/DAY 1000
Hydraulic Conductivity (T-C)
0.001 FT/DAY 1000
Hydraulic Conductivity (SOE)
0.001 FT/DAY 1000
580
600
620
640
660
680
700


720
740
760
780
800
820
840
860
880
900
920


940
960
980
1000
1020
1040
1060
1080
1100
1120
1140


1160
1180
1200
1220
1240
1260
1280
1300
1320
1340
1360


1380
1400
1420
1440
1460
1480
1500
1520
1540
1560

COLOG

borehole geophysics / hydrophysics

810 Quail Street
Suite E
Lakewood, Colorado
80215
Office: 303.279.0171
Fax: 303.278.0135
www.colog.com

Magnetic Resonance Water Volume & Hydraulic Conductivity

Company Montana Tech
Well BFF#5
Project FVDeep
County Flathead
State Montana

COMPANY Montana Tech
WELL BFF#5
PROJECT FVDeep
COUNTY Flathead **STATE** MT

LOCATION
Lat: 48.10353 Long: -114.18193

QTR SE1/4SE1/4 **SEC** 18 **TWP** 27N **RGE** 20W

OTHER SERVICES
Normal Resistivity
Full Waveform Sonic
Magnetic Resonance
Fluid Temperature & Conductivity
Neutron
Density
Three Arm Caliper
Natural Gamma

PERMANENT DATUM NA **ELEVATION** 2907.64
LOG MEAS. FROM Ground Surface NA **ABOVE PERMANENT DATUM**
DRILLING MEAS. FROM Ground Surface

DATE ACQUIRED	9-10 Oct 2021			
RUN NUMBER	Four			
LOG TYPE	Caliper			
DEPTH-DRILLER	1600.0'			
DEPTH-LOGGER	1575.0'			
BTM LOG INTERVAL	1575.0			
TOP LOG INTERVAL	550.0'			
RECORDED BY	N. Welsh, M. Culig			
WITNESSED BY	A. Bobst			
PROBE TYPE, S/N	JPX350 004			
LOGGING SPEED	2.0 ft/min			
A.S.D.E./Sample Interval	3.30' / .1'			
Fluid Level/Fluid Type	60' / WBM			

BOREHOLE RECORD				CASING RECORD			
RUN No.	**BIT**	**FROM**	**TO**	**SIZE**	**WGT.**	**FROM**	**TO**
One	9.25"	540.0'	1600.0'	10"	Steel	0.0'	540.0'
				12"	Steel	0.0'	380.0'

COMMENTS

NA - Not Available, N/A - Not Applicable

Source Folder: BFF#5_Outer2shellonly_10-Oct-2021

Only outer 2 shells (13.5" & 15.0") Processed. Inner shell (12.0") affected by borehole conditions.

NMR Processed Parameters

Processing Parameters used to generate the results in this folder.
This file was auto-generated during data export

Date of Export: 10-Oct-2021 09:32:46
Version of Javelin Pro Plus used: 4.6.1

ACQUISITION METADATA
=====================

	Tr1	Tr2
Averages (#):	4	24
Tr Recovery Time (sec):	5.00	0.20

PROCESSING OPTIONS
==================

Frequency indices included in stack: 2 3
Stacking method: Noise-weighted
Q-scaling: Applied

Depth averaging method: none

Manual depth offset: 0.00
T2 Regularization: 30

PHASE ROTATION
===============
Phase rotation method used: AUTO

F1: -1.3 [-1.3]
F2: 0.3 [0.3]
F3: 0.9 [0.9]

NOTE: First value is the phase rotation applied to data (in degrees). The value in brackets is the auto-calculated phase rotation.

