Computed Tomography Scanning and Geophysical Measurements of Core from the State Charlton #4-30 Well

22 November 2019
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Cover Illustration: A picture of an industrial computed tomography (CT) scan, representing the contact between the Bois Blanc Formation and Bass Island Group (3,441.0–3,443.0 ft).


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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/st-charlton4-30
Computed Tomography Scanning and Geophysical Measurements of Core from the State Charlton #4-30 Well

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22 November 2019

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<th>Description</th>
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<tr>
<td>2D</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
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<td>CT</td>
<td>Computed tomography</td>
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<td>CTN</td>
<td>CT Number</td>
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<td>EDX</td>
<td>NETL's Energy Data eXchange</td>
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<td>HU</td>
<td>Hounsfield Units</td>
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<tr>
<td>LRST</td>
<td>Leidos Research Support Team</td>
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<td>MGS</td>
<td>Michigan Geological Survey</td>
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<tr>
<td>MLEF</td>
<td>Mickey Leland Energy Fellowship</td>
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<tr>
<td>MRCSP</td>
<td>Midwest Regional Carbon Sequestration Partnership</td>
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<tr>
<td>MSCL</td>
<td>Multi-Sensor Core Logger</td>
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<tr>
<td>MSL</td>
<td>Mean sea level</td>
</tr>
<tr>
<td>NETL</td>
<td>National Energy Technology Laboratory</td>
</tr>
<tr>
<td>ORISE</td>
<td>Oak Ridge Institute for Science and Education</td>
</tr>
<tr>
<td>XRF</td>
<td>X-ray fluorescence</td>
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</table>
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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 Bass Island, Bois Blanc, and Amherstburg Formations from a vertical well (State Charlton #4-30) from Otsego County, Michigan at depths 3,030.0 to 3,090.0 ft and 3,400.0 to 3,520.5 ft. The primary impetus of this work is a collaboration between the Michigan Geological Survey (MGS) and NETL to characterize core to better understand the potential of carbon dioxide (CO₂) sequestration within formations in the Michigan Basin. As part of this effort, bulk CT scans of core were obtained from the State Charlton #4-30 well, provided by the MGS. This report, and the associated scans generated, provide detailed datasets not typically available for researchers to analyze. The resulting 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.doc.gov/dataset/st-charlton4-30.

All equipment and techniques used were non-destructive, enabling future examinations and analyses to be performed on the cores. Low-resolution CT images obtained with the NETL medical CT scanner were obtained for the entire core and high-resolution CT images acquired with the NETL industrial CT scanner were obtained for selected sections of the core. Qualitative analysis of the medical CT images coupled with X-ray fluorescence (XRF) measurements from the MSCL were useful in identifying zones of interest for more detailed analysis. 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 this core and descriptions of the core that are relevant for many subsurface examinations that have traditionally been performed at NETL.
1. INTRODUCTION

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. 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 a digital representation of the core that could be preserved.

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, universities, 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. Bulk scans of core were performed using fast scanning techniques to obtain base-line information on sample condition and characteristics.

The State Charlton #4-30 well (45.043917 N, 84.485306 W; API#21-137-57916) (Figures 1 and 2) was drilled by Core Energy LLC as a carbon dioxide (CO2) sequestration well in Otsego County, Michigan. The core was retrieved from depths ranging from 3,030.0 to 3,090.0 ft and 3,400.0 to 3,520.5 ft (Harrison et al., 2009). Extraction of the core was completed in November 2006 and included recovered intervals from the Bass Islands Group, the Bois Blanc, and Amherstburg Formations. The stratigraphy encompasses strata from the Upper Silurian (Bass Islands Group) through Middle Devonian age (Bois Blanc Formation and Amerherstburg Formation) (Bacon et al., 2009; Sminchak et al., 2009; Carter et al., 2010).

