Seismic Interpretation and Well Log Analysis of Jay County, Indiana, Focused on Lithologic Units below the Mt. Simon Formation

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Seismic Interpretation and Well Log Analysis of Jay County, Indiana, focused on lithologic units below the Mt. Simon Formation

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

By

Jennifer Michelle Welder
B.S., University of Cincinnati 2012

2014
Wright State University
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Jennifer Michelle Welder ENTITLED Seismic Interpretation and Well Log Analysis of Jay County, Indiana, focused on lithologic units below the Mt. Simon Formation BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science.

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ABSTRACT

Welder, Jennifer. M.S. Department of Earth and Environmental Sciences, Wright State University, 2014. Seismic Interpretation and Well Log Analysis of Jay County, Indiana, focused on lithologic units below the Mt. Simon Formation.

Cuttings recovered from two Benegar wells in Jay County, Indiana, have led to the recognition of a lithic arenite and limestone layer beneath the Mt. Simon Sandstone, the regional basal sandstone of the Paleozoic platform sequence. This lithic arenite is interpreted as the Middle Run Formation which has been observed in numerous wells within the Western Ohio, Northern Kentucky, and Indiana region. However, the limestone layer in these Benegar wells is unique, with only one other instance of limestone beneath the Mt. Simon being in the Mattison #1 well in southeast Clark County, Ohio. During the summer of 2013 students and faculty of Wright State University’s Earth and Environmental Science Department conducted a 2D seismic reflection survey adjacent to the Benegar wells in Jay County, Indiana, to examine the seismic signature and setting of this stratigraphy. Sonic and density logs obtained from nearby wells located in both Indiana and Ohio were used to produce synthetics for comparison to the seismic profile. Available driller or logging documents were used to pick the tops of the Eden Shale, Trenton, Knox, Eau Claire, Mt. Simon, and Middle Run Formation on the stacked seismic section. Documents obtained for the original Benegar wells lead to the successful identification of the limestone layer reflection within the
Middle Run Formation. The parallel layering observed in these Precambrian reflections that mirrors the layering of the younger Paleozoic formations suggests a lack of structural complexity (at least in an EW direction) and an apparent lack of Grenville foreland deformation as indicated in parts of western Ohio.
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I. Introduction
In August of 2013, students and professors from Wright State University’s Earth and Environmental Science Department together with the assistance of industry professionals from Precision Geophysical collected a seismic line in Jay County, Indiana. Motivation for this seismic line stemmed from the recognition of lithic arenite and limestone below the Mt. Simon Sandstone in cuttings from two wells (Benegar wells 141770 and 141771) drilled in Jay County in the 1940’s.

Regionally the Mt. Simon Sandstone is the formation that directly overlays the Precambrian basement. Sandstone associated with the Mt. Simon formation was observed from a depth of roughly 3,000 feet to a depth of 3,330 feet in both wells. Below this depth, a change in lithology was observed through collected cuttings of quartzite, marble, quartz conglomerate and lime. Because the Mt. Simon typically overlies the Precambrian basement, drillers associate this change in lithology to be the boundary between that base of the Mt. Simon and the top of the Precambrian basement. At the time the wells were drilled, it was unbeknownst that another formation may actually lie in between the Mt. Simon and Precambrian basement.

Discovery of the Middle Run Formation
In 1991, Well DGS 2627 was drilled in Warren County, Ohio, and at a depth greater than 1058 meters observed a clastic sedimentary unit below the Cambrian basal sandstone instead of the anticipated igneous or metamorphic rock. This sedimentary unit was originally thought to have been a previously undefined facies of the Mount Simon Sandstone, but was interpreted as a new sedimentary stratigraphic unit called the
Middle Run Formation (Shrake, 1991). This interpretation obtained validity when a seismic survey displayed the Middle Run as the upper part of a dipping layered sequence beneath the Paleozoic sedimentary rocks (Shrake, 1991).

The Middle Run is composed of thick bedded, red to gray, fine to medium grained lithic sandstone with minor red siltstones and shales (Shrake et al., 1991; Indiana Geologic Survey, 2011). Discovery of the Middle Run formation lead to the reanalysis of many deep drill holes and recognition lithic arenite like the Middle Run throughout the region. The original driller logs of the Benegar wells describe quartzite and marble; however, when the drill chips at the Indiana Geological Survey were examined the ‘quartzite’ was found to be a lithic arenite and the ‘marble’ a fine grained light to medium gray limestone (Hauser, pers.com.).

Regionally, since the discovery of the Middle Run Formation, sequences of lithic arenites have been encountered in several deep wells in western Ohio, northern Kentucky, and Indiana. In Kentucky, the lithic arenites below the Mt. Simon are interbedded with mafic and felsic volcanic rocks (Drahovzal, 2004). Jay County, Indiana, is only one of two sites in the region where boreholes have encountered a limestone below the Mt. Simon. The other site being the Mattison #1 well located in Clark County, Ohio.

