XCT ANALYSIS OF DECREASING POROSITY IN THE TRENTON LIMESTONE OF WILLIAMS COUNTY, OHIO

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By

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ABSTRACT

The Trenton limestone is found in the Michigan and Appalachian Basins, beneath the Utica-Point Pleasant and Antrim shales. The Trenton is of Ordovician age and consists of a fine, light-grey to dark-brown matrix, stylolites, and secondary dolomite. In Williams County, Ohio, the Trenton limestone displays a decreasing neutron porosity in well log data, and this thesis investigates the porosity decrease.

Four boxes of Trenton limestone from Core 3256 were obtained from the Ohio Department of Natural Resources. The Trenton spans a depth of 2267.2 to 2497.8 feet. For this thesis, the following intervals were scanned: 2268–2270 feet (Box 208), 2290–2300 feet (Box 211), 2310–2320 feet (Box 213), and 2330–2340 feet (Box 215). The core is light grey, and significant oil staining and mineralization are present. The core contains large vugs, many of which are filled with dolomite crystals. This core was scanned using an X-ray computed tomography (XCT) scanner to provide density data in the form of Hounsfield units (HU), and to visualize internal structures and vug frequency. The scans produced average HU values that ranged from +2600 to +2800. Scan images displayed vugs concentrated from 2290–2300 feet, mineralized zones containing dolomite crystals, shale laminations, and fractures in cores.

I have used well log data as a comparison to HU values from the XCT scanner to examine the Trenton porosity which continually decreases with depth from 10% to 1% by 2323.5 feet. The porosity may decrease because there is increased mineralization with depth, a decrease in the amount of vugs with depth, or the limestone matrix may change to an increased amount of magnesium (dolomitization); if this is the case, more magnesium-rich rock should occur near the top of the core and decrease with depth.

I find that while mineralization and vuggy porosity decrease with depth, the dolomitized zone is the significant factor. The porosity is decreasing as a function of core density and matrix type, as the Trenton limestone transitions from the upper dolomitized zone to a calcite-rich limestone.

ACKNOWLEDGEMENTS

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INTRODUCTION

Across the Appalachian and Michigan Basins, the upper section of the Trenton limestone serves as a porous reservoir and is heavily dolomitized (Wickstrom et al., 1992). Once the dolomitized member transitions into a calcite-rich limestone, porosity decreases rapidly (Keith, 1986). It is this relationship between porosity and matrix density that I studied in my thesis research, by way of scanning sections of core from the Trenton limestone provided by the Ohio Department of Natural Resources (ODNR).

Trenton limestone core was scanned using an X-ray computed tomography (XCT) scanner to provide density and porosity data, by way of non-destructive three-dimensional imaging (Ketcham and Carlson, 2001). Scan images and statistics from the core were compared to geophysical well log data to compare density and porosity while evaluating three possible factors as to why the neutron porosity is decreasing. The three factors are 1) increased mineralization with depth, 2) decrease in the amount of vugs with depth, or 3) a change in the limestone matrix with depth. Work was done under the hypothesis that porosity is decreasing as a result of the dolomitized zone ending at a depth of 2323.5 feet, where the Trenton becomes more calcite-rich, less vuggy and less porous.

For this research, intervals of Core 3256 from Williams County, Ohio were scanned to examine the dolomite-limestone transition, and to provide an excellent look at how the Trenton in the Appalachian and Michigan Basins has evolved over time. The Trenton limestone in this region often displays evidence of mineralization, fluid migration, and dissolution. These features can result from fracturing in the rock and develop a dolomite cap in many locations (Wickstrom and Gray, 1988).

Historical Context

The Trenton limestone is a historically significant lithology in the Appalachian region, notably in the Appalachian and Michigan Basins. The discovery of natural gas and oil in the Trenton near Findlay, Ohio in 1884 led to the nation’s first petroleum boom (Keith, 1986; Orton, 1889). The hydrocarbon prospects of the Trenton were discussed at length by Edward Orton Sr. in the 1880s, and the petroleum industry soon followed. Drilling became rampant, and soon there were around 100,000 wells (Keith, 1986) spread throughout Ohio, Indiana, Michigan, and New York targeting various structural features. The Trenton limestone served as the principal reservoir rock along the Lima-Indiana trend and the Albion-Scipio trend in southern Michigan, where more than half a billion barrels of oil were produced (Keith, 1986). However, since the early 1900s production from the Trenton limestone in Ohio has been very low. Most hydrocarbon production from the Trenton limestone was from areas that were heavily dolomitized, and along linear fracture zones such as the previously mentioned Albion-Scipio Trend in Michigan (Chan et al., 2000). In Ohio, Trenton production comes from smaller fields around the northwest part of the state, and from the more well-known Findlay-Lima field (Chan et al., 2000).

In the late 1980s and early 1990s more detailed geologic surveys were completed to further understand the geologic setting of Ohio and the Ordovician-age rock units that stretch across the state. Nowadays, a thorough understanding of the Ordovician age lithologies is crucial, as the Trenton limestone is directly overlain by the Utica-Point Pleasant shales in the Appalachian

Basins, and the Antrim shale in the Michigan Basin (Wickstrom, et. al, 1992). These shale units represent enormous natural gas reservoirs, which fueled the 2010s shale natural gas boom throughout Ohio, Pennsylvania, West Virginia, and New York (Popova, 2017). Detailed research on lithologies surrounding prominent hydrocarbon producing units is key to building a regional understanding of the subsurface and the future of hydrocarbon production in the Appalachian region.

CORE GEOLOGY AND GEOLOGIC SETTING

Core Geology

The Trenton limestone was deposited in the Ordovician Period of the Paleozoic Era, about 450 million years ago. In Core 3256 the Trenton is first seen 2267.2 feet below the surface and extends down to 2497.8 feet. It is beneath the Point Pleasant formation and overlies the Black River Limestone. From a core description provided by the ODNR, 2267.2 to 2323.5 feet is dominantly dolomite, pale brown to light gray in color with numerous dolomite crystal-filled vugs from 2298.0 to 2313.0 feet. Carbonaceous stylolites are present, as are relic bryozoan fossils. Vuggy porosity is visibly more abundant in the dolomite section of the core, and oil staining is common in some sections. From 2323.5 feet to 2497.8 feet, the Trenton exists as a light grey to pale brown limestone, with medium to coarse crystalline biosparite. It darkens downward, shows oil in places, and contains abundant carbonaceous stylolites.

Dolomitization

Dolomitization is the key factor in any Trenton oil and gas exploration, as well as coming to an understanding of how the rock unit has evolved since deposition during Ordovician times. Dolomitization is the result of some of the calcium ions within a carbonate rock dominantly made of calcite being replaced with magnesium ions to form the mineral dolomite. Several of the most common dolomitization methods are evaporation in a sabkha environment, rising fluids in a fracture environment, and dolomite resulting from shale dewatering, in which fluids expelled from the overlying shales migrated downward into the more permeable limestone (Keith, 1986 and Haeri-Ardakani et al., 2012).

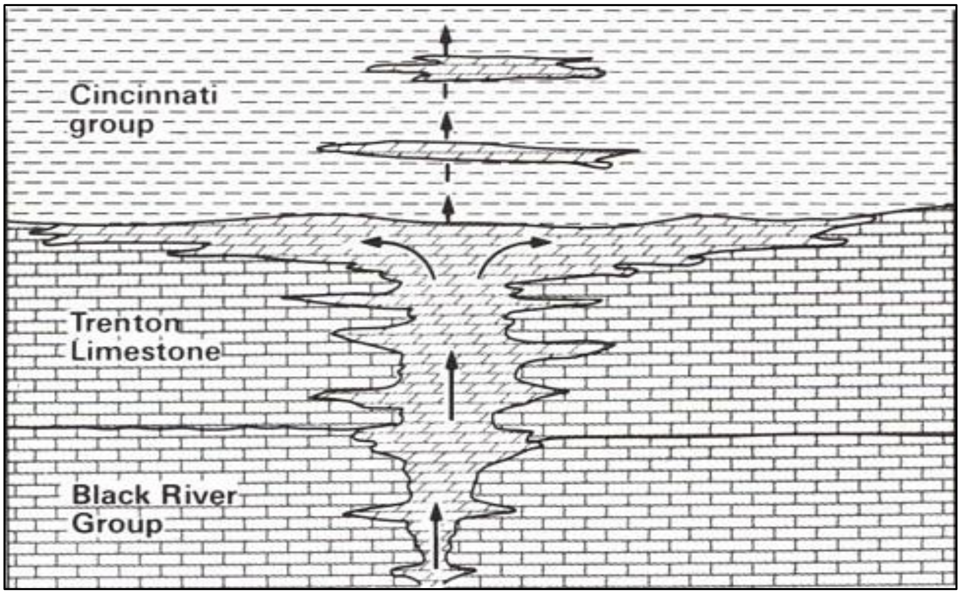

Figure 1. Cross section and model of dolomitization by fluid flow along fracture trends in northwest Ohio, from Wickstrom et al., 1992. Small fractures provide a pathway for brine trapped below to travel upwards, interacting with the Trenton and precipitating magnesium-rich dolomite. In this figure, the slanted bricks represent dolomitized limestone.

