Computed Tomography Scanning and Geophysical Measurements of the Marcellus Formation from the Whipkey ST 1 Well

22 May 2018
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Cover Illustration: Left: Photograph of Whipkey ST 1 core from a depth of ~7,865 to 7,866 ft. Middle: Individual medical computed tomography image of this core. Right: Reconstructed 3D medical computed tomography scan of this core with high density zones isolated.

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https://edx.netl.doe.gov/dataset/whipkey-well
Computed Tomography Scanning and Geophysical Measurements of the Marcellus Formation from the Whipkey ST 1 Well

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NETL-TRS-12-2018

22 May 2018

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# Acronyms, Abbreviations, and Symbols

<table>
<thead>
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<th>Term</th>
<th>Description</th>
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<td>2D</td>
<td>Two-dimensional</td>
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<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>CT</td>
<td>Computed tomography</td>
</tr>
<tr>
<td>CTN</td>
<td>Computed tomography number</td>
</tr>
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<td>EDX</td>
<td>NETL's Energy Data eXchange</td>
</tr>
<tr>
<td>EIA</td>
<td>U.S. Energy Information Administration</td>
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<tr>
<td>HU</td>
<td>Hounsfield unit</td>
</tr>
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<td>IEDA</td>
<td>Interdisciplinary Earth Data Alliance</td>
</tr>
<tr>
<td>IGSN</td>
<td>International Geo Sample Number</td>
</tr>
<tr>
<td>MSCL</td>
<td>Multi Sensor Core Logger</td>
</tr>
<tr>
<td>NETL</td>
<td>National Energy Technology Laboratory</td>
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<tr>
<td>SESAR</td>
<td>System for Earth Science Sample Registration</td>
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<td>WVU</td>
<td>West Virginia University</td>
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<td>XRF</td>
<td>X-ray fluorescence</td>
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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) Morgantown, West Virginia site were used to characterize core of the Marcellus Formation from a vertical well drilled in Greene County, Pennsylvania by the Energy Corporation of America. The core is from the Whipkey ST 1 well, in the Carmichaels Field, and is comprised primarily of the Marcellus Formation from depths of 7,719 to 7,910.8 ft. Core was provided by Tim Carr and Keithan Martin (West Virginia University and ORISE).

The primary impetus of this work is a collaboration between West Virginia University (WVU) and NETL to characterize core from multiple wells to better understand the structure and variation of the Marcellus and Utica Shale Formations. As part of this effort, bulk scans of core were obtained from the Whipkey ST 1 well. This report, and the associated scans, provide detailed datasets not typically available from unconventional shales for analysis. 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/whipkey-well.

All equipment and techniques used were non-destructive, enabling future examinations to be performed on these cores. None of the equipment used was suitable for direct visualization of the shale pore space, although fractures and discontinuities were detectable with the methods tested. Low resolution CT imagery 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 as well as fractured zones. 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 provided a multi-scale analysis of this core and provided both a macro and micro description of the core that is relevant for many subsurface energy related examinations that have traditionally been performed at NETL.
1. **INTRODUCTION**

Evaluation of reservoir samples can support resource estimation and determination of effective extraction methodologies. 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 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 report, data collected from a Marcellus Shale production well in Greene County, Pennsylvania are presented as one part of a broader collaborative effort by West Virginia University (WVU) and NETL to better characterize this important, spatially heterogeneous, formation.

In this study, the primary objective was to characterize core from depth with methods not available to most researchers. The data is presented in several formats here and online that are potentially useful for various analyses, but little detailed analysis is presented in this report. The research objective was not to do a site characterization, but rather to develop the data for others to utilize and to create a digital representation of the core that could be preserved.

The core described here is from the Whipkey ST 1 well, from the Carmichaels Field (API No: 37-059-24715) the geographic coordinates for the well are: 39.9000020N, -80.0199970W (Figures 1 and 2). As shown in Figures 1 and 2, the Marcellus Shale in this area is expected between a depth of 6,000 to 7,000 ft below sea level and to be approximately 100 to 150 ft thick (U.S. Energy Information Administration (EIA, 2017, 2018).

As part of this collaboration between WVU and NETL to characterize core from multiple wells to better understand the structure and variation of the Marcellus Formation, bulk scans of core were obtained which provided base-line information on sample condition and characteristics using fast scanning techniques on large batches of samples.