**Origins of the Middle Run Formation**

Various hypotheses have been proposed for the setting of the Middle Run lithic arenites -- an East Continent Rift Basin, Grenville foreland basin, or a combination of both. In the first hypothesis the East Continent Rift is described as the extension of the
Keeweenawan Rift south from Michigan into eastern Ohio (Drahovzal, 2004). The extent of the proposed East Continent Rift Basin (ECRB) in Ohio, Indiana, and Kentucky is shown in Figure 1.

The second hypothesis suggests that the Middle Run can occupy a foreland basin setting west of the Grenville Front in western Ohio (Hauser, 1993). The Grenville Front or Grenville tectonic zone is a tectonic boundary that separates the metamorphic rocks of the ~1 Ga Grenville Province from the older granitic igneous rocks of the Granite-Rhyolite province to the west. The Grenville orogeny has long puzzled geoscientists by the lack of a foreland fold-and-thrust belt or foreland basin common to contractional...
orogens (Hauser, 1993). The possibility of Grenville foreland thrust-belt structures (Figure 2) was interpreted by Hauser (1993) on Consortium for Continental Reflection Profiling (COCORP) line OH-1 and the short seismic line in southwestern Ohio (Shrake et al., 1991) where the Middle Run was originally discovered.

The third hypothesis (Hauser, 1996; Baranoski et al., 2009) combines both the above hypotheses with some Middle Run lithic arenite possibly associated in places with the East Continental Rift and in places with a Grenville foreland basin. Hauser (1996) inferred that a possible continuation of the Keeweenawan Rift system south from Michigan, possibly as a series of pull-apart basins, was remobilized as the locus of the Grenville Front in Ohio. In this model the lithic arenite collectively identified as the Middle Run Formation might variously be associated with a rift or a subsequent Grenville foreland basin at different locations. Baranoski et al. (2009) reinterpreted a
reprocessed COCORP OH-1 profile and the very limited well data (Figure 3) to create a generalized model for the latter part of the Grenville Orogeny and the relative timing of the formation of a ‘Fort Wayne Rift’ and East Continental Rift System with respect to the Grenville Orogeny (Baranoski et al., 2009).

Geological Setting

The state of Indiana occupies roughly 36,290 square miles in the middle of the stable North American craton. This area has undergone only minor tectonic activity relative to

Figure 3: Model showing the East Continent Rift System and foreland basin development interpreted by Baranoski (Baranoski, 2009).
the Paleozoic tectonism of the Appalachian orogen to the east. The middle of the North American Craton is covered with sedimentary rocks of the Interior Platform (Figure 1) that vary in thickness from 3,500 to in excess of 20,000 feet in thickness (Rupp, 2011). The Precambrian basement craton is composed of old igneous and metamorphic bedrocks while the overlying sedimentary rocks comprise interbedded sandstones, limestones, and shales. The bedrock that is observed in much of Indiana also fills both the Michigan and Illinois Basin.

The Precambrian basement in Indiana experienced rifting 650 million years ago. During this period, the craton began to pull and break apart generating rifts. This rifting was the only real big tectonic event that ever happened in Indiana’s geologic history (Rupp, 2011). Where rifting occurred, faults were created and the structurally sound basement complex broke apart.

Sediments were deposited between 650-290 million years ago during a setting of quiet marine and river
waters. These waters could transport sediments from various erosional settings around the craton and deposit them in Indiana. The cyclic compaction of these deposited sediments has formed the sedimentary rocks that cover the state today (Rupp, 2011).

The Northeastern and Eastern Central portions of Indiana lie on a structural high. This is due to the influence of both the Kankakee Arch and the Cincinnati Arch; as seen in Figure 4. The Kankakee Arch is observed in northwest portions of Indiana as the southeasterly extension of the Wisconsin Arch. The Northwest portion of the Cincinnati Arch- that extends southward through Ohio, Kentucky, and Tennessee- is observed throughout much of Southeast and Central Indiana. The two arches join near a structurally low feature bordered by the Royal Center Fault near Logansport in Northwestern Indiana (Schaffer, 1981). The Cincinnati Arch is a broad, north-south oriented structural uplift that began in the Late Ordovician and underlies much of the central United States. The axis of the arch is east of Cincinnati and continues northward until it splits into the Findlay Arch to the north and the Kankakee Arch to the west (Hansen, 1997).

The Cincinnati and Kankakee Arches were not formed from regional uplift resulting in anticline structures. Rather, these areas remained stable while the surrounding basins subsided and form a broad, relatively flat area of about 10,000 square miles. Sedimentary rocks dip from the crest of the arches into the neighboring basins at 25 to 60 feet per mile- but dip steepens toward the center of the basins (Schaffer, 1981).
Older rocks are observed in the arch regions while younger rocks are observed in the basin areas.

**Stratigraphic Setting**
A generalized stratigraphic column of Paleozoic rocks found in Indiana (Polly, 2012) is shown in Figure 5, and Figure 6 displays a large scale stratigraphic cross section of Indiana oriented northwest (left) to southeast (right) using a number of early deep boreholes (Gutstadt, 1968).

