ANALYSIS OF SMALL-SCALE CYCLICITY IN THE WILLIAMSPORT SANDSTONE MEMBER AND THE LOWER WILLS CREEK FORMATION IN PENNSYLVANIA AND MARYLAND

A Thesis

Submitted to

The Temple University Graduate Board

In Partial Fulfillment

of the Requirements for the Degree

MASTER OF ARTS

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by

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August, 1999

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ABSTRACT

Allocyclic analysis of a 25-meter interval of Upper Silurian peritidal siliciclastic and carbonate facies of Maryland and central Pennsylvania reveals a four-tiered hierarchic cyclic fabric correlative over 125 kilometers. The structure of this correlative framework in the Williamsport Member of the Bloomsburg Formation and the Lower Wills Creek Formation is consistent with predictions of the orbital forcing model, suggesting that precession was the fundamental cycle-producing mechanism and that eccentricity modulated precession at three scales. Fundamental meter-scale cyclicity of the study interval was produced by rapid sea-level changes caused by the 20 thousand-year precessional cycle of the Earth's orbit. These sixth-order cycles are distinguished by disjunct facies changes at non-depositional surfaces produced by rapid sea-level rises; cycles typically contain sandstone and/or carbonate at the base, and shale at the top. Sixth-order cycles are bundled by the short-eccentricity (100 thousand-year) cycle to produce asymmetric fifth-order sequences, averaging 3 meters in thickness. Eccentricity modulation also produced fourth-order (400 thousand-year) and third-order (2 million-year) sequences consisting of bundles of fifth-order and fourth-order sequences, respectively.

The study interval consists of two, 400 thousand-year, fourth-order sequences deposited during a period of relatively constant subsidence in shallow marine and non-marine environments. Lateral facies change within correlative cycles indicates that the southern localities were consistently more marine than the central Pennsylvania locality during the 800 thousand-years of depositional history. While subsidence and

paleogeographic position contributed to the thickness of the interval and the nature of the facies, orbitally forced eustatic sea-level fluctuations were responsible for the hierarchic allocyclic framework.

ACKNOWLEDGMENTS

Thank you, Pete for your patience and encouragement-your help and guidance were beyond compare. Also, thank you, Andy and Dr. Grandstaff for keeping me honest. Without your help, this thesis would not be the same. Thanks to Jon Inners of the Pennsylvania Geological Survey and the Pennsylvania Department of Conservation and Natural Resources for generous funding of the fieldwork. Thanks to Anne for your invaluable computer experience, and to Dave, Andy, and Steve for your help and friendship in the field. Finally, thanks to Shelah Burgess and Roger Cuttita for your support.

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CHAPTER 1

INTRODUCTION

Purpose and Scope

The purpose of this study is to analyze the cyclicity of Appalachian Basin Upper Silurian strata including the uppermost segment of the Williamsport Sandstone Member of the Bloomsburg Formation and the lower section of the Wills Creek Formation using the Milankovitch model of orbital forcing in conjunction with the Punctuated Aggradational Cycle (PAC) Hypothesis (Goodwin and Anderson, 1985). The PAC Hypothesis maintains that allogenic processes control stratigraphic accumulation, producing correlative shallowing-upward packages (PACs) separated by non-depositional surfaces produced by rapid relative sea-level rises. When the PAC Hypothesis is employed in conjunction with the theory of orbital forcing as the allogenic mechanism, a nested hierarchy of bundled PACs as larger-scale sequences is predicted (Goodwin and Anderson, 1997). The objective of this thesis is to compare the cyclic patterns of the Williamsport Sandstone and the Lower Wills Creek Formation, with the predictions of this model.

The interval (the Williamsport Sandstone and Lower Wills Creek Formation) was chosen because of its stratigraphic significance in the Silurian section. This dominantly siliciclastic interval, which marks the beginning of the Salina Supersequence (Figure 1), is part of a significant facies change from the carbonate-rich McKenzie Formation of the Mifflintown Supersequence below. Both the Salina Supersequence and the Mifflintown Supersequence below are initiated by siliciclastic deposits and terminated by carbonates.

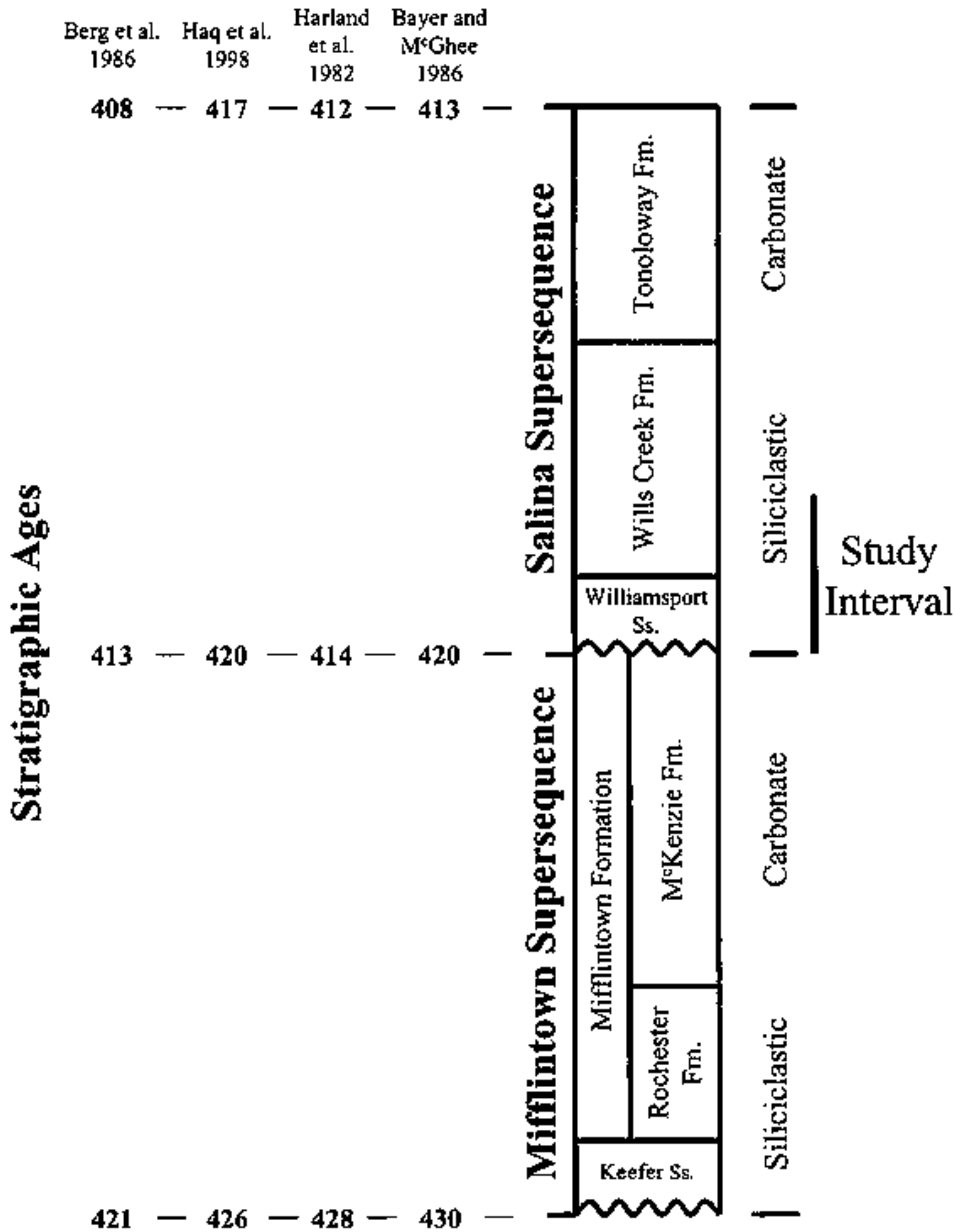


Figure 1. Traditional Silurian Stratigraphy and Allogenic Supersequences. Each supersequence (approximately 10 my duration) begins with a thin sandstone unit, contains a medial shale sequence and is capped by a thick carbonate interval. Stratigraphic age markers for significant horizons are included (from Bayer and McGhee, 1986). All stratigraphic ages are millions of years ago. Thickness not drawn to scale.

In both sequences, the initial siliciclastic deposits are iron-rich. Positioning these stratigraphically significant deposits in a cyclic hierarchy and describing their deposition in terms of allogenic processes are objectives of this study.

The Williamsport Sandstone is composed dominantly of subtidal iron-rich sandstone beds interlayered with non-marine red shales. The Lower Wills Creek Formation is also composed of interbedded sandstones and nearshore (green) to onshore (red) shales. The abrupt change in facies from carbonates in the Mifflintown Supersequence to clastics in the Salina Supersequence must be explained to understand large-scale depositional mechanisms at work during the Silurian Period. The Williamsport Sandstone, previously studied by Shelton (1995) was included in this study because of the close relationship between it and the Lower Wills Creek Formation. Shelton (1995) described the internal cyclic fabric of the Williamsport Sandstone but did not resolve the larger-scale cyclic relationship with the Wills Creek Formation.