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<th>Core</th>
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<th>Depth Range (ft)</th>
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<tr>
<td>Core 2</td>
<td>20 (missing boxes 1, 2, 10, 15)</td>
<td>7,785–7,837.3</td>
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<tr>
<td>Core 3</td>
<td>14 (missing box 7)</td>
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<td>Core 4</td>
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<tr>
<td>Core 4, 1/3</td>
<td>2</td>
<td>7,898–7,910.8</td>
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<tr>
<td>Core 4, No. 1</td>
<td>5</td>
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Figure 1: Whipkey ST 1 well location map including depths to the Marcellus Formation boundary (ft below sea level); shapefiles from U.S. Energy Information Administration (EIA, 2017, 2018).

Figure 2: Whipkey ST 1 well location map including isopach contours of the Marcellus Formation (ft); shapefiles from EIA (2017, 2018).
2. **CORE DESCRIPTION**

The Whipkey ST 1 core contains a dark, fine-grained, shale from the Marcellus Formation that becomes more calcareous and fossil-rich at depth; it is interbedded with Onondaga Limestone at the base. Fine to medium silt-sized quartz and mica are present with minor calcite cement as well as occasional pyrite. The core is from a vertical well, drilled perpendicular to bedding. Several bedding surfaces in the fine-grained mudstone are now highlighted as horizontal fracture surfaces. Iron staining is prevalent along the majority of the core. Salt is precipitated on several surfaces. A few bedding planes are disrupted and appear to be relict storm surfaces and/or the result of bioturbation. Rounded clasts, mainly concretions and reworked fossils, are present throughout the section at various points. There are missing sections that have already been sub-sampled by various research groups over the years.

These cores were entered in the System for Earth Science Sample Registration (SESAR), a registry that catalogs and preserves sample data and allows access for industry, academic institutes, researchers and the public to view this data online (Interdisciplinary Earth Data Alliance, IEDA, 2018). Each core box is assigned an International Geo Sample Number (IGSN) which allows unique identification and referencing. These SESAR IGSN listings for the Whipkey ST 1 well are shown in Table 2.

<table>
<thead>
<tr>
<th>Field Name</th>
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### Table 2: SESAR IGSN sample names (cont.)

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<th>Field Name</th>
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<td><a href="https://app.geosamples.org/sample/igsn/IENTL00XI">https://app.geosamples.org/sample/igsn/IENTL00XI</a></td>
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<td>Whipkey ST 1 C2 20/20</td>
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<td><a href="https://app.geosamples.org/sample/igsn/IENTL00XJ">https://app.geosamples.org/sample/igsn/IENTL00XJ</a></td>
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<tr>
<td>Whipkey ST 1 C3 1/14</td>
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<tr>
<td>Whipkey ST 1 C3 2/14</td>
<td>IENTL00XL</td>
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<tr>
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<td>IENTL00XM</td>
<td><a href="https://app.geosamples.org/sample/igsn/IENTL00XM">https://app.geosamples.org/sample/igsn/IENTL00XM</a></td>
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<td>Whipkey ST 1 C3 4/14</td>
<td>IENTL00XN</td>
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<tr>
<td>Whipkey ST 1 C3 5/14</td>
<td>IENTL00XO</td>
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</tr>
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<td>Whipkey ST 1 C3 6/14</td>
<td>IENTL00XP</td>
<td><a href="https://app.geosamples.org/sample/igsn/IENTL00XP">https://app.geosamples.org/sample/igsn/IENTL00XP</a></td>
</tr>
<tr>
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<td>IENTL00XQ</td>
<td><a href="https://app.geosamples.org/sample/igsn/IENTL00XQ">https://app.geosamples.org/sample/igsn/IENTL00XQ</a></td>
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<tr>
<td>Whipkey ST 1 C3 9/14</td>
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<td>Whipkey ST 1 C3 10/14</td>
<td>IENTL00XS</td>
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<td>Whipkey ST 1 C3 11/14</td>
<td>IENTL00XT</td>
<td><a href="https://app.geosamples.org/sample/igsn/IENTL00XT">https://app.geosamples.org/sample/igsn/IENTL00XT</a></td>
</tr>
<tr>
<td>Whipkey ST 1 C3 12/14</td>
<td>IENTL00XU</td>
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<td>Whipkey ST 1 C3 13/14</td>
<td>IENTL00XV</td>
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<tr>
<td>Whipkey ST 1 C3 14/14</td>
<td>IENTL00XW</td>
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<tr>
<td>Whipkey ST 1 C4 3/6</td>
<td>IENTL00XX</td>
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<td>Whipkey ST 1 C4 4/6</td>
<td>IENTL00XY</td>
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<tr>
<td>Whipkey ST 1 C4 5/6</td>
<td>IENTL00XZ</td>
<td><a href="https://app.geosamples.org/sample/igsn/IENTL00XZ">https://app.geosamples.org/sample/igsn/IENTL00XZ</a></td>
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<td>Whipkey ST 1 C4 6/6</td>
<td>IENTL00Y0</td>
<td><a href="https://app.geosamples.org/sample/igsn/IENTL00Y0">https://app.geosamples.org/sample/igsn/IENTL00Y0</a></td>
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<td>IENTL00Y1</td>
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<tr>
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<td>IENTL00Y2</td>
<td><a href="https://app.geosamples.org/sample/igsn/IENTL00Y2">https://app.geosamples.org/sample/igsn/IENTL00Y2</a></td>
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<tr>
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<td>IENTL00Y3</td>
<td><a href="https://app.geosamples.org/sample/igsn/IENTL00Y3">https://app.geosamples.org/sample/igsn/IENTL00Y3</a></td>
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<td>Whipkey ST No.1 C4 2/5</td>
<td>IENTL00Y4</td>
<td><a href="https://app.geosamples.org/sample/igsn/IENTL00Y4">https://app.geosamples.org/sample/igsn/IENTL00Y4</a></td>
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Table 2: SESAR IGSN sample names (cont.)