The stratigraphic unit that is observed regionally overlying the Precambrian basement is the Mt. Simon Sandstone. It is a medium to coarse grained poorly consolidated sandstone that can range in thickness from 300 feet in eastern Indiana to well over 2,000 feet in northwestern Indiana (Hasenmuelle, 2014). The basal portion of this unit has a distinct reddish tint that is indicative of high feldspar content. Due to the characteristics of the Mt. Simon, it may serve as a permeable bed that allows the transmission of fluids throughout the basin.

Above the Mt. Simon lies a conformable boundary with the Eau Claire Formation. The Eau Claire is composed of thin beds of various rock types, including: dolostone, feldspathic, and partly glauconitic siltstone; very fine grained to fine-grained, generally well sorted sandstone; maroon and dark-brown micaceous shale; silty dolostone; and oolitic limestone (Gutstadt, 1968). The thickness of this formation ranges from more than 1,000 feet in southwestern Indiana to around 400 feet in northeastern Indiana.
The Knox Dolomite is made up of relatively pure dolomite which conformably overlies the Eau Claire Formation. The gray, white, and tan finely crystalline dolomite thins northward due to depositional thinning and erosional truncation of younger beds (Schaffer, 1981). The Knox can be observed in the subsurface of the entire state of Indiana and can range in thickness from less than 20 feet to more than 4,500 feet in southwestern Indiana (Gutstadt, 1968). A major unconformity is observed between the top of the Knox and the directly overlying St. Peter Sandstone.

The Trenton also overlies the Knox and is a southward thinning rock group that consists of tan fine to medium-grained limestone that ranges in thickness from 0 to 225 feet in thickness. Towards the northwestern portions of Indiana, the Trenton is extensively dolomitized. Many vugs with dolomite rhombs are present in dolomitized areas and pyrite is common in upper parts (Shaffer, 1981). In East-Central Indiana and northwestern Ohio, the Trenton was a major reservoir for oil and gas during the late 1800’s and early 1900’s.

The Kope Formation lays directly on the Trenton in Jay County Indiana. In other portions of the state the Kope overlies the Plattin Formation of the Black River Group or the Lexington Limestone. The Kope Formation is known by a suite of other names including the Eden Shale, McMicken, Southgate, and Economy Formations. The Kope Formation is chiefly made up of shale. It is exposed in portions of southeast Indiana as blue-gray shale (Hasenmuelle, 2014) and the typical thickness of the Kope ranges between 300 to 400 feet.
Figure 5: General Stratigraphic Column for Paleozoic Rocks in Indiana (Polly, 2012)
Figure 6: Subsurface stratigraphy of various rock formations found in Indiana. The depths and thicknesses of each layer are displayed in a northwest (left) to southeast (right) trend. Indiana county names are designated along the top with their associated stratigraphy information shown directly below (Gutstadt, 1968).
Seismic Data Acquisition
Recognition of the lithic arenite and limestone underneath the Mt. Simon in the Benegar wells of Jay County, Indiana, instigated a plan to collect seismic data by faculty at Wright State University. The goal of the seismic line was to both train students in field acquisition methods and to explore the pre-Mt Simon stratigraphy there. The present study expanded that primary acquisition purpose by identifying and digitizing available sonic and density logs from nearby boreholes for construction of synthetic seismic traces to interpret the stratigraphy of the seismic line and help identify the seismic response in of this unique carbonate layer below the Mt. Simon.

In August of 2013, a reflection seismic survey was conducted in Jay County Indiana by geophysics graduate students and faculty of the Wright State Earth and Environmental Sciences Department with assistance from experienced professionals and employees of Precision Geophysical. About five miles northwest of Portland, Indiana, a roughly two-mile long east-west receiver array was deployed along road W 500 N. Figure 7 show the location and extent of the seismic survey in relation to the two Benegar wells that encountered the pre Mt. Simon carbonates.
The Wright State truck-mounted drill rig augered shot holes nominally 4 foot deep every 82.5 feet, with some less accessible sites drilled by a backpack drill provided by Precision Geophysical. The shot holes were loaded with single 90 g charge of seismic explosive, backfilled and tamped. The seismic line consisted of 110 shot holes and 74 geophone arrays. More sources were used than receivers to increase the fold of coverage on both ends of the survey.

II. Methods

Seismic Processing
Tom McGovern of Seismic Earth Resources Technology (SERT) processed these seismic data and supplied Wright State with fully processed stacked SEGY data as well as the moved-out unstacked CDP Gathers for AVO analysis. The final processed seismic line in Figure 8 included the following processing sequence:
1. Demultiplex
2. Shot/Trace Edits
3. Geometry
4. Geophone De-Phase
5. Surface Consistent Deconvolution
6. Spherical Divergence Gain Recovery
7. Resample
8. Sort into CDP Gathers
9. Datum Corrections
10. Zero-Phase Spectral Balancing
11. Velocity Analysis-3 passes
12. NMO Correction
13. Muting
14. Filtering: Zero Phase
15. Trace Balance
16. Surface Consistent Statistics
17. CDP Trim Statics
18. Common Depth Point Stack
19. FX Convolution
20. Migration
21. Frequency Domain Balancing
Figure 8: Final processed seismic line from Jay County. Processing was completed by Tom McGovern.
The simple general layered geology of Jay County is apparent in the processed seismic line. Strong, coherent, and continuous reflections can be observed down to about 1 second, below which the section lacks significant reflections.