The Bass Islands Dolomite, a subunit of the Bass Islands Group, is of particular interest due to its great potential as a reservoir unit for CO2 sequestration; specifically, the Bass Islands may be useful for sequestering CO2 byproduct from productive natural gas plays in the region (i.e. Antrim Shale Formation) (Sminchak et al., 2009) and industrial CO2 emissions. Organizations such as the Michigan Geological Survey (MGS) and the Midwest Regional Carbon Sequestration Partnership (MRCSP) have analyzed the Bass Islands Group to determine subsurface storage potential within this saline unit. The State Charlton #4-30 well core consists of 70 boxes for analysis at NETL, with results published within this report.
Figure 1: Location and structure contour map for the Bass Islands Dolomite and State Charlton #4-30 well, adapted from Landes (1945). The Bass Islands structure contours are relative to mean sea level (MSL). The depth to formation at the State Charlton #4-30 well site is approximately 2,200 ft below MSL.
Figure 2: Location and isopach map for the Bass Islands Dolomite with the location of the State Charlton #4-30 well, adapted from Harrison et al. (2009).
1.1 GEOLOGIC BACKGROUND

During the Early Cambrian, the Iapetus Ocean began to shrink as the Avalonian terrain and the Taconic island arc approached Laurentia. This mountain building event, the Taconic Orogeny, culminated during the Late Ordovician and created many dynamic structural features. One feature, the Cincinnati Arch, is believed to have formed by the uplift of Precambrian basement rock during this collisional event. The Cincinnati Arch is a positive structural feature roughly trending north to south, buckling downward at its most northern extent (Hansen, 1997; Potter, 2007). The approximately 5 km of subsidence at the northern extent of the Cincinnati Arch is known as the Michigan Basin (Hansen, 1997; Howell and van der Pluijm, 1999). Water filled the Michigan Basin to form an epicontinental sea, with sea levels transgressing and regressing with accordance to the cratonic sea level megasequences (Gillespie et al., 2008; Bornhorst, 2016). The shifting sea levels within the Michigan Basin dictated sedimentary deposition, leading to mud- and carbonate-rich rock formations as well as lack of sediment seen at the Tippecanoe-Kaskaskia unconformity.
2. **CORE DESCRIPTION**

The State Charlton #4-30 slabbed well core was described from intervals 3,030.0 to 3,520.5 ft with a substantial gap from 3,090.0 to 3,400.0 ft. The received core was comprised of three depth intervals, listed in Table 1. The Bass Islands Group, consisting of the Bass Islands Dolomite and the Bass Islands Anhydrite, is described from depths 3,442.4 to 3,520.5 ft within the core. The Bass Islands Dolomite composes the majority of the Bass Islands Group recovered from the State Charlton #4-30 well and is the main CO₂ injection target. This interval is defined as meter-scale shallowing upward cycles of bioturbated, skeletal wackestone; minor cross-bedded and sandy dolograinstones; and laminated mudstones. The bottom 6.7 ft of core is characterized as the top of the high-density Bass Islands Anhydrite interval. Despite the presence of two distinct lithologies within the Bass Islands Group, the group is often referred to simply as the Bass Islands Dolomite (as seen in Figures 1 and 2). Immediately overlaying the Bass Islands Dolomite is the Tippecanoe-Kaskasia unconformity at 3,442.4 ft, representing the contact with the overlying Bois Blanc Formation. This interval is described from 3,400.0 to 3,442.4 ft and consists of a mixture of moderately-burrowed, fossiliferous, chert-rich limestone; cherty dolostone; and cherty dolomitic limestone. Nodular blue-gray chert is present throughout the Bois Blanc Formation, with less than ten percent of chert nodules exhibiting minor irregular alteration. The Amherstburg Formation overlays the Bois Blanc Formation and is present from 3,030.0 to 3,090.0 ft within the core. This interval is defined by fossiliferous, dense, skeletal wackestone to mud-rich packestone. A detailed log of the core can be found on the following pages, adapted from Catacosinos et al. (2000).

<table>
<thead>
<tr>
<th>Core Box</th>
<th>Depth (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core One</td>
<td>3,030–3,063</td>
</tr>
<tr>
<td>Core Two</td>
<td>3,063–3,090</td>
</tr>
<tr>
<td>Core Three</td>
<td>3,400–3,520.5</td>
</tr>
</tbody>
</table>
Figure 3: Part of the generalized Michigan stratigraphic column representing the Upper Silurian and Lower to Middle Devonian strata, as modified from Catacosinos et al. (2000). The Silurian-Devonian boundary is located at the top of the Bass Islands Group. The Mackinac Breccia, Garden Island Formation, and Sylvania Sandstone are not found in Otsego County (Harrison et al., 2009).
2.1  CORE PHOTOGRAPHS

Photographs of the nominal 3.5-in. diameter core are presented on the following pages.