<table>
<thead>
<tr>
<th>Field Name</th>
<th>IGSN</th>
<th>Link</th>
</tr>
</thead>
<tbody>
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<td>IENTL00Y5</td>
<td><a href="https://app.geosamples.org/sample/igsn/IENTL00Y5">https://app.geosamples.org/sample/igsn/IENTL00Y5</a></td>
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<td>Whipkey ST No.1 C4 4/5</td>
<td>IENTL00Y6</td>
<td><a href="https://app.geosamples.org/sample/igsn/IENTL00Y6">https://app.geosamples.org/sample/igsn/IENTL00Y6</a></td>
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<tr>
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<td>IENTL00Y7</td>
<td><a href="https://app.geosamples.org/sample/igsn/IENTL00Y7">https://app.geosamples.org/sample/igsn/IENTL00Y7</a></td>
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</tbody>
</table>

2.1 CORE PHOTOGRAPHS

Photographs of the 2/3 slabbled core.

![核心区照片](image1)

Figure 3: Whipkey ST 1 core photographs, from 7,719 to 7,737 ft.
Figure 4: Whipkey ST 1 core photographs, from 7,737 to 7,755 ft.
Figure 5: Whipkey ST 1 core photographs, from 7,755 to 7,772.75 ft.
Figure 6: Whipkey ST 1 core photographs, from 7,772.75 to 7,797 ft. Missing section from 7,774.3 to 7,785 ft.
Figure 7: Whipkey ST 1 core photographs, from 7,797 to 7,815 ft. Missing section from 7,806 to 7,809 ft.
Figure 8: Whipkey ST 1 core photographs, from 7,815 to 7,836 ft. Missing section from 7,821 to 7,824 ft.
Figure 9: Whipkey ST 1 core photographs, from 7,836 to 7,854 ft. Missing section from 7,857 to 7,860 ft.
Figure 10: Whipkey ST 1 core photographs, from 7,854 to 7,875 ft.
Figure 11: Whipkey ST 1 core photographs, from 7,875 to 7,895 ft. Missing 7,879.7 to 7,886 ft.
Computed Tomography Scanning and Geophysical Measurements of the Marcellus Formation from the Whipkey ST 1 Well

Figure 12: St. Whipkey ST 1 core photographs, from 7,898 to 7,910.8 ft.

7,898–7,904 ft  7,904–7,910 ft  7,910–7,910.8 ft
Figure 13: Whipkey ST 1 core photographs of 1/3rd, from 7,898 to 7,910.8 ft.
3. **DATA ACQUISITION AND METHODOLOGY**

The core was evaluated using computed tomography (CT) scanning and traditional core logging. CT scans and core logging were performed on the 2/3 slabbed cores.