The geographic scope of this study is limited to three localities: Mount Union, Pennsylvania; Cedar Cliff, Maryland; and Pinto, Maryland (Appendices A1, A2, and A3). Mount Union is located 125 kilometers (km) north-northeast of the Maryland localities, which are separated by 5.25 km (Figure 2). The sections were examined to describe and interpret lithologies, record the observed cyclicity, and establish detailed correlations among the localities to offer a genetic explanation of the potentially correlative cyclic fabric. Preliminary work in a limited part of this interval suggests that a four-tiered allocyclic hierarchy controlled by orbital parameters characterizes the Williamsport-Lower Wills Creek interval (Shelton, 1995; Zeliznak et al., 1997). The intention of this

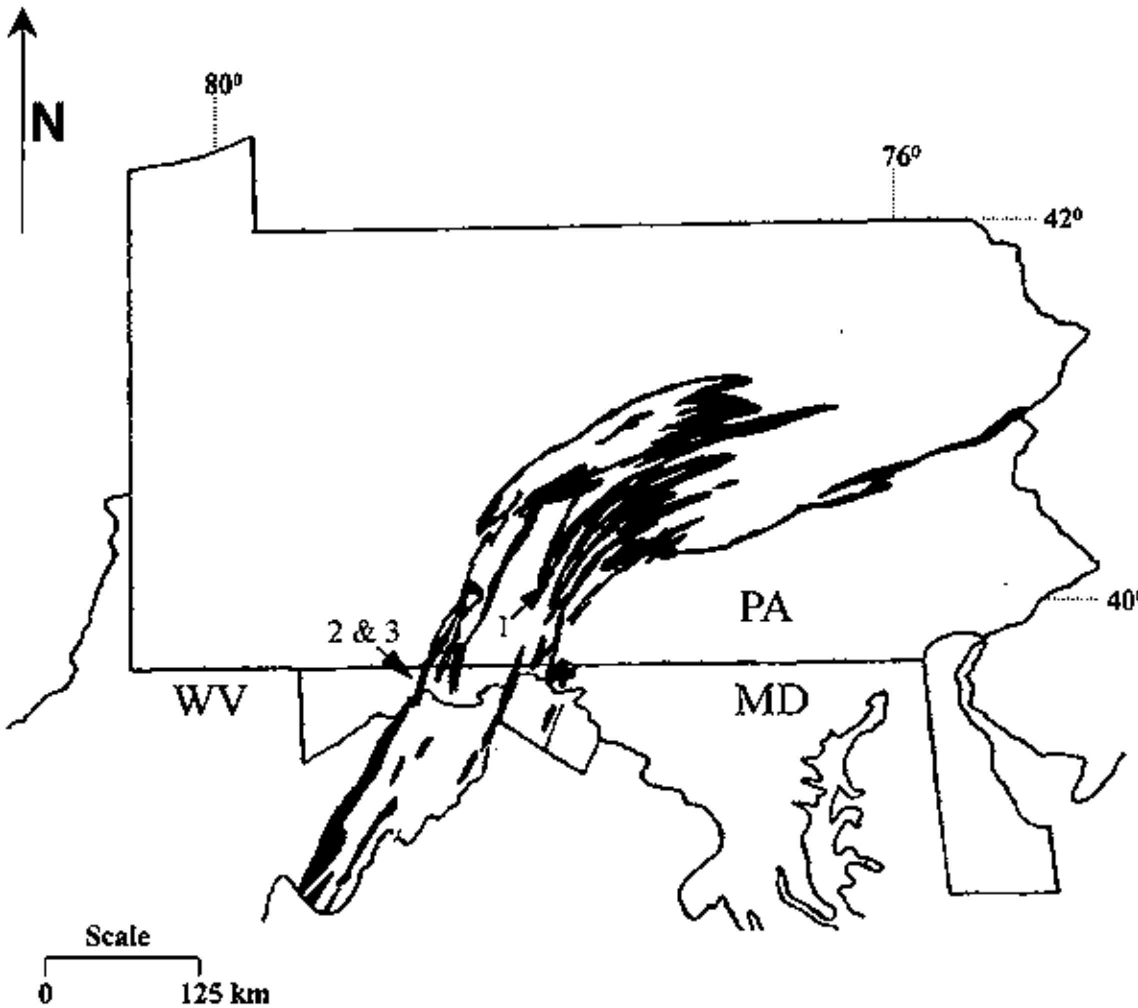


Figure 2. Study Localities. Silurian outcrop of Pennsylvania, Maryland, and West Virginia. Outcrops examined in this study are designated by arrows. Mount Union (1) is 125 km NNE of Pinto (2) and Cedar Cliff (3), which are separated by 5.25 km. Detailed locations are in Appendix A.

study, then, is to expand the examined stratigraphic interval and fully document the patterns of cyclicity within the Williamsport Sandstone and Lower Wills Creek Formation. Furthermore, the study will attempt to explain the relationship between the Williamsport Sandstone and the Lower Wills Creek Formation in the context of larger-scale cyclicity.

Historical Perspective

Since the late seventies, there has been a growing movement to examine sections using episodic models rather than gradualistic models of stratigraphic accumulation. This paradigm shift began with differing perspectives generated by three different types of allostratigraphers. Seismic stratigraphers in the oil industry, working at a large scale, mainly in continental margin sedimentary sections, used seismic data augmented by well-log data and outcrop evidence to develop a theory that long-term fluctuations in sea-level produced globally correlative unconformity-bounded, large-scale cyclic units called depositional sequences (Vail et al., 1977). The depositional sequence was defined as a stratigraphic unit composed of relatively conformable successions of genetically related strata and bounded at the top and base by unconformities or their correlative conformities (Mitchum et al., 1977).

At the same time, investigations of Pleistocene and Holocene strata revealed oxygen isotope cyclicity whose periods were similar to those of orbital cycles, specifically precession and eccentricity (e.g., Mesollela et al., 1969; Imbrie and Imbrie, 1980; Berger, 1988, 1989; Shackleton et al., 1990). These investigators used geochemical and geophysical data, such as $^{18}O/^{16}O$ ratios, ^{14}C dating, and magnetostratigraphy to determine the composition and age of each bed to see if these changes could be attributed to any allocyclic mechanism (Mesollela et al., 1969). Similarly, outcrop stratigraphers were interpreting pervasive small-scale cyclicity as a fundamental allogenic stratigraphic fabric useful in stratigraphic analysis (e.g., Goodwin and Anderson, 1985; Anderson et al., 1984; Goldhammer et al., 1987, 1990, Mitchum and Van Wagoner, 1991; Goldhammer et al., 1994; Goodman and Brett, 1994).

Recently, these efforts at establishing episodic accumulation as an alternative to stratigraphic gradualism have produced a variety of approaches to the analysis of a hierarchic stratigraphic record (e.g., Mitchum and Van Wagoner, 1991; Goldhammer et al., 1994; Strasser, 1994; and Goodwin and Anderson, 1997). While significantly different in concepts of hierarchy and in methods of analysis, these efforts have all attributed a hierarchic stratigraphic fabric to allogenic processes affecting eustatic sea-level fluctuations, specifically the processes of precession and eccentricity (Table 1). This study incorporates the approach of Goodwin and Anderson (1997), who developed a process-determined hierarchy in which each rank is associated with a specific periodic process.

The Wills Creek Formation was named by G.W. Stose (1912), from exposures along the Wills Creek in Cumberland, Maryland. C.K. Swartz (1923) and F.M. Swartz (1934) measured and correlated the Salina Group and Wills Creek Formation at localities in Pennsylvania and Maryland. D.M. Hoskins (1961) correlated the Williamsport Sandstone with the Bloomsburg Formation of Eastern Pennsylvania. These interpretations were then used by L.V. Rickard (1962) to correlate the Salina Group

Sequence Stratigraphy Mitchum and Van Wagoner, 1991	**Recurrence Interval** Goodman and Brett, 1994	**Compartments-of-Time** Goldhammer et al., 1994	**Process-Determined** Goodwin and Anderson, 1997
———	First-order >50 my	First-order >100 my	———
Supersequence 9 to 10 my	Second-order 5 to 50 my	Second-order 10 to 100 my	Second-order 10 my (tectono-eustasy)
Sequence 1 to 2 my	Third-order 3 to 5 my	Third-order 1 to 10 my	Third-order 2 my (eccentricity ?)
Parasequence Set 100 to 200 ky	Fourth-order 1 to 1.5 my	Fourth-order 0.1 to 1 my	Fourth-order 400 ky (long eccentricity)
Parasequence 10 to 20 ky	Fifth-order 400 to 500 ky	Fifth-order 10 to 100 ky	Fifth-order 100 ky (short eccentricity)
———	Sixth-order 50 to 100 ky	———	Sixth-order 20 ky (precession)
———	Seventh-order Rhythms 26 ky	———	———

Table 1. Models of Hierarchy. Types of hierarchies employed to study allocyclicity. Only the method used by Goodwin and Anderson (1997) has components directly related to periodic orbital processes. Periods of cyclicity determined in millions of years (my) and thousands of years (ky).

sections of Pennsylvania and Maryland with the Vernon Formation of New York. The cyclic nature of the Wills Creek Formation was examined by J.E. Lacey (1960) and T.J. Tourek (1970), as part of their master's and doctoral theses, respectively. While examining the interval in Pennsylvania and Maryland for faunal content and correlations, both authors gave possible allogenic and autogenic mechanisms for the observed cyclicity but neither could attribute the cyclicity to a specific mechanism.