Figure 4: State Charlton #4-30 core photographs, from Core One at depths 3,030.0 to 3,046 ft, approximately 3.5-in. diameter core. The shallowest depth of the section is located to the top left with the deepest depth location to the bottom right of the image.
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3. DATA ACQUISITION AND METHODOLOGY

The core was evaluated using computed tomography (CT) scanning and traditional core logging. CT scans were performed on whole cores to maximize the internal area of the core that could be visualized.

3.1 CORE LOGGING

Geophysical measurements of P-wave travel time, magnetic susceptibility, and attenuated gamma counts can be obtained with a Geotek® Multi-Sensor Core Logging (MSCL, Figure 16) system on a competent core. For the State Charlton #4-30 core the P-wave velocity, gamma density, and magnetic susceptibility were measured and are reported. Additionally, the system was used to measure bulk elemental chemistry with a built-in, an integrated portable-X-ray fluorescence (XRF) spectrometer. For a full description of the MSCL capabilities at NETL, please see Crandall et al. (2017).

3.1.1 Magnetic Susceptibility

Magnetic susceptibility is a measure of the degree of magnetization in the sample. Due to the large core diameter, the Magnetic Susceptibility Point Sensor was used. The Magnetic Susceptibility Point Sensor works by passing samples under the sensor, where an oscillator circuit produces a low intensity alternating magnetic field (~80 A/m RMS and 2 kHz) and is changed according to magnetic susceptibility of the sample. 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 2) (Geotek Ltd. Multi-Sensor Core Logger Manual, Version 05-10).
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 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 Gamma Density

Gamma density is 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.

3.1.4 X-Ray Fluorescence Spectrometry

In addition to the geophysical measurements a portable handheld Innov-X® X-Ray Fluorescence Spectrometer was used to measure relative elemental abundances. The Mining-Plus Suite was run at 6 cm resolution for 60 second 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...
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 17). Elemental abundances are reported relative to the total elemental composition, i.e. out of 100% weight.

<table>
<thead>
<tr>
<th>Periodic Table</th>
<th>Mining-Plus</th>
</tr>
</thead>
<tbody>
<tr>
<td>H, Li, Be</td>
<td></td>
</tr>
<tr>
<td>B, C</td>
<td></td>
</tr>
<tr>
<td>N, O</td>
<td></td>
</tr>
<tr>
<td>F, Ne</td>
<td></td>
</tr>
<tr>
<td>Na, Mg</td>
<td></td>
</tr>
<tr>
<td>Al, Si</td>
<td></td>
</tr>
<tr>
<td>P, S</td>
<td></td>
</tr>
<tr>
<td>Cl, Ar</td>
<td></td>
</tr>
<tr>
<td>K, Ca</td>
<td></td>
</tr>
<tr>
<td>Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr</td>
<td></td>
</tr>
<tr>
<td>Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd</td>
<td></td>
</tr>
<tr>
<td>Ag, Cd, In, Sn, Sb, Te, I, Xe</td>
<td></td>
</tr>
<tr>
<td>Cs, Ba, Lu, Hf, Ta</td>
<td></td>
</tr>
<tr>
<td>W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At, Rn</td>
<td></td>
</tr>
<tr>
<td>Fr, Ra, Lr, Rf, Db, Sg, Bh, Hs, Mt, Un, Uu, Uub, Uug</td>
<td></td>
</tr>
</tbody>
</table>

Figure 17: Periodic table showing elements measurable by the Innov-X® X-Ray Fluorescence Spectrometer using the Mining-Plus (shaded).

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 18. 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. Scans were conducted at 200 mA, with high and low energy scans conducted at voltages of 135 kV and 80 kV, respectively. Both high and low energy scans were used to calculate dual energy densities of the core samples. Images of the high energy medical CT scans and the calculated dual energy density of the core are presented below. 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 (Rasband, 2019). 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. The greyscale images represent less dense material as darker regions.
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 INDUSTRIAL CT SCANNING

Detailed scans of several sections of interest were performed by the North-Star Imaging Inc. M-5000® Industrial Computed Tomography System (Industrial CT) at NETL. The system was used to obtain higher resolution scans of several sections of interest from the State Charlton #4-30 core, with a voxel resolution of \((28.1 \, \mu m)^3\) and capture the details of certain features clearly. Features in the core from depths of 3,053, 3,442, and 3,469 ft were imaged using this technique, providing illustrations of the Amherstburg, Tippecanoe-Kaskaskia Unconformity, and the Bass Island Dolomite, respectively.

