Core Characterization of Bakken Shale from the Bedwell 33-52-1-1H Well, Sheridan County, Montana

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Cover Illustration: The cover illustration is a three-dimensional (3D) orthoslice rendering of a sample taken from a depth of 8,262.15 ft in the Bedwell 33-52-1-1H core. Porosity (green) was extracted to quantify the overall pore space in the sample and illustrate the complexity of the pore network.


An electronic version of this report can be found at:

The data in this report can be accessed from NETL's Energy Data eXchange (EDX) online system (https://edx.netl.doe.gov) using the following link: https://edx.netl.doe.gov/dataset/bedwell-33-52-1-1h-well.

An electronic version of this report can be found at: https://netl.doe.gov/energy-analysis.
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3 November 2021

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<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>Al</td>
<td>Aluminum</td>
</tr>
<tr>
<td>ATR</td>
<td>Attenuated total reflectance</td>
</tr>
<tr>
<td>Bbl</td>
<td>Barrel of Oil</td>
</tr>
<tr>
<td>BDL</td>
<td>Below detection limit</td>
</tr>
<tr>
<td>BSE</td>
<td>Backscattered electron</td>
</tr>
<tr>
<td>Ca</td>
<td>Calcium</td>
</tr>
<tr>
<td>CT</td>
<td>Computed tomography</td>
</tr>
<tr>
<td>CTN</td>
<td>CT numbers</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy-dispersive X-ray spectroscopy</td>
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<tr>
<td>EDX</td>
<td>NETL's Energy Data eXchange</td>
</tr>
<tr>
<td>EIA</td>
<td>U.S. Energy Information Administration</td>
</tr>
<tr>
<td>FTIR</td>
<td>Fourier transform infrared</td>
</tr>
<tr>
<td>HU</td>
<td>Hounsfield Units</td>
</tr>
<tr>
<td>ICP-OES</td>
<td>Inductively coupled plasma-optical emission spectroscopy</td>
</tr>
<tr>
<td>LE</td>
<td>Light elements</td>
</tr>
<tr>
<td>Mcf</td>
<td>One Thousand Cubic Feet of Natural Gas.</td>
</tr>
<tr>
<td>Mg</td>
<td>Magnesium</td>
</tr>
<tr>
<td>MSCL</td>
<td>Multi-Sensor Core Logger</td>
</tr>
<tr>
<td>NETL</td>
<td>National Energy Technology Laboratory</td>
</tr>
<tr>
<td>RPM</td>
<td>rotations per minute</td>
</tr>
<tr>
<td>S</td>
<td>Sulfur</td>
</tr>
<tr>
<td>SE</td>
<td>Secondary electron</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscopy</td>
</tr>
<tr>
<td>Si</td>
<td>Silica</td>
</tr>
<tr>
<td>XRF</td>
<td>X-ray fluorescence</td>
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</tbody>
</table>
Acknowledgments

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ABSTRACT

The computed tomography (CT) facilities and the Multi-Sensor Core Logger (MSCL) at the National Energy Technology Laboratory (NETL) in Morgantown, West Virginia were used to characterize core of the Bedwell 33-52-1-1H well (API 25-091-21920), a wildcat field in Sheridan County, Montana.

The primary impetus of this work is to provide a unique dataset to researchers at universities, national laboratories, geological surveys, and other locations for additional analyses. The resultant datasets are presented in this report and can be accessed from NETL's Energy Data eXchange (EDX) online system using the following link: https://edx.netl.doe.gov/dataset/bedwell-33-52-1-1h-well.

The equipment and techniques used to characterize the full core were non-destructive, enabling future examinations and analyses to be performed on these cores. However, none of the equipment used was suitable for direct visualization of the pore space in fine-grained structures such as those found in shales; fractures, discontinuities, and millimeter scale features were readily detectable with the methods tested. Imaging with the NETL medical CT scanner was performed on the entire core. Qualitative analysis of the medical CT images, coupled with X-ray fluorescence (XRF), P-wave, and magnetic susceptibility measurements from the MSCL were useful in identifying zones of interest for more detailed analysis.

A selection of samples (Table 1) were cored, sliced, and powdered for additional characterization analyses. These analyses did involve destructive subsampling of the full core at discrete sections, and the results are presented here in the context of the larger core description. Selected sections of the core were removed from the full core for detailed analyses using the following destructive techniques: bulk inductively coupled plasma-optical emission spectroscopy (ICP-OES), isolation of carbon and sulfur, Fourier transform infrared (FTIR) spectroscopy, scanning electron microscopy (SEM), and higher resolution CT scan with NETL’s micro-CT scanning systems.

