2013

Analysis of the cyclostratigraphy at the Devonian-Carboniferous boundary in south-central Oklahoma

Ryan Michael Todd Ellis

Louisiana State University and Agricultural and Mechanical College, rellis7@tigers.lsu.edu

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_theses

Part of the Earth Sciences Commons

Recommended Citation

https://digitalcommons.lsu.edu/gradschool_theses/929

This Thesis is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Master’s Theses by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
ANALYSIS OF THE CYCLOSTRATIGRAPHY AT THE DEVONIAN–CARBONIFEROUS BOUNDARY IN SOUTH-CENTRAL OKLAHOMA

A Thesis
Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science
in
The Department of Geology and Geophysics

by
Ryan Ellis
B.S., Marietta College, 2007
May 2013
Acknowledgements

Numerous people were critical to the completion of this project. I would first like to thank my major professor, Dr. Brooks Ellwood. From the time I contacted him the summer before my first semester at LSU, I have felt at home and supported in our lab group. He has provided constant guidance, and I have learned an immense amount over the last 2 years. I would also like to thank my committee members Dr. Wei-Hsung Wang, Dr. Sophie Warny, and Dr. Kristine DeLong. They have all generously contributed their time and expertise, and helped steer me in new directions. I would also like to thank Dr. Nancy Hasenmueller for arranging access to the Indiana Geological Survey core, and Drs. Jeff Over and Jed Day for answering my numerous questions throughout the research process.

I am also greatly indebted to the other members of the LSU Rock Magnetism Laboratory. Sue Ellwood and Jacob Grosskopf volunteered a great deal of their time in field sample collection. Amber Ellwood assisted with magnetic susceptibility laboratory measurements, both in teaching me and in running samples. Mathew Clark helped introduce me to the statistical methods used in time-series. Tom Schram provided beneficial advice for managing the various responsibilities of graduate school, and was a valuable person to bounce ideas off of. Tiia Carraway and Lindsey Protho were also great in listening to new ideas I had, and Tiia also showed me the ropes in the HPGe lab.

I would also like to take the opportunity to thank my family, in particular my parents. I have been blessed with a family that stressed the value of education, and encouraged me to strive to reach my goals and not just settle for mediocre results. I am where I am today because of their efforts.
Finally, I want to thank my beautiful fiancé, Kristin Lutes. The time away for graduate school has been rough, but I am so blessed to have you in my life. Anytime I felt like giving up, you have always been there to encourage me and support me. I cannot wait to start our life’s journey together this summer.
# Table of Contents

Acknowledgements .............................................................................................................. ii

Abstract ............................................................................................................................. vi

1. Introduction ...................................................................................................................... 1
   1.1. Global Boundary Stratotype Sections and Points (GSSP)s ............................................ 1
   1.2. Cyclostratigraphy ....................................................................................................... 1
   1.3. Magnetic Susceptibility ($\chi$) ................................................................................... 2
   1.4. Gamma Radiation ..................................................................................................... 3

2. Devonian–Carboniferous Boundary .............................................................................. 5
   2.1. D–C GSSP ............................................................................................................... 5
   2.2. D–C Conodont Zonation ........................................................................................... 6
   2.3. Hangenberg Extinction Event ................................................................................... 7
   2.4. D–C Boundary in South-Central Oklahoma ............................................................... 8
   2.5. New Albany Shale .................................................................................................... 9
   2.6. Time-Series Analysis .............................................................................................. 11

3. Methods .......................................................................................................................... 14
   3.1. Study Sites Chosen .................................................................................................. 14
   3.2. Field Methods ........................................................................................................ 15
   3.3. Laboratory Methods ............................................................................................... 17
   3.4. Statistical Methods ............................................................................................... 18

4. Results ............................................................................................................................. 20
   4.1. Correlation by Geophysical Proxy ........................................................................... 20
   4.2. Time-Series Analysis .............................................................................................. 24
   4.3. Wapanucka Shale Pit .............................................................................................. 24
   4.4. I-35 Road Cut .......................................................................................................... 28
   4.5. Johnson County Core ............................................................................................. 29

5. Discussion ......................................................................................................................... 34
5.1. Correlation Between the Oklahoma Outcrops ................................................................. 34
5.2. GSSP Candidacy .............................................................................................................. 36
5.3. Findings from Cyclostratigraphy .................................................................................... 36

6. Conclusions .......................................................................................................................... 39

7. References .......................................................................................................................... 40

8. Appendix ............................................................................................................................. 44
   Vita .......................................................................................................................................... 45
Abstract

An outcrop in La Serre, France, was officially ratified by the ICS in 1989, and the IUGS in 1990, as the location of the Global Boundary Stratotype Section and Point (GSSP) for the Famennian–Tournaisian, and subsequently the Devonian–Carboniferous (D–C) boundary. GSSPs, like this one, are official outcrops that provide physical representations of geologic time boundaries, essentially geological standards that define geologic time, providing a vital framework to model a variety of interpretations of geological phenomena from paleoclimate to paleontological. It has been acknowledged that the GSSP in La Serre, France is in need of revision due to fossil reworking and general outcrop quality. The D–C boundary has also traditionally been a challenging boundary to place with precision because of problems associated with Siphonodella sulcata, whose first occurrence is the current definition of the boundary.

With the aim of improving D–C boundary correlation, especially in the central United States, outcrops from the Woodford Shale in south-central Oklahoma and a New Albany Shale core from Johnson County, Indiana have been analyzed for cyclostratigraphy through measurement of mass-dependant, low-field magnetic susceptibility (χ), and also gamma radiation (GR). Gamma Ray Spectroscopy (GRS; field based) measurements were used for general correlation, along with previous conodont biostratigraphic work. Combined use of χ and GR measurements for $^{40}$K allows for a deeper layer of stratigraphic comparison. With the combined statistical techniques of the periodogram, multi-taper method (MTM), and wavelet analysis, a detailed timescale was pieced together for both the Oklahoma outcrops and Indiana core by comparing the periodic elements of the cyclostratigraphic signal represented by these geophysical proxies. Future work studying faunal assemblages can be compared with the cyclostratigraphic framework provided here to allow greater precision in interpretation.
1. Introduction

1.1. Global Boundary Stratotype Sections and Points (GSSP)s

In 1976 the International Union of Geological Sciences (IUGS), International Commission on Stratigraphy (ICS), mandated the creation of a working group to establish the Global Boundary Stratotype Section and Point (GSSP) for the Devonian–Carboniferous boundary (Brand et al., 2004). GSSPs, like this one, are official outcrops that provide physical representations of geologic time boundaries, essentially geological standards that define geologic time, specifically the beginning of each geologic Stage. Other study areas can then be compared to these standards and tied into the international stratigraphic framework. Usually, new stages are defined by the first occurrence of a new species within an evolutionary lineage. There is also an emphasis on refining dates using abiotic methods (Ellwood et al., 2011). The global network of GSSPs and their accurate dating provides a vital framework to model a variety of interpretations of geological phenomena from paleoclimate to paleontological.