The unstacked CDP gathers provided for amplitude versus offset AVO analysis, which was performed using Hampson Russell software. AVO is an important method of seismic analysis regarding identification of amplitude anomalies associated with increasing source-receiver offset related to various rock attributes such as fluid content, porosity, and density.

The processing used for Common Depth Point (CDP) Gather Processing were as follows:

1. Geometry
2. Geophone De-Phase
3. Surface Consistent Deconvolution
4. Spherical Divergence Gain Recovery
5. Resample

Promax and Hampson Russell software were both used to further interpret and analyze the CDP gathers and stacked seismic data. Promax was used for:

- Time/Depth Conversion
- Wavelet Extraction from Seismic
- Raw Data Processing and Stacking of CDP Gathers for NMO analysis

Hampson Russell was used for:
Display and Analysis of Well Logs

Wavelet Extraction from Well Logs

Horizon Picking

Radon Filtering of CDP Gathers

AVO Analysis

Neuralog software that was used to digitize all PDF well log files into .las files. These .las files were then uploaded into Hampson Russell for processing and analysis.

Well Log Utilization
In conjunction with the acquired seismic data, well logs were obtained online from the Indiana Geological Survey (IGS) website. This public website is a resource for geological information in the state of Indiana. On this particular website, the Petroleum Database (PDSM) contains information on more than 70,000 petroleum related wells drilled in Indiana since the 1940’s. The available data includes information on well locations, completion zones, logs, operators, lease names, tests, hydrocarbon shows, samples, cores, geologic formations and tops.

The two Benegar wells in Jay County do not have any electric log records available for digitization and interpretation – only the driller’s log. As a result, the PDMS website was used to locate wells within a ten mile radius of the seismic survey location that had both sonic and density logs such that the acoustic impedance and a synthetic seismic trace could be calculated for comparison to the seismic section to aid the picking of formation tops. A ten-mile radius was defined to minimize potential lateral variations. Figure 9
shows the location of the seismic survey and the six Indiana wells nearby that had both sonic and density logs.

Figure 9: Location of the six chosen Indiana wells in relation to the Jay County seismic line.

Unfortunately none of these six wells penetrated through the entire Eau Claire formation into the Mt. Simon. Consequently, to help interpret the seismic data to greater depth two Ohio wells in Vanwert and Auglaze counties at a greater distance but which had sonic and density logs were also selected for analysis. The location of these Ohio wells in comparison to the Jay County seismic line is shown in Figure 10. The A&M Miller well had sonic and density logs available but the Hoelscher #1 well only had drillers log and a summary of stratigraphic picks from cuttings.
III. Synthetic Generation

Generating a synthetic seismogram is a way to predict the seismic response of the Earth. It models how acoustic energy reflects from the various layers of the subsurface. A synthetic is generated by:

- Computing an impedance log from the sonic and density logs
- Reflection coefficients are calculated at the step changes in the newly created impedance log
- Convolving the extracted seismic wavelet with the reflection coefficients. Each reflection coefficient creates its own unique wavelet packet - whose amplitude is proportional to the strength of the reflection coefficient
- Sum all individual wavelets to yield a synthetic seismic trace
The well logs from both the Indiana and Ohio wells were digitized using Neuralog. The .las files generated were then imported into Hampson Russell software. Because all wells had both an associated sonic and density log, Hampson Russell automatically generated a computed impedance and reflectivity log for each well.

Wavelets were extracted from the seismic section to convolve with the impedance logs to generate the synthetic trace for comparison with the seismic section. Wavelets were extracted from three different time intervals of reflections to examine the effect of attenuation. The wavelets were extracted from the final stacked seismic section in Promax using the Derive Average Wavelet processor, which averages the spectra of traces within a specified time-and-space-variant gate to produce the wavelet spectrum (Halliburton, 2014). The processors had the option to either show or not show the spectral plot of the desired wavelet. If the option to show the spectral plot was enabled, the wavelet would not be saved. Therefore, the processor was run twice, initially with the spectral plot enabled to check and verify the resulting wavelet, then run again with the spectral plot disabled so that the wavelets could be saved. The SEG-Y Output processor was then used to export the three generated wavelets from Promax into a format that could be imported into the Hampson Russell software.