The ability to quickly identify key areas for more detailed study with higher resolution will save time and resources in future studies. The combination of methods used provides a multi-scale analysis of the core; the resulting macro and micro descriptions are relevant to many subsurface energy related examinations traditionally performed at NETL.
1. **INTRODUCTION**

Evaluation of reservoir samples can provide estimations of lithology, mineralogy, porosity, permeability, and many other geologic parameters. While it is common for commercial entities to perform these characterizations, the resources necessary to conduct these analyses are not always available to the broader interest base, such as state agencies, academic institutions, and research-based consortiums. To meet the growing need for comprehensive and high-quality lithologic data for collaborative research initiatives, the National Energy Technology Laboratory (NETL) has used available resources in conjunction with previous techniques and new, innovative methodologies to develop a systematic approach for the evaluation of cores.

In this study, the primary objective was to characterize core from depth with methods not available to most researchers using the computed tomography (CT) facilities and the Multi-Sensor Core Logger (MSCL) at NETL in Morgantown, West Virginia. The data is presented in several formats here and online from NETL's Energy Data eXchange (EDX) (https://edx.netl.doe.gov/dataset/bedwell-33-52-1-1h-well) that are potentially useful for various analyses. However, little detailed analysis is presented in this report as the research objective was not to do a site characterization, but rather to develop the data for others to utilize and to create an enhanced digital representation of the core that could be preserved.

1.1 **SITE BACKGROUND**

Bedwell 33-52-1-1H was drilled in a wildcat field in Sheridan County, Montana near the Town of Westby. The well was completed on September 10, 2012, at a total depth of 11,683 ft. The target reservoir for this field was the Bakken Formation, specifically the Middle Bakken. The well produced 16,301 cumulative barrel of oil (Bbl) and 15,124 cumulative thousand cubic feet (Mcf) of natural gas. The Bakken petroleum system is one of the most prolific oil resources in North America. The Bakken formation is in the Williston Basin which stretches across Montana, North Dakota, South Dakota, and into Saskatchewan and Manitoba, Canada (Zhou et al., 2008). Further information on the oil and gas exploration, resources, and production of the Williston Basin can be accessed via the U.S. Energy Information Administration’s (EIA) Map section on Oil and Gas Exploration, Resources and Production (eia.gov).

1.2 **GEOLOGIC BACKGROUND**

The Williston Basin is an intracratonic basin characterized by cyclic transgression and regression of sea level with high organic content and dominated by carbonates in the Paleozoic (Pitman et al., 2001). The Williston Basin formed when North Dakota was situated in a tropical zone near the equator and was part of an embayment (Nordeng, 2009, Osadetz and Snowdon, 1995). The Bakken formation was deposited during the Late Devonian and Early Mississippian and does not have a uniformly recognized environment of deposition (Aderoju and Bend, 2018). With the rise and fall of sea-level, cycles of deposition and erosion transpired and the organics within the Bakken petroleum system were preserved by rapid burial, subsidence, and infilling of the basin throughout the Mississippian (Nordeng, 2009). It is generally believed that the Lower and Upper Bakken shale formations were deposited during periods of sea level rise in an offshore marine environment with an anaerobic bottom-water allowing for the ubiquity of pyrite, high organic-matter content, and rare benthic fauna (Pitman et al., 2001). The Upper and Lower Bakken shales act as the source rock for the Middle Bakken reservoir (Sorensen and Terneus, 2008). The Upper Bakken is characterized as an organic rich black carbonaceous and petroliferous shale. The
Lower Bakken is a dark grey to black organic rich shale with abundant disseminated pyrite and trace calcite inclusions (lithologic description provided by Southwestern Energy). However, recent studies have found chondrites and burrowing activity in the Lower Bakken which could suggest periods of dysoxic conditions (Smith and Bustin, 2000; Angulo et al., 2008; Angulo and Buatois, 2012) (Figure 1). This study is contrary to the common theory that the Bakken formed under anoxic conditions. The Middle Bakken was deposited in a coastal environment following a rapid drop in sea level and contains argillaceous and highly fossiliferous siltstones (Pitman et al., 2001).

Figure 1: Modified schematic diagram displaying Lower Bakken chondrite fossils (Angulo and Buatois, 2012).
2. **CORE DESCRIPTION**

2.1 **CORE PHOTOGRAPHS**

The following core photographs (Figures 2 to 6) can be accessed from NETL’s EDX online system using the following link: [https://edx.netl.doe.gov/dataset/bedwell-33-52-1-1h-well](https://edx.netl.doe.gov/dataset/bedwell-33-52-1-1h-well).
Figure 2: Bedwell 33-52-1-1H core photos from 8,220 to 8,274 ft.
Figure 3: Bedwell 33-52-1-1H core photos from 8,274 to 8,328 ft.
Figure 4: Bedwell 33-52-1-1H core photos from 8,328 to 8,334.6 ft and from 8,340.6 to 8,385 ft.
Figure 5: Bedwell 33-52-1-1H core photos from 8,385 to 8,439 ft.
2.2 SELECT SAMPLES FOR DESTRUCTIVE ANALYSES

To provide a more detailed geologic characterization of the Bedwell 33-52-1-1H core, three samples (Table 1) were selected for further analyses. The three samples selected may serve as a proxy to the upper Bakken (Bak-229), the middle Bakken (Bak-254), and the lower Bakken (Bak-300). Additional analyses include bulk inductively coupled plasma-optical emission spectroscopy (ICP-OES), carbon/sulfur analysis, infrared spectroscopy, and scanning electron microscopy (SEM).