1.2. Cyclostratigraphy

In general Earth’s climate can be considered a complex system of both chaotic and periodic, or quasi-periodic components. Throughout the Phanerozoic one of the primary drivers of climate cyclicity has been changes in Earth’s orbit (Hays et al., 1976). These drivers known as Milankovitch cycles can be grouped into three catagories, eccentricity, obliquity, and precessional bands (Berger et al., 1992). Eccentricity refers to the elliptical shape of Earth’s orbit around the sun; obliquity refers to changes in tilt of Earth’s axis; and precession is a measure of the wobble around Earth’s rotational axis. These patterns were initially shown to be stable throughout the Quaternary (Hays et al., 1976), and through later calculation deduced to be predictable throughout the Phanerozoic (Berger et al., 1992). The imprint that these various
orbital characteristics have left on the rock record allows for an unmatched level of
dchronostratigraphic resolution (Hays et al., 1976). These climatic cycles can be traced through
many proxies including the magnetic and gamma ray spectroscopic properties of sediments
(Hartl et al., 1995; Weedon et al., 1999; Hladil et al., 2003; Ellwood et al., 2011; Ellwood et al.,
2013). With a robust data set, a detailed timescale can be pieced together from the cyclic
variations in the signature of geophysical proxies.

1.3. Magnetic Susceptibility ($\chi$)

One of the leading geophysical proxies in cyclostratigraphic analysis is laboratory-based,
mass-dependant, low-field magnetic susceptibility ($\chi$). $\chi$, represented by units of $\text{m}^3\text{kg}^{-1}$, is a
measure of the induced magnetization produced in a very low power, alternating magnetic field
(Ellwood, 2007). All substances are either ferromagnetic or ferrimagnetic (exhibiting a very
powerful $\chi$), paramagnetic (exhibiting a small positive $\chi$), or diamagnetic (exhibiting a small
negative $\chi$). Ferrimagnetic minerals, including magnetite and maghemite, acquire an intrinsic
remanent magnetism. Paramagnetic minerals, including clay minerals, iron sulfides such as
pyrite, and ferromagnesian minerals such as biotite, loose their inducted magnetization when the
inducing field is removed. Diamagnetic minerals, such as quartz or calcite, have a negative $\chi$ and
are so weakly magnetic they have little effect on the overall signal in the sample (Ellwood et al.,
2000; Febo, 2007). $\chi$ is not to be confused with the remanent magnetism of ferrimagnetic
minerals that provide the basis for polarity studies in Earth history (Ellwood et al., 2006).

Climatic changes related to Milankovitch cycles have been shown to have great influence
on erosion of sediment and produce cyclic pulses in detrital/eolian flux into the marine system
(Weedon et al., 1999). In particular $\chi$ has been demonstrated to be a sensitive indicator of
climatic cycles that can be used to determine sediment accumulation rates (Mead et al., 1986;
Weedon et al., 1999; Ellwood et al., 2006; Ellwood et al., 2011). χ in the marine setting can also be affected by carbonate production and diagenesis, but the effect is slight (Ellwood et al., 2000; da Silva et al., 2009). Diagenesis usually destroys detrital/eolian magnetite due to sulfate reducing bacterial organisms, altering the signal. Because it is often controlled by primary depositional facies, diagenesis can even enhance the original signal (da Silva et al., 2009). What makes χ such a strong geophysical proxy lies in the fact that the dominant factor forming the signal is often the paramagnetic detrital/eolian component of the marine sediment being analyzed (Ellwood et al., 2000; Ellwood et al., 2006). A small amount of paramagnetic minerals in a system can overpower much more abundant diamagnetic minerals such as quartz and calcite (Ellwood et al., 2000). Diagenesis also acts quickly within the shallowest 0.5 m in sediments in the marine setting (Karlin and Levi, 1983), while overall iron content is preserved thus locking in the primary signal pattern (Ellwood et al., 2006). In general, higher χ values are seen in sediments closer to shore and following current drift patterns, compared to sediments in the more distal regions of the basin (Sachs and Ellwood, 1988; Ellwood et al., 2006).

1.4. Gamma Radiation

Another well-studied geophysical proxy is gamma radiation (GR). Both GR (laboratory based), and Gamma Ray Spectroscopy (GRS; field based) measurements of the individual element components in samples, have been used for widespread and well-established stratigraphic correlation and sequence stratigraphic studies, forming one of the most important geophysical logging methods used in the petroleum industry (Hesselbo, 1996; Simicek et al., 2012). Gamma ray methods serve as a recording of both detrital/eolian provenance and sediment transport/facies distribution (Simicek et al., 2012). GR/GRS methods are used in measuring the gamma radiation emitted from the decay of unstable isotopes, including $^{40}$K, and the daughter
products of $^{232}$Th, and $^{238}$U. The industry standard is to report these elements’ signals in K%, and Th and U in parts per million (ppm) (Simicek et al., 2012). Similar to $\chi$, the GR signal is a function of detrital/eolian fluxes (Simicek et al., 2012). In general, slow sedimentation or major marine transgressions increase the background sediment signal, while periods of low sea level produce more dust and suspended sediment output (Hladil et al., 2003). Potassium is bound to many common types of detrital minerals, such as illite, smectite, and glauconite (Hesselbo, 1996), and once deposited in the marine environment has a lower mobility than Th and U (Ellwood et al., 2013). With a higher mobility in Th and U, a key difference lies in the general insolubility of Th in water versus the high solubility level of U in fluvial and marine settings (Hesselbo, 1996). There is not always an exact correlation between laboratory GR, and field GRS due to differences in counting time, sample size, detection orientation, and instrument sensitivity, though overall patterns should remain the same (Simicek et al., 2012). For this study laboratory GR measurements are reported in counts/gram/hour (cts/g/hr). This provides a normalized set of data for which effective time-series work can be conducted (Ellwood et al., 2013). To date, not much cyclostratigraphic work has been done with laboratory-derived GR. Field derived GRS incorporates a very large cone of acquisition when compared to the sampling rate, thus smoothing the data, rendering cyclostratigraphic evaluation too coarse. However, it is a highly useful tool for broad-scale correlation (Ellwood et al., 2013). $^{40}$K is the chosen proxy over $^{232}$Th and $^{238}$U for a number of reasons. It has high concentrations, excellent resolution using GR methods, it is a direct measurement not relying on daughter products, its decreased mobility leads to increased signal stability, and because there is potential that $^{40}$K and $\chi$ can act as useful independent cross checks of Milankovitch cycles (Ellwood et al., 2013).
2. Devonian–Carboniferous Boundary