3.1 **CORE LOGGING**

Geophysical measurements of core thickness deviation, P-wave travel time, magnetic susceptibility, and attenuated gamma counts were obtained with a Geotek® Multi-Sensor Core Logging (MSCL, Figure 14) system on competent sections of core. For the 2/3 slabbed core that was scanned as part of this analysis the P-wave velocity was measured and reported. Additionally, the system was used to measure bulk elemental chemistry with a built-in, portable X-ray fluorescence (XRF) spectrometer. For a full description of the MSCL capabilities at NETL, please see Crandall et al. (2017).

![Figure 14: Representation of generalized MSCL with all attached instruments. From Geotek Ltd., Geotek Multi-Sensor Core Logger Flyer, Daventry, UK (2009).](image)

3.1.1 **Magnetic Susceptibility**

Magnetic susceptibility is a measure of the degree of magnetization in the sample. The sample is passed through a ring apparatus with an oscillating magnetic field, where the interference to this field is proportional to the magnetism of the sample, and thus a relative measurement can be taken. The measurement unit used is dimensionless (abbreviated simply as SI units) and is based on the original calibration, which is done via stable iron oxides, and reference minerals, which have known ranges of susceptibility (Table 3) (Geotek Ltd. Multi-Sensor Core Logger Manual, Version 05-10).
Table 3: Magnetic susceptibility values for common minerals (Modified from Geotek Ltd. Multi-Sensor Core Logger Manual, Version 05-10, 2010)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>X (×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>Illite, Montmorillonite</td>
<td>330 to 410</td>
</tr>
<tr>
<td>Pyrite</td>
<td>5 to 3,500</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>

3.1.2 P-wave Velocity

P-wave velocity measurements are 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/or 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 ± 3 m/s with a resolution of 1.5 m/s (Geotek Ltd. Multi-Sensor Core Logger Manual, Version 05-10; Geotek Ltd., 2010).

3.1.3 X-ray Fluorescence Spectrometry

In addition to the geophysical measurements a portable handheld Delta Standard Innov-X® X-Ray Fluorescence Spectrometer was used to measure relative elemental abundances of aggregated “light elements” up to and including sodium, and also various heavy elements which were measured individually (Figure 15). Elemental abundances are reported relative to the total elemental composition, i.e. out of 100% weight.
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.

### 3.2 MEDICAL CT SCANNING

Core scale CT scanning was done with a Toshiba® Aquilion TSX-101A/R medical scanner (medical CT) as shown in Figure 16. 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 200 mA. Subsequent processing and combining of stacks was 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 (Rasband, 2018). The variation in greyscale values observed in the CT images indicates changes in the CT number obtained from the CT scans, which is directly proportional to changes in the attenuation and density of the scanned rock. Darker regions are less dense. As can be seen in Figures 17–28, filled fractures, open fractures, and changes in bedding structure can all be resolved via careful examination of the CT images. While the medical CT scanner was not used for detailed characterization in this study, it allowed for non-destructive bulk characterization of the core, and thus complimented the MSCL data on the resultant logs.
3.3 DATA COMPILATION

Strater® by Golden Software® was used to compile the MSCL and medical CT data into a series of geophysical 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/whipkey-well.
4. **RESULTS**

Processed 2D slices of the medical CT scans through the cores are shown first, followed by the XRF and magnetic susceptibility measurements of the core from the MSCL. The core from the Whipkey ST 1 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).

4.1 **MEDICAL CT SCANS**

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

Core was scanned in 3 ft or smaller sections corresponding to each core box. In the following images the overall depth for each scanned sub-section of core is listed.

Many interesting features can readily be seen in the following images including pyrite nodules, defined fracture planes, and fine scale layering.
Figure 17: 2D isolated planes through the vertical center of the medical CT scans of the Whipkey ST 1 core from 7,719 to 7,734 ft.
Figure 18: 2D isolated planes through the vertical center of the medical CT scans of the Whipkey ST 1 core from 7,734 to 7,749 ft.
Figure 19: 2D isolated planes through the vertical center of the medical CT scans of the Whipkey ST 1 core from 7,749 to 7,764 ft.
Figure 20: 2D isolated planes through the vertical center of the medical CT scans of the Whipkey ST 1 core from 7,764 to 7,788 ft.
Figure 21: 2D isolated planes through the vertical center of the medical CT scans of the Whipkey ST 1 core from 7,788 to 7,803 ft.
Figure 22: 2D isolated planes through the vertical center of the medical CT scans of the Whipkey ST 1 core from 7,803 to 7,821 ft.
Figure 23: 2D isolated planes through the vertical center of the medical CT scans of the Whipkey ST 1 core from 7,824 to 7,838.3 ft.
Computed Tomography Scanning and Geophysical Measurements of the Marcellus Formation from the Whipkey ST 1 Well