Table 1: Samples Selected for Additional Characterization

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Depth (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bak-229</td>
<td>8,229.8</td>
</tr>
<tr>
<td>Bak-254</td>
<td>8,254.7</td>
</tr>
<tr>
<td>Bak-300</td>
<td>8,300.0</td>
</tr>
</tbody>
</table>
3. **DATA ACQUISITION AND METHODOLOGY**

The full core was evaluated using CT scanning, MSCL, and X-ray fluorescence (XRF) spectrometry.

### 3.1 MEDICAL CT SCANNING

Core-scale CT scanning was done with a Toshiba® Aquilion TSX-101A/R medical scanner as shown in Figure 7. The medical CT scanner generates images with a resolution in the millimeter range, with scans having voxel resolutions of 0.43 x 0.43 mm in the XY plane and 0.50 mm along the core axis. The scans were conducted at a voltage of 135 kV and at a current of 200 mA. Subsequent processing and combining of stacks were performed to create three-dimensional (3D) volumetric representations of the cores and a two-dimensional (2D) cross-section through the middle of the core samples using ImageJ (Schneider et al., 2012). The variation in greyscale values observed in the CT images indicates changes in the CT number (CTN), which is directly proportional to changes in the attenuation and density of the scanned rock; i.e., darker regions are less dense. Careful examination of the CT images allows for identification of open fractures, filled fractures, density variations, and bedding structure. While the medical CT scanner was not used for detailed characterization in this study, it allowed for non-destructive bulk characterization of the core.

![Toshiba® Aquilion™ Multislice Helical CT scanner at NETL used for core analysis.](image-url)

Figure 7: Toshiba® Aquilion™ Multislice Helical CT scanner at NETL used for core analysis.
3.2 CORE LOGGING

Geophysical measurements of P-wave travel time, magnetic susceptibility, and attenuated gamma counts were obtained with a Geotek® Multi-Sensor Core Logging system on competent sections of core from the Bedwell 33-52-1-1H (Figure 19) (Geoktek Ltd, 2009). Additionally, the system was used to measure bulk elemental chemistry with a built-in, portable XRF spectrometer. The compiled core logs were scaled to fit on single pages for rapid review of the combined data from the medical CT scans and XRF readings.

3.2.1 Magnetic Susceptibility

Magnetic susceptibility is a measure of the degree of magnetization in a sample. The sample is exposed to an external magnetic field and magnetic susceptibility is the measured magnetic response to that field:

\[ J = kH \]

Where, \( J \) is the magnetic response (per unit volume), \( k \) is volume susceptibility, and \( H \) is an external magnetic field. The measurement unit is dimensionless (abbreviated simply as SI).

All materials have magnetic susceptibility. Positive values of magnetic susceptibility indicate that materials are paramagnetic and occur in rocks that consist of the majority ferromagnetic, ferrimagnetic, or antimagnetic (iron bearing) materials. Negative values of magnetic susceptibility indicate that materials are diamagnetic and occur in rocks dominated by non-iron material (i.e., calcite or quartz). Table 1 lists examples of common magnetic susceptibility ranges (Hunts et al., 1995).

Magnetic susceptibility was measured using the Bartington point sensor, where a 1-cm diameter, low intensity (8.0 A/m RMS), non-sensitive, alternating magnetic field (2 kHz) is generated for 10 s. To minimize any potential drift in the oscillating field the point sensor was zeroed at the beginning and end of the sample, as well as, after every 5th measurement. The point sensor due to the small field, was limited in whole core measurements, and additionally was temperature dependent (Geotek Ltd. Multi-Sensor Core Logger Manual, Version 05-10; Geotek Ltd., 2010).
Table 2: Magnetic Susceptibility Values for Common Minerals (Hunts et al., 1995)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>(x \times 10^6) SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>9</td>
</tr>
<tr>
<td>Calcite</td>
<td>-7.5 to -39</td>
</tr>
<tr>
<td>Halite, Gypsum</td>
<td>-10 to -60</td>
</tr>
<tr>
<td>Shale</td>
<td>63 to 18,600</td>
</tr>
<tr>
<td>Illite, Montmorillonite</td>
<td>330 to 410</td>
</tr>
<tr>
<td>Pyrite</td>
<td>5 to 3,500</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>23 to 400</td>
</tr>
<tr>
<td>Hematite</td>
<td>500 to 40,000</td>
</tr>
<tr>
<td>Magnetite</td>
<td>1,000,000 to 5,700,000</td>
</tr>
</tbody>
</table>