The present study is part of an ongoing project at Temple University to tie this formation and most of the Silurian section in Pennsylvania and Maryland to specific allocyclic processes. Previous undergraduate research by Mauriello and Ketterer (1993) and Master's thesis research by Mauriello (1994), Shelton (1995), and Brown (1999) have been helpful in defining small-scale cyclicity for the Williamsport-Wills Creek interval. This study builds on these studies by placing this sixth- and fifth-order cyclicity in a fourth- and third-order hierarchic allocyclic structure.

Methods

This study encompasses the uppermost 5 meters of the Williamsport Sandstone and the first 20 meters of the Lower Wills Creek Formation at three localities (Figure 1 and Appendices A1, A2, and A3). The lower part of the interval includes 5 meters of sandstone and shale mapped as M^{c}Kenzie Formation by C.K. Swartz (1923), but included as Williamsport Sandstone in this study because of lithologic similarity. All relevant lithofacies, biofacies, textures, sedimentary structures, and patterns of facies change were recorded at each of the three outcrops.

Sixth-order cycle boundaries were defined by field interpretation of disjunct facies change across a stratigraphic surface. Differences in degree of facies change were used to discriminate ranks in the hierarchic fabric. For example, fifth-order sequences were delineated by patterns of sixth-order facies changes in which a fifth-order boundary was drawn at a major facies change marking the end of a progressive shallowing sequence of sixth-order cycles. Fourth-order sequences were defined by patterns of facies change among fifth-order sequences.

Representative thin sections were generated from oriented hand samples collected from the bases of the lowermost and uppermost sixth-order cycles of each fifth-order sequence. These thin sections were examined for faunal, textural, compositional, and sedimentary structural features to determine the environment of deposition, including relative water depth and current activity (Table 2). This information was used to generate water depth curves for each section.

Correlations were made between the sections by comparing patterns of facies change, as expressed by water depth curves, linked to known marker beds (e.g., a correlative iron-rich sandstone at the base of the Wills Creek Formation). Analysis of lateral facies change within each sequence permitted fine-scale paleogeographic and paleoenvironmental interpretations of the Silurian Appalachian Foreland Basin.

All figures included in this study were scanned into Adobe PhotoShop LE® at a resolution of 300 DPI (dots per inch) using 24 bit color. Modifications were performed using Microsoft Power Point® and Corel Draw©. Scanning hand drawn columns was

	Facies	Characteristics	Paleoenvironmental Interpretation
Terrigenous Clastics	Red Sandstone	Red, moderately- to poorly-sorted (0.1 to .01 mm), subangular to subrounded, clay, silt and very fine quartz sand, hematitic, no fossils	intertidal (?)
	Hematitic Sandstone	Red, poorly-sorted, angular, silt to very fine quartz sand, hematitic, 0.5 to 1 mm mica grains, no fossils	restricted subtidal
	Quartz Sandstone	Gray-brown, green, or gray, poorly- to well-sorted, subangular to subrounded, very fine quartz sand and calcarenite, sometimes wavy-bedded, bioturbated, or ostracod-rich	restricted subtidal
	Finely-Bedded Gray Sandstone	Gray, poorly sorted, subrounded, very fine quartz sand, parallel lamination, ripple cross stratification	intertidal sand flats
	Red Shale	Red, clayey, silty, fissile, hematitic, no fossils	supratidal to non-marine
	Green Shale	Green, clayey, silty, reduced iron, no fossils	intertidal to supratidal
	Gray Shale	Gray, clayey, silty, no fossils	shallow subtidal to intertidal
	Red Siltstone	Red, silty, fissile, hematitic, no fossils	supratidal to non-marine
	Siltstone	Green or Gray, silty, clayey, fissile, no fossils	subtidal to intertidal
Carbonate	Calcisiltite	Very fine calcarenite, poorly sorted, 0.05 mm average grain diameter	intertidal
	Calcarenite	Green or gray, poorly- to well- sorted, very fine calcarenite and silt, no fossils, sometimes wavy-bedded	subtidal to intertidal
	Ostracod-rich Calcarenite	Poorly sorted, 0.1 mm average grain diameter, ostracod-rich	restricted subtidal
	Oolitic Calcarenite	Poorly sorted, 0.1 mm average grain diameter, oolitic, pelletal, ostracod-rich	subtidal
	Thrombolites	Poorly sorted, very-fine calcisiltite, laminated, oolitic	subtidal to intertidal
	Cryptalgal Laminites	Micritic, argillaceous, mudcracked algal mats	intertidal to supratidal
	Laminated Calcarenite	Poorly-sorted calcarenite, 0.1 mm average grain diameter, laminated	intertidal
	Dolomitic Limestone	Poorly sorted dolomitized calcarenite, 0.1 mm average grain diameter, mudcracked	intertidal to supratidal

Table 2. Characteristics and Paleoenvironmental Interpretations of Facies.

preferred to using computer generated columns to preserve observational detail and because more fine detail and variation could be included in each figure.

Objectives

In order to determine the genesis of the hierarchic cyclic structure of the Williamsport Sandstone and the Lower Wills Creek Formation, five distinct objectives must be met.

1. Describe and interpret the Williamsport Member and the Lower Wills Creek Formation as a hierarchic sequence of cycles.
2. Correlate this hierarchic structure among the three localities.
3. Compare these correlative hierarchical patterns with the predictions of the orbital forcing model.
4. Reconstruct the paleoenvironments and paleogeography of the interval.
5. Document the role of eustatic sea-level fluctuations in Silurian Foreland Basin dynamics.

Favorable comparison of correlative cyclic patterns with predictions of the orbital forcing model will support the hypothesis that orbital forcing was a control for Silurian stratigraphic accumulation. Detailed correlation within the allocyclic fabric of this interval will form the foundation for fine-scale paleoenvironmental and paleogeographical reconstructions. This study has the potential of serving as a model for analysis of other hierarchic cyclic sequences.

CHAPTER 2

ALLOCYCLIC STRATIGRAPHIC MODELS

Introduction

Over the past two decades there has been increasing recognition that the stratigraphic record is hierarchic in structure and allogenic in origin. However, approaches to describing and interpreting that hierarchic structure are varied (Table 1). For example, in sequence stratigraphy, Vail et al. (1977) and Mitchum and Van Wagoner (1991) used a four-tiered hierarchy (supersequences, sequences, parasequence sets, and parasequences) that is specifically not related to process. Each tier in this hierarchy is not well defined in time or thickness. At the small scale, outcrop stratigraphers utilized many different approaches. For example, Goodman and Brett (1994) calculated recurrence intervals for each rank in their hierarchy, ending up with a range of values for each rank, most of which had little connection to process. In a different approach, Goldhammer et al. (1987) and Goldhammer et al. (1994), working with a hierarchy defined as compartments of time (e.g., fifth-order equals 10^4-10^5 years) have had difficulty distinguishing between two high-frequency processes (e.g., precession and eccentricity) whose periodicities fall within a single rank. Goodwin and Anderson (1997) used a process-determined model that accommodates stratigraphic incompleteness by discriminating ranks on symmetry, thickness, and degree of facies change. In their model, each rank in the hierarchy is specifically linked to a periodic process (Table 1).

All of these stratigraphic models of deposition attempt to connect the stratigraphic record to Milankovitch orbital forcing using different methods and arriving at different results. In order to explain the significance of the genetic relationship to process and the differences between the models, the effects of precession, obliquity, short eccentricity, and long eccentricity must be explained in detail.

Orbital Forcing Model

The orbital forcing model is based on cyclic perturbations of the Earth's rotation and orbit around the Sun. Milutin Milankovitch (1941) developed this hypothesis by calculating insolation values for the Earth over the past 1 my, and correlating times of minimum summer insolation in the Northern Hemisphere to glacial periods. Insolation is defined as the amount of solar energy received at the surface of the Earth per unit area. Precession, obliquity, and eccentricity affect insolation, measured in Watts/m^2, at critical high latitudes on regular periodic intervals. The theory of orbital forcing is composed of four parts (Berger and Loutre, 1992):

1. The theoretical computation of the long-term variations of the Earth's orbital parameters and related geometrical insolations.
2. The design of climatic models to transfer the insolation into climate.
3. The collection of geological data and their interpretation in terms of climate.
4. The comparison of these proxy data to the simulated climatic variables.

The precession of the Earth's axis and the eccentricity of the Earth's orbit around the Sun are the primary cyclic orbital mechanisms. Variations in the orientation of the Earth's axis and in the shape of its orbit around the Sun cause variation in the distribution and intensity of insolation at the surface of the Earth. These variations will affect the accumulation of glacial ice. Maximum insolation occurs when the summer solstice coincides with perihelion of the orbit, at which times the volume of glacial ice decreases by melting. Minimum insolation occurs when the summer solstice coincides with aphelion of orbit, during which times the volume of glacial ice increases with less ice melting in relatively cool summers (Figure 3).