Figure 24: 2D isolated planes through the vertical center of the medical CT scans of the Whipkey ST 1 core from 7,839 to 7,854 ft.
Figure 25: 2D isolated planes through the vertical center of the medical CT scans of the Whipkey ST 1 core from 7,854 to 7,872 ft.
Figure 26: 2D isolated planes through the vertical center of the medical CT scans of the Whipkey ST 1 core from 7,872 to 7,892 ft.
Computed Tomography Scanning and Geophysical Measurements of the Marcellus Formation from the Whipkey ST 1 Well

Figure 27: 2D isolated planes through the vertical center of the medical CT scans of the Whipkey ST 1 core from 7,892 to 7,907 ft.
Figure 28: 2D isolated planes through the vertical center of the medical CT scans of the Whipkey ST 1 core from 7,907 to 7,910.8 ft.
4.2 ADDITIONAL CT DATA

Additional CT data can be accessed from NETL's EDX online system using the following link: https://edx.netl.doe.gov/dataset/whipkey-well. The original CT data is available as 16-bit tif stacks suitable for reading with ImageJ (Rasband, 2018) or other image analysis software. In addition, videos showing the variation along the length of the cross-section images shown in the previous section are available for download and viewing. A single image from these videos is shown in Figure 29, where the distribution of high-density minerals in a cross section of the core around a depth of 7,796 ft is shown. Here, the red line through on the XZ-plane image of the core shows the location of the XY-plane displayed above. The videos on https://edx.netl.doe.gov/dataset/whipkey-well show this XY variation along the entire length of the core.

![Figure 29: Single image from a video file available on EDX showing variation in the Whipkey ST 1 core from 7,794 to 7,797 ft. Image above shows the variation in composition within the matrix perpendicular to the core length. Note the two, bright mineral-filled vertical fractures in the matrix at ~7,796 ft.](image)

4.3 DUAL ENERGY CT SCANNING

Dual energy CT scanning uses two sets of images, produced at different x-ray energies, to approximate the density ($\rho_B$) and the effective atomic number ($Z_{\text{eff}}$) (Siddiqui and Khamees, 2004; Johnson, 2012). The technique relies on the use of several standards of known $\rho_B$ and $Z_{\text{eff}}$ 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 30). 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 30a). 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 30b).
Medical grade CT scanners are typically calibrated to known standards, with the output being translated in CT numbers (CTN) or Hounsfield Units (HU). Convention for HU defines air as -1000 and water as 0. A linear transform of recorded HU values is preformed 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 3 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 4). Most materials denser than water or with higher atomic masses have a non-linear response to differing CT energies (Table 5).

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho_s$ (g/cm$^3$)</th>
<th>$Z_{eff}$</th>
</tr>
</thead>
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<tr>
<td>Air</td>
<td>0.001</td>
<td>7.22</td>
</tr>
<tr>
<td>Water</td>
<td>1</td>
<td>7.52</td>
</tr>
<tr>
<td>Graphite</td>
<td>2.3</td>
<td>6</td>
</tr>
<tr>
<td>Sodium Chloride</td>
<td>2.16</td>
<td>15.33</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.7</td>
<td>13</td>
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<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>
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<tr>
<td>Sodium Chloride</td>
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<td>1,237</td>
<td>34,614</td>
<td>34,005</td>
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<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 $\rho_B$ and $Z_{\text{eff}}$ (Siddiqui and Khamees, 2004):

$$\rho_B = mCTN_{\text{low}} + pCTN_{\text{high}} + q$$

$$Z_{\text{eff}} = \frac{(rCTN_{\text{low}} + sCTN_{\text{high}} + t)}{(0.9342 + \rho_B + 0.1759)^{3.6}}$$

Where $[m, p, \text{and } q]$ and $[r, s, \text{and } t]$ are unknown coefficients that can be solved by setting up a system of equations with four 3 x 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 $\rho_B$ and $Z_{\text{eff}}$ were both solved for each pixel in the 3D volume and saved as two new separate image stacks.