3.2.2 P-wave Velocity

P-wave velocity measurements were performed to measure the acoustic impedance of a geologic sample with compressional waves. Acoustic impedance is a measure of how well a material transmits vibrations, which is directly proportional to density and material consolidation. An example of a material that has a high acoustic impedance would be air, with a wave speed of 330 m/s, whereas granite would have low acoustic impedance, with a wave speed of >5,000 m/s. These measurements can be proxies for seismic reflection coefficients and can be translated to field use when doing seismic surveys.

The software associated with the MSCL measures the travel time of the pulse with a resolution of 50 ns. The absolute accuracy of the instrument measurements is \(\pm 3\) m/s with a resolution of 1.5 m/s (Geotek Ltd. Multi-Sensor Core Logger Manual, Version 05-10; Geotek Ltd., 2010).

3.2.3 Gamma Density

Gamma density was acquired by subjecting the sample to gamma radiation and then measuring the attenuation of that radiation. The attenuation is directly proportional to the density of the sample and is acquired by measuring the difference between radiation energy at the emission source and after it passes through the sample. Specifically, the MSCL software calculates the bulk density, \(\rho\), by using the following equation:

\[
\rho = \left(\frac{1}{\mu d}\right) \ln \left(\frac{I_o}{I}\right)
\]

Where \(\mu\) = Compton attenuation coefficient, \(d\) = thickness, \(I_o\) = source intensity, and \(I\) = measured intensity.
3.3 X-RAY FLUORESCENCE SPECTROMETRY

In addition to the geophysical measurements, a portable handheld Innov-X® XRF was used to measure relative elemental abundances. One suite was run, the Mining-Plus Suite, at 6 cm resolution for 60 s exposure time per beam. The Mining-Plus Suite utilizes a 2-beam analysis that resolves major elements (Mg, Al, Si, P, S, Cl, Fe, K, Ca, and Ti), minor elements (V, Cu, Ni, Cr, Mn, and Pb), trace elements (Co, Zn, As, Zr, Mo, Ag, Cd, Sn, Sb, Hf, W, and Bi) and an aggregated “light element” (H to Na) (Figure 8). Elemental abundances are reported as a percentage, relative to the total elemental composition.

The XRF spectrometer measures elemental abundances by subjecting the sample to X-ray photons. The high energy of the photons displaces inner orbital electrons in the respective elements. The vacancies in the lower orbitals cause outer orbital electrons to “fall” into lower orbits to satisfy the disturbed electron configuration. The substitution into lower orbitals causes a release of a secondary X-ray photon, which has an energy associated with a specific element. These relative and element specific energy emissions can then be used to determine bulk elemental composition.

![Figure 8: Periodic table showing elements measurable by the Innov-X® XRF spectrometer using the Mining-Plus.](image)

3.4 DATA COMPILATION

Strater® by Golden Software® was used to compile the medical CT data into a series of logs. The data used to generate these logs can be accessed from NETL’s EDX online system using the following link: [https://edx.netl.doe.gov/dataset/bedwell-33-52-1-1h-well](https://edx.netl.doe.gov/dataset/bedwell-33-52-1-1h-well).
3.5 GEOCHEMISTRY
Several instruments were utilized to capture basic geochemical information on the samples. This information is of particular use as a tool to compare the XRF derived information and for potentially modelling the geochemical interactions of these lithologies.

3.5.1 Bulk ICP-OES
While XRF provides elemental abundances, it has a limited scope and is a surface analysis. Bulk ICP-OES provides a more robust elemental analysis of the whole rock but requires crushing, powdering, and digestion of the rock specimen. Three samples were selected from the core (Table 1) at various depths to act as proxies for the Upper, Middle, and Lower Bakken. Portions of these samples were crushed with mortar and pestle, sieved to 74 µm, and dissolved into solution using molten salt fusion and mineral acid digestion methods. A PerkinElmer Optima 7300 DV ICP-OES was then used to analyze the solution for a variety of elements following EPA Method 6010C. Elements analyzed via ICP-OES include: Ag, Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Sb, Se, SiO2, Sn, Sr, Ti, V, Zn, and Zr.

3.5.2 Carbon and Sulfur Analysis
Carbon and sulfur analysis was performed on the selected samples from Table 1 using a PerkinElmer 2400 Series II CHNS/O analyzer. Powdered samples were first analyzed to determine total carbon and sulfur contents. Then the samples were processed using an acid fumigation method to remove inorganic carbon. The samples were re-analyzed for total carbon which is now measuring only the organic carbon portion left in the samples. The organic carbon value is subtracted from the total carbon value to provide total inorganic carbon.