2.1. D–C GSSP

An outcrop in La Serre, France, was officially ratified by the ICS in 1989, and the IUGS in 1990, as the location of the GSSP for the Famennian–Tournaisian, and subsequently the Devonian–Carboniferous (D–C) boundary (Brand et al., 2004). It is acknowledged that the GSSP at La Serre, France, is a terrible section, but it presented the best working proposal during the ratification process and contained a diverse range of conodont fossils to constrain the age of the outcrop (Paproth et al., 1991). Unfortunately, later work has shown that GSSP outcrop age estimates need adjustment due to reference fossils being reworked (Kaiser et al., 2006b). To help mitigate the problem of reworking, two Auxiliary Stratotype sections have been designated, one near Hasselbachtal, Germany, and the other near Nanbiancun, China (Brand et al., 2004).

Fig. 1. Map of the D–C GSSP at La Serre, France. Reworking of the conodonts and thin vertical extent of the section has led to auxillary GSSPs in Germany and China. (Adapted from Kaiser and Corradini, 2011).
2.2. D–C Conodont Zonation

There has been considerable work done in recent years to refine the conodont zonation leading up to, and crossing, the D–C boundary (Corradini, 2008; Kaiser et al., 2009; Corradini et al., 2011; Kaiser and Corradini, 2011). The current conodont zonation across the D–C boundary is presented in Fig. 2. Part of the problem stems from the fact that the defining conodont species for the boundary, *Siphondella sulcata*, is often absent from many outcrops worldwide (Kaiser and Corradini, 2011). This has led to correlation difficulties when the marker species is absent. Exacerbating the problem is the problem of distinguishing between members of the *Siphonodella praesulcata* to *Siphondella sulcata* lineage (Kaiser and Corradini, 2011). Identification based on personal bias can lead to inconsistency in boundary placement when different outcrops are studied by different workers. This has necessitated a re-evaluation of the biostratigraphic definition of the D–C boundary, and possibly substituting a new species. There have been difficulties in finding replacement species because many potential candidates, like the *Protagnathus* lineage, either do not have their first appearance (FA) precisely at the boundary, or are too inconsistently distributed globally to be of correlation use (Corradini et al., 2011). The current conodont zonation used to define the boundary includes the praesulcata, costatus-kockeli interregnum, kockeli, sulcata, bransoni, and duplicata zones (Corradini, 2008; Kaiser et al., 2009; Corradini et al., 2011; Kaiser and Corradini, 2011). Major proposed changes to the standard zonation include the deletion of the middle praesulcata zone, the addition of the costatus-kockeli interregnum, and the re-branding of the upper praesulcata to the kockeli zones. The middle praesulcata zone was discarded due to a lack of useful widespread marker fossils. The lower praesulcata zone was re-branded because of the widespread prevalence of *Protagnathus kockeli* as opposed to the less abundant *Siphonodella praesulcata* (Kaiser et al., 2009; Corradini et al.,
The revised conodont zonation shows the replacement of the FA *Si. praesulcata* with the FA of *Pr. kockeli* to indicate the end of the Hangenberg Event, and the redefined Upper praesulcata zone as the kockeli zone. (Adapted from Corradini et al., 2011).

### 2.3. Hangenberg Extinction Event

One of the largest extinction events in Earth history, the Hangenberg extinction event, named for its association with the Hangenberg black shale in Europe, immediately proceeds, and ends at the D–C boundary. It is believed that at this time, 30% of marine taxa and 20% of all known taxa at the family level went extinct at various rates and levels of abruptness (Wang et al., 1993). Overall, the extinction rate across all genera was in excess of 45% (Kaiser et al., 2006a). The Hangenberg Event is identified by the disappearance of key conodont taxa including *Palmatolepis gracilis*, many species of *Bispathodus*, *Pelekysgnathus guizhouensis*, and *Pseudopoygnathus marburgensis trigonicus*. Despite the large number of extinctions, more taxa appear to have survived than reached extinction, including *Siphonodella praesulcata* (sensu...
lato), and several species of Protognathus, Bispathodus, and Polygnathus (Kaiser et al., 2009). The Hangenberg Event appears to exhibit patterns similar to other mass extinctions in the Phanerozoic (Wang et al., 1993; Kaiser et al., 2006a). The δ¹³C variations show that there was an overall decrease in sea surface temperatures from the early to late praesulcata zone, followed by a short-lived glacial pulse in Gondwana. Later melting of these ice sheets, associated with latest Devonian warming, helped trigger global sea-level rise and broad oceanic shelf anoxia (Kaiser et al., 2006a), though it could not have accounted for all the transgressive–regressive fluctuations in the Late Devonian (Johnson et al., 1985). This anoxia helped trigger a mass extinction and increased burial of organic carbon, as evidenced by the positive δ¹³C excursion that occurs within the praesulcata zone (Brand et al., 2004). Similar to other extinction events, there are anomalous iridium values present around the D–C boundary, that are likely due to paleo-redox changes (Wang et al., 1993). Unlike the Cretaceous–Paleogene boundary, there is at present no evidence to suggest an impact occurred at this time. Understanding the timing of events associated with the D–C boundary are crucial for refining models of faunal succession and global climate changes.