Three types of dolomite are found in the Trenton in northwest Ohio: cap dolomite, regional dolomite, and fracture dolomite (Wickstrom and Gray, 1988). Cap dolomite can be found in some wells and well cuttings and ranges in thickness from 4.9 feet to 49.2 feet in some zones (Keith, 1986). The cap is fine grained and exhibits little to no porosity. A thin pyrite surface also exists at the top of the capped formation. Regional dolomite is similar in texture to the cap dolomite but contains less iron (Keith, 1986). Fracture dolomite is full of secondary mineralization, to the point where much of the porosity can be sealed in some zones. Many fractures and vugs found in core sections are filled by calcite and dolomite crystals (Wickstrom and Gray, 1988). Secondary mineralization in cores with fracture dolomite increases with depth, and is found in Michigan and along the Bowling Green Fault Zone in northwest Ohio (Keith, 1986; Wickstrom et al., 1992).

In Core 3256, the upper zone of Trenton limestone (2267.2–2323.5 feet) is dominated by secondary dolomite mineralization resulting from fracture and fluid flow. It exhibits vuggy porosity filled with dolomite crystals, oil staining, and mineralized zones along fractures in the core sections.

Geologic Setting

Core 3256 was drilled in Williams County, Ohio, located in the southern flank of the Michigan Basin and west of the Finley Arch (Wickstrom et al., 1992). The Trenton limestone was deposited during the Ordovician Period. The middle and upper Ordovician strata of northwest Ohio represent a transgressive sequence in an epeiric sea during the Paleozoic Era. Events during Trenton deposition took place at the end of the Taconic Orogeny (Wickstrom and Gray, 1988). The transgressive unit is bounded below by the Cambrian-Ordovician Knox unconformity, and above by an unconformity that followed the Ordovician (Wickstrom et al., 1992), marking the Ordovician-Silurian boundary. Depositional and geologic history of the Ordovician transgressive sequence in northwest Ohio is described below (Figures 3 and 4), (Wickstrom et al., 1992, Wickstrom and Gray, 1988, Keith, 1986, and Chan et al., 2000). The sequence of events included:

1) Shallow sea cover results in deposition of the Wells Creek Formation, a mix of clastics and carbonate sequences.
2) Following the Wells Creek, the Black River Group was deposited in a shallow, epeiric sea environment where the sea transgressed from east to west.
3) After Black River deposition the epeiric sea became deeper and developed an open-shelf facies that now represents part of the Trenton limestone. This open-shelf indicates the increasing intensity of the Taconic orogeny to the east.
4) A shift in depositional strike and shift in the Appalachian Basin brought upon a shallowing of the waters over northwest Ohio, evidenced by the deposited platform facies representing the other part of the Trenton limestone. Southeast of the carbonate platform, waters deepened as they reached closer to the orogenic front. Deposits in the deeper water represent the Point Pleasant-Utica formations, which at times grade into the Trenton as the Trenton decreases in thickness eastward.

5) End of Trenton deposition and beginning of Cincinnati group deposition is marked by a rapid subsidence of the landmass, and a deepening of the waters. This led to the widespread deposition of shales and limestones we know today, including formations like the Utica shale mentioned in 4).
6) A shallowing of the waters and emergence of the late Ordovician to early Silurian carbonate shelf signifies the end of the middle to upper Ordovician interval, and the end of Cincinnati Group deposition.

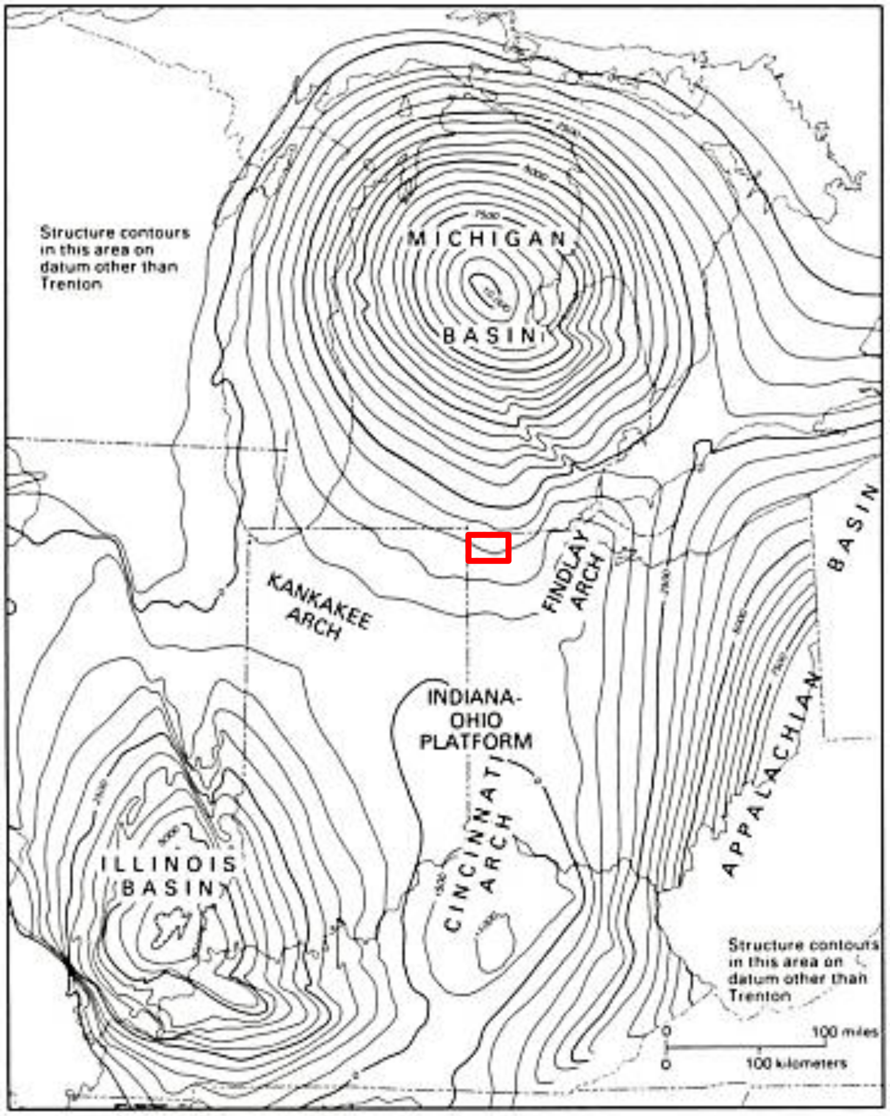

Figure 2. Regional structure contour map of drawn on top of the Trenton limestone in the Appalachian, Michigan, and Illinois Basins. Approximate location of Williams County is outlined in red. Figure from Wickstrom et al., (1992).