3.6 SCANNING ELECTRON MICROSCOPE ANALYSIS
A FEI Quanta environmental SEM with energy-dispersive X-ray spectroscopy (EDS) was used to image select core samples. Slices (0.25 in.) thick were cut off 1-in. cores and the surfaces were polished using a Fischione Model 1061 Ar ion mill. Milling was performed at 5 kV, with a 5° angle, using continuous rotation of 3 rotations per minute (RPM), for 1.5 hrs. Samples were imaged using secondary electron (SE) and backscattered electron (BSE) detectors. Montage images were created by stitching hundreds of images together taken in BSE mode at 100x magnification.
4. RESULTS

The core from the Bedwell 33-52-1-1H well was scanned with a Toshiba Aquilion TSX-101A/R medical CT scanner at a sub-millimeter core-scale resolution (430 µm by 430 µm by 500 µm). Processed 2D slices of the medical CT scans through the cores are shown here (Figures 11–19).

4.1 MEDICAL CT SCANS

As was discussed previously, the variation in greyscale values observed in the medical CT images indicate changes in the CTN obtained, which is directly proportional to changes in the attenuation and density of the scanned rock (i.e., darker regions are less dense).

Polar transforms were created by concatenating and re-slicing the medical CT scans (Figure 9). The original X/Y CT image is “unwrapped” and converted from polar coordinates to cartesian coordinates. In the polar transformed images, the y-axis represents the angle from 0 to 360 and the x-axis represents the distance from the center of the image. This is done for all slices in the volume. The resulting volume is resliced perpendicular to the X/Y plane and an isolated plane is taken along the outer most portion of the core. The polar transforms can be accessed through the EDX link: https://edx.netl.doe.gov/dataset/bedwell-33-52-1-1h-well.

Figure 9: Polar transform of transform of 8,244 to 8,247 ft from the Bedwell 33-52-1-1H well.

4.1.1 X/Z Planes

A 2D image through the center of each core can be found in Figure 11–19. These are referred to as X/Z planes, a schematic of which is shown as Figure 10. The retrieved core has a diameter of 4 in. (10.16 cm) for reference; a 1-in. scale bar in red is shown on each X/Z slice as well. The labels below each 2D X/Z plane in Figure 11 through Figure 19 are the depth at the bottom of each core; the full range of core lengths shown in each figure is listed in the figure captions. The grayscale display was shifted to a narrower but consistent display range for the entire image set to better display structural features. The native calibrated grayscale value was unchanged.
Figure 10: Schematic of the XZ isolated plane through the vertical center of the medical CT scans
4.2 BEDWELL 33-52-1-1H

Figure 11: 2D isolated planes through the vertical center of the medical CT scans of the Bedwell 33-52-1-1H core from 8,220 to 8,250 ft. Red scale bar is 1 in.
Figure 12: 2D isolated planes through the vertical center of the medical CT scans of the Bedwell 33-52-1-1H core from 8,250 to 8,279 ft. Red scale bar is 1 in.
Figure 13: 2D isolated planes through the vertical center of the medical CT scans of the Bedwell 33-52-1-1H core from 8,279 to 8,310 ft. Red scale bar is 1 in.
Figure 14: 2D isolated planes through the vertical center of the medical CT scans of the Bedwell 33-52-1-1H core from 8,310 to 8,335 ft and from 8,341 to 8,343 ft. Red scale bar is 1 in.
Figure 15: 2D isolated planes through the vertical center of the medical CT scans of the Bedwell 33-52-1-1H core from 8,343 to 8,373 ft. Red scale bar is 1 in.
Figure 16: 2D isolated planes through the vertical center of the medical CT scans of the Bedwell 33-52-1-1H core from 8,373 to 8,403 ft. Red scale bar is 1 in.
Figure 17: 2D isolated planes through the vertical center of the medical CT scans of the Bedwell 33-52-1-1H core from 8,403 to 8,433 ft. Red scale bar is 1 in.
Figure 18: 2D isolated planes through the vertical center of the medical CT scans of the Bedwell 33-52-1-1H core from 8,433 to 8,463 ft. Red scale bar is 1 in.
4.3 ADDITIONAL CT DATA

The original CT data is available as 16-bit tif stacks suitable for reading with ImageJ (Schneider, 2012) or other image analysis software. Additional CT reslices as well as polar transforms and higher resolution scans not presented here can be accessed from NETL’s EDX online system: https://edx.netl.doe.gov/dataset/bedwell-33-52-1-1h-well.