2.4. D–C Boundary in South-Central Oklahoma

For the past billion years or so, the Central United States has had a stable and largely inactive tectonic history due to its residence over the stable North American craton (Ham and Wilson, 1967). During the Paleozoic, this area was largely free of igneous activity and rocks deposited here are mainly marine. On this craton, Oklahoma represents a unique situation from the normal epeirogenesis, because the Anadarko and Arkoma basins, framing study area, were much deeper during the Paleozoic than were other basins. As a result, the Arbuckle mountains form a prominent high point between these two basins (Ham and Wilson, 1967). The Arbuckle
mountains are a direct result of Late Pennsylvanian deformation, with overlying sediment consisting of lower Devonian platform carbonate rocks overlain by Upper Devonian Frasnian terrigenous deposits (Ham and Wilson, 1967; Over, 1992). The base of the Woodford Shale is equivalent to the base of the Kaskaskia sequence of the North American craton (Sloss, 1963), and the base of the Kaskaskia sequence is truncated by many unconformities from Transgressive–Regressive cycles (Sloss, 1963). These are readily apparent in the Lawrence uplift, where there are many breaks in the conodont zonation due to hiatuses (Over, 1992). The Kaskaskia sequence is broken up into Devonian and Carboniferous tectonic cycles that are bounded by tectonic stability during D–C boundary time (Sloss, 1963). The Woodford Shale represents a North American marine, black shale that has a robust conodont fossil record through the D–C boundary, from the *Siphonodela praesulcata* to *Siphonodela duplicata* assemblages, with areas of continuous sedimentation in the Arbuckle mountains (Over, 1992). Studying this area provides another opportunity to help confine the timing of the events through the D–C boundary interval.

2.5. New Albany Shale

The New Albany Shale (Fig. 3) represents a contemporaneous black shale, crossing the D–C boundary, that can serve as a case study outside the south-central Oklahoma area. Figure 3 presents the stratigraphy for the New Albany Shale, which covers a region from western Kentucky to southeastern Illinois, and is one of many black shales in the United States that traverses the D–C boundary (Hasenmueller, 1993; Strapoc et al., 2010). Many of these shales are believed to have been deposited as a result of epicontinental sea fluctuations (Johnson et al., 1985). The New Albany Shale was deposited from a deep-water basin within a stratified water column (Hasenmueller, 1993)
<table>
<thead>
<tr>
<th>Chronostratigraphic Units</th>
<th>Rock Units</th>
<th>Lithology</th>
<th>Thickness Ranges (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>New Providence Shale</td>
<td>Brownish-black shale</td>
<td>27 to 76</td>
</tr>
<tr>
<td>N. Amer.</td>
<td>Rockford Limestone</td>
<td>Greenish-gray shale</td>
<td>0.6 to 6.7</td>
</tr>
<tr>
<td></td>
<td>Ellsworth Member</td>
<td>Gray to dark-gray shale</td>
<td>0 to 25</td>
</tr>
<tr>
<td>Carboniferous</td>
<td>Clegg Creek Member</td>
<td>Pyrite</td>
<td>22 to 49</td>
</tr>
<tr>
<td>Mississippian</td>
<td>Camp Run Member</td>
<td>Spore</td>
<td></td>
</tr>
<tr>
<td>Tournaisian</td>
<td>Morgan Trail Member</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinderhookian</td>
<td>Selmier Member</td>
<td></td>
<td>6 to 61</td>
</tr>
<tr>
<td>New Albany Shale</td>
<td>Blocher Member</td>
<td></td>
<td>2 to 24</td>
</tr>
<tr>
<td>Devonian</td>
<td>North Vernon Limestone</td>
<td></td>
<td>0 to 37</td>
</tr>
</tbody>
</table>

Fig. 3. Stratigraphic Column for the New Albany Shale in the Illinois Basin. (Adapted from Strapoc et al., 2010).
A core drilled through the New Albany Shale, the Johnson County core (file #670, index #291 located at Section 10, 11N, 4E), was made available to this study for sampling by the Indiana Geological Survey for sampling and analysis. The New Albany Shale lies above the North Vernon Limestone and below the Rockford Limestone (Fig. 3). The D–C boundary lies within the Clegg Creek and Ellsworth members of the New Albany Shale (Strapoc et al., 2010). Due to the recent changes in the conodont biostratigraphy, the Clegg Creek member now falls within the kockeli zone, and is estimated to terminate at the D–C boundary, with the Ellsworth member above occurring within the sulcata zone (Sandberg et al., 1994; Kaiser et al., 2009). This core was sampled because it was believed that time-series analysis of these samples would provide valuable data for comparison of a contemporaneous succession deposited within a similar depositional environment but from a different region. In addition, data from the core would support ongoing work studying the conodont and brachiopod biostratigraphic successions in the Illinois basin across the D–C boundary (Jed Day, personal communication, 2013).

2.6. Time-Series Analysis

An integral part of cyclostratigraphic evaluation is performing a time-series analysis on the signal provided by geophysical proxies. Three such analytical methods are used here including the periodogram, the multi-taper method (MTM), and wavelet analysis. For all three statistical methods, the assumption was made that a uniform change in vertical sediment distance is equal to a uniform change in time. The less this assumption holds the more noise that will be present in the data (Ellwood et al., 2011). One of the classic spectral estimation methods is the periodogram, but a major problem facing this method is that variance at a particular frequency does not decrease as sample size increases (Ghil et al., 2002). To mitigate this problem, a data-set window can be used, such as the Hanning window, that provides a good balance between
spectral resolution and spectral leakage (Mann and Lees, 1996; Ghil et al., 2002). Even when such a window is employed, the periodogram is not the most accurate spectral estimation tool, but it does provide a useful initial benchmark. MTM analysis is used here to evaluate statistically significant peaks beyond the 95% confidence level. MTM offers a superior variance, versus resolution trade-off, compared to conventional periodogram smoothing, and it has been successfully employed in a variety of geophysical signal analyses (Ghil et al., 2002). MTM analysis can also be extended to analyze coherence between two different time-series, thus provides a powerful second line of statistical analysis to bolster initial results from the periodogram method (Ghil et al., 2002). It is important to note that these methods can register several false positives because many factors can contribute to the $\chi$ signature (Vaughan et al., 2011). When outcrop observations are combined with adherence to the expected ratios of Milankovitch cyclicity, these problems can be reduced (Ellwood et al., 2012).