ImageJ (Rasband, 2018) was used to reslice the image stacks to produce 2D representative cross-sections of the entire core-length. A 6-shade look up table was used to apply a gradational color scale to the image with the total range of values limited to densities from 2 to 4.5 g/cm$^3$; this eliminated much of the noise in the air portion of the scans and at the edges of the sample. The average density along the length of the cores was calculated by excluding all densities below 2 g/cm$^3$. This study assumed that the cores were free of water and liquids as they were air dried and that the cores do not contain an appreciable quantity of material with densities lower than 2.0 g/cm$^3$.

### 4.4 COMPILED CORE LOGS

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. Due to the total length of the core the data is presented along two intervals, from 7,719–7,812 ft and 7,812–7,910.8 ft to enable visualization. Two sets of logs are presented for each section, the first set with data from the CT scans and the second set with calculated ratios from the XRF scans, P-wave, gamma density, and notable features from the core listed.

Data from the MSCL that was obtained with P-wave velocity less than 330 m/s has been removed from these logs. This low P-wave velocity is less than the anticipated velocity through air, indicating a highly fractured zone and unreliable readings. The locations of these fractured zones were confirmed through visual examination and with the medical CT scanned images.

The elemental results from the XRF were limited to Ca, Si and the remaining top twelve elements (S, Al, Fe, K, Ti, Mg, V, Zn, Cl, Mn, Cu, and P). Of the remaining top twelve elements, S was the most abundant with a maximum occurrence of 123,418 ± 467 ppm at one location in the core, and P was the least abundant element with a maximum occurrence of 2,242 ± 93 ppm at...
one location in the core. All other elements measured (Figure 15), but not listed, were observed to have maximum occurrences of less than 720 ppm.

These combined analyses enable determination of mineral phases present (such as pyrite) from magnetic susceptibility and geochemical compositions. More specifically, trends in elemental ratios can provide insight into mineral composition, oxidation state and depositional setting. Examples include: Ca/Si, which provides information on relative abundance of calcium carbonates versus silicates; Ca/Al, which gives approximate amounts of calcium carbonate versus clays and feldspar; and K/Al, which provides information on the abundance of illite and micas versus other clays. 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. Natural gamma is a proxy for organic carbon as well. These broad trends can quickly give information on large suites of core and direct more focused research.

The CT derived dual energy density calculations were cropped at 3 g/cm³ as that was the largest calibration standard used.

These logs are presented in the following images, Figures 31–34.
Figure 31: Compiled core log for Whipkey ST 1 well, from 7,719 to 7,812 ft.

Whipkey ST 1
API: 37-059-24715
Eclipse Resources
Lat: 39.9000020 N
Long: 80.099970 W
Greene County, PA

Measurements performed at the US Department of Energy National Energy Technology Laboratory Morgantown, WV 2018

Analysis By: Dustin Crandall, Johnathan Moore, and Sarah Brown
Data Collection: Paige Mackey and Scott Workman
Project Oversight: Dustin McIntyre and Tim Carr

Equipment:
- Mag. Sus
- GeoTek Multi-Sensor Core Logger XRF
- Inov-X Delta handheld XRF analyzer
- Computed Tomography Imagery
- Toshiba Aquilion
Figure 32: Compiled core log for Whipkey ST 1 well, from 7,812 to 7,910.7 ft.

<table>
<thead>
<tr>
<th>Depth (feet)</th>
<th>Magnetic Susceptibility ( \times 10^{-6} )</th>
<th>Light Elements ( \text{at.} % )</th>
<th>Li (%)</th>
<th>Na (%)</th>
<th>Mg (%)</th>
<th>Al (%)</th>
<th>Si (%)</th>
<th>Fe (%)</th>
<th>Ca (%)</th>
<th>Ti (%)</th>
<th>V (%)</th>
<th>Cr (%)</th>
<th>Mn (%)</th>
<th>Cu (%)</th>
<th>Remainig (%)</th>
</tr>
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<tbody>
<tr>
<td>7810</td>
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<tr>
<td>7815</td>
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Whipkey ST 1
API: 37-059-24715
Eclipse Resources
Lat: 39.39000020 N
Long: 80.0199970 W
Greene County, PA

Measurements performed at the US Department of Energy National Energy Technology Laboratory Morgantown, WV 2018

Analysis By: Dustin Crandall, Johnathan Moore, and Sarah Brown
Data Collection: Paige Mackey and Scott Workman
Project Oversight: Dustin McIntyre and Tim Carr

Equipment:
- Mag. Sus
- GeoTek Multi-Sensor Core Logger XRF
- Innov-X Delta handheld XRF analyzer
- Computed Tomography Images
- Toshiba Aquilion
Figure 33: Compiled core log with elemental ratios for Whipkey ST 1 well, from 7,719 to 7,812 ft.