HYDROLOGY ESTIMATORS
====================

Clay cutoff (ms): 3
Cap. cutoff (ms): 33

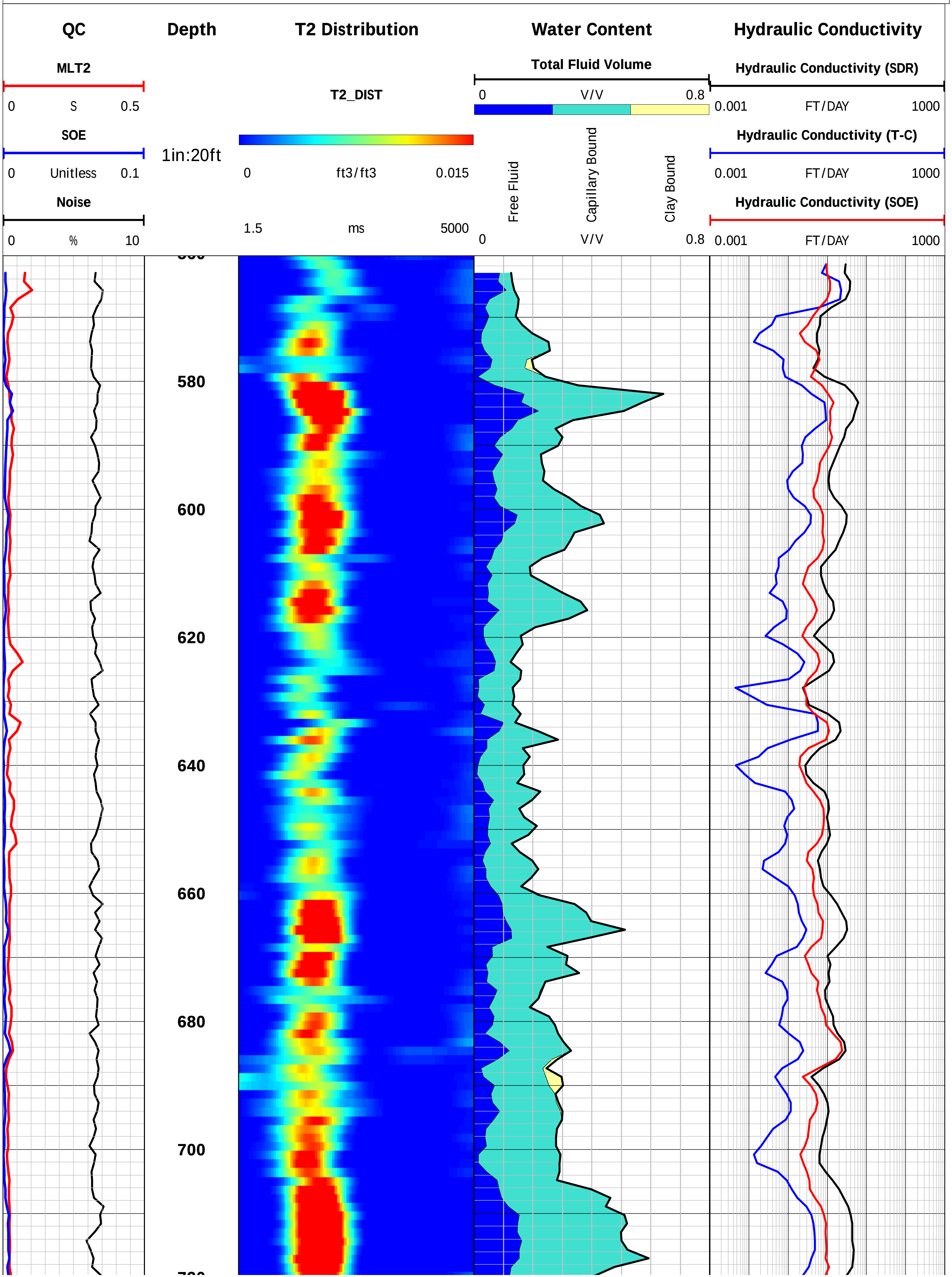
C_SDR: 8900
N_SDR: 2.0

C_SOE: 420
SOE_win: 500

C_TC: 3.0
N_TC: 2.0

SOURCE FILE INFORMATION
======================

Seed file:
C:\VC_NMR_DATA\Javelin_Wireline\MontanaTech\FVDeeps\BFF#5\MAIN\COMBO\MAIN_1.jrd