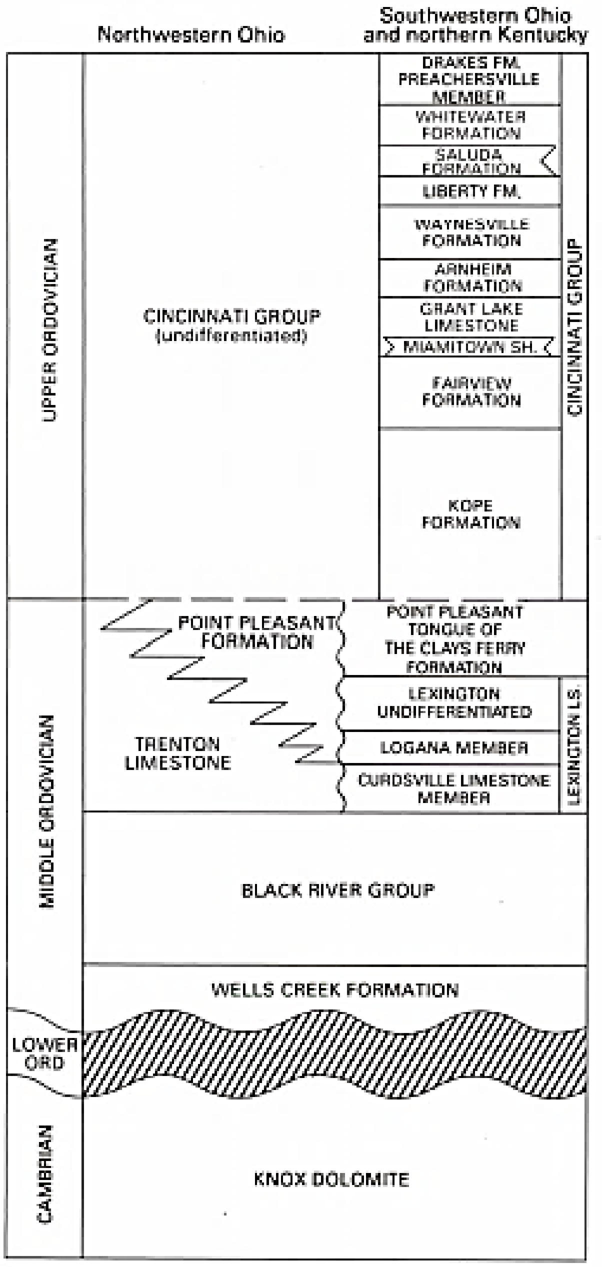

Figure 3. Stratigraphic column of Cambrian and Ordovician rocks of northwest and southwest Ohio and northern Kentucky. Figure from Wickstrom et al., (1992).

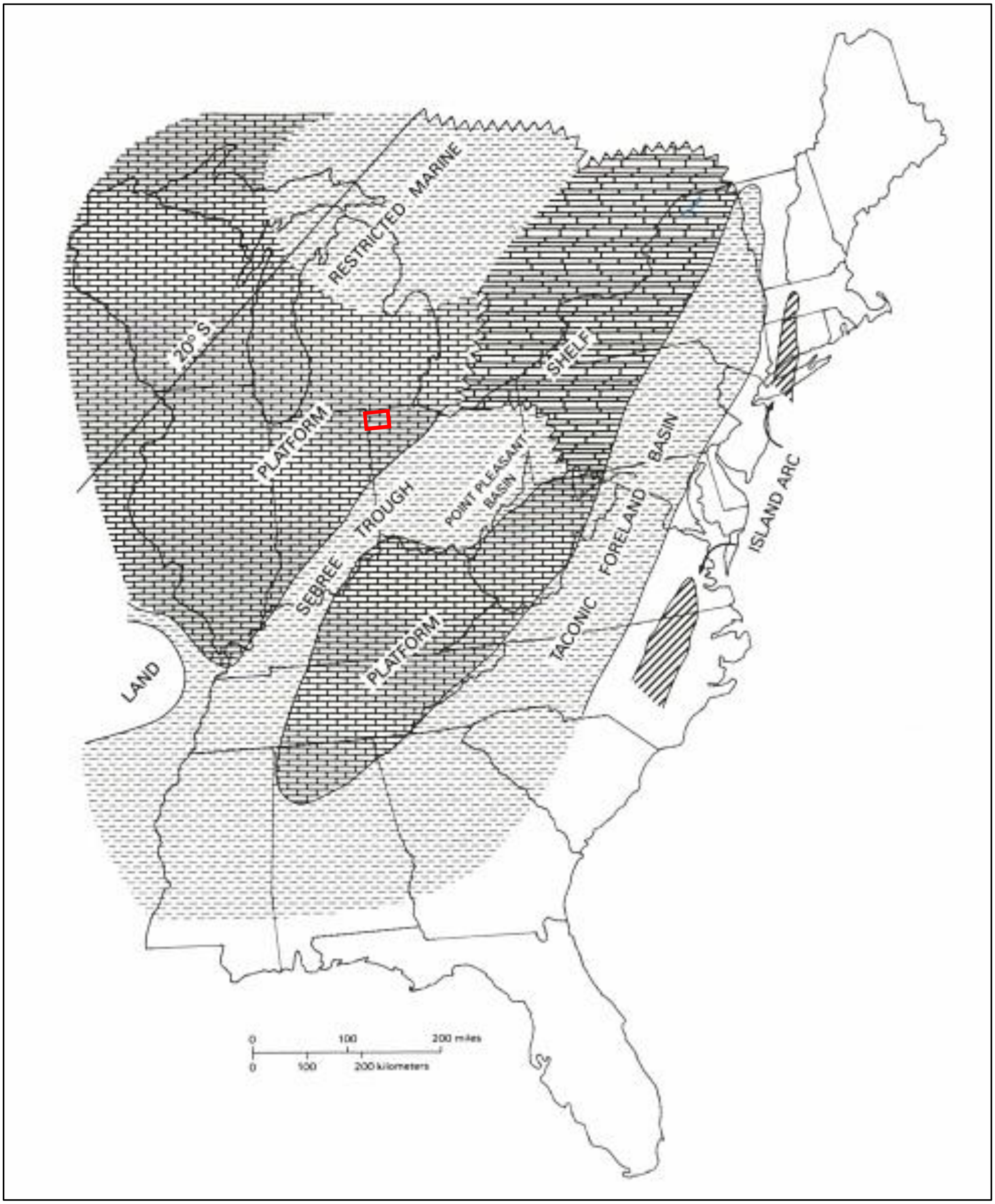

Figure 4. Regional model of the major depositional and tectonic events that took place during the mid-upper Ordovician Period. Williams County is outlined in red and sits in the marine platform resulting from the flexural basin to the east. Figure from Wickstrom et al., (1992).

METHODS

In February of 2018 four boxes of Core 3256 from Williams County, Ohio were obtained on loan from the ODNR Core Repository in Alum Creek, Ohio and taken back to the XCT Lab at The Ohio State University for scanning. Prior to picking up core, the dolomitized zone (2267.2–2323.5 feet) of the Trenton limestone was identified as the interval to be examined. Sections of this limestone were chosen in an attempt to study the decreasing porosity seen in well log data. The data included a gamma ray log, neutron porosity log, bulk density log, and a caliper log, and were provided by ODNR geologists Erika Danielsen and Christopher B.T. Waid. From a selection of more than a dozen boxes of core spanning most of the Trenton limestone at this location, the four boxes scanned for this thesis were chosen based on completeness of core, oil staining and mineralization observed (Figure 5). Choice of core sections for analysis were also chosen to reflect the changing porosity by obtaining core from different sections of the dolomitized zone (see Table 1).

Table 1. Trenton limestone in Core 3256 and the intervals of interest to this thesis. Intervals include entire Trenton limestone in core, dolomitized zone, and the four boxes scanned.

Section of Core 3256	Interval in Core 3256
Trenton limestone in core 3256	2267.2–2497.8 feet
Dolomitized upper zone	2267.2–2323.5 feet
Box 208	2260–2270 feet
Box 211	2290–2300 feet
Box 213	2310–2320 feet
Box 215	2330–2340 feet

XCT

XCT scanning is a tool that allows the user to evaluate density, porosity, and permeability by non-destructive three-dimensional imaging (Ketcham and Carlson, 2001). Similar to a CT scan one would receive at a hospital, the XCT scanner produces three-dimensional images with higher CT attenuation (shown as lighter colors) that correspond to higher density areas, and lower CT attenuation (shown as darker colors) that correspond to lower density areas. The scanner records density values in Hounsfield Units (HU). The HU scale provides a quantitative scale to determine the radiodensity of an object, and most CT scanners are calibrated with reference to the linear attenuation of water and air (Bollinger et al., 2009). Air normally produces a HU value of -1000 or greater, soft tissue +100 to +300, and for the case of this experiment, limestone rock core +2500 to +2800.