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<th>Depth (feet)</th>
<th>Dual Energy Density (g/cc)</th>
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### Notable Features

- Shale with horizontal fractures, iron staining and salt precipitation
- Ferroblende (0.1 by 0.3 inches)
- Shale with horizontal fractures, iron staining and salt precipitation
- Fine-grained, layered shale with horizontal fractures, iron staining and salt precipitation and calcite horizontal surfaces
- Fine-layering in shale, marine fossils present, Fe nodules, shell fragments, iron staining
- Vertical calcite veins, calcite surfaces spread throughout
- Compressional
- Organic rich shale, thinly layered, broken up
- Fine layering, fractures horizontal to bedding, pyrite nodules 1 – 1.5 cm (at 7798 feet) and siltstone layers (7801 feet)
- Compressional
- Fine layering, fractures horizontal to bedding

---

**Whipkey ST 1**
- **API:** 37-059-24715
- **Eclipse Resources**
- **Lat:** 39.9000020 N
- **Long:** 80.0199970 W
- **Greene County, PA**

**Measurements performed at the US Department of Energy**
- National Energy Technology Laboratory
- Morgantown, WV

**Analysis By:** Dustin Crandall, Johnathan Moore, and Sarah Brown
**Data Collection:** Paige Mackey and Scott Workman
**Project Oversight:** Dustin McIntyre and Tim Carr

**Equipment:**
- Mag. Sus.
- GeoTalk Multi-Sensor Core Logger
- XRF
- Innov-X Delta handheld XRF analyzer
- Computed Tomography Images
- Toshiba Aquilion
Figure 34: Compiled core log with elemental ratios for Whipkey ST 1 well, from 7,812 to 7,910.7 ft.

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**Notable Features**

- Fine layering, fractures horizontal to bedding
- Calcareous shale
- Lenticular calcite veins parallel to bedding (7819 ft), fossils present
- Core missing
- Black shale with occasional Fe staining and pyrite layers
- Rounded nodules, up to 2.5 inches in diameter, lots of iron staining
- Very dark, organic rich shale
- Core missing
- At 7862 ft, shale becomes more calcareous, vertical calcite veins throughout, layers
- Calcareous shale with 5-inch-long, anachronous fractures filled with calcite and pyrite
- Layered calcareous shale
- Less calcareous shale
- Fractured
- Core missing
- Finely laminated and fractured with limestone and calcareous shale, vertical calcite veins, shell fragments
- Limestone interbedded with shale, rare fossils, undulating, broken, matrix fossils and pyrite present
- Finely laminated shale interbedded with limestone and calcareous shale, vertical calcite veins, shell fragments
- Wackestone Limestone, shells, storm ripples, undulating layers, clasts

**Whipkey ST 1**

- API: 37-059-24715
- Eclipse Resources
- Lat: 39.9006020 N
- Long: 80.0199070 W
- Greene County, PA

**Measurements performed at the US Department of Energy National Energy Technology Laboratory, Morgantown, WV, 2018**

**Analysis By:** Dustin Crandall, Jonathan Moore, and Sarah Brown

**Data Collection:** Paige Mackey and Scott Workman

**Project Oversight:** Dustin McIntyre and Tim Carr

**Equipment:**
- Mag Sus - GeoTalk Multi-Sensor Core Logger, XRF
- Innow X Delta handheld XRF analyzer, Computed Tomography, Images
- Toshiba Aquilion
5. **DISCUSSION**

The measurements of the magnetic susceptibility, P-wave velocity, XRF, and CT analysis provide a unique look into the internal structure of the core and macroscopic changes in lithology. These techniques:

- Are non-destructive
- 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
6. REFERENCES


Geotek Ltd. Multi-Sensor Core Logger Manual; Version 05-10; Published by Geotek, 3 Faraday Close, Daventry, Northamptonshire NN11 8RD, 2010. info@geotek.co.uk, www.geotek.co.uk


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