QC
Depth
T2 Distribution
Water Content
Hydraulic Conductivity
MLT2
0 S 0.5
SOE
0 Unitless 0.1
Noise
0 % 10
1in:20ft
T2_DIST
0 ft3/ft3 0.015
1.5 ms 5000
Total Fluid Volume
0 V/V 0.8
Free Fluid
Capillary Bound
Clay Bound
0 V/V 0.8
Hydraulic Conductivity (SDR)
0.001 FT/DAY 1000
Hydraulic Conductivity (T-C)
0.001 FT/DAY 1000
Hydraulic Conductivity (SOE)
0.001 FT/DAY 1000
580
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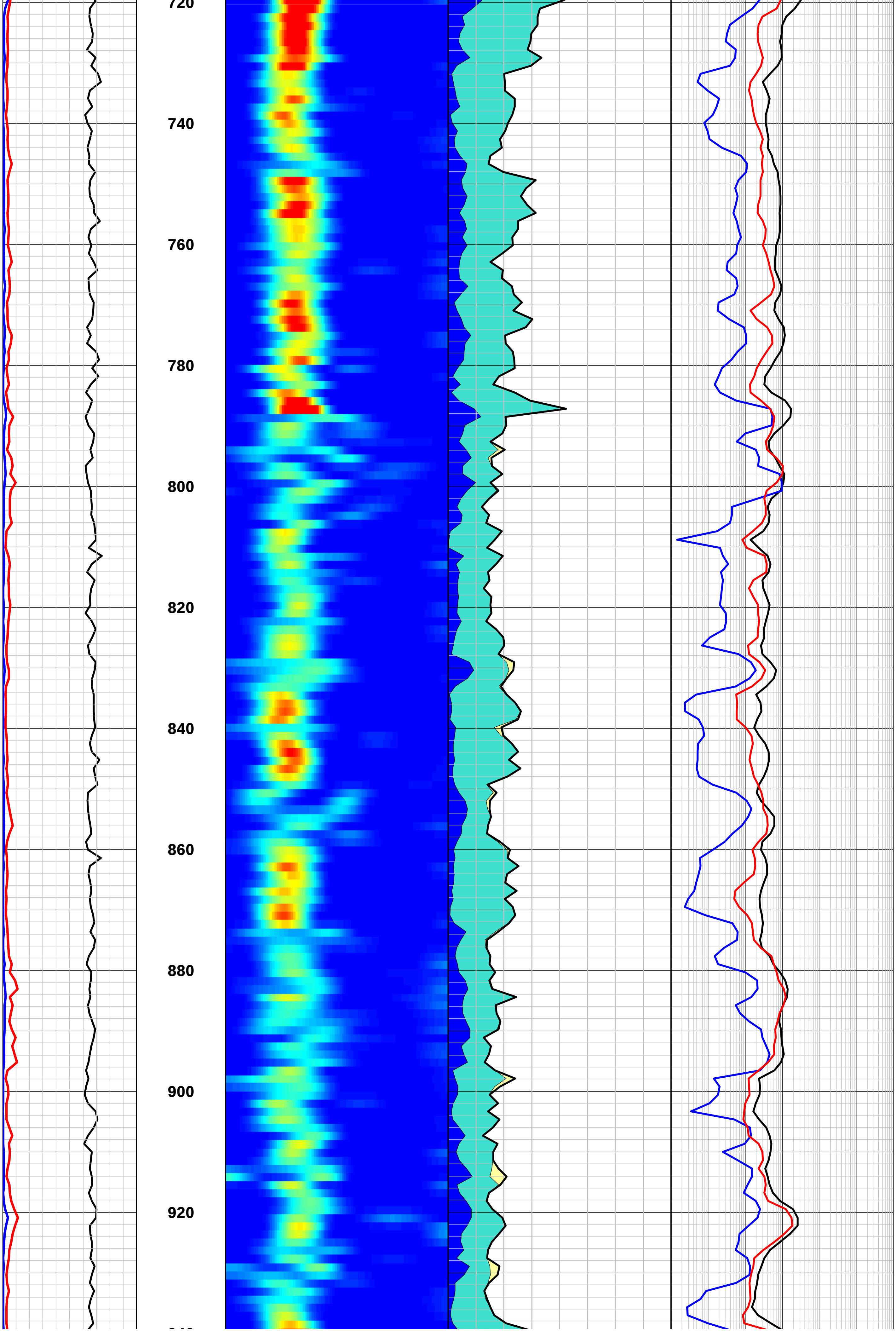