4.4 DUAL ENERGY CT SCANNING

Dual energy CT scanning uses two sets of images, produced at different X-ray energies, to approximate the density ($\rho_B$) (Siddiqui and Khamees, 2004; Johnson, 2012). The technique relies on the use of several standards of known $\rho_B$ to be scanned at the same energies as the specimen. These scans are performed at lower energies (<100 KeV) and higher energies (>100 KeV) to induce two types of photon interactions with the object (Figure 20). The lower energy scans induce photoelectric absorption, which occurs when the energy of the photon is completely absorbed by the object mass and causes ejection of an outer orbital electron (Figure 20a). The high energy scans induce Compton scattering, which causes a secondary emission of a lower energy photon due to incomplete absorption of the photon energy in addition to an electron ejection (Figure 20b).

Figure 20: Photon interactions at varying energies. A) Photoelectric absorption, B) Compton scattering. Modified from Iowa State University Center for Nondestructive Evaluation (2021).
Medical grade CT scanners are typically calibrated to known standards, with the output being translated in CTN or Hounsfield Units (HU). Convention for HU defines air as -1,000 and water as 0. A linear transform of recorded HU values is performed to convert them into CTN. This study used CTN as it is the native export format for the instrument, but it is possible to use HU. Dual energy CT requires at least three calibration points and it is prudent to utilize standards that approximate the object or material of interest. Pure samples of aluminum, graphite, and sodium chloride were used as the calibration standards as they most closely approximate the rocks and minerals of interest (Table 3). Most materials denser than water or with higher atomic masses have a non-linear response to differing CT energies (Table 4).

Table 3: Dual Energy Calibration Standards, Bulk Density (gm/cm³)

<table>
<thead>
<tr>
<th>Material</th>
<th>ρ (gm/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>-0.001</td>
</tr>
<tr>
<td>Water</td>
<td>1</td>
</tr>
<tr>
<td>Graphite</td>
<td>2.3</td>
</tr>
<tr>
<td>Sodium Chloride</td>
<td>2.16</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Table 4: Dual Energy Calibration Standards, HU and CTN for “Low” and “High” Energies

<table>
<thead>
<tr>
<th>Material</th>
<th>HU 80 KeV</th>
<th>HU 135 KeV</th>
<th>CTN 80 KeV</th>
<th>CTN 135 KeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>-993</td>
<td>-994</td>
<td>31,775</td>
<td>31,774</td>
</tr>
<tr>
<td>Water</td>
<td>-3.56</td>
<td>-2.09</td>
<td>32,764</td>
<td>32,766</td>
</tr>
<tr>
<td>Graphite</td>
<td>381</td>
<td>437</td>
<td>33,149</td>
<td>33,205</td>
</tr>
<tr>
<td>Sodium Chloride</td>
<td>1,846</td>
<td>1,237</td>
<td>34,614</td>
<td>34,005</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2,683</td>
<td>2,025</td>
<td>35,451</td>
<td>34,793</td>
</tr>
</tbody>
</table>

Dual energy CT utilizes these differences to calibrate to the X-ray spectra. Two equations with three unknowns each are utilized to find $\rho_B$ (Siddiqui and Khamees, 2004):

$$\rho_B = m_{CTN_{low}} + p_{CTN_{high}} + q$$
Where \([m, p, \text{ and } q]\) are unknown coefficients that can be solved by setting up a system of equations with four \(3 \times 3\) determinants. The CTN is obtained from the CT scans for each of the homogenous calibration standards.

In this study the high and low energy image stacks were loaded into Python as arrays. A 3D Gaussian blur filter with a sigma of 2 was used to reduce noise in the images. The scipy.solv module of Python was then employed to solve for the coefficients based on the calibration CTN values. The \(\rho_B\) was solved for each pixel in the 3D volume and saved as two new separate image stacks.

### 4.5 COMPILED CORE LOG

The compiled core logs were scaled to fit on single pages for rapid review of the combined data from the medical CT scans and MSCL readings (Figures 21 and 22). Two sets of logs are presented for the core; the first contains data from the CT scans and XRF, and the second set with calculated ratios from the XRF scans, porosity, and permeability. Features that can be derived from these combined analyses include determination of mineral locations, such as pyrite, from magnetic susceptibility and using the XRF to inform geochemical composition and mineral form.

The following compiled core logs have been filtered in order to accurately represent the data displayed. P-wave velocities have been filtered to remove values less than 1,000 m/s and greater than 3,200 m/s. P-wave velocities less than 1,000 m/s are less than the anticipated velocity through water and minerals, indicating a highly fractured zone and unreliable readings. The location of these fractured zones was confirmed through visual examination and with the medical CT scanned images. P-wave velocities greater than 3,200 m/s are filtered out to remove inferred erroneous highs. The gamma density has been filtered to remove points less than 1 g/cm\(^3\). Resistivity (acoustical impedance) data less than 1,000 \((10^3 \text{ kg/m}^2 \text{ s}^{-1})\) have been filtered out. The Silica to Aluminum (Si/Al) ratio, and percentages of Silica (Si), Aluminum (Al), Calcium (Ca) and Magnesium (Mg) have been filtered to remove points less than 1 ppm.