Precession is the migration of the Earth's axis through a cone, dependent on the combined effects of solar and lunar attraction to the equatorial bulge (Berger, 1988). While precession has a calculated value of 26 ky (DeBoer and Smith, 1994), the actual value of the Earth's precession is less owing to the counter rotation of the Earth's elliptical orbit. Actual values range from 14 ky to 28 ky (Berger, 1988), with two modes at 19 ky and 23 ky, and an average of 21.74 ky (Bassinot et al., 1994). Over the life of the Earth, there is evidence that the precessional period has lengthened as the Earth's rotation has slowed because of tidal friction (Fischer and Bottjer, 1991). As a result, in the geologic past, more precessional cycles may have been included within an eccentricity cycle.

Eccentricity is a measurement of the ellipticity of the Earth's orbit around the Sun. Change in ellipticity affects the distance of the Earth to the Sun (Figure 4). Orbital eccentricity is determined as the ratio of the focal length to the radius of the semimajor axis. The eccentricity of the Earth changes from nearly circular to an orbit that is three percent elliptical. The period of an eccentricity cycle from

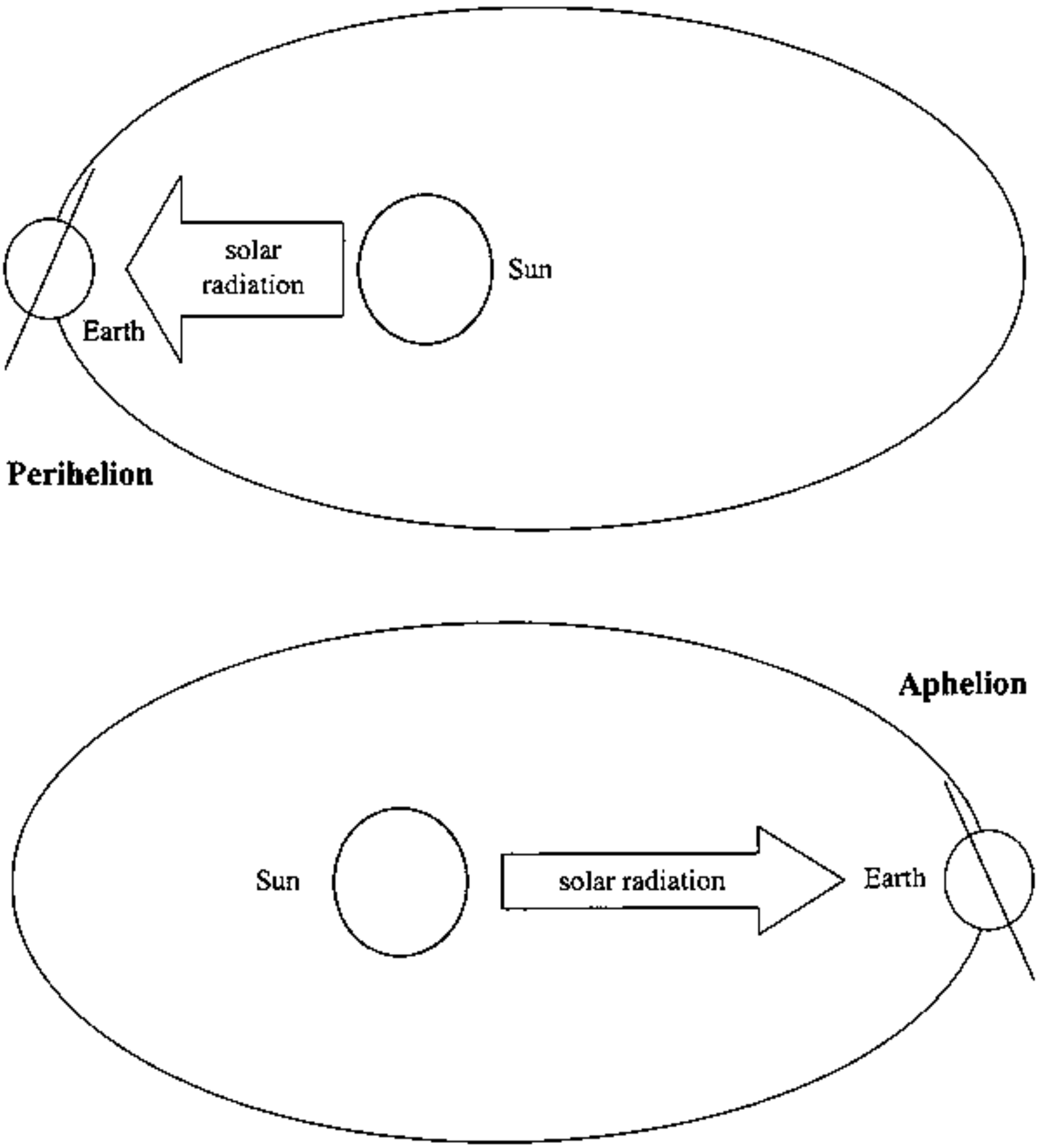
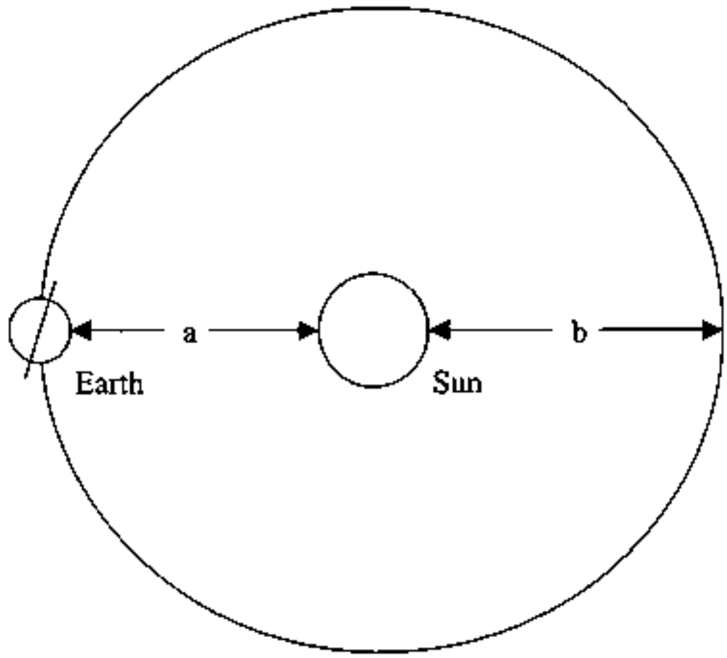
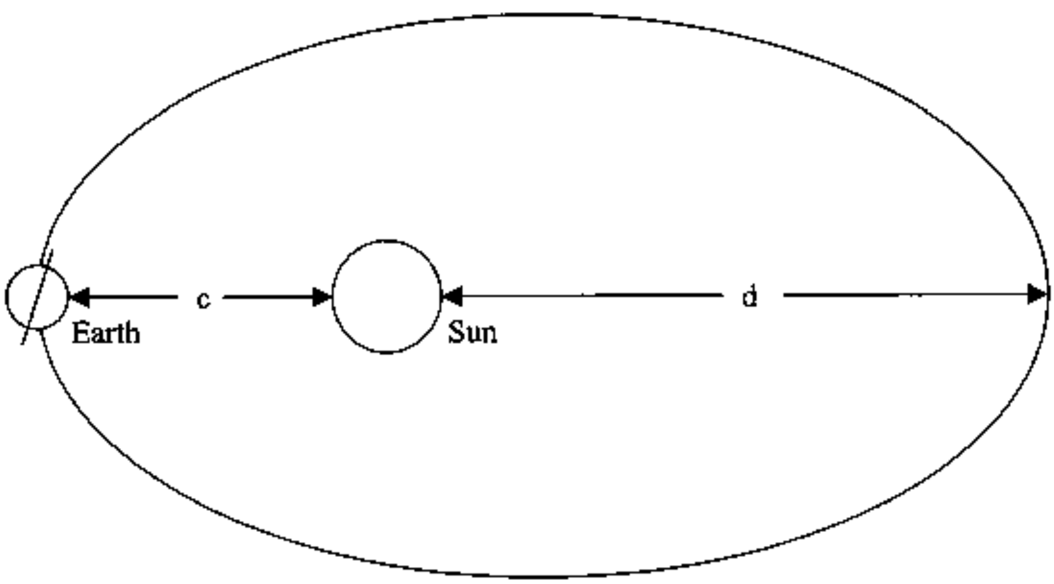


Figure 3. Insolation of the Earth. In the Northern Hemisphere, summer insolation varies from a relative maximum (upper diagram) to a relative minimum (lower diagram). The inverse is true for the Southern Hemisphere.



Minimum Eccentricity



Maximum Eccentricity

Figure 4. Orbital Eccentricity. Change from minimum to maximum eccentricity is 50 ky. At minimum eccentricity a=b and at maximum eccentricity c<d and c<a. (Note: The Northern Hemisphere of the Earth is in the summer position.)

elliptic to circular, and back again, is approximately 100 ky (DeBoer and Smith, 1994).