The three wavelets were taken at the time intervals of:

- 100-400 ms
- 350-800 ms
- 750-2000 ms
The wavelet time gates overlap to ensure that all seismic data were included. The three extracted wavelets and their associated spectral plots are shown in Figures 11, 12, and 13. The largest amplitude side lobes are observed in wavelet 100-400 ms, while the lowest amplitude side lobes are seen in the wavelet for the 750-2000 ms interval. The peak frequency for both the 100-400ms and 750-2000ms wavelets were 30 Hz while the wavelet with the 350-800 ms time gate displayed a little higher peak frequency of 42.5 Hz. The average of the three peak frequencies was taken to yield the dominant frequency.
Figure 11: Wavelet amplitude and associated frequency spectrum extracted from the final processed seismic data at a time interval of 100-400 ms

Figure 12: Wavelet amplitude and associated frequency spectrum extracted from the final processed seismic data at a time interval of 350-800 ms
The three wavelets that were extracted from various time intervals of the seismic data were convolved with the calculated impedance logs to generate synthetic traces.

**Analysis of Formation Tops**

Formation tops were picked based on the following criteria:

- The Eden Shale formation is seen as one of the shallowest negative reflections that has an associated increased gamma response.
- The Trenton Limestone lies at a boundary between pure shale and a relatively clean limestone. This is distinguished in the logs as a distinctive decrease in gamma radiation and an increase in the density, sonic, and impedance values.
- The similarity between the lithology of the Knox and overlying Glenwood Formation; which is made up of interbedded shale, limestone, and dolomite; makes it hard to distinguish the formation top. Therefore, the driller’s logs were used to pick the top of the Knox.
• The Eau Claire is at a boundary between fine grained dolomite and fine grained sandstone that is cemented by silica and interlaminated with shale. This is observed as both a decrease in both sonic and density values.

• The only well that was drilled down into the Mt. Simon was Ohio Well A&M Miller. Due to the close proximity of the top of the Mt. Simon to the total depth of the well, resolution of the well log was diminished. Driller’s logs were therefore used to pick this formation. Through doing so, it was observed that the top of the Mt. Simon has associated lower density and gamma ray values.

Comparison of Well Log Formation Picks and Generated Synthetics
Figures 14-20 show the synthetics generated using the wavelets extracted from the three time intervals adjacent to the digitized well logs, overlain with the formation tops. Comparing the synthetics generated from one specific well, there is little discrepancy between them. All three synthetics show similarities in regards to the pattern, number, and depths of reflections. The only notable difference might be that a reflection may be sharper in one synthetic and more elongated in another due to slightly different characteristics of the wavelets. The frequency spectrum of both the 100-400ms and 350-800ms wavelets were very similar; however; the wavelet for the deepest interval was different. The spectrum of the first two was very smooth and broad with only one distinctive peak frequency. The last wavelet had the same broad frequency however it was a lot spikier than the first. This could have been a factor in the production of a synthetic. Other factors include the well log quality, amplitudes of the side lobes, and the ability to extract a representative wavelet from seismic data.
The synthetics from all Indiana wells closely correlate with one another. The same patterns of reflections were observed in the wells; however the amplitude and distinguishability varied. The top of the Trenton is the only reflection that had consistent and distinguishable amplitude throughout all six Indiana wells. The Eden Shale Formation can only be distinguished in Well 141744 by a very shallow, prominent, negative reflection. This reflector coincides with the formation pick in Well 141744. In all of the other wells, this reflection is stretched out and no reflector can be clearly distinguished. As with the Eden Shale Formation, the synthetics only have clear reflectors for the top of the Knox in some of the wells.

The Indiana wells all displayed similar synthetic characteristics due to their close proximity. The Indiana wells were all within 10 miles of each other however the Ohio well is 40-45 miles away. This greater lateral distance will result in greater stratigraphic differences, so greater variation between the seismic data and synthetic is to be expected.
Figure 14: Comparison of the generated synthetics (left-right: 100-400 ms, 350-800 ms, and 750-2000 ms) and picked formation tops associated with well 141744

Figure 15: Comparison of the generated synthetics (left-right: 100-400 ms, 350-800 ms, and 750-2000 ms) and picked formation tops associated with well 153115
Figure 16: Comparison of the generated synthetics (left-right: 100-400 ms, 350-800 ms, and 750-2000 ms) and picked formation tops associated with well 134404

Figure 17: Comparison of the generated synthetics (left-right: 100-400 ms, 350-800 ms, and 750-2000 ms) and picked formation tops associated with well 149600
Figure 18: Comparison of the generated synthetics (left-right: 100-400 ms, 350-800 ms, and 750-2000 ms) and picked formation tops associated with well 149653

Figure 19: Comparison of the generated synthetics (left-right: 100-400 ms, 350-800 ms, and 750-2000 ms) and picked formation tops associated with well 141330
Seismic Time to Depth Conversion
To be able to compare the synthetics, logs, and formation picks, two Promax processors were used to convert the original time domain seismic image into a depth domain seismic image -- *Velocity Manipulation* and *Time/Depth Conversion*. The *Velocity Manipulation* processor is capable of applying different algorithms to the input velocity. One can convert RMS, interval, or average velocities in time or depth into any other type of velocity function, multiply a velocity function by a scalar, or move a velocity function to a datum. In this case, the *Velocity Manipulation* processor was used to convert an RMS (stacking) velocity to an interval velocity by using the Dix Equation.