Thirty-two feet of Core 3256 were scanned using an x-ray computed tomography (XCT) scanner at The Ohio State University. Core scans covered 1–3 feet of core per scan, under service mode in the XCT Scanner. Scans were completed in service mode, allowing the scanner to run for several hours at a time and thoroughly cover each core section (Figure 6). Images collected during XCT scans were stored and then uploaded to the free image processing software Fiji ImageJ, allowing concatenation of thousands of scan images into the black and white core images (Figures 7, 8, 9, 10).

Figure 5. Box 211 from Core 3256, Williams County, Ohio, from top (top right) to bottom (bottom left), box of core covers a depth range of 2290–2300 feet beneath the surface. Each column represents two feet of rock. Core provided by the Ohio Department of Natural Resources.

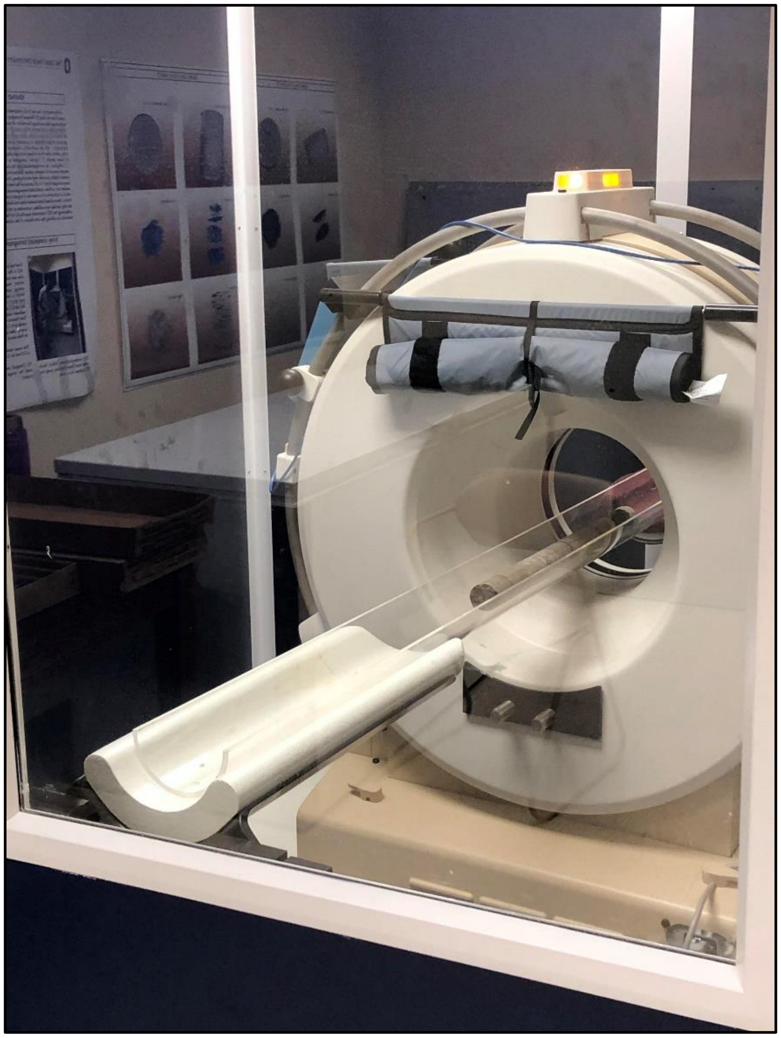

Figure 6. Trenton limestone core being scanned with the XCT scanner in Mendenhall Laboratory, The Ohio State University.

RESULTS

In core scan images, large porous zones are more concentrated at the top of the Trenton section, in the dolomitized zone. After the dolomitization ceases at a depth of 2323.5 feet, the number of porous zones decreases rapidly, as does the mineralization. Fractured sections of core contain air, and when scanned produce low density (black) images with less than +1000 HU. Core images are presented with depth from top (closer to surface) to bottom (deeper in depth).

Box 208

Core scans from Box 208 covered two feet of Trenton core, from 2268–2270 feet. Most of the interval (2260–2270 feet) is dominated by the Point Pleasant Formation. Trenton from Box 208 produced average HU values ranging from +2750 to +2800, with peaks in mineralized zones corresponding to dolomite crystals seen in visual inspection and recorded in descriptions provided by the ODNR. Present in Box 208 are two large porous zones near the Point Pleasant-Trenton contact.

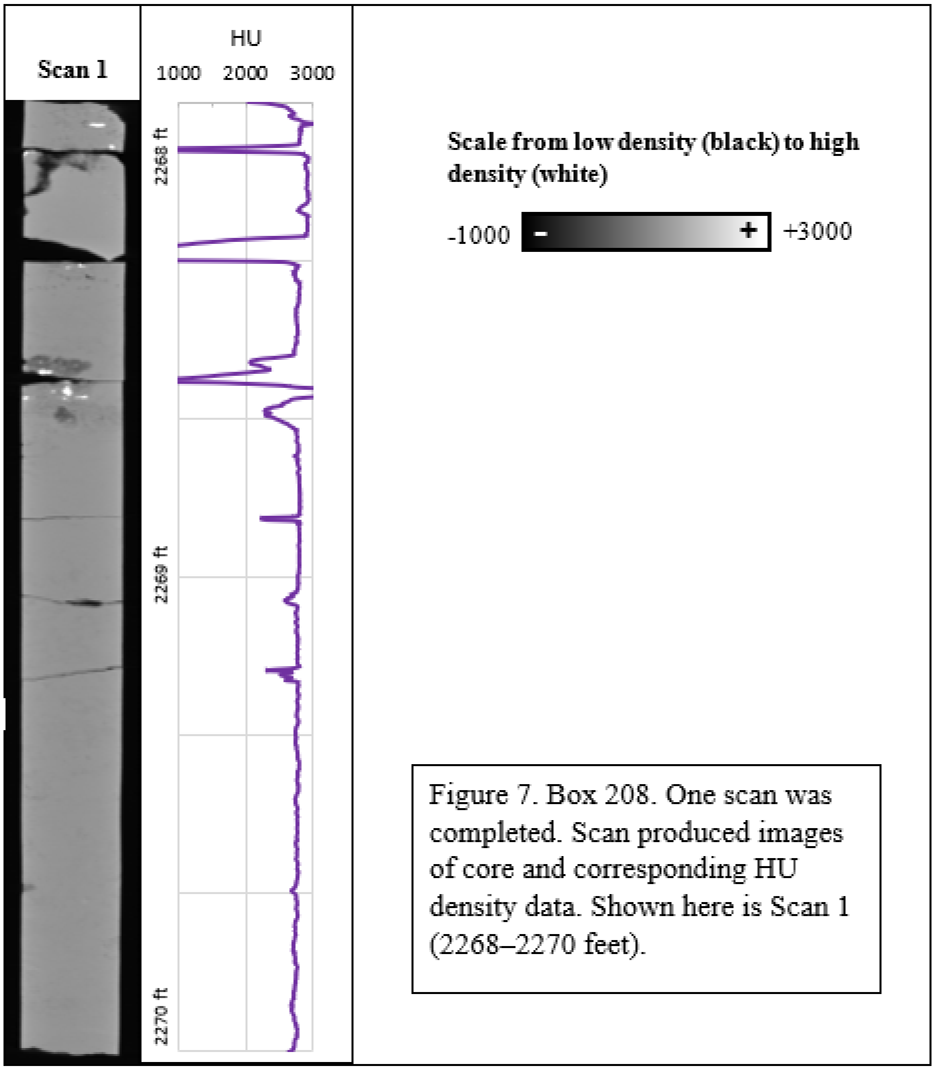

Figure 7. Box 208. One scan was completed. Scan produced images of core and corresponding HU density data. Shown here is Scan 1 (2268–2270 feet).