The precessional signal is amplified during times of maximum eccentricity and dampened during times of minimum eccentricity. Within an eccentricity cycle, precessional cycles can vary in number from three to seven cycles with the average just under five cycles (Fischer and Bottjer, 1991). Eccentricity is further modulated at periods of 400 ky and 2 my, owing to the interactions of other planets with the Earth-Moon-Sun system (Peltier, 1994).

Approaches to a Hierarchic Stratigraphic Record

Approaches to interpreting a hierarchic stratigraphic record differ significantly in concepts of hierarchy, concepts of cyclicity and interpretation of incomplete sections. These differences in approach yield very different results despite the common goals of allostratigraphers. Comparison of these approaches and their results led to the choice of the process-determined approach of Goodwin and Anderson (1997) for this study.

Each of the three hierarchic models is based on different methods of relating cycle rank to process. Using a recurrence-interval approach, Goodman and Brett (1994) interpreted the stratigraphic hierarchy as cyclic packages of rocks bounded by unconformable surfaces. Once they delineated their various cycles, they divided the study interval duration by the total number of each type of cycle to determine the recurrence interval of each rank within their hierarchy. Their calculated recurrence intervals do not have a direct relationship to any known periodic process. For example, using their method of determining cycle duration, fourth-order sequences have a recurrence interval of 1 to 1.5 my (Table 1). Because there are no known processes with periodicities in the ranges of some of Goodman and Brett's groupings, it must be concluded that either their ranks are not genetic, or the hierarchic record is a response to a combination of aperiodic processes.

Similarly, the compartments-of-time approach, in which ranks are defined as large, arbitrary intervals of geologic time, does not readily discriminate between two small-scale cycles whose mechanisms may have periods within one compartment. The most common problems with this approach are in the fourth and fifth-order compartments (Table 1). Because each compartment contains at least two orbital processes, determining which process is responsible is problematic. For example, Goldhammer et al. (1994) could not consistently determine whether precession or eccentricity produced fourth-order cycles in the Pennsylvanian of Utah.

In contrast, Goodwin and Anderson (1997) developed a process-determined model in which each rank is linked to a specific process and has specific identifying characteristics of symmetry, patterns of facies change and thickness. For example, the sixth-order PAC, generated by the 20 ky precessional cycle, is a meter-scale, shallowing-upward succession of facies bounded by sharp surfaces of disjunct facies change. Fifth-order sequences, in turn, are bundles of five sixth-order cycles grouped by the modulating effect of short-eccentricity (100 ky). These sequences are identified by a consistent pattern of deepening for two sixth-order rises followed by episodic shallowing resulting from smaller eccentricity-dampened rises. The ideal stacking patterns (Figure 5) and

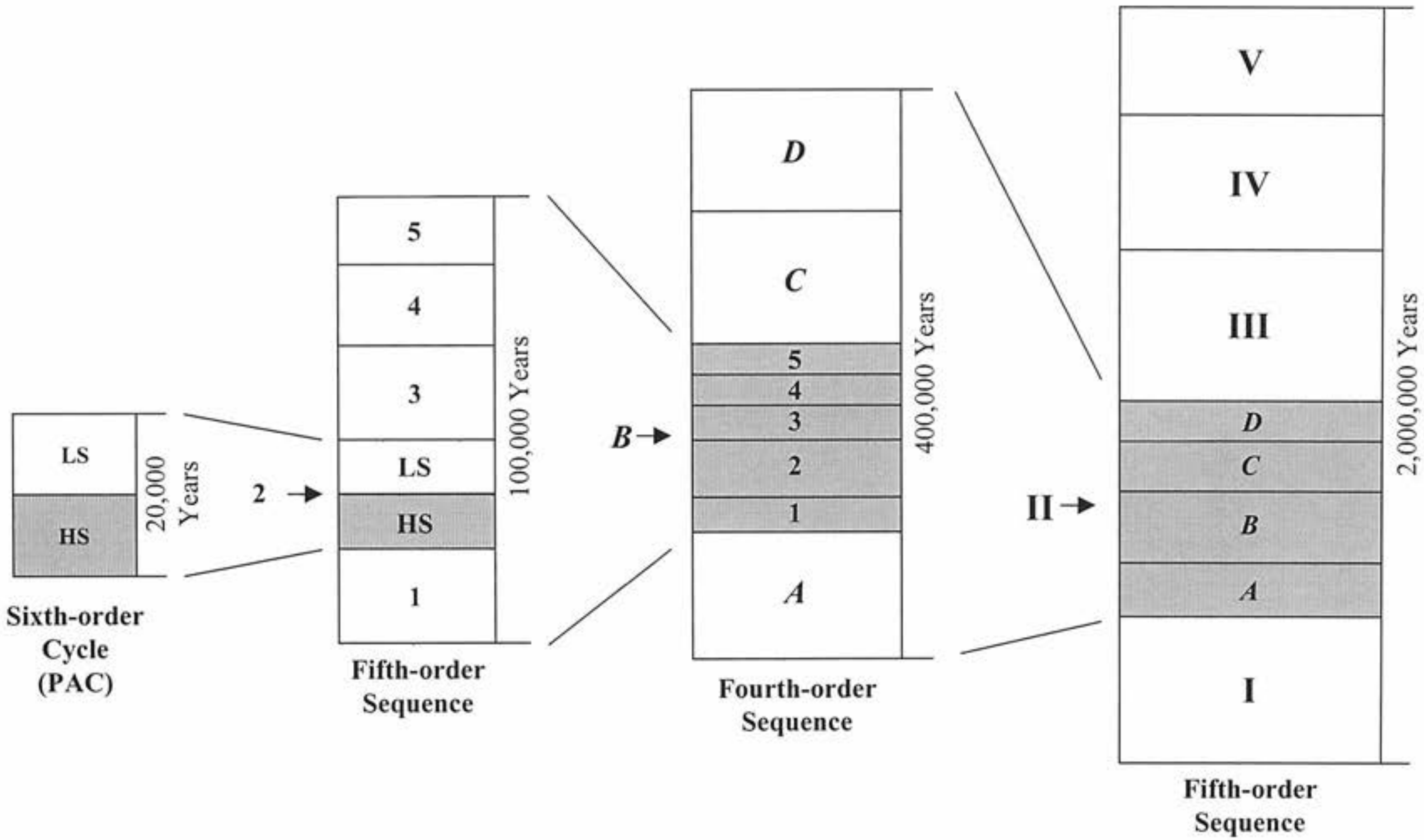


Figure 5. Hierarchic Stacking Patterns. Genetic hierarchy of allocycles controlled by orbital processes. Precession controls deposition of the fundamental cycle (PAC). Fifth, fourth, and third-order sequences are produced by three cycles of eccentricity, which act as modulators of the precessional signal. Shaded intervals contain the deepest facies for each type of cycle/sequence. (HS=Highstand; LS=Lowstand).

specific characteristics of each type of cycle allow discrimination of cycles not readily distinguished by the other two approaches.

Differences in cycle definition also contribute to different results. Goodwin and Anderson (1997) define cycles on patterns of facies change, while others (e.g., Goodman and Brett, 1994; and Goldhammer et al. 1994) rely more on repetition of specific lithologies. In the PAC model, environmentally disjunct facies changes determine cycle boundaries, not the return to a specific facies. This method permits identification of PACs in facies where cycles would be overlooked using a repetitive lithology approach. For example, Goodwin and Anderson (1988) recognized and correlated a large number of subtidal cycles in the Manlius Formation, in facies previously thought to consist of larger-scale, non-correlative peritidal cycles capped with sea-level cryptalgal laminites.

In contrast, Goodman and Brett (1994) used degree or magnitude of unconformities and degree of vertical facies changes to determine the rank of each type of cycle. With this method, only cycles with major changes in facies, or sequence boundaries with obvious evidence of unconformity (e.g., rip-up clasts, exposure surfaces, and/or paleosols) can be delineated. Cycles or sequence boundaries with subtle changes in lithology (e.g., changes in faunal content within a single lithology) will be overlooked. Their reliance on lithologic features rather than patterns of facies change led them to defining cycles (of the same rank) with inconsistent symmetries and thicknesses. For example their fifth-order cycles exhibit both shallowing-upward and deepening-upward motifs and range in thickness from 1 to 10 meters. Such inconsistency indicates that their cycles are either not produced by periodic cyclic processes, or that their method of cycle delineation is flawed.

Goldhammer et al. (1994) delineated their cycles according to the repetition of indicator facies and the presence of exposure surfaces. This approach yielded supposedly comparable cycles (in the same rank) with widely varying thicknesses, internal symmetries, and stacking patterns. Such wide variation is not to be expected from a set of periodic hierarchic allogenic processes operating in a stable tectonic setting. Rather, it appears that Goldhammer et al. (1994) overlooked a number of cycles which could have been recognized if they had adopted a more genetic concept of cycle definition.