The final statistical method used here is wavelet analysis. One limitation of traditional spectral analysis techniques is that they treat frequency components of a signal using the assumption that these are consistent through time. Wavelets offer the advantage of analyzing a signal and breaking it down through the use of a wavelet function, allowing tracking of changing periodicities through time. As such they have been employed in a wide range of fields, including cyclostratigraphic studies (Torrence and Compo, 1998; Grinsted et al., 2004; de Vleeschouwer et al., 2012). There are two different types of wavelet analyses: (1) continuous wavelet transform (CWT), and (2) discreet wavelet transform (DWT). DWT is a more compact representation of the data, while CWT is much better in extracting components from signals that have a large signal to noise ratio (Grinsted et al., 2004). Because of this, CWT is most appropriately used when analyzing cyclostratigraphic data. Wavelet analysis can be used to compare two different
time-series, as can MTM. Cross Wavelet Transforms (XWT) can be used to compare zones of shared high statistical significance between two time-series, while wavelet coherence (COH) is a measure of how in-sync the two time series are with respect to one another (Grinsted et al., 2004). The combination of these statistical techniques and their respective coherence comparisons provides a robust analysis of any potential cyclicity present in a geophysical proxy, especially when observed cyclicities in two different proxies are coherent and coeval.
3. Methods

3.1. Study Sites Chosen

Figure 4. Map showing the location of the Wapanucka shale pit and I-35 road cut. (Adapted from Over, 1992).

This study incorporates two outcrops from south-central, Oklahoma, and one core from Johnson County, Illinois. The Oklahoma outcrops include the Wapanucka shale pit, located in the eastern Arbuckle Mountains, and a road cut on interstate I-35 in the southern Arbuckle Mountains near Ardmore, OK (Fig. 4).

Figure 5 displays the measured sections for the Wapanucka shale pit and I-35 road cut (Over, 1992). These outcrops were chosen on the basis of vertical extent, the occurrence of the D–C boundary in the sections, and previous conodont zonation studies at the sites (Over, 1992). Thanks to access granted from the Indiana Geological Survey, a core from Johnson County, Indiana through the New Albany shale provides a distant outside reference point for the D–C boundary in the United States, where conodont zonation study has also been conducted.
(Sandberg et al., 1994). Recent revisions to the standard conodont zonation were taken into consideration when evaluating the outcrops and core (Corradini, 2008; Kaiser et al., 2009; Corradini et al., 2011). Approximate absolute ages for the conodont zones were derived from the 2012 Geologic Time Scale (Gradstein et al., 2012).

3.2. Field Methods

The two Oklahoma outcrops were first scraped and cleaned. Samples were then taken for χ measurement at a 5 cm sampling interval covering 13.15 m of vertical section at the Wapanucka shale quarry, and 7.7 m of vertical section for the outcrop on I-35 (Fig. 5). An RS-230 BGO portable GRS instrument, manufactured by Radiation Solutions Inc., was used at a 10
cm interval, at every other \( \chi \) sample, to collect measurements for U and Th progenies and \( ^{40} \text{K} \) at both outcrops. GRS field data were collected using a two minute counting time. The cone of acquisition for the device covers approximately 0.5–0.9 m in width, to a depth of about 0.15–0.35 m (Simicek et al., 2012). Chips were collected from The Johnson County core at 5 cm intervals, through 12.2 m and measured for \( \chi \).

![Image](image.jpg)

**Fig. 6.** Pictured is the freshly cleaned and measured Wapanucka shale pit. The trench was first cleared and cleaned, then samples were taken at 5 cm intervals of vertical section. (Photo courtesy of Sue Ellwood).
3.3. Laboratory Methods

Following the field work, samples were processed for both outcrops and the core. Physical samples were crushed and weighed to ~10 g. This provided a means of mass standardization, as $\chi$ is best calculated in reference to mass not volume, because volume is very difficult to measure with a high degree of accuracy (Ellwood et al., 2011). The randomized orientation of the small lithic fragments also helps neutralize any $\chi$ anisotropy present in the samples (Ellwood, 2007). Samples were measured in a very low-intensity, alternating magnetic field using the Williams susceptibility bridge (balanced coil system) in the Rock Magnetism Laboratory at LSU, and $\chi$ was calculated from measured values.

All material from each of the Oklahoma outcrop samples measured for $\chi$ was then recombined, stored in small plastic bags, and run through a Canberra high purity germanium radiation detection system (HPGe), with 8192 nominal energy channels (50keV to 2 MeV), to determine the activity of $^{40}$K, $^{232}$Th, and $^{238}$U. $^{40}$K has the advantage of being directly detected, while $^{232}$Th and $^{238}$U rely on the detection of daughter products. $^{212}$Pb was measured as a proxy for $^{232}$Th, and $^{214}$Bi was measured as a proxy for $^{238}$U, because both elements do not give off gamma radiation during decay, unlike their respective daughter products. Samples from the Johnson County core were not processed for GR due to custody time constraints. HPGe GR samples were counted for 1 hour and measurements were recorded in counts/gram/hour (cts/gr/hr). It has been found that having samples of at least 10 g counted for this time provides an efficient result, while still providing minimal variance (Ellwood et al., 2013).

For ease of comparison between different sections and data sets, bar-logs were constructed in a similar fashion to bar-logs derived from magnetic polarity data. Filled in bar-log
segments correspond to higher χ values, while open bar-log segments correspond to relatively lower χ values.

3.4. Statistical Methods

Time-series analysis, using the periodogram, MTM, and CWT methods, was performed using χ data for the Oklahoma outcrops and Indiana core, and also on the GR 40K data for samples from the Oklahoma outcrops. MTM coherence, CWT, and COH were performed on the χ and 40K data sets for both the Wapanucka shale pit and the I-35 road cut. Coherence testing was only enacted for the two data sets from the same Oklahoma outcrops because significant variation in the sedimentation rate at each outcrop would render the efforts ineffectual.

