Computed Tomography Scanning and Geophysical Measurements of the T.R. McMillen #2 Core

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Cover Illustration: Multiple cross-sections of the T.R. McMillen #2 core at a depth of 6,282–6,286 ft. Red lines in the core-length cross-section indicate the location of the cross-core sections directly above each image.


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Computed Tomography Scanning and Geophysical Measurements of the T.R. McMillen #2 Core

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<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>CO\textsubscript{2}</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>CT</td>
<td>Computed tomography</td>
</tr>
<tr>
<td>CTN</td>
<td>Computed tomography number</td>
</tr>
<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
</tr>
<tr>
<td>EDX</td>
<td>NETL's Energy Data eXchange</td>
</tr>
<tr>
<td>HU</td>
<td>Hounsfield Units</td>
</tr>
<tr>
<td>IL</td>
<td>Illinois</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>ORISE</td>
<td>Oak Ridge Institute for Science and Education</td>
</tr>
<tr>
<td>XRF</td>
<td>X-ray fluorescence</td>
</tr>
</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 from the Carbon Safe Christian County project, T.R. McMillen #2 well (API 1202125650).

The primary impetus of this work is a collaboration between the U.S. Department of Energy (DOE) and the Illinois State Geologic Survey at the University of Illinois, Urbana-Champaign. 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/carbonsafe-tr-mcmillen-2.

All equipment and techniques used were non-destructive, enabling future examinations and analyses to be performed on these cores. None of the equipment used was suitable for direct visualization of the pore space in fine grained structures; 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. 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 support resource estimations for geologic carbon dioxide (CO₂) injection. 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 consortia. 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 a U.S. Department of Energy (DOE)-funded CarbonSAFE field project (Sullivan et al., 2019) with several non-destructive methods and make this data publicly available. The data is presented in several formats here and online 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 a digital representation of the core that could be preserved.

1.1 SITE BACKGROUND

The CarbonSAFE Cristian County project is in Christian County, Illinois (IL), approximately 3 miles east of Mt. Auburn, IL, in the Mt. Auburn Oil field (Figure 1). This project was originally planned in Macon County Illinois, but was moved one county westward to Christian County (Whittaker and Freiburg, 2018). A stratigraphic characterization well, T.R. McMillen #2 (API 1202125650), was drilled in pursuit of establishing a commercial-scale geological storage complex in close proximity to large source CO₂ emitters (Whittaker and Freiburg, 2018). Over the course of the CarbonSAFE project at Cristian County, IL, the storage complex is planned to accept 50 million tons or more of industrial sourced CO₂. The Mt. Simon storage complex, which has shown promise of good reservoir quality (Whittaker, 2019), is the target formation at this site.

1.2 GEOLOGIC BACKGROUND

The T.R. McMillen #2 well was drilled through the Mt. Simon Sandstone into the Precambrian. The Mt. Simon Sandstone, of Cambrian origin, is a sedimentary rock that underlies all of Illinois, excluding few hills where it failed to cover the Precambrian surface. The formation ranges in thickness from less than 500 ft to greater than 2,600 ft in select areas (Figure 1). The greatest thickness can be observed in northeastern Illinois. The Mt. Simon Sandstone mainly consists of quartz, with poorly sorted, coarse grains. The lower portion of the Mt. Simon Sandstone has shown to have good reservoir quality. Upper sections of the Mt. Simon Sandstone have also shown evidence of good reservoir quality, making the formation a viable target for long-term geologic CO₂ storage.
Figure 1: Map of Illinois illustrating the extent and thickness of the Mt. Simon formation. Red star indicates site location of the T.R. McMillen #2 core. (Modified from Freiburg et al., 2016).
2. CORE DESCRIPTION

2.1 CORE PHOTOGRAPHS

Figure 2: T.R. McMillen #2 core photographs, from 6,240.0 to 6,276.0 ft.
Figure 3: T.R. McMillen #2 core photographs, from 6,276.0 to 6,299.6 ft.
3. DATA ACQUISITION AND METHODOLOGY

The core was evaluated using computed tomography (CT) scanning and X-ray fluorescence (XRF) spectrometry on the slabbed cores.

3.1 MEDICAL CT SCANNING

Core scale CT scanning was done with a medical Toshiba® Aquilion TSX-101A/R medical scanner as shown in Figure 4. 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 (Rasband, 2019). The variation in greyscale values observed in the CT images indicates changes in the CT number (CTN) 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 Figure 8 through Figure 13, filled fractures, open fractures, and changes in bedding structure can all be resolved via careful examination of the CT images.

Figure 4: Toshiba® Aquilion™ Multislice Helical Computed Tomography Scanner at the 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 (MSCL) system on a competent core. For the T.R. McMillen #2 core the P-wave velocity, attenuated gamma counts, and magnetic susceptibility were measured and are reported (Figure 16). 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. Core scale CT scanning was done with a medical Toshiba® Aquilion TSX-101A/R medical Scanner.

3.2.1 Magnetic Susceptibility

Magnetic susceptibility is a measure of the degree of magnetization in 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 1) (Geotek Ltd. Multi-Sensor Core Logger Manual, Version 05-10).

<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>Haematite</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 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).

### 3.2.3 Gamma Density

Gamma density is determined 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® X-Ray Fluorescence Spectrometer was used to measure relative elemental abundances. Two suites were run, the Mining-Plus Suite and Soil 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). The Soil Suite utilizes a 3-beam analysis that resolves major elements (P, S, Cl, Ca, K, Fe, and Ti), minor elements (V, Cr, Mn, Fe, Co, Ni, Cu, and Zn), trace elements (Rb, Sr, Y, Zr, Nb, Mo, Ag, Cd, Sn, Sb, Cs, Ba, Th, U, W, Hg, Pb, and Bi), and a retroactively calculated aggregated “light element” (H to Si) (Figure 5). 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.
Figure 5: Periodic table showing light (green) and heavy (red) elements measurable by the Innov-X® X-Ray Fluorescence Spectrometer using the Mining-Plus (top) and Soil (bottom) modes.