The elemental results from the XRF were limited to Ca, Si, Al, Mg, Sulfur (S) and light elements (LE). Of these elements listed, Ca concentrations are an average of 10.1% for the entire core and with a maximum point concentration of 426,444 ppm (42.6%) at one location. Silica is the second most abundant element making up 5.5% of the entire core with a maximum point concentration of 277,794 ppm (27.7%). Of the five XRF elements displayed in Figure 22, Al had the lowest maximum concentration at 64,495 ppm (64.5%).

Trends in elemental ratios can provide insight into mineral composition. The aforementioned core logs included Si/Al, which provides information on the abundance of illite and micas versus other clays, and the abundance of cherts to clays. The ratio of Ca/Si could also be compared, which would provide information of carbonate to chert/detrital influence, Mn/Fe and S/Fe which informs redox trends, and Mg/Ca which can help to discern if carbonate is dolomite or calcite (note: there is no information in the top portion of the well due to the presence of siliciclastic rocks). Additionally, magnetic susceptibility in “normal” rock matrices (carbonate and siliciclastic) are low due to unfavorable conditions for metals and magnetic minerals. Magnetic susceptibility can test for iron sulfides (reducing) or oxidized Fe and sulfate. Pyrite (reduced) should have low magnetic susceptibility; Fe oxide or hydroxide should have high magnetic
susceptibility. These broad trends can quickly give information on large suites of core and direct more focused research.

Additionally, Figures 21 and 22 represent all the data compiled in this report and provide a more detailed visual representation of the well. The header provides the general log information and where the data in the log plots is sourced. Figure 21 contains the p-wave velocity (m/s), CT, density from the MSCL gamma density (g/cc), resistivity (acoustic impedance), LE (ppm), and XRF mineralogy (Si, Al, Ca, and S). Figure 22 contains a Si/Al ratio, XRF percentages for Si, Al, Ca, and Mg, porosity (ambient %), and permeability (to air mD). This data can be accessed on EDX: https://edx.netl.doe.gov/dataset/bedwell-33-52-1-1h-well.
Figure 21: Compiled core log for Bedwell 33-52-1-1H well, from 8,220 to 8,480 ft.
Figure 22: Additional compiled core log for Bedwell 33-52-1-1H well, from 8,220 to 8,480 ft.
4.6 BULK GEOCHEMISTRY RESULTS

The bulk elemental composition of the three selected samples varied significantly as expected given their relative lithologic makeup (Table 5). In general, there are two fine grained shales, Bak-229 and Bak-300, while Bak-254 is more heavily carbonate with both a high Ca and high TIC content (Table 6). The relatively high TOC content for Bak-229 combined with the relatively high Fe content suggests it is likely a darker black shale derived of anoxic conditions.

Table 5: ICP-OES Results (ppb)*

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Detection Limit</th>
<th>Bak-229</th>
<th>Bak-254</th>
<th>Bak-300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>570</td>
<td>45,223</td>
<td>29,073</td>
<td>23,943</td>
</tr>
<tr>
<td>Ba</td>
<td>10</td>
<td>188</td>
<td>207</td>
<td>110</td>
</tr>
<tr>
<td>Be</td>
<td>1</td>
<td>5</td>
<td>BDL</td>
<td>BDL</td>
</tr>
<tr>
<td>Ca</td>
<td>73</td>
<td>16,918</td>
<td>86,068</td>
<td>5,408</td>
</tr>
<tr>
<td>Cd</td>
<td>3</td>
<td>BDL</td>
<td>BDL</td>
<td>16</td>
</tr>
<tr>
<td>Co</td>
<td>13</td>
<td>27</td>
<td>13</td>
<td>33</td>
</tr>
<tr>
<td>Cr</td>
<td>13</td>
<td>131</td>
<td>73</td>
<td>56</td>
</tr>
<tr>
<td>Cu</td>
<td>53</td>
<td>125</td>
<td>BDL</td>
<td>65</td>
</tr>
<tr>
<td>Fe</td>
<td>23</td>
<td>41,967</td>
<td>15,297</td>
<td>30,947</td>
</tr>
<tr>
<td>K</td>
<td>3,057</td>
<td>34,420</td>
<td>22,210</td>
<td>18,420</td>
</tr>
<tr>
<td>Mg</td>
<td>803</td>
<td>15,430</td>
<td>42,050</td>
<td>5,963</td>
</tr>
<tr>
<td>Mn</td>
<td>7</td>
<td>155</td>
<td>4,84</td>
<td>74</td>
</tr>
<tr>
<td>Mo</td>
<td>12</td>
<td>276</td>
<td>BDL</td>
<td>106</td>
</tr>
<tr>
<td>Na</td>
<td>5,520</td>
<td>12,910</td>
<td>5,700</td>
<td>BDL</td>
</tr>
<tr>
<td>Ni</td>
<td>21</td>
<td>654</td>
<td>BDL</td>
<td>249</td>
</tr>
<tr>
<td>SiO2</td>
<td>145</td>
<td>444,118</td>
<td>505,118</td>
<td>684,318</td>
</tr>
<tr>
<td>Sr</td>
<td>6</td>
<td>52</td>
<td>79</td>
<td>39</td>
</tr>
<tr>
<td>Ti</td>
<td>11</td>
<td>2,950</td>
<td>2,950</td>
<td>1,644</td>
</tr>
<tr>
<td>V</td>
<td>11</td>
<td>1,575</td>
<td>65</td>
<td>392</td>
</tr>
<tr>
<td>Zn</td>
<td>4</td>
<td>284</td>
<td>BDL</td>
<td>2,567</td>
</tr>
<tr>
<td>Zr</td>
<td>13</td>
<td>107</td>
<td>439</td>
<td>34</td>
</tr>
</tbody>
</table>