The Dix Equation is given by the equation: $V_n = [(V_n^2t_n - V_{n-1}^2t_{n-1})/(t_n - t_{n-1})]^{1/2}$

Figure 20: Comparison of the generated synthetics (left-right: 100-400 ms, 350-800 ms, and 750-2000 ms) and picked formation tops associated with Ohio well A&M Miller.
Where $V_{n-1}$ and $V_n$ are the stacking velocities from the datum to reflectors above and below the layer and $t_{n-1}$ and $t_n$ are reflection arrival times (SEG Wiki). It’s a formula used to calculate the interval velocity within a series of flat, parallel layers (Schlumberger Oilfield Glossary, 2014). The Promax processor *Time/Depth Conversion* was used to convert the original time domain seismic image into a depth domain seismic image using the interval velocity output from the velocity manipulation processor.

**Tie to Seismic Section**

The generated synthetics for all wells were compared to the time-depth converted seismic section. For comparison, the synthetics and seismic were plotted side by side and overlain by the picked formation tops for that well, as seen in Figures 21-27. The picked formation tops from the Ohio A&M Miller well were not overlain on the seismic section to ensure that there wouldn’t be an inadvertent interpretation of formation tops from the Ohio well to the Indiana seismic data. The close proximity of the Indiana wells to the seismic line provides negligible variation in observed formation top depth and can be more directly correlated. The increased distance (roughly 40 miles) of the Ohio well created large, observable differences in formation depths and the depths of the picked formation tops cannot be directly projected onto the Jay County seismic section.

The synthetics that were generated from all of the Indiana wells correlate reasonably well with the seismic section, however the distance between a well and the seismic line does appear to have an impact. The overall pattern of the sequence of reflections of
each synthetic is the main criteria used to identify the formation tops on the seismic data, together with the driller log of the Benegar wells adjacent to the seismic line.
Figure 21: Synthetics from the wavelet time gates (left-right) 100-400ms, 350-800ms, and 750-2000ms) for well 134404 are displayed next to the time-depth converted seismic to aid in formation picking.
Figure 22: Synthetics from the wavelet time gates (left-right) 100-400ms, 350-800ms, and 750-2000ms) for well 141330 are displayed next to the time-depth converted seismic to aid in formation picking.
Figure 23: Synthetics from the wavelet time gates (left-right) 100-400ms, 350-800ms, and 750-2000ms) for well 141744 are displayed next to the time-depth converted seismic to aid in formation picking.
Figure 24: Synthetics from the wavelet time gates (left-right) 100-400ms, 350-800ms, and 750-2000ms) for well 149600 are displayed next to the time-depth converted seismic to aid in formation picking.
Figure 25: Synthetics from the wavelet time gates (left-right) 100-400ms, 350-800ms, and 750-2000ms) for well 149653 are displayed next to the time-depth converted seismic to aid in formation picking.
Figure 26: Synthetics from the wavelet time gates (left-right) 100-400ms, 350-800ms, and 750-2000ms) for well 153115 are displayed next to the time-depth converted seismic to aid in formation picking.
Figure 27: Synthetics from the wavelet time gates (left-right) 100-400ms, 350-800ms, and 750-2000ms) for the Ohio A&M Mill well are displayed next to the time-depth converted seismic to aid in formation picking. Due to the increased distance observed between the Ohio wells and the Indiana survey, the picked formation tops cannot be directly projected onto the seismic. The red and blue dashed line represents the interpreted depth of the corresponding formation top.
Horizon Picks
Comparison of the synthetics to the acquired seismic data resulted in the picking of five significant formation tops. Well’s 149600 and 149653 had extremely accurate ties to the Eden Shale formation which was picked as the very shallow, negative polarity reflection that lies beneath the strong, topmost positive reflection. Well 149653 was used to pick the top of the Trenton. This formation top is distinguished by the strong, coherent, positivity reflection observed at a depth of roughly 1000 feet.

The tops of both the Knox and Eau Claire were picked using the synthetics generated from Well 134404. The top of the Knox was hard to distinguish in the seismic section because it wasn’t distinctive in the synthetics and or the well logs. The bottom of the overlying Trenton is interbedded with siltstone overlying the dolomite of the Knox, which might not generate much of a reflection. The Eau Claire was easily picked as the negative polarity reflection sandwiched in between two strong reflections at a depth of 2,400 feet.