Box 211

Core scans from Box 211 covered the entire ten feet contained in the box, 2290–2300 feet (Figure 8). Box 211 produced HU values at or near +2600 with few to no heavily mineralized zones appearing in core image or Hounsfield graph until 2294.5 feet (Figure 8, Scan 3), where several porous zones become apparent and significant mineralization occurs. There are substantial porous zones at 2294.5 feet (Scan 3), 2296.5 feet (Scan 4), and throughout the section 2298–2299 feet (Scan 5). The porous zone at 2296.5 feet (Scan 4) also contains visible oil staining, as does the entire final scan, 2298–2300 feet (Scan 5). Core images display stylolites and microstructures throughout each scanned section. Vugs are common in the second half of Box 211 with bright minerals appearing in vugs near porous zones (Scans 3, 4, 5).

At 2295.3–2296 feet (Scan 3), the core appears brighter in color yet low in HU value (less than +1000 HU); this section only contained half of the standard cylinder of core.

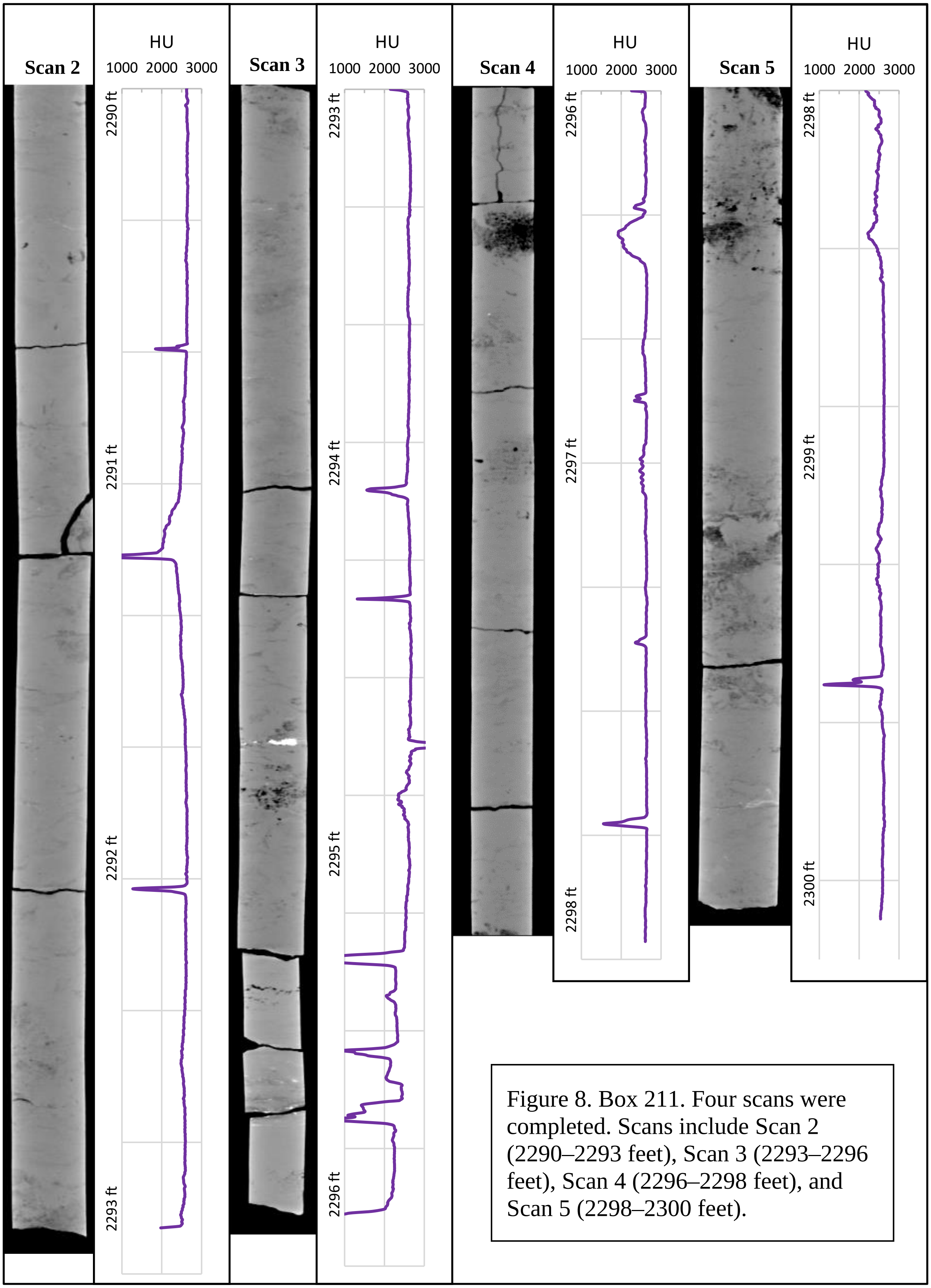

Figure 8. Box 211. Four scans were completed. Scans include Scan 2 (2290–2293 feet), Scan 3 (2293–2296 feet), Scan 4 (2296–2298 feet), and Scan 5 (2298–2300 feet).

Box 213

Core scans from Box 213 covered the entire ten feet contained in the box, 2310–2320 feet. Core scans produce similar HU values as Box 211, at or near +2600 throughout the entire ten-foot interval (Figure 9). Small mineralized zones and vugs are present through 2310–2313 feet (Scan 6), as are carbonaceous and shaley stylolites. Shale laminations are present at 2316 feet (Scan 8). Below the shale, the core exhibits a uniform consistency of vugs, mineralization and laminations to a depth of 2319 feet in Scan 9. At this point a mineralized zone occurs in both core scans and HU values.

An increase in HU value to +2750 can be seen at 2314.5 feet in Scan 7 and continues for several inches. This sudden bright spot in the interval only contained half of the standard cylinder of core.