The final difference in these approaches to interpreting a hierarchic stratigraphic record is the way each approach treats incomplete sections. Investigators recognize that sections are incomplete, but few have a systematic approach to determining where and how many cycles are missing. For example, in giving a range of 3 to 5 my for sequences and 1 to 1.5 my for sub-sequences, Goodman and Brett (1994) did not present a model for the structure of a complete sequence. Thus, while incompleteness is implied by the unconformable boundaries of sequences, the amount and location of missing sub-sequences cannot be determined. Similarly, Goldhammer et al. (1994) recognized a high degree of incompleteness in their shelfal sequences relative to the Paradox Basin evaporite sequence, but were unable to quantify that incompleteness or to determine which cycles are missing because their model was not genetically related to process. A model including predicted stacking patterns and detailed characteristics of each rank in the hierarchy would enable those determinations.

In contrast, Goodwin and Anderson (1997) developed a five-tiered, process-determined model that accommodates stratigraphic incompleteness by discriminating ranks on symmetry, thickness, and patterns of facies change. Using these criteria, the amount and position of incompleteness can be deciphered by examining the patterns observed in the section and comparing it to the stacking patterns for an ideal complete section. For example, by applying their comprehensive model to the Manlius/Coeymans (Thacher/Olney) unconformity of the Helderberg Group of New York State, Goodwin and Anderson (1988 and 1997) determined amounts of non-deposition (hiatus) and erosion (vacuity). By comparing the observed interval with the assumptions of the model, they determined that PAC 5 of Fourth-order Sequence *B* and Fourth-order Sequences *C* and *D* were eroded below the unconformity at the Munnsville, Clockville-Perryville, and Syracuse localities (Figures 8, 9, and 11 in Goodwin and Anderson 1997). By comparing the degree of facies change vertically at the localities, they further determined that PACs 3 and 4 of Fourth-order Sequence *B* were eroded at Clockville-Perryville, indicating that their model for stratigraphic accumulation can be used to determine vacuity in 20 ky increments. Above the unconformity, Goodwin and Anderson determined that Fourth-order Sequence *A* and PACs 1, 2, and 3 of Sequence *B* were deposited at the Munnsville and Clockville-Perryville localities, while they were not deposited at the Syracuse locality (Figures 8, 9, and 11 of Goodwin and Anderson, 1997). Using this information, it was determined that onlap at Syracuse occurred 140 ky later than at Munnsville, 45 km away. Successful application of this model to stratigraphic intervals can be used for high definition interpretations of deposition and basin dynamics.

For the current study the Goodwin and Anderson (1997) approach was adopted because it has the most promise of linking specific processes to orders of cycles in a hierarchic record. Other approaches have yielded internally inconsistent results because their concepts of hierarchy and their definitions of cycles (i.e., repetition of lithology) do not permit discrimination of cycles in the Milankovitch band. Also, the approach of Goodwin and Anderson permits explanation of incompleteness because departures from ideal stacking patterns indicate location and amount of missing cycles.

PACs in a Process-Determined Hierarchy

Goodwin and Anderson (1997) developed a five-tiered, process-determined model that accommodates stratigraphic incompleteness by discriminating ranks on symmetry, thickness, and patterns of facies change. In this model, the smallest observable cycle, the PAC, or sixth-order cycle, is caused by the 20 ky cycle in the precession of the Earth's axis. Each PAC is composed of components deposited during the relative high-stand and low-stand of sea level with surfaces of nondeposition being generated during times of maximum rate of sea-level rise and fall (Figure 6). In a characteristic PAC, highstand deposition occurs after a sea-level rise. Deposition is interrupted by a sea-level fall, generating a sea-level-fall surface. Deposition may resume during the lowstand part of the cycle, and is terminated by the next sea-level rise. In places of low subsidence and at times of low to moderate ice volume, PACs are generally less than one meter in thickness.

PACs are bundled by short eccentricity (100 ky) into fifth-order sequences, averaging 3 to 5 meters in thickness, and ideally consisting of five sixth-order cycles.

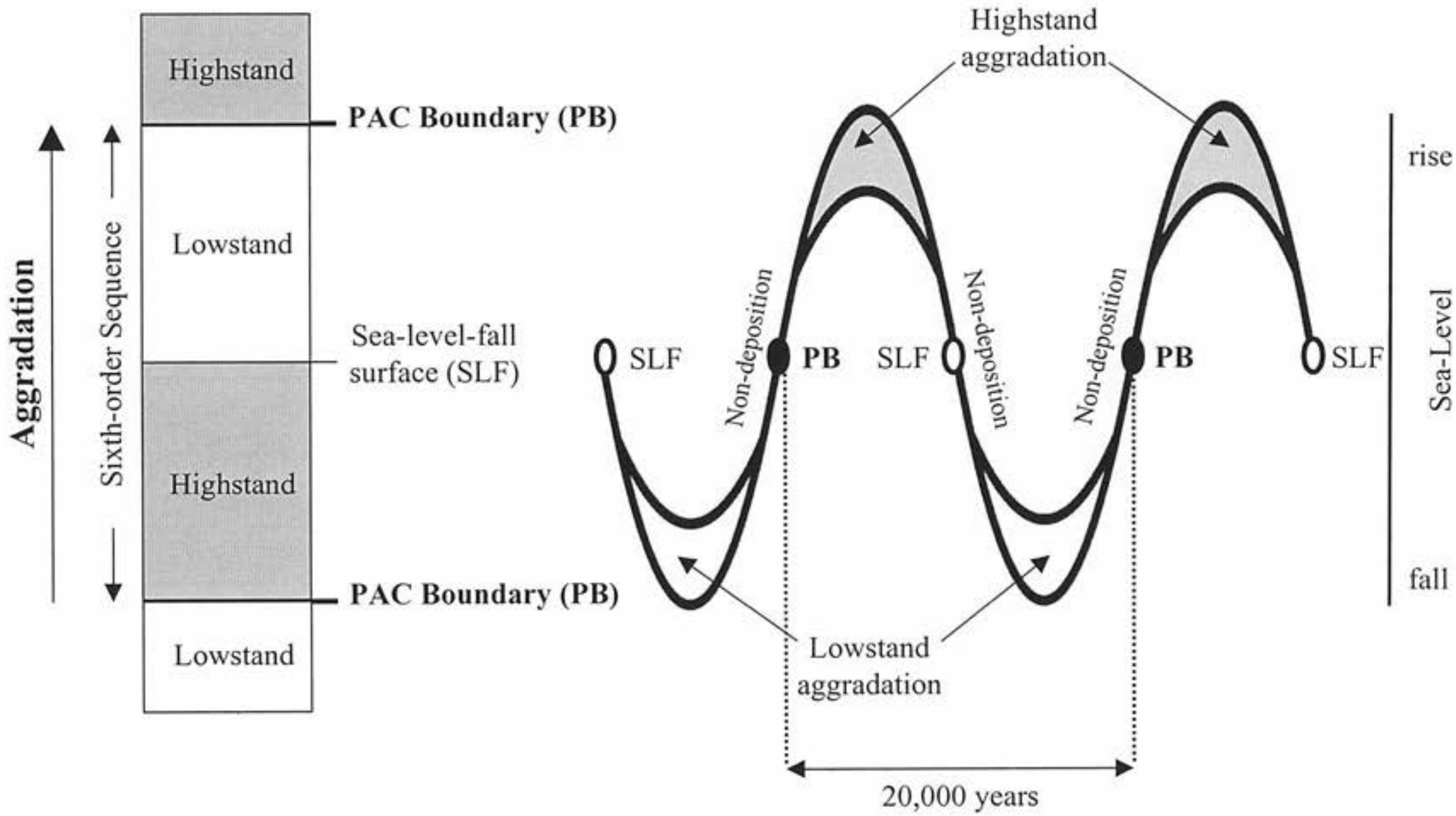


Figure 6. Relationship of PACs to Relative Sea Level. PAC boundaries are surfaces of non-deposition formed during times of maximum rates of sea-level rise. Sea-level-fall surfaces are formed during times of maximum rates of sea-level fall. Aggradation occurs during times of low rates of sea-level change (after Goodwin and Anderson, 1997).

Periods of high eccentricity define the lower parts of these sequences, enhancing precessional rises (and falls) and producing two successively deeper sixth-order cycles (Figure 7). Dampened precessional rises (and falls) during times of low eccentricity generate cycles 3, 4, and 5, which exhibit progressively shallower facies with each subsequent cycle.

At larger scales, long-term eccentricity and tectono-eustasy further modulate PACs and fifth-order sequences. Fourth-order sequences are generated by modulation of the precessional signal by the 400 ky cycle of eccentricity. This process bundles fifth-order sequences into sets of 4, with the second fifth-order sequence containing the deepest facies and normally being the thickest fifth-order sequence in the fourth-order sequence. The third and fourth fifth-order sequences are successively more shallow and thinner, reflecting decreasing amounts of accommodation space during times of low eccentricity (Figure 8). These 400 ky sequences are generally 15 to 20 meters thick.

Goodwin and Anderson (1997) hypothesized that a 2 my cycle of eccentricity combined with tectonics produce third-order sequences. These third-order sequences are internally composed of five fourth-order sequences, the second of which contains the deepest facies and is potentially the thickest fourth-order sequence (Figure 9). These sequences in turn can be tentatively grouped into second-order supersequences possibly produced by a 10 my cycle of tectonically controlled changes in the volume of the ocean basins (tectono-eustasy). Thus each rank in this hierarchy is identified by specific characteristics produced by a specific process.