740
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800
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860
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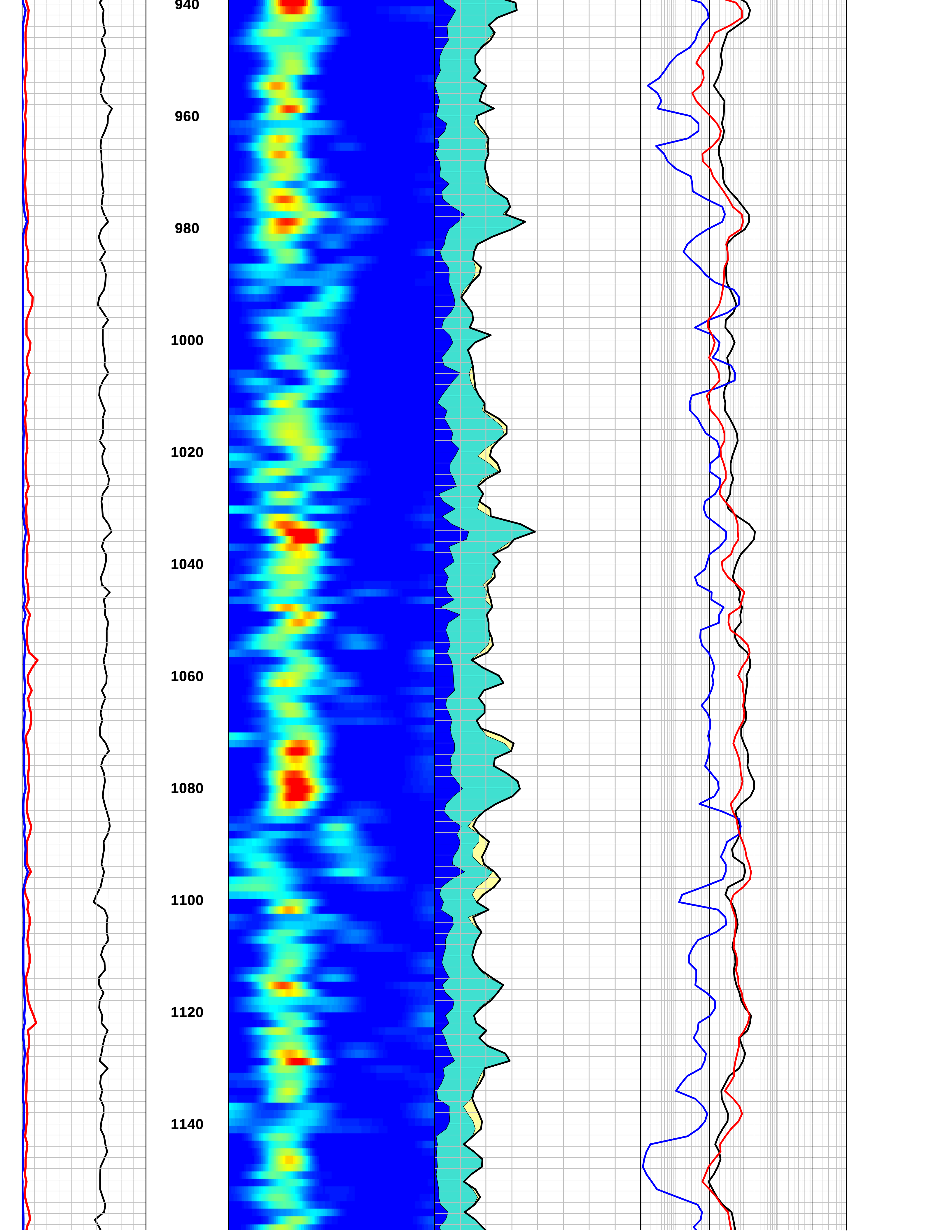
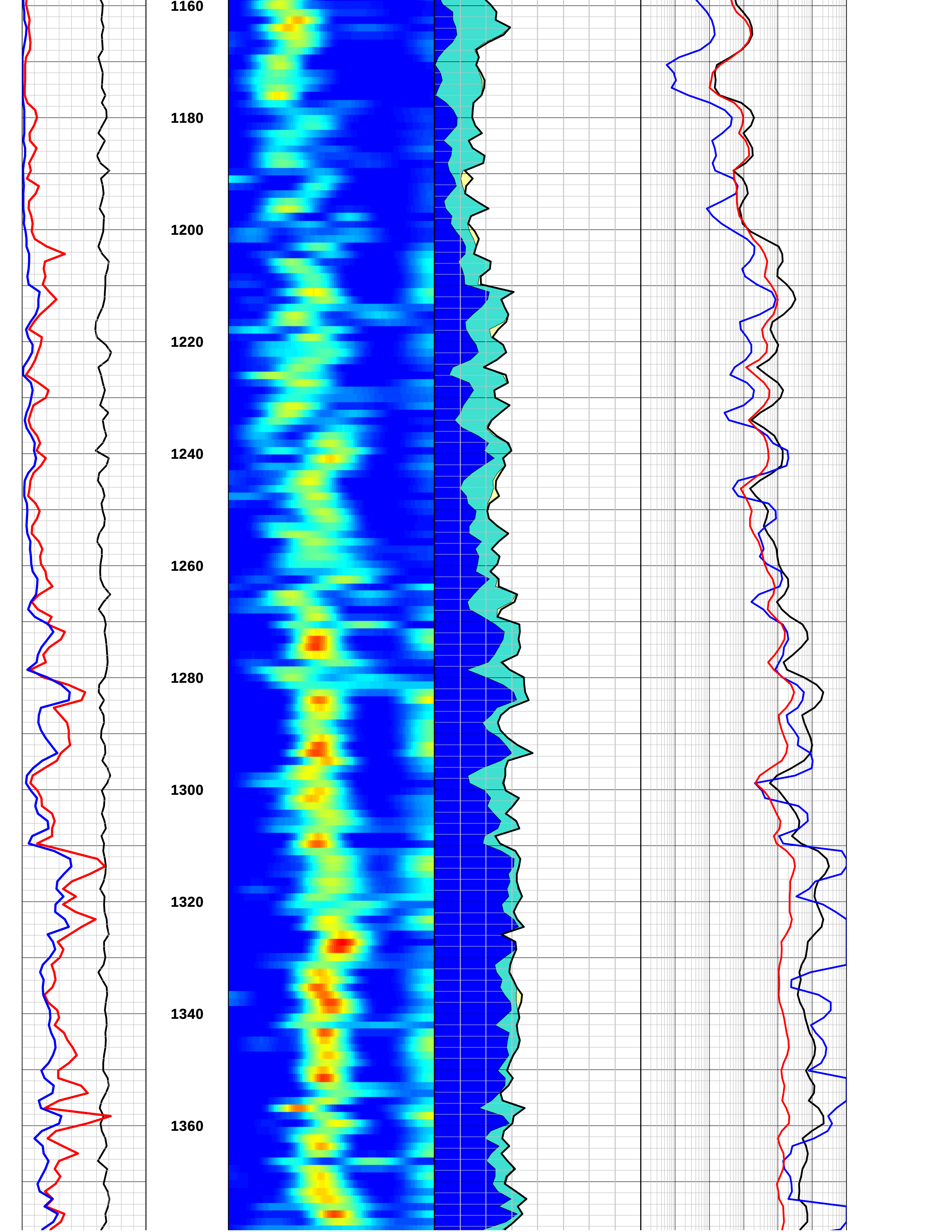
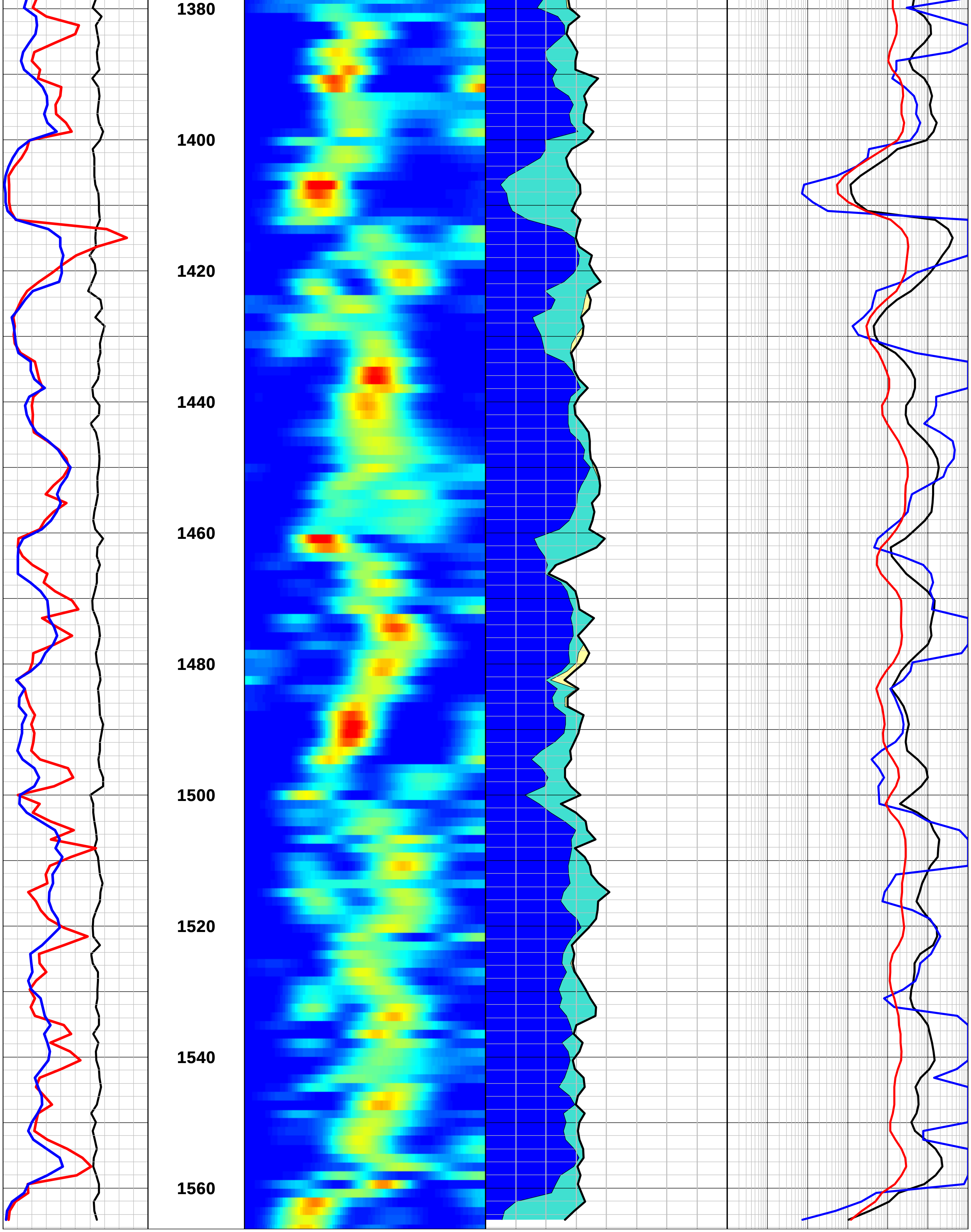
900
920


940
960
980
1000
1020
1040
1060
1080
1100
1120
1140


1160
1180
1200
1220
1240
1260
1280
1300
1320
1340
1360



1380
1400
1420
1440
1460
1480
1500
1520
1540
1560

APPENDIX

LIMITATIONS

LIMITATIONS

COLOG's logging was performed in accordance with generally accepted industry practices. COLOG has observed that degree of care and skill generally exercised by others under similar circumstances and conditions. Interpretations of logs or interpretations of test or other data, and any recommendation or hydrogeologic description based upon such interpretations, are opinions based upon inferences from measurements, empirical relationships and assumptions. These inferences and assumptions require engineering judgment, and therefore, are not scientific certainties. As such, other professional engineers or analysts may differ as to their interpretation. Accordingly, COLOG cannot and does not warrant the accuracy, correctness or completeness of any such interpretation, recommendation or hydrogeologic description.

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