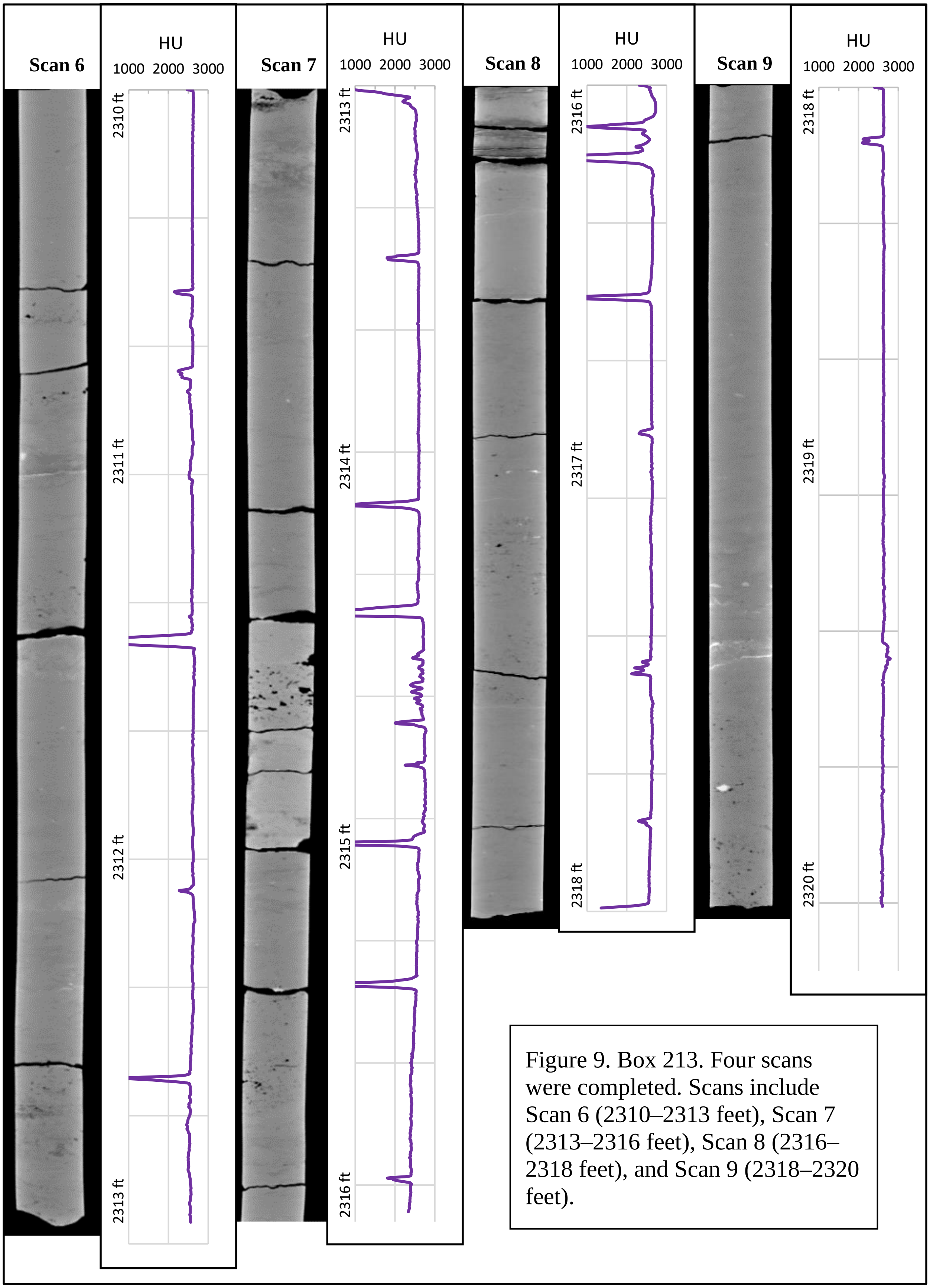

Figure 9. Box 213. Four scans were completed. Scans include Scan 6 (2310–2313 feet), Scan 7 (2313–2316 feet), Scan 8 (2316–2318 feet), and Scan 9 (2318–2320 feet).

Box 215

Core scans from Box 215 covered the entire ten feet contained in the box, 2330–2340 feet. Scans yielded HU values greater than Boxes 211 and 213, with values consistently ranging from +2800 to +2900. The core exhibits consistent HU density, brightness, and microstructures until the section at 2336–2338 feet is reached (Figure 10, Scan 12). The HU values from Scan 12 compare similarly to the previous two boxes scanned, producing values near +2600. This section also contains mineralized vugs and large porous zones. Below the low HU interval, the core resumes the brightness and high HU values displayed across Scans 10 and 11 for the remainder of Scan 13.

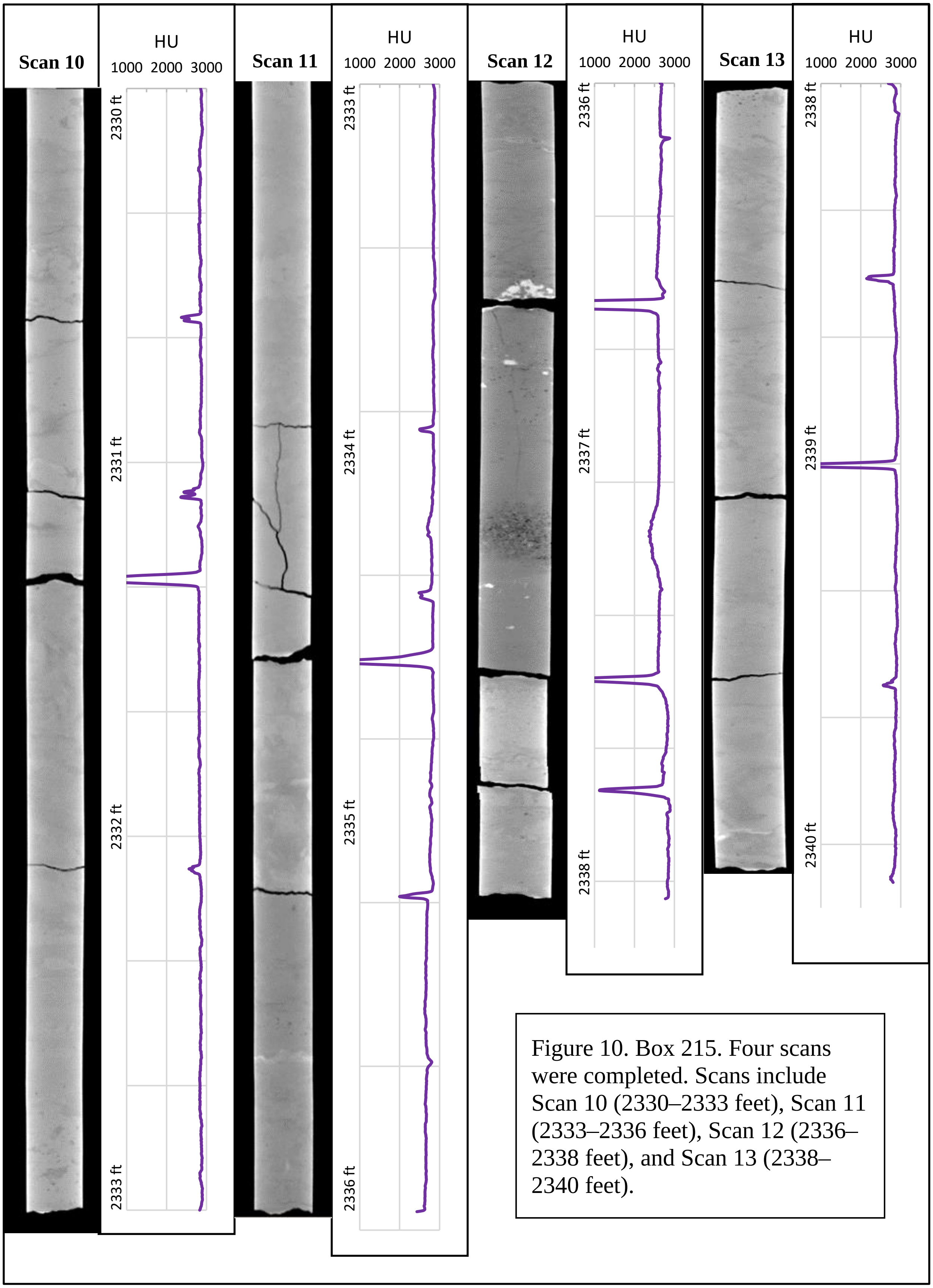

Figure 10. Box 215. Four scans were completed. Scans include Scan 10 (2330–2333 feet), Scan 11 (2333–2336 feet), Scan 12 (2336–2338 feet), and Scan 13 (2338–2340 feet).

Well Log Data

Well log data provided by the ODNR included caliper log, gamma ray log, bulk density log, and neutron porosity log over the depth of Core 3256. Graphed below are the gamma ray log (Figure 11), bulk density log (Figure 12), and neutron porosity log (Figure 13) from 2250 feet (just above the Point Pleasant – Trenton contact at 2267.2 feet) to 2500 feet (just below the Trenton interval ends at 2497.8 feet, at the contact with the Black River limestone).

Gamma Ray Log

Gamma ray log (Figure 11) displays low API (American Petroleum Institute) values for the entire Trenton limestone interval, ranging from 10-30 API units. There is a small increase in API at 2316 feet, where values rise to 54 API.