Patterns in the synthetics generated from the Ohio well logs, as well as the Benegar well drillers logs and picks from later drill chip analysis were used to pick the deeper formations of the Mt. Simon and Middle Run Formations. The Ohio synthetics suggest that the Mt. Simon is an apparent negative polarity reflection. Tables 1 and 2 indicate the depths of the Mt. Simon and Middle Run in the Benegar wells as determined from the cuttings by both the Indiana Geologic Survey (IGS, 2011) and Droste (IGS, 2009).
The stratigraphic picks in Tables 1 and 2 show slight variations in interpreted formation depths, however the variations are negligible on the scale of the seismic section. These picks indicate that the top of the Mt. Simon lies somewhere around 3,000 feet and might be a negative reflection according to the synthetics generated from the Ohio well. The top of the Middle Run is described at a depth of roughly 3,330 feet. All formation picks are annotated on the seismic section in Figure 28.

<table>
<thead>
<tr>
<th>Well Number</th>
<th>Trenton</th>
<th>Knox</th>
<th>Eau Claire</th>
<th>Mt. Simon</th>
<th>Precambrian Middle Run Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>141770</td>
<td>1,021 ft.</td>
<td>1,450 ft.</td>
<td>2,425 ft.</td>
<td>2,998 ft.</td>
<td>3,333 ft.</td>
</tr>
<tr>
<td>141771</td>
<td>1,010</td>
<td>1,432 ft.</td>
<td>2,423 ft.</td>
<td>3,014 ft.</td>
<td>3,351 ft.</td>
</tr>
</tbody>
</table>

Table 1: Stratigraphy picks from cuttings- as observed by the Indiana Geologic Survey (IGS, 2011).

<table>
<thead>
<tr>
<th>Well Number</th>
<th>Trenton</th>
<th>Knox</th>
<th>Eau Claire</th>
<th>Mt. Simon</th>
<th>Precambrian Middle Run Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>141770</td>
<td>1,020 ft.</td>
<td>1,450 ft.</td>
<td>2,425 ft.</td>
<td>3,000 ft.</td>
<td>N/A</td>
</tr>
<tr>
<td>141771</td>
<td>1,020 ft.</td>
<td>1,450 ft.</td>
<td>2,425 ft.</td>
<td>3,000 ft.</td>
<td>3,333 ft.</td>
</tr>
</tbody>
</table>

Table 2: Stratigraphy picks from cuttings- as observed by Droste (IGS, 2009).
Figure 28: Jay County seismic data with horizon picks for the top of the Eden Shale, Trenton Limestone, Knox Dolomite, Eau Claire, Mt. Simon, and Middle Run.
**Middle Run Interpretation**

As shown in Figure 4, the two Benegar wells that instigated this study are located a short distance due south of the seismic line. Figure 29 shows the nearest Benegar well (Well 141771) projected due north into the Jay County seismic line together with labels of the observed stratigraphic picks determined from cuttings (Tables 1 and 2).

Figure 30 shows an enlarged portion of the deeper part of the seismic section with Benegar well 141771 projected as in Figure 29. From cuttings the limestone layer lies roughly 50 feet below the top of the Middle Run or somewhere around 3,380 feet. The seismic signature of this lithic arenite to carbonate boundary would be expected to be a positive reflection.

![Figure 29: The projection of Benegar well 141771 and associated formation picks onto the Jay County seismic line.](image)
The limestone as indicated in the Benegar wells is interpreted to be represented on the seismic section by the positive reflection at roughly 3,380 feet (Figure 30). Notably, more layered reflections are observed at depths below 3,400 feet. In most interpretations of the Middle Run Formation such reflections would be interpreted to be silty or shaley layers or mafic flows or sills; however, could these strong reflections represent additional limestone layers? Only a drill hole will determine this.

Additionally, although this seismic line is quite short and only an E-W 2D section, the lack of apparent folding or structural disruption of the layered reflections below the Mt. Simon suggests that any Grenville foreland deformation likely.
The horizontal layering of the Paleozoic and Precambrian rocks that is observed in the above Jay County seismic has also been observed in Allen County, Ohio.

Many uncertainties remain that still need to be addressed. The thickness of the limestone is unknown, as is the lateral extent of the limestone layer? The seismic section of Figure 30 indicates the reflection associated with the limestone extends a few hundred feet in both to the east and west of the well but may continue intermittently across the entire section. What is the origin of the limestone? What is it’s age? These questions are beyond the scope of this study, but clearly limestone exists beneath the Mt. Simon and associated with the Middle Run Formation and it may be much more extensive than presently appreciated.

Figure 31: A portion of the processed seismic data collected in Lima, OH. Paleozoic formation tops are labeled along with the Middle Run reflection. Note how the deep Precambrian reflections parallel the shallower Paleozoic reflections. (Paramo, 2002)
IV. AVO
An amplitude verse offset (AVO) analysis was performed on the data to try and model amplitude characteristics that are specifically associated with Pre Mt. Simon carbonates. AVO analysis is widely used in hydrocarbon detection, lithology identification, and fluid parameter analysis due to the fact that seismic amplitudes at the boundaries are affected by the variations of the physical properties just above and just below the boundaries.

AVO analysis is most effective when the data that is to be AVO analyzed is prestack, unmigrated, and thoroughly processed. The original CDP gathers with the following processing steps were loaded into the Hampson Russell software for AVO analysis.