The scans were performed at a voltage of 185 kV and a current of 400 μA, which provided the best balance of resolution and energy to penetrate the samples. The samples were rotated 360° and 1,440 radiograph projections of the samples were obtained, averaging 12 individual radiographs at each step to create the reconstruction.

3.4 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 Energy Data eXchange (EDX) online system using the following link: https://edx.netl.doe.gov/dataset/st-charlton4-30.
4. **RESULTS**

The following section presents the data collected from the medical CT, industrial CT, and MSCL. The compiled core logs show the processed vertical 2D slices of the medical CT scans, followed by the XRF and geophysical measurements of the core from the MSCL.

4.1 **MEDICAL CT SCANS**

The medical CT scans were done in sequence of 2.3 to 2.5 ft, which represented one row in the 3 ft core boxes. Detailed information in log books and photographs of cores were used to merge multiple scans of the core. 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 interfaces of salt and siltstone, grain size and layering changes, fault surfaces, fractures and clast shape and orientation.

The unprocessed data is available on EDX using the following link: [https://edx.netl.doe.gov/dataset/st-charlton4-30](https://edx.netl.doe.gov/dataset/st-charlton4-30).
Figure 19: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core One at depths 3,030.0 to 3,043.4 ft.
Figure 20: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core One at depths 3,043.4 to 3,056.8 ft.
Figure 21: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Cores One and Two at depths 3,056.8 to 3,070.0 ft (core depths from Core Two are rounded to the nearest whole number to correlate with box labels).
Figure 22: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core Two at depths 3,071.0 to 3,085.0 ft (core depths from Core Two are rounded to the nearest whole number to correlate with box labels).
Figure 23: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core Two at depths 3,085.0 to 3,090.0 ft (core depths from Core Two are rounded to the nearest whole number to correlate with box labels).
Figure 24: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core Three at depths 3,400.0 to 3,413.1 ft.
Computed Tomography Scanning and Geophysical Measurements of Core from the State Charlton #4-30 Well

Figure 25: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core Three at depths 3,413.1 to 3,425.9 ft.
<table>
<thead>
<tr>
<th>Depth Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,425.9–3,428.2</td>
<td>2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core Three at depths 3,425.9 to 3,437.0 ft.</td>
</tr>
<tr>
<td>3,428.2–3,430.6</td>
<td></td>
</tr>
<tr>
<td>3,430.6–3,432.6</td>
<td></td>
</tr>
<tr>
<td>3,432.6–3,434.7</td>
<td></td>
</tr>
<tr>
<td>3,434.7–3,437.0</td>
<td></td>
</tr>
</tbody>
</table>
Figure 27: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core Three at depths 3,437.0 to 3,446.0 ft.
Figure 28: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core Three at depths 3,446.0 to 3,460.0 ft.
Figure 29: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core Three at depths 3,460.0 to 3,472.1 ft.
Figure 30: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core Three at depths 3,472.1 to 3,485.5 ft.
Figure 31: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core Three at depths 3,485.5 to 3,498.3 ft.
Figure 32: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core Three at depths 3,498.3 to 3,512.8 ft.
Figure 33: 2D isolated planes through the vertical center of the medical CT scans of the State Charlton #4-30 core from Core Three at depths 3,512.8 to 3,520.5 ft.
4.2 INDUSTRIAL CT SCANS

The industrial CT scans were conducted at a resolution of 28.1 µm at depths of 3,441 and 3,468 ft and scanned at a resolution of 32.2 µm at a depth of 3,053 ft. Several of the industrial scans were processed in ImageJ for beam hardening artifacts using an automated correction (BeamHardening_Correction) (Romano, 2018). The corrected greyscale values in the following images were used to isolate and visually differentiate objects of interest in the scans. The increased resolution decreases the amount of attenuation “shadowing” of high-density features and allows us to have a better understanding of the geometry of these features.

The premise of isolating features is to first segment out the feature based on its unique greyscale value. Once this isolation has occurred, the next steps are to differentiate multiple isolated features and then combine them into one coherent visual representation. Figures 34 and 35 show these feature isolations to enhance the ability of the reader to discern differences observed in the State Charlton #4-30 core. Only portions of the core were scanned and analyzed as part of this report because of the time involved in scanning with this system (over 2 hours per scan). Unaltered CT images are available for additional analysis on https://edx.netl.doe.gov/dataset/st-charlton4-30.
Figure 34: Industrial CT-scan vertical isolated planes at 3,468 ft, representing a halite crystal within pink dolomite.
Figure 35: Industrial CT montage image (A.) XZ isolated planes and (B.) XY isolated planes representing the Tippecanoe/Kaskaskia unconformity (red line), which separates the Bois Blanc Formation from the Bass Island Group (3,441 to 3,443 ft.)
4.3 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/st-charlton4-30. The original CT data is available as 16-bit tif stacks suitable for reading with ImageJ (Rasband, 2019) 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 36, where the distribution of high-density minerals in a cross section of the core around a depth of 3,404 ft is shown. Here, the red line through 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/st-charlton4-30 show this XY variation along the entire length of the core.