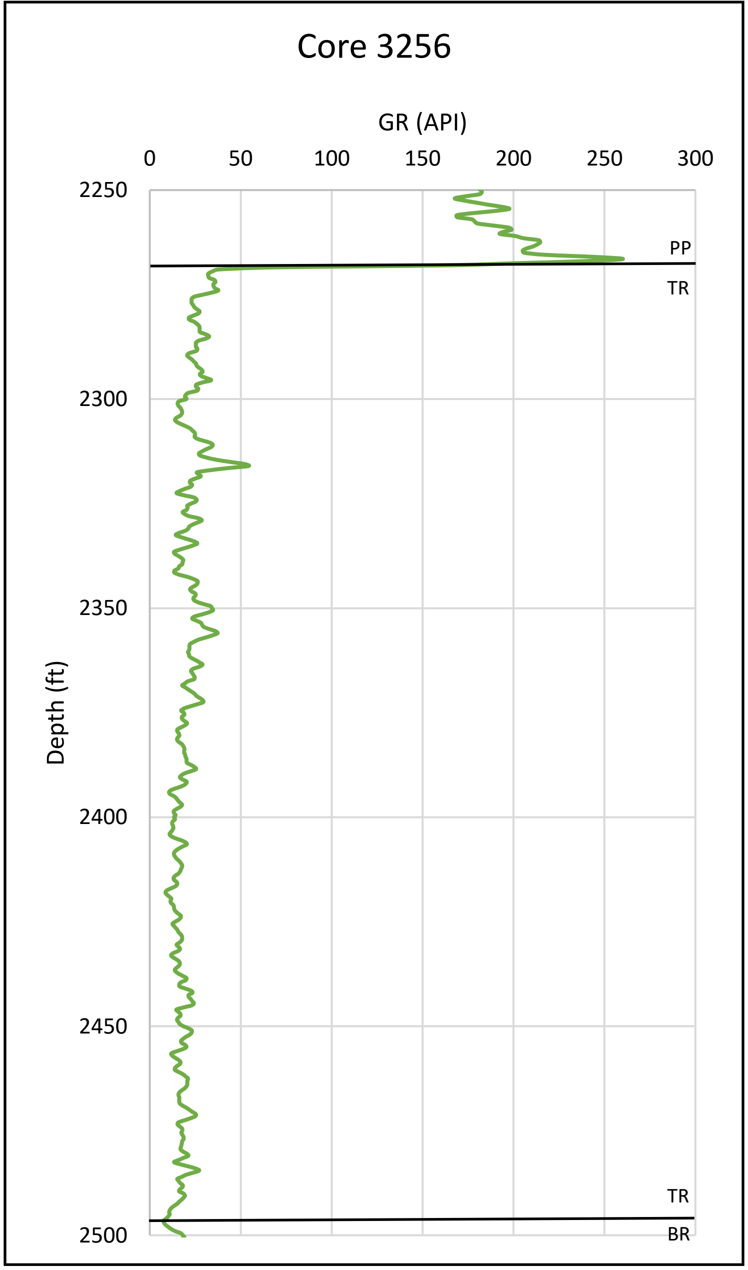

Figure 11. Gamma ray is plotted in green. Contacts between Point Pleasant (PP) and Trenton (TR) and between the Trenton (TR) and Black River (BR) are plotted as horizontal black lines.

Bulk Density Log

Bulk density log (Figure 12) displays average values of 2.64 g/cc until the upper dolomitized zone ends at 2323.5 feet. From 2323.5 feet to 2389 feet the average bulk density decreases to 2.6 g/cc. From 2389 feet to the end of the Trenton limestone interval at 2497.5 feet, the average bulk density is 2.65 g/cc.

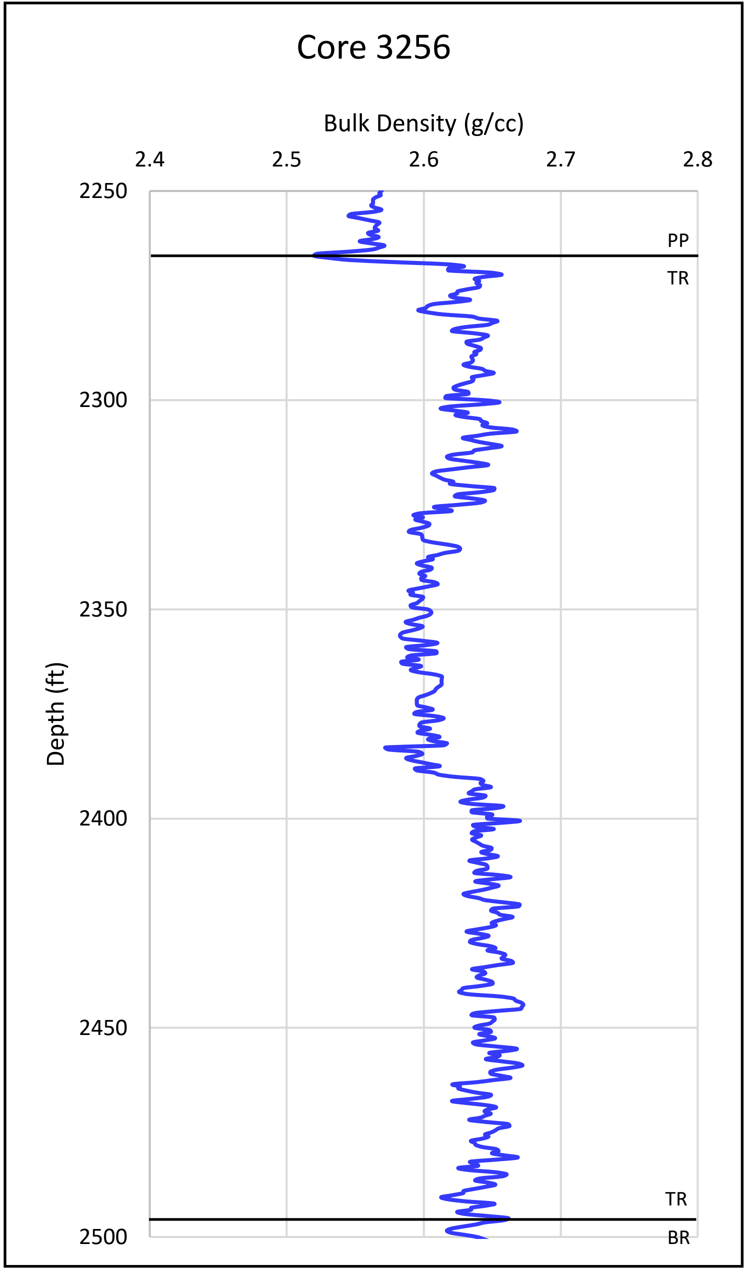

Figure 12. Bulk density is plotted in blue. Contacts between Point Pleasant (PP) and Trenton (TR) and between the Trenton (TR) and Black River (BR) are plotted as horizontal black lines.

Neutron Porosity Log

Neutron porosity log (Figure 13) displays decreasing porosity values throughout the entire dolomitized zone (2267.2 feet to 2323.5 feet), as porosity value decreases from 10% to 1% or less at the end of the interval. The remainder of the Trenton limestone interval displays an average porosity of 1% or less until the bottom of the unit at 2497.8 feet.

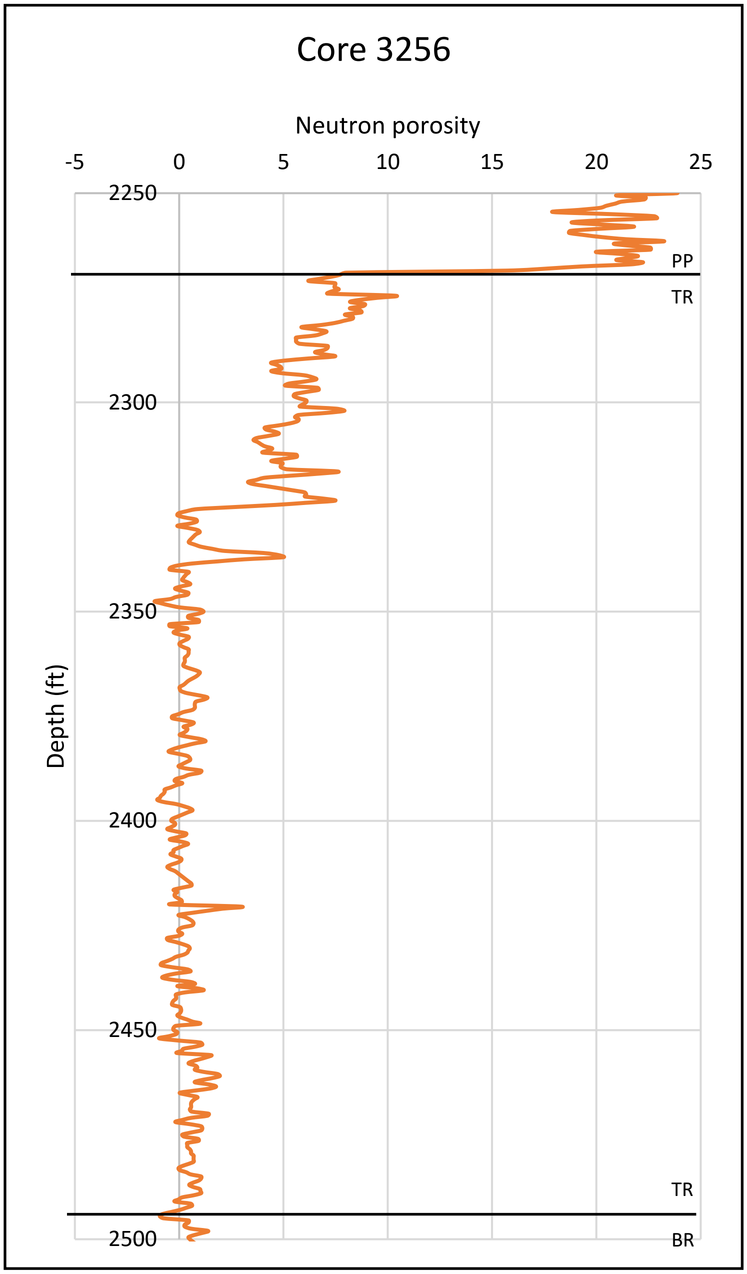

Figure 13. Neutron porosity is plotted in orange. Contacts between Point Pleasant (PP) and Trenton (TR) and between the Trenton (TR) and Black River (BR) are plotted as horizontal black lines.