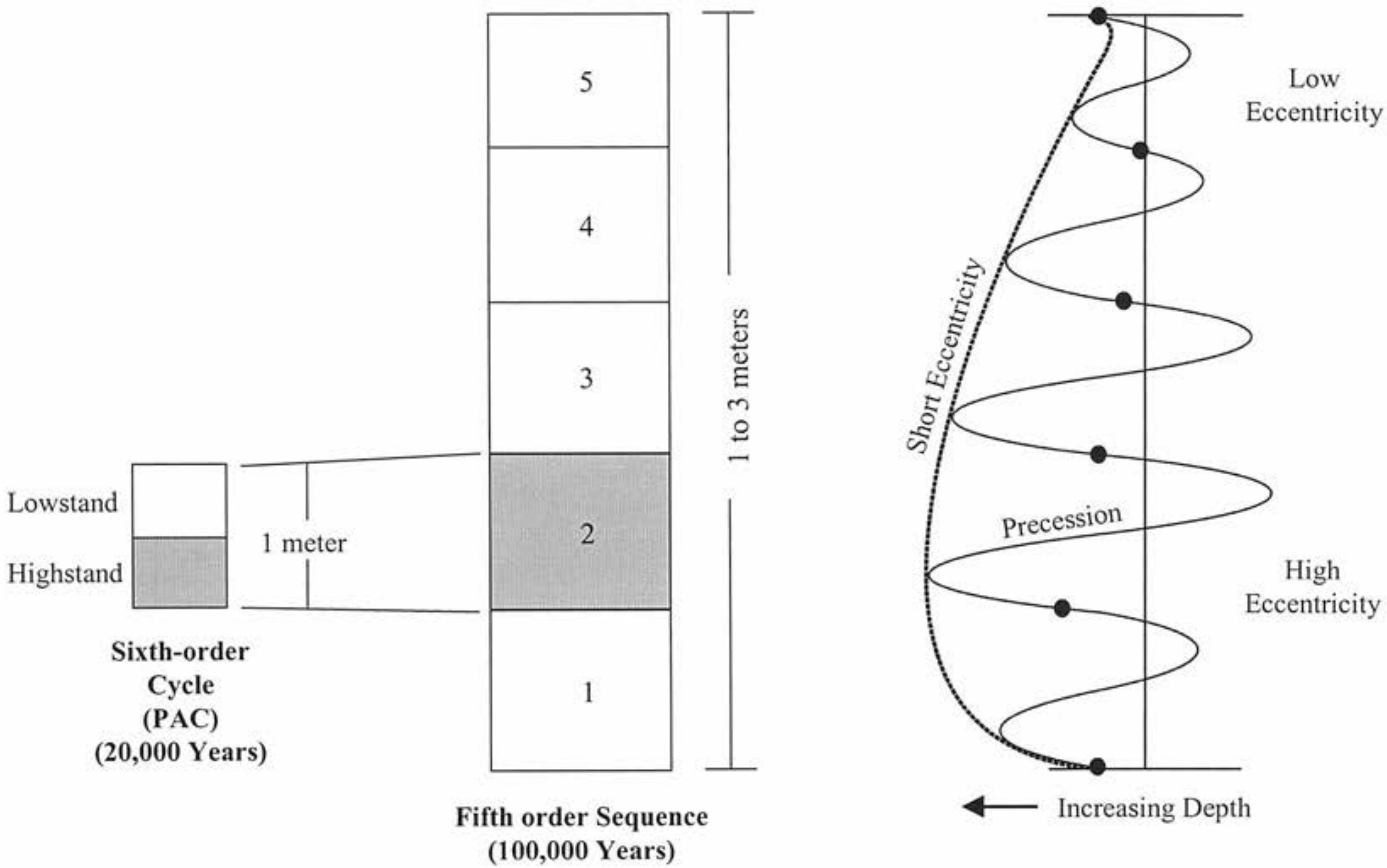


Figure 7. Ideal Fifth-order Sequence. Fifth-order sequences are composed of sixth-order cycles. In a complete sequence, there are five sixth-order cycles internal to the fifth-order sequence with the second sixth-order cycle exhibiting the deepest facies.

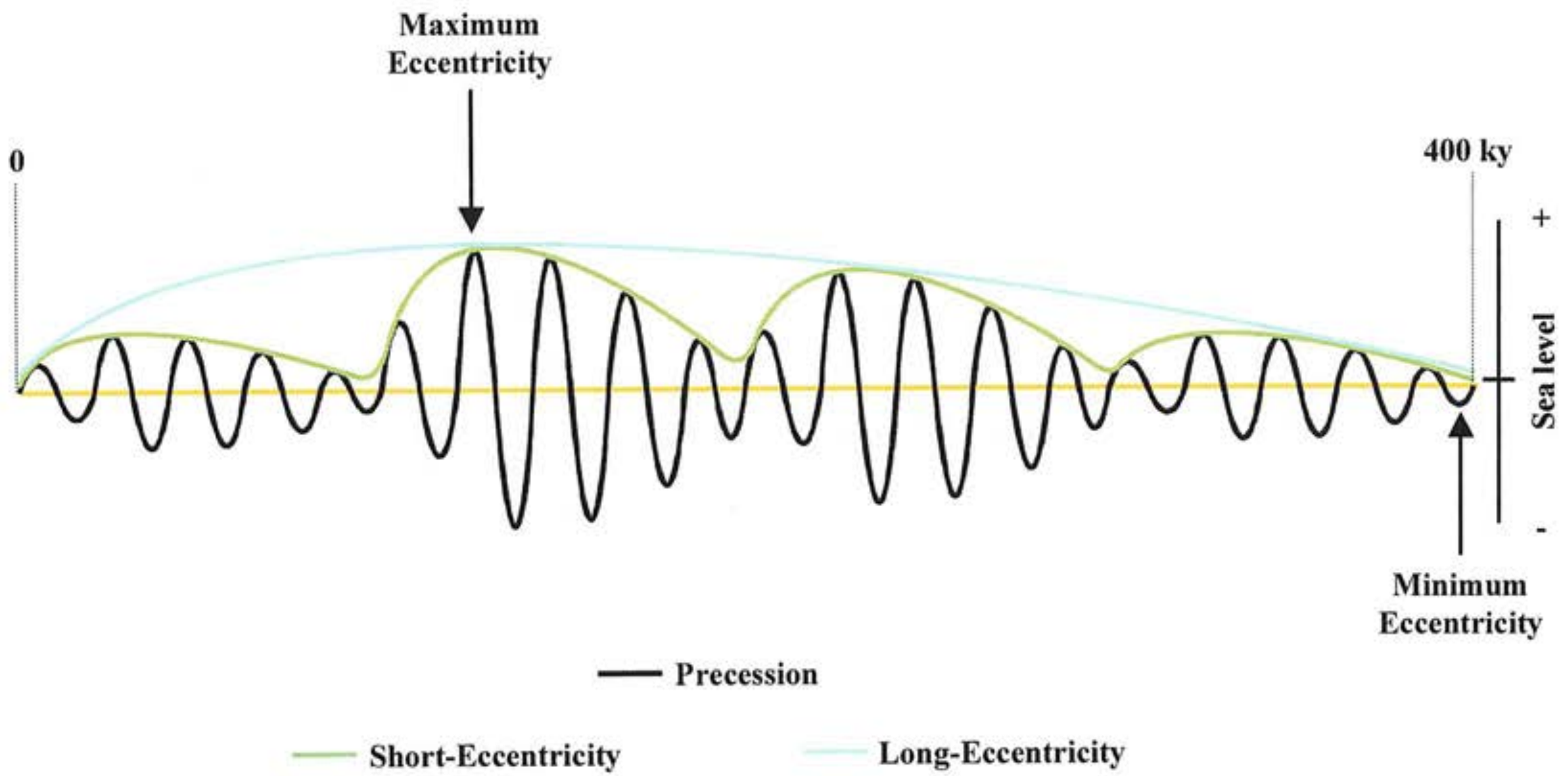


Figure 8. Fourth-order Modulation of Precessional Cyclicity. Sea-level curve illustrating modulation of the precession component of orbital forcing by the 100 ky cycle and 400 ky cycle of eccentricity. During times of high eccentricity, precessional sea-level fluctuations are augmented, while during times of low eccentricity, precessional sea-level fluctuations are dampened. Subsidence (yellow line) is set at zero to illustrate only the effects of orbital forcing on sea-level.