*BDL = Below detection limit
Table 6: Carbon and Sulfur Analysis Results (Wt. %)

<table>
<thead>
<tr>
<th>Sample</th>
<th>TOC</th>
<th>TIC</th>
<th>TC</th>
<th>Sulfur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bak-229</td>
<td>19.18</td>
<td>0.21</td>
<td>19.39</td>
<td>3.19</td>
</tr>
<tr>
<td>Bak-254</td>
<td>0.51</td>
<td>3.49</td>
<td>4.00</td>
<td>BDL</td>
</tr>
<tr>
<td>Bak-300</td>
<td>7.42</td>
<td>0.37</td>
<td>7.79</td>
<td>2.56</td>
</tr>
</tbody>
</table>

*BDL = Below detection limit (0.5 wt. %)

4.7 SCANNING ELECTRON MICROSCOPY RESULTS

Basic SEM analysis revealed the differences in fabric between the three samples (Figure 23, Figure 24, and Figure 25). Sample Bak-229 is a largely homogenous sample without variation to suggest significant lamination with Bak-330 being much the same, but laminations are prominent due to bright mineral inclusions that highlight bedding. Sample Bak-254 is much different, in that it is highly bedded with what is interpreted as secondary mineralization and deformation of bedding. Additionally, porosity is much more evident in Bak-254 as observed in Figure 24 and Figure 26. The magnified views shown in Figure 26 illustrate the relative heterogeneity of each sample, which is not evident in the hand specimen analysis, CT or even larger SEM views.
Figure 23: SEM-BSE montage image of Bak-229 at 100x magnification.
Figure 24: SEM-BSE montage image of Bak-254 at 100x magnification.
Figure 25: SEM-BSE montage image Bak-300 at 100x magnification.
Figure 26: SEM-BSE images of Bak-229, Bak-254, and Bak-300 at 1,000x magnification.
5. DISCUSSION

The combined analysis presented using the MSCL and CT scanning provide unique insights into the internal core structure, mineralogy and macroscopic changes in lithology. These techniques:

- Are non-destructive on the whole, with the exception of the few grams of core that were destructively analyzed.
- When performed in parallel, give insight into the core beyond what one individual technique can provide.
- Can be used to identify zones of interest for detailed analysis, experimentation, and quantification.
- Provide a detailed digital record of the core, before any destructive testing or further degradation, that is accessible and can be referenced for future studies.

The findings on the Upper, Middle and Lower Bakken formations are as follows:

- The Middle and Lower Bakken have relatively high resistivity readings of approximately 14,000, while the Upper Bakken has relatively high resistivity as it gets closer to the Middle Bakken member reaching a height of 13,000 ft.
- The Upper and Lower Bakken shales have a higher p-wave velocity of approximately 3,000 m/s compared to the Middle Bakken silty sandstone, which peaked at approximately 2,800 m/s. This is because the shales are denser (more compact) than sandstones and tend to have significantly less porosity.
- The upper facies of the Middle Bakken, which is a silty sandstone, contained the highest abundance of LE.
- Calcium and Silica have the highest percentages of the selected XRF species (Si, Al, Ca, Mg) and reach their highest percentages within the Middle Bakken silty sandstone. In zones where these elements are less abundant, there are other heavy metals that are prominent, and this data is available on EDX through: https://edx.netl.doe.gov/dataset/bedwell-33-52-1-1h-well.
- The highest Si/Al ratio, which is indicative of high sandstone content, is found within the upper and lower facies within the Middle Bakken silty sandstone.
- On average and relative to one another, the highest readings of porosity and permeability are found within the Middle Bakken silty sandstone. The Lower Bakken contains relatively high values for porosity and permeability. The Upper Bakken contains relatively low values for porosity and permeability.
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6. REFERENCES


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