Periodogram analysis was conducted using MATLAB R2012a with a built in periodogram function and window construction tool box. In the case of this study the data were detrended and subjected to a Hanning window to mitigate spectral leakage and increase dynamic range (Ellwood et al., 2011). MTM analysis was conducted through use of the kSpectra software suite based on the research of Ghil et al. (2002). This software suite is available from spectraworks.com. Three tapers were used, and statistical significance was calculated using a robust, adaptive red noise model. CWT, XWT, and COH were also conducted through Matlab R2012a using the Matlab Software code provided by Grinsted et al. (2004), and available from http://noc.ac.uk/using-science/crosswavelet-wavelet-coherence. As is normally recommended, a Morlet wavelet function with a wave number of 6 was used. A cone of influence was calculated to label sections of the time-frequency space-plot that have edge effects that may lead to erroneous interpretation (de Vleeschouwer et al., 2012; Grinsted et al., 2004). Graphs for the periodogram and MTM analyses were plotted on a semi-log y-axis to best represent statistical
power without distorting higher frequency peaks that might be useful for cyclostratigraphic interpretation.
4. Results

4.1. Correlation by Geophysical Proxy

![Graph showing GRS counts for Wapanucka Total GRS and I-35 Total GRS](image)

Fig. 7. Raw total GRS counts for the Wapanucka shale pit and I-35 road cut. Note that it is difficult to precisely correlate with confidence using the field GRS data alone, given that there may be depositional breaks at the I-35 road cut.

As Figure 7 shows, raw field GRS data are insufficient to correlate among these two sections. Over (1992) has argued that conodont biozones around the Lawrence Uplift and Arbuckle Mountains indicate the deposition was not always continuous across the D–C boundary at all of his 1992 study locations. The I-35 outcrop has the problem of not having enough sample control or resolution to pinpoint exactly the boundary location from conodonts and lithology observations (Over, 1992). The D–C boundary at the I-35 road cut can at least be placed between biostratigraphic samples 85A and 6 as shown in Figure 8 (sample numbers from Over, 1992). Sample 85A has the last known occurrence of *Branmehla inornata* and *Palmatolepsis gracilis gracilis*, which disappear before the *sulcata* zone. Samples 6 and 86 contain *Siphonodella duplicata* and *Siphonodella obsoleta*, indicating the rapid appearance of the
duplicata zones. This is in contrast with the Wapanucka shale pit, which has higher confidence for the lower praesulcata through the sulcata zone. This result is based on a progression of Palmatolepis gracilis gracilis and Pseudopolygnathus marburgensis trigonicus through biostratigraphic samples 16–18; Protognathus kockeli in biostratigraphic sample 20; and possible Siphonodella sulcata in sample 25 (Over, 1992).

Fig. 8. GRS $^{40}$K counts/min for the Oklahoma outcrops. Black numbered dots correspond to the samples taken by Over (1992). The large green dot corresponds to the Ardmore Geologic Survey Benchmark. The D–C boundary has been marked by the dashed line and is based on the fossil data alone in this graph. As discussed below, the boundary has since been moved in light of the geophysical proxies.

Presented in Figures 8–10 is the approximate D–C boundary interval derived strictly from the fossil data. It is possible to correlate between the two outcrops as shown in Figure 8. This also provides a close approximation to the boundary interval. It is then possible, using abiotic proxies and the better biostratigraphic data sets from the region surrounding the Johnson County Core, to place the boundary location with greater precision within the I35 and Wapanucka successions compared to just using the fossil data or geophysical proxies alone.
Fig. 9. Combined plots of the total and $^{40}$K field GRS data collected at the Wapanucka and I35 outcrops. Figures 9a and 9b show the total combined GRS counts for Wapanucka and I-35 measured in counts per minute compared to vertical section measured. Figures 9c and 9d show the $^{40}$K cts/min for Wapanucka and I-35.
Fig. 10. Combined plots of the field Th and U GRS data collected at the Wapanucka and I35 outcrops. Figures 10a and 10b show the Th cts/min for Wapanucka and I-35. Figures 10c and 10d show the Th cts/min for Wapanucka and I-35.
It is clear from inspection of Figures 8–10, that the Wapanucka and I-35 data sets are not readily correlated using GRS data. This matches the scenario described by Over (1992), in that I-35 likely had periods of erosion or inconsistent deposition, in this case the region from ~4–6 m of vertical sampled section in the Wapanucka shale pit is missing from the I-35 road outcrop. The field GRS data are useful for simple correlation, but the cone of acquisition is far too large for it to be useful for cyclostratigraphic interpretation (Simicek et al., 2012). Whereas the $\chi$ and HPGe GR are measured solely on individual samples, the hand-held gamma ray probe has a large smoothing effect on the data, thereby destroying any chance for useful spectral resolution (Ellwood et al., 2013).

4.2. Time-Series Analysis

Time-series analysis was calibrated for Milankovitch band-drift through time (Berger et al., 1992). The 2012 Geologic Time Scale (Gradstein et al., 2012) gives an age of ~358.9 Ma for the D–C boundary. Appendix A details the process for calculating the duration of Milankovitch bands at a given time in the Phanerozoic. From these calculations it is possible to keep the ratios of each cycle consistent to avoid subjectivity. Having at least 3 spectral peaks from the time-series analysis identified with major power in the data set is a good indication that actual cycles instead of random noise are being recorded by the data.

4.3. Wapanucka Shale Pit

The Wapanucka shale pit produced the strongest overall cyclostratigraphic results. This was to be expected given the continuous sedimentation rate and the well constrained fossil data. Figure 11 gives the results for $\chi$ data, while Figure 12 presents the GR $^{40}$K results, and Figure 13 shows the combined wavelet results for both geophysical proxies. When all peaks were held to
Milankovitch band spacing, every peak from the ~405 kyr E2 to the 17 kyr P1 cycle, corresponds with a spike in the spectral power (Fig. 11a). Results were similar for the periodogram for GR $^{40}$K data (Fig 12a). More reliable testing is derived by comparing Figure 11a to Figure 11b, and Figure 12a to Figure 12b. The E2, O1 (32.8 kyr), and P2 (20.1 kyr) spectral peaks reach statistical significance testing levels, with the E2 and P2 reaching the 95% confidence level (Fig. 11b). Figure 12b showed possible statistical significance only for the P2 and P1 bands, with a possible offset of the E2. Coherence between the $\chi$ and GR $^{40}$K (Fig. 11c and 12c) reached above the 95% confidence level on all peaks except for the P1 band. Figure 13 shows two strong trends between 0.5–1 cycles/m and 1–2 cycles/m. The band at ~1–2 cycles/m is interpreted to correspond to the E2 band. Figures 13c and 13d provide strong evidence that both the $\chi$ and GR proxies are related to each other, because they exhibit strong shared statistical power and shared coherence. In particular, the arrows in Fig. 13c and 13d represent whether the two data sets are in phase or out of phase. An arrow pointing to the right represents a completely in-phase pair, while an arrow pointing to the left represents an out-of-phase angle of 180 degrees. There is strong correspondence between the phase angles for both XWT and wavelet coherence. Overall spectral peaks are present at frequencies of 1.34, 3.33, 4.11, 6.7, and 7.94 cycles/m, and correspond to the E1, O2, O1, P2, and P1 peaks, respectively, among the various statistical plots in Figure 11–13.
Fig. 11. Wapanucka shale pit-time series for $\chi$. 