![Figure 36: Single image from a video file available on EDX showing variation in the 3-in. diameter State Charlton #4-30 core from 3,403 to 3,405 ft. Image shows the variation in composition within the matrix.](image)

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 37). 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 37a). 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 37b).
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 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 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 2). Most materials denser than water or with higher atomic masses have a non-linear response to differing CT energies (Table 3).

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho_B$ (g/cm$^3$)</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>
<thead>
<tr>
<th>Material</th>
<th>HU</th>
<th>CTN</th>
<th>HU</th>
<th>CTN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80 KeV</td>
<td>135 KeV</td>
<td>80 KeV</td>
<td>135 KeV</td>
</tr>
<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 3 unknowns each are utilized to find $\rho_B$ (Siddiqui and Khamees, 2004):

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

Where $[m, p, and q]$ and $[r, s, and t]$ are unknown coefficients that can be solved by setting up a system of equations with four 3x3 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 3-D 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.

ImageJ (Rasband, 2019) 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/cm³; 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/cm³. 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 elements with densities lower than 2.0 g/cm³.

### 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. Two sets of logs are presented for the core; the first set with data from the CT scans and XRF data, and the second set with calculated ratios from the XRF scans and P-wave measurements. Features that can be derived from these combined analyses include determination of mineral locations from magnetic susceptibility and using the XRF to inform geochemical composition and mineral form.

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 location of these fractured zones was confirmed through visual examination of the core and with the medical CT scanned images.

The elemental results from the XRF were corrected for errors exceeding 20% of the measurement and limited to display the top elemental proportions: S (max: 191,132 ppm), Cl (max: 62,152 ppm), Fe (max: 21,994 ppm), Al (max: 28,333 ppm), Ti (max: 4,303 ppm), Mn (max: 3,379 ppm), Cr (max: 1,120 ppm), Zr (max: 890 ppm), Sb (max: 341 ppm), and Sn (max: 214 ppm).

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 and anhydrite versus silicates; and Ca/Mg, which provides
information on the presence and abundance of limestone or dolostone. Magnetic susceptibility can test for more clay-rich intervals that generally have higher values, relative to evaporites and carbonates. Gamma density gives a quick look at differences between low density evaporite intervals and high density calcareous shale. These broad trends can quickly give information on large suites of core and direct more focused research. These logs are presented in the following images, Figures 38 to 41.
Figure 38: Compiled core log for Cores One and Two from the State Charlton #4-30 core.
Figure 39: Compiled core log for Cores One and Two from the State Charlton #4-30 core with elemental ratios.
Figure 40: Compiled core log for Core Three from the State Charlton #4-30 core.

State Charlton #4-30
API: 21-137-57916
Core Energy LLC
Latitude: 45.043917 N
Longitude: 84.485303 W
Otsego County, Michigan

Measurements performed at the U.S. Department of Energy National Energy Technology Laboratory Morgantown, West Virginia June and July 2019

Analysis By: Jamie Vormlocher, Charity Betters, Dustin Crandall, and Johnathan Moore
Data Collection: Jamie Vormlocher, Charity Betters
Project Oversight: Dustin McIntyre

Equipment:
- Magnetic Susceptibility
- GeoTek® Multi-Sensor Core Logger XRF
- Innov-X Delta handheld XRF analyzer
- Toshiba Aquilion
Figure 41: Compiled core log for Core Three from the State Charlton #4-30 core with elemental ratios.
5. **DISCUSSION**

The measurements of the magnetic susceptibility, P-wave velocity, XRF, and CT analysis provide a unique look into of 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](http://www.geotek.co.uk)


Romano, C. *Automated High Accuracy, Rapid Beam Hardening Correction in X-Ray Computed Tomography of Multi-Mineral, Heterogenous Core Samples*; University of Strathclyde, 2018. DOI:10.15129/2fb54088-1187-48f2-832b-ef76cf5e7bc1.


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