- Geometry
- Geophone Dephase
- Minimum Phase Compensation for Zero Phase Correlated Data
- Surface Consistent Deconvolution Source and Receiver
- Normal Moveout
- No First Arrival Muting- allowing wider angles
- Residual Normal Moveout
- Residual Automatic Statics
- Wide Bandpass Filter 3-205 Hz
- Full Trace Equalization (2000 Millisecond Window)
- Automatic Gain Control
- Super Gather
To remove noise on the CDP stacks and to diminish multiples, a radon filter was also applied. The stacking velocities from the final processed seismic data were imported into the AVO processor such that the intercept and gradient attributes could be calculated. Calculations are analyzed as a function of angle and any arrivals outside of the predefined angle range are omitted. These values were determined by an underlying algorithm that computes various AVO attributes by fitting a curve through a distribution of data amplitudes as a function of incidence angle or square sine of the estimated incidence angle and outputs the attributes (CGG 2006). In this case, the greatest angle of incidence is 30 degrees.

Figure 32 is the AVO volume with the attributes gradient and intercept of the best fitting
AVO curve displayed. The gradient is displayed as the trace; with the curves to the right distinguishing positive values and to the left negative. The intercept is shown in the color with blue as the negative value and red as the positive.

There are five types of AVO relationships that were originally defined by Rutherford and William’s (1989) and later modified by Ross, Kinman, and Castagna (1997). The five classes are as follows:

1. Class 1: High Impedance with decreasing AVO
2. Class 2: Near Zero Impedance Contrast
3. Class 2p: Near Zero Impedance Contrast that exhibits a small polarity change from positive to negative with offset
4. Class 3: Low impedance with increasing AVO
5. Class 4: Low impedance with decreasing AVO

Modeling AVO Classes Hapsari (2014) described each of the above classes in complete detail. Figure 33 is an excerpt from the document and illustrates these five types of classes. The red line indicates the degree and polarity of impedance and the color key shows the increase or decrease in AVO.
Based on the formation top picks from the stacked seismic section, the blue colored reflection at 200 ms is interpreted as the Trenton. The Trenton exhibits an extremely high impedance, therefore falling into Category 1. There is a possible anomaly along the Trenton reflector at CDP 238 that shows brighter intercept values than the surrounding areas. The reflection at 350 ms is interpreted as the Eau Claire. The Eau Claire has low impedance and falls into either a Class 3 or 4.

The top of the Mt. Simon is interpreted to be around 450 ms, which means that the pre Mt. Simon carbonates are located below this time. AVO wasn’t able to generate any interpretable results below the Mt. Simon. Therefore, no observable characteristics could be associated with the pre Mt. Simon from the AVO analysis. Due to time limitations, no further AVO analysis was performed.
V. Summary and Conclusions
The purpose of the research was to examine the structure and setting of Pre Mt. Simon carbonate rocks in Jay County, Indiana, where drill chip samples lead to the recognition of a limestone layer within the lithic arenite of the Middle Run. Only one other location in the region (Clark County, Ohio) is known to exhibit a limestone below the Mt Simon.

In order to get a better understanding of these carbonate rocks, a seismic reflection survey was conducted in Jay County Indiana by the student and faculty of the Wright State University Earth and Environmental program, and professionally processed by Tom McGovern of SERT. Wells with sonic and density logs within 10 miles of the seismic line and also western Ohio were used to create synthetics for comparison with the seismic data to aid picking the tops of Paleozoic formations on the seismic section.

Synthetics were generated for all wells using wavelets that were extracted from the seismic section. Due to the depth limitation displayed by the shallow Indiana wells, the deeper Ohio wells and the documents obtained from the original two Benegar wells were essential in determining the tops of the deeper formations. All wells and their corresponding logs were used in the interpretation of the seismic, and the tops of the Eden, Trenton, Knox, Eau Claire, Mt. Simon, and Middle Run Formations were picked.

The CDP Gathers were used to create an AVO volume to try and determine potential anomalies. The Trenton reflector produced Class 1 AVO behavior while the Eau Claire corresponded to either Class 3 or 4. Due to the CDP Gathers lack of fold of coverage at the potential Pre-Mount Simon carbonate, AVO analysis was inconclusive.
With the guidance of the stratigraphic picks from cuttings documents that were obtained for both Benegar well 141770 and 141771, the limestone layer within the Middle Run formation was successfully picked on the seismic section as a positive reflection at a depth of 3,3,80 feet. Due to the limited well depth, the thickness of this limestone layer is unknown.

In order to better understand the setting of the pre-Mt. Simon limestone, both a longer East-West line and a perpendicular North-South seismic line needs to be acquired. A perpendicular line would constrain the dip and reveal its extent in a N-S direction. Deeper drill holes may show that there are actually multiple limestone layers within the Middle Run. This location appears to be a good candidate for a well of opportunity to deepen, core and further study this pre-Mt Simon limestone.
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