It should be noted that while the porosity is decreasing, the tool used to log the well was calibrated for a "clean" limestone (calcite-rich), rather than a dolomite-rich limestone or dolostone. This means that the porosity values produced by the tool for the non-dolomitized zone of the Trenton limestone (2323.5-2497.8 ft) is more accurate than the upper dolomitized zone

(2267.2-2323.5 ft). Re-calibration of the neutron porosity values for dolomite was attempted, but the exact calibration charts used by the service company that logged the well (BPB Wireline Services) could not be obtained. While the upper zone can not be re-calibrated, the data and overall decreasing trend can be still be used for this thesis. The fact that the upper and lower zones produce bulk densities of 2.64 g/cc and 2.6 g/cc respectively allows the neutron porosity values to be used, since the limestone matrices will respond similarly to the limestone calibrated tool.

DISCUSSION

This thesis research was conducted to identify factors responsible for the steady decrease in neutron porosity observed from the upper to lower zones of the Trenton limestone in Core 3256. Factors considered included 1) increased mineralization with depth, 2) decrease in the amount of vugs with depth, or 3) a change in the limestone matrix with depth.

When evaluating the relationship between porosity and density in this thesis, Equation 1 was used:

$$\rho_b = \rho_f \varphi + \rho_g (1 - \varphi)$$

Where,

$\rho_b = bulk\ density$

$\rho_f = fluid\ density$

$\rho_g = grain\ density$

$\varphi = porosity$

Equation 1 defines the bulk density (g/cc) of a material as the sum of fluid density (g/cc) multiplied by porosity, and matrix grain density (g/cc) multiplied by the fraction of rock. From the log data, fluid in cores was brine, and while in the XCT Scanner, fluid in cores was air. The relationship defined in Equation 1 was applied specifically when considering the changing matrix of the Trenton limestone and the decrease in vuggy porosity in the scanned intervals. A series of calculations using Equation 1 to solve for porosity as a comparison to the neutron porosity was not completed for this thesis work.

Mineralization

Core scans and core descriptions both indicate a decrease in limestone mineralization down core. In the four boxes scanned, dolomite crystals are concentrated in Box 211, from 2290–2300 feet in Core 3256 (Figure 8), but are present in all four boxes. The moderate decrease in dolomite mineralization can be attributed to the decreasing porosity in the dolomitized zone, and can also be attributed to the changing Trenton limestone matrix. However, the moderate decrease in apparent mineralization does not appear to be a significant factor contributing to the overall decrease in porosity.

Vugs

Vuggy porosity is concentrated in core sections stored in Box 211 (Figure 8). The observed decrease in neutron porosity well log data (Figure 13) applies to the vuggy porosity, the ODNR core descriptions describe more vugs in the dolomitized zone, and the scan images display fewer vugs with depth (see Figures 9 and 10). The decrease in vug space can explain the decrease in neutron porosity, even more so when paired with the HU values produced from core scans. The HU values increase from averages of +2600 to +2800 HU by a depth of 2340 feet. The core image brightness of this transition can be seen, most notably in Box 215 (Figure 10). In this Box, Scans 10, 11, and 13 are all visibly brighter, indicating those intervals are denser, while Scan 12 is darker and therefore less dense than the surrounding intervals. The increase in HU values (a measure of density) is directly related to the decrease in pore space of the unit, as shown in

Equation 1. The decrease in vug space is a reflection of the overall porosity decrease and is not a significant factor to the porosity decrease in the Trenton limestone in Core 3256.

Matrix Change

The matrix of the Trenton limestone is not constant in Core 3256, and the changing matrix is responsible for the observed decrease in neutron porosity. From the bulk density log (Figure 12), the core density shifts from 2.64 g/cc to 2.6 g/cc at the bottom of the dolomitized zone at 2323.5 feet. This density shift corresponds to a change of matrix from dolomite (~2.84 g/cc) to calcite (~2.71 g/cc). In Core 3256 the bulk density can be compared with the HU values, which also change down core. As stated above, the average values increase from +2600 to +2800 HU by the end of scanned sections, signaling an increase in density of the unit scanned. While these two density measurements can appear contradictory, together they explain the porosity decrease in the scanned intervals. While a brighter HU does mean denser materials down core, it also is related to the available pore space. With little pore space at the transition zone from a dolomite-rich matrix to a calcite-rich matrix, the HU values are going to be elevated, compared to more porous intervals like those in Boxes 208 and 211. The resulting bright HU value is a direct effect of the changing matrix and corresponds with the bulk density shift. This shift is the primary factor in the porosity decrease seen in well log data throughout the upper zone of the Trenton limestone in Core 3256.

CONCLUSIONS

The Trenton limestone and rock units of similar age and depth across the Michigan and Appalachian Basins will continue to be heavily studied in the coming years. Their proximity to natural gas producing formations like the Point Pleasant-Utica and Antrim shales will continue to underscore the importance of developing a detailed understanding of the subsurface surrounding these two economically crucial hydrocarbon plays.

XCT image analysis proved to be a valuable tool in completing this thesis research. Development of a three-dimensional image of the rock core, with corresponding density values allowed for clear comparisons with the well-log data and core descriptions.

From this research, it is clear that several factors are at play when considering the porosity of the Trenton limestone of Williams County, Ohio. Limestone mineralization decreases moderately with depth, vuggy porosity decreases with depth, and the dolomitized zone appears to be a significant factor in the decrease in neutron porosity from 2267.2 to 2323.5 feet. Correlation of the well log data from the ODNR with the HU scan values and scanned core images confirmed that the porosity is decreasing as a function of core density and matrix type. The decrease is a result of the upper dolomitization, followed by a transition to a calcite-rich Trenton limestone.

RECOMMENDATIONS FOR FUTURE WORK

The results of this thesis could be taken further, and a 3D object counter test could be run for the scanned core sections. A 3D object counter test would allow for the mineralized zones and dolomite crystals in vugs to be quantified. It is also a method for pore spaces and vuggy porosity to be quantified. The test is run using Fiji ImageJ, the same software used to concatenate the core scan images into slices and slabs.

Further porosity analysis can be completed by way of solving Equation 1 for porosity at each point where bulk density was measured, corresponding with the density of the dolomite or calcite zone.

Mineralogy of the cores could also be studied, both in thin section analysis under a petrographic microscope and by scanning electron microscope. Knowledge of exact mineralogy of the cores would serve to support the conclusions of this thesis and support the density findings.

Future work of this nature (XCT scanning to evaluate density and porosity) is valid and able to be performed for a variety of fields. It is an accurate method to examine an object or sample, and an excellent tool that allows the user to create a 3D image to further understand the structure and characteristics of the rock one is dealing with.

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APPENDIX

A1: Box 208, Point Pleasant shale from 2260–2267.2 feet and Trenton limestone from 2267.2–2270 feet.

A2: Box 211, Trenton limestone from 2290–2300 feet.

A3: Box 213, Trenton limestone from 2310–2320 feet.

A4: Box 215, Trenton limestone from 2330–2340 feet.