Wapanucka $\chi$ Periodogram

Wapanucka $\chi$ MTM

Wapanucka $\chi$-40K Coherence
Fig. 12. Wapanucka shale pit time series for GR $^{40}$K.
Fig. 13. Wavelet analysis for both the $\chi$ and $^{40}$K data sets for Wapanucka. Figure 14a is the CWT for $\chi$, Figure 14b is the CWT for $^{40}$K, Figure 14c is the XWT between the two graphs to the left, and Figure 14d is the wavelet coherence.

4.4. I-35 Road Cut

The I-35 Road Cut was not as prolific in generating significant peaks as the Wapanucka shale pit, given the concerns about possible breaks in sedimentation and less quality conodont data. Never the less, there were still enough matches for good confidence in the assignment of Milankovitch bands. Figure 14 gives the results for $\chi$ data, while Figure 15 illustrates the $^{40}$K results, and Figure 16 shows the combined wavelet results for both the $\chi$ and $^{40}$K geophysical proxies. When all peaks were held to Milankovitch band spacing, every peak corresponds with a spike in the spectral power (Fig. 14a), similar to the Wapanucka shale pit. Results were similar for the periodogram for $^{40}$K (Fig 15a), though most peaks were far more subdued compared with Fig. 14a. More reliable testing is derived from comparing Figure 14a to 14b, and Figure 15a to 15b. The O2, P1, and possibly O2 spectral peaks reach statistical significance testing levels, with
the O2 and P1 bands reaching the 95% confidence interval for Figure 14b. Figure 15b showed statistical significance for these three bands as well, with the P2 and P1 bands reaching the 95% confidence level. Coherence between the $\chi$ and $^{40}$K in Figures 14c and 15c reached above the 95% confidence level for the E2, O2, O1, and P1 peaks. While Figure 16 shows far less well-defined trends, compared to the Wapanucka shale pit, there is still a possible trend corresponding to the E2 band between 2–3 cycles/m. Figures 16c and 16d show a weaker relationship between both proxies. Not only is there lower statistical power compared the Wapanucka shale pit, but the phase angles are largely out of step. This may be linked to the suspected unconformities in sedimentation in the section. It is also possible that weathering from being exposed for a long time in the road cut has altered the samples, introducing more noise. Overall, spectral peaks are present at 3.23, 6.52, and 7.71 cycles/m, and correspond to the O2, P2, and P1 peaks, respectively, among the various statistical plots (Figs. 14–16).

4.5. Johnson County Core

The Johnson County core provides a unique opportunity for an analog outside the southern Oklahoma area. Because $^{40}$K data were not measured, the time-series is not as extensive for the core. The Johnson County core had a similar range of matching cyclicities as did the Wapanucka section (Fig. 17). Peaks with power correspond to the E2, O1, P2, and P1 bands. When all peaks were held to Milankovitch band spacing, every peak, except for the E1 and O2 bands, corresponds with a spike in spectral power. More reliable testing is derived from comparing Figures 17a and 17b. The E2, O1, P2, and P1 spectral peak frequencies reach above the 95% statistical significance level. Overall spectral peaks are present at 0.374, 4.62, 7.54, and 8.92 cycles/m, and correspond to the E2, O1, P2, and P1 bands, respectively.
Fig. 14. I-35 time-series for $\chi$. 
Fig. 15. I-35 time-series for GR $^{40}$K.
Fig. 16. Wavelet analysis for both the $\chi$ and $^{40}$K data sets for I-35. Fig. 17a is the CWT for $\chi$. Fig. 17b is the CWT for $^{40}$K. Fig 17c is the XWT between the two graphs to the left, and Fig 17d is the wavelet coherence.
Figure 17: Johnson County Core time-series for $\chi$. 
5. Discussion

5.1. Correlation Between the Oklahoma Outcrops

Over (1992) made a clear point of not trying to assign absolute age determinations to conodont zonations. This makes sense when only intermittent conodont data are available, and with many missing fauna in some of the sampled successions, as well as lack of some key taxa (Corradini et al., 2011; Kaiser and Corradini, 2011). In instances like the I-35 section, where there is no clear boundary point, it can cause problems in interpretation. Incorporating abiotic geophysical proxies allows for independent evaluation of the chronostratigraphy of outcrops. The combined field GRS and conodont biozones show that the D–C boundary can be placed within a meter or two because of the good biostratigraphic and proxy framework provided by the Wapanucka section. This is bolstered when comparing the bar-log correlation.

χ measurements for the Oklahoma outcrops and the Johnson County core are presented in Fig. 18. The raw χ data are plotted along with smoothing splines representing the ~405 kyr (E2) and ~100 kyr (E1) Milankovitch bands as determined by time-series analysis.

Fig. 18. Raw χ data are presented with the black dashed line, accompanied by smoothing splines representing ~405 kyr E2 cycllicity in blue. Cyclicities were derived from the time-series analysis. The D–C boundary has been marked in red. Bar logs to the side of each graph represent the E2 half cycle, with periods of higher χ values corresponding to more transgressive times filled in.
Fossil data constraining the D–C boundary and placement of the sulcata and kockeli conodont zones allows for approximate estimation of outcrop age. An age of ~1.7 myr is estimated for the Wapanucka shale pit in Figure 18a, ~1.0 myr for the I-35 outcrop in Figure 18b, and ~1.8 myr for the Johnson County core in Figure 18c. There are ~8–9 E2 half cycles in the Wapanucka shale pit and ~8–10 for the Johnson County Core, whereas there are only ~4–6 E2 half cycles present in the limited vertical section of the I-35 road cut.