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 Energy Data eXchange (EDX) online system using the following link: https://edx.netl.doe.gov/dataset/carbonsafe-macron-well.
4. **RESULTS**

Processed 2D slices of the medical CT scans through the cores are shown in Figures 8–13. The core from the T.R. McMillen #2 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**

The variation in greyscale values observed in the medical CT images indicates 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).

Core was scanned in 6 ft or smaller sections. Detailed information in log books and photographs of the core were used to confirm the locations of missing core and depths.

4.1.1 **X/Z Planes**

A 2D image through the center of each core can be found in Figures 8 through 13 (on left of each column). These are referred to as X/Z planes with the coordinates shown in Figure 6. There is no scale bar shown in these images; the retrieved core has a diameter of 4 in. (10.16 cm) for reference. The labels below each 2D X/Z plane in Figure 8 through 13 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 greyscale values were shifted in these images to best represent the structure of the core in each image.

![Diagram](image)

*Figure 6: Schematic of the XZ isolated plane through the vertical center of the medical CT scans.*
4.1.2 Polar Transform

A 2D image through the circumference of the core can be found in Figures 8 through 13 (on right of each column). There images are referred to as “Polar Transform” images. The original X/Y CT image is “unwrapped” from polar coordinates to cartesian coordinates where, the y-axis represents the angle from 0 to 360° and the x-axis represents the distance from the center of the image (Figure 7). 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 core was slabbed prior to arrival at NETL for scanning. The removed section of core is shown as black void space on the right of each polar transform image.

![Figure 7: Schematic of the polar transform isolated plane around the circumference of the medical CT scans. (A) Original CT image slice, (B) Cartesian “remapping” image, and (C) Polar transform image](image-url)
Figure 8: 2D isolated planes through the vertical center (left) and a polar transform (right) of the outside of the medical CT scans of T.R. McMillen #2 core from 6,240.0 to 6,250.0 ft.
Figure 9: 2D isolated planes through the vertical center (left) and a polar transform (right) of the outside of the medical CT scans of T.R. McMillen #2 core from 6,250.0 to 6,262.0 ft.
Figure 10: 2D isolated planes through the vertical center (left) and a polar transform (right) of the outside of the medical CT scans of T.R. McMillen #2 core from 6,262.0 to 6,270.0 ft.
Figure 11: 2D isolated planes through the vertical center (left) and a polar transform (right) of the outside of the medical CT scans of T.R. McMillen #2 core from 6,270.0 to 6,282.0 ft.
Figure 12: 2D isolated planes through the vertical center (left) and a polar transform (right) of the outside of the medical CT scans of T.R. McMillen #2 core from 6,282.0 to 6,292.0 ft.
Figure 13: 2D isolated planes through the vertical center (left) and a polar transform (right) of the outside of the medical CT scans of T.R. McMillen #2 core from 6,292.0 to 6,299.6 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/carbonsafe-tr-mcmillen-2. 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 14, showing distribution of mm- to cm-scale quartz cobbles in a cross-section of the core around a depth of 6,284 ft is shown. The red line through the XZ-plane image of the core shows the location of the XY-plane displayed above. The videos on EDX show this XY variation along the entire length of the core.

![Figure 14: Single image from a video file available on EDX showing variation from 6,282 to 6,286 ft. Image above shows the variation in composition within the matrix perpendicular to the core length. Note the bright (high-density) cobbles in the matrix and the cross-cutting fractured zone.](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 ($\rho_B$) (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 15). 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 15a). 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 15b).
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 -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 2: Density of Dual Energy Calibration Standards

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho_b \ (\text{g/cm}^3)$</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 3: Attenuation of Dual Energy Calibration Standards

<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 \([m, p, \text{and } q]\) and \([r, s, \text{and } t]\) are unknown coefficients that can be solved by setting up a system of equations with four \(3 \times 3\) 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 3-D Gaussian blur filter with a sigma of 2 was used to reduce noise in the images. The scipy.solve 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.

### 4.4 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, and the second set with calculated ratios from the XRF scans, P-wave data, and notable features. 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.

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 and with the medical CT scanned images.

The elemental results from the XRF were limited to Al\(_{\text{MINING PLUS}}\), Si\(_{\text{MINING PLUS}}\), Cl\(_{\text{SOIL}}\), K\(_{\text{SOIL}}\), and the remaining top nine elements (K, Fe, Cl, Ti, S, V, Zr, Cd, and Mn). Of the remaining top ten elements, K was the most abundant with a maximum occurrence of 72,293 ppm at one location in the core, and Cd was the least abundant element with a maximum occurrence of 351 ppm at one location in the core. All other elements measured, but not listed, were observed to have maximum occurrences of less than 250 ppm.

Trends in elemental ratios can provide insight into mineral composition. Examples include: K/Al, which gives approximate amounts of feldspars versus clays; Si/Al, which provides information on the abundance of illite and micas versus other clays, and additional broad prediction of grain size; and Fe/Si, which provides information on the abundance of Fe oxide minerals versus quartz, particularly in cements. Additionally, magnetic susceptibility can test for iron sulfides (reducing) or oxidized Fe and sulfate. Pyrite (reduced) should have low magnetic susceptibility, while 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.
Figure 16: Compiled core log for T.R. McMillen #2 Well, from 6240 to 6299.6 ft.
Figure 17: Compiled core log with elemental ratios for T.R. McMillen #2 Well, from 6,240 to 6,299.6 ft.
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.
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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