In the same way that data were plotted for the raw χ data, raw GR $^{40}$K measurements for the Oklahoma outcrops are presented in the Figure 19. Figure 19a shows ~8–10 E2 half cycles for the $^{40}$K, largely agreeing with the 8–9 half cycles in the χ data in Figure 18a. Figure 19b has ~4–5 half cycles present, largely agreeing with the 4–6 half cycles shown in Figure 18b. Clearly there are some variations between the two different geophysical proxies, but the overall cyclicity patterns appear to be generally similar.

*Fig. 19.* Raw GR data for K counts/gram/hour are presented (black dashed line), accompanied by smoothing splines representing ~405 kyr E2 cyclicity in blue. Cyclicities were derived from the time-series analysis. The D–C boundary has been marked in red. Bar logs to the side of each graph represent the E2 half cycle, with periods of higher $^{40}$K counts corresponding to more transgressive times filled in.
5.2. GSSP Candidacy

It has long been acknowledged that the D–C GSSP needs to be replaced, and the search continues through the Devonian–Carboniferous Boundary Working group from the International Commission on Stratigraphy (Brand et al., 2004). Initially, the Wapanucka section seemed like it might be a possible alternative, with a full conodont zonation and no known major unconformities. However, at the present time the Wapanucka shale pit lacks other fossil groups preferred for GSSPs. A good outcrop with GSSP potential needs more than just one lineage of fossils, rather, it should have multiple lineages along with other data sets, such as isotopes. Currently for the Wapanucka shale pit only conodonts have been identified. Given that the Woodford shale proves difficult for preserving additional fauna, it might be possible to bolster the candidacy of the site with analysis of palynology, as palynological zonation for the entire Famennian has been successfully correlated to the standard conodont zonation (Maziane et al., 1999).

5.3. Findings from Cyclostratigraphy

A robust cyclostratigraphic record has been preserved in the Oklahoma outcrops and the Johnson County core. The combination of both the MTM and wavelets methods was found to have a synergistic effect. This has been the case in other studies where wavelets were successfully used to track modulations in the actual imprint left from orbital forcing (de Vleeschouwer et al., 2012). With the tradeoff of higher individual component resolution, MTM is always in danger of picking up aliasing and attenuation. In this study, the wavelet coherence was a powerful indicator that sedimentary processes had been disrupted at I-35 compared to the Wapanucka section, in a manner that was largely invisible to the MTM. The XWT and wavelet
coherence showed great synchronicity between the $^{40}$K and the $\chi$ for the Wapanucka shale pit. When comparing that with the XWT and wavelet coherence of I-35, there is hardly any coherence. Having unconformities in the record of preservation or weathering could have altered the samples at I-35, contributing to increasing the background noise level (Ellwood et al., 2011). This is directly observed in both the MTM and wavelet analysis. Overall, as Figures 20 and 21 display, there is great similarity between the bar-logs constructed from the $\chi$ and $^{40}$K data.

Differences can be attributed to the particular sensitivities of the respective techniques, and the differences associated with the proxies. The bar-log comparison technique can be used as a powerful correlation and characterization tool as future work on the D–C boundary in North America unfolds, including implications for the continued study of the Hangenberg Event.

**Fig. 20.** This comparison of the Wapanucka $\chi$ and $^{40}$K shows the overall similarity in the smoothed time-series.
Fig. 21. This comparison of the I-35 $\chi$ and $^{40}$K shows the overall similarity in the smoothed time-series.
6. Conclusions

The D–C boundary in south-central Oklahoma has proven to be a challenging boundary for stratigraphic interpretation, given the limited types of fauna preserved, and the common breaks in sedimentation in many sections. The prevailing correlation tool to date has been conodont zonation and field GRS. The combined use of $\chi$ and $^{40}$K allows for a deeper layer of stratigraphic comparison. With the combined statistical techniques of the periodogram, MTM, and wavelet analysis it is possible to determine the cyclostratigraphic signal represented by these geophysical proxies.

The Wapanucka shale pit proved to be a high-quality cyclostratigraphic record that can serve as a benchmark to compare to other sections in the south-central Oklahoma area. The Johnson County Core proved to be a valuable contemporaneous analog outside the Oklahoma region. In all 3 sections, at least 3 Milankovitch bands were found to fit the interpreted time-series data, and both geophysical proxies, $\chi$ and $^{40}$K, were found to be in agreement on the cyclicity. The E2 band was found to be sufficiently powerful in the Wapanucka shale pit and the Johnson County Core to establish reference bar-logs at the E2 half cycle (~200 kyr) for the D–C interval. Though not as statistically significant in the I-35 section, it was still found that a useable bar-log could be constructed for this succession. Lack of low-frequency power in the I-35 section can be attributed to unconformities in sedimentation or weathering effects. Future work studying faunal assemblages can be compared with the cyclostratigraphic framework provided here to allow greater precision in interpretation.
7. References


Kaiser, S. I., Steuber, T., Becker, R. T., and Rasser, M. W., 2006b, The Devonian/Carboniferous boundary stratotype section (La Serre E’, Montagne Noire) revisited: United Kingdom, Publisher unknown, United Kingdom, p. 43.


Appendix

Calculations of the changes in Milankovitch cycle duration throughout geologic history are given in Berger et al. (1992). Polynomial curves can be fit for specific obliquity (O2 and O1) and precessional values (P2 and P1) calculated throughout the Phanerozoic. E2 and E1 are assumed to maintain 405,000 and 100,000 year cyclicity with minimal change throughout the Phanerozoic. The following equations are used for the remaining Milankovitch peaks: O2 \( y = -0.006x^2 - 35.379x + 53938.462 \); O1 \( y = -0.007x^2 - 20.270x + 40956.643 \); P2 \( y = -0.005x^2 - 6.209x + 22964.336 \); and P1 \( y = -0.003x^2 - 4.581x + 19006.294 \) with \( r^2 > 0.97 \). The following cyclicities are calculated from the 358.5 Ma age (Gradstein et al., 2012) given for the outcrops used in this study: O2 = 40.4 kyr, O1 = 32.8 kyr, P2 = 20.1 kyr; and P1 = 17.0 kyr.
Vita

Ryan Ellis was born in Woodbridge, Virginia. Shortly thereafter he moved to Parkersburg, West Virginia and completed high school there in 2007. Ever since a dinosaur display was featured in the local mall when he was very young, Ryan has been fascinated with the Earth’s past. He pursued a degree in geology at Marietta College, including joining a dinosaur dig in Utah. After completing his B.S in Geology in 2011, he came to LSU to further his geology training.