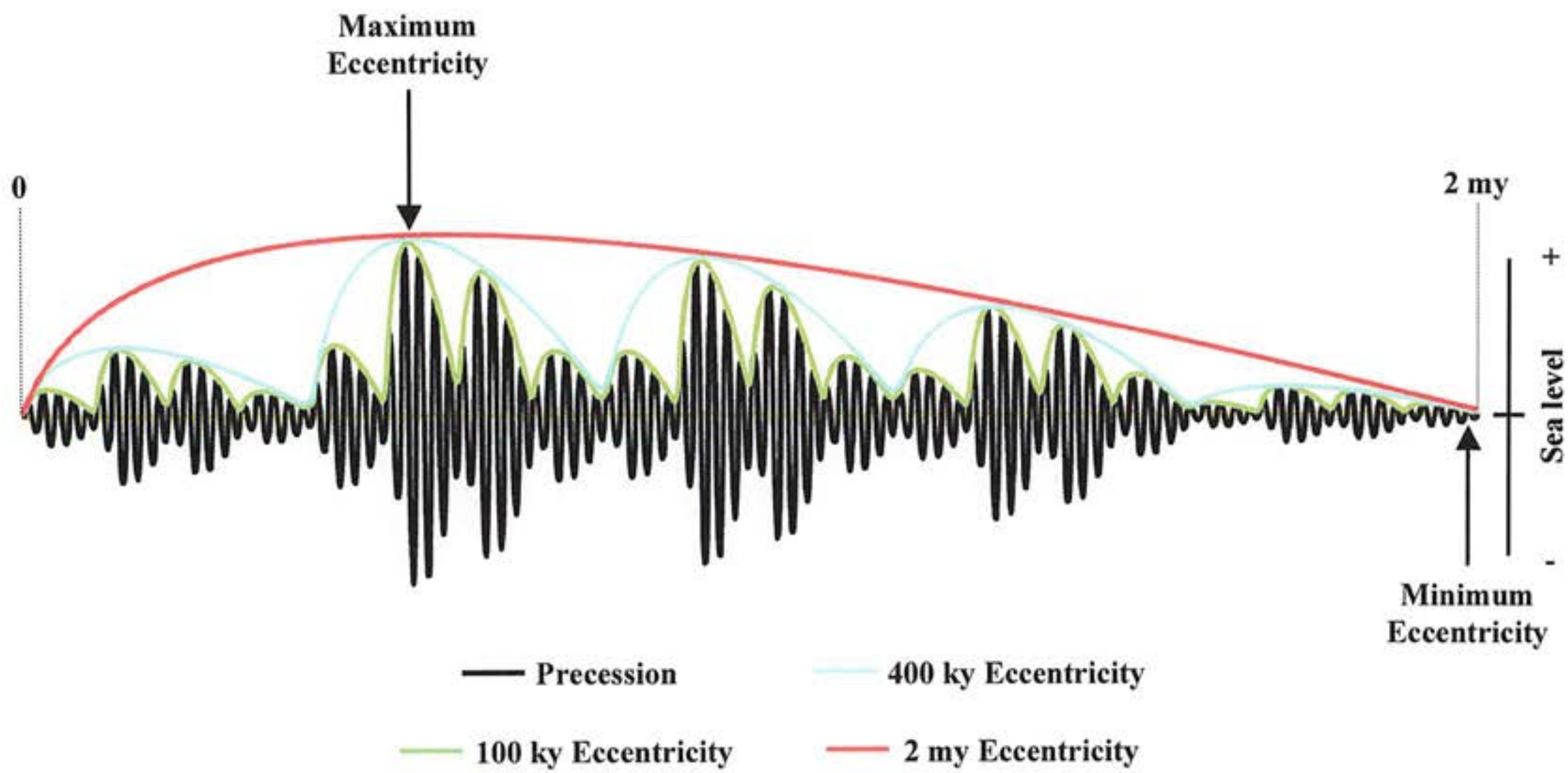


Figure 9. Third-order Modulation of Precessional Cyclicity. Sea-level curve illustrating third-order modulation of precessional sea-level fluctuation by eccentricity. During times of high eccentricity, the effects of precession are augmented, while during times of low eccentricity, the effects of precession are dampened. Subsidence (yellow line) is set at zero to illustrate only the effects of orbital forcing on sea level.

CHAPTER 3

ALLOCYCLICITY IN THE WILLIAMSPORT MEMBER AND LOWER WILLS CREEK FORMATION

Second-order and Third-order Sequences

The Upper Silurian Salina Group, here considered a second-order, 10 My supersequence (Haq et al., 1987), contains five, third-order sequences (Figure 10). Within this supersequence, the siliciclastic Williamsport Sandstone Member of the Bloomsburg Formation and the mixed carbonate-shale Wills Creek Formation constitute the first two third-order sequences (Brown, 1999), and the carbonate-rich Tonoloway Formation contains the final three (Chadwick, 1993 and Smith et al., 1992). Previous studies in the Salina Supersequence, specifically of the Williamsport Sandstone interval (Shelton, 1995), Lower Wills Creek interval (Mauriello and Ketterer, 1993), Middle Wills Creek (Brown, 1999), and the Tonoloway Formation (Chadwick, 1993), indicated that these intervals are characterized by pervasive hierarchic allocyclicity. This study examines the cyclicity of the first two of three preserved fourth-order sequences of the highly incomplete third-order Sequence A of the Salina Supersequence (Figure 11), with the objective of discriminating the contributions of various stratigraphic processes to the hierarchic structure of the interval.

Third-order Sequence A of the Salina Supersequence is important in determining the depositional nature of the supersequence as a whole. It is the thinnest third-order sequence in the Salina Supersequence (Figure 10) and is also unique in having the largest proportion of siliciclastics. These characteristics are similar to those of the Keefer

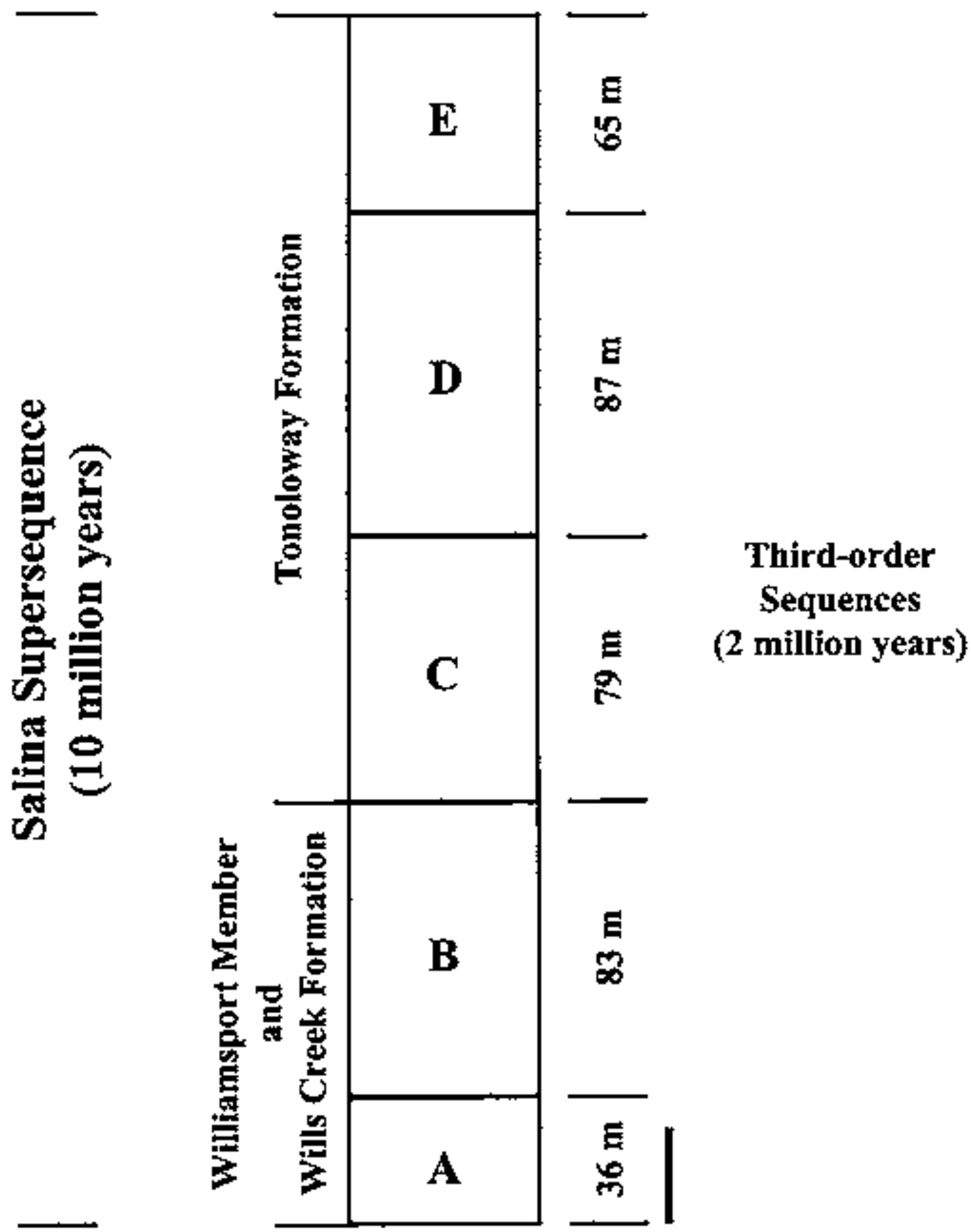


Figure 10. Third-order Structure of the Salina Supersequence. Third-order Sequences A-E have durations of 2 million years. Thickness in meters for each third-order sequence is included along right edge of column. Study interval (denoted by black bar) includes two fourth-order sequences in incomplete Third-order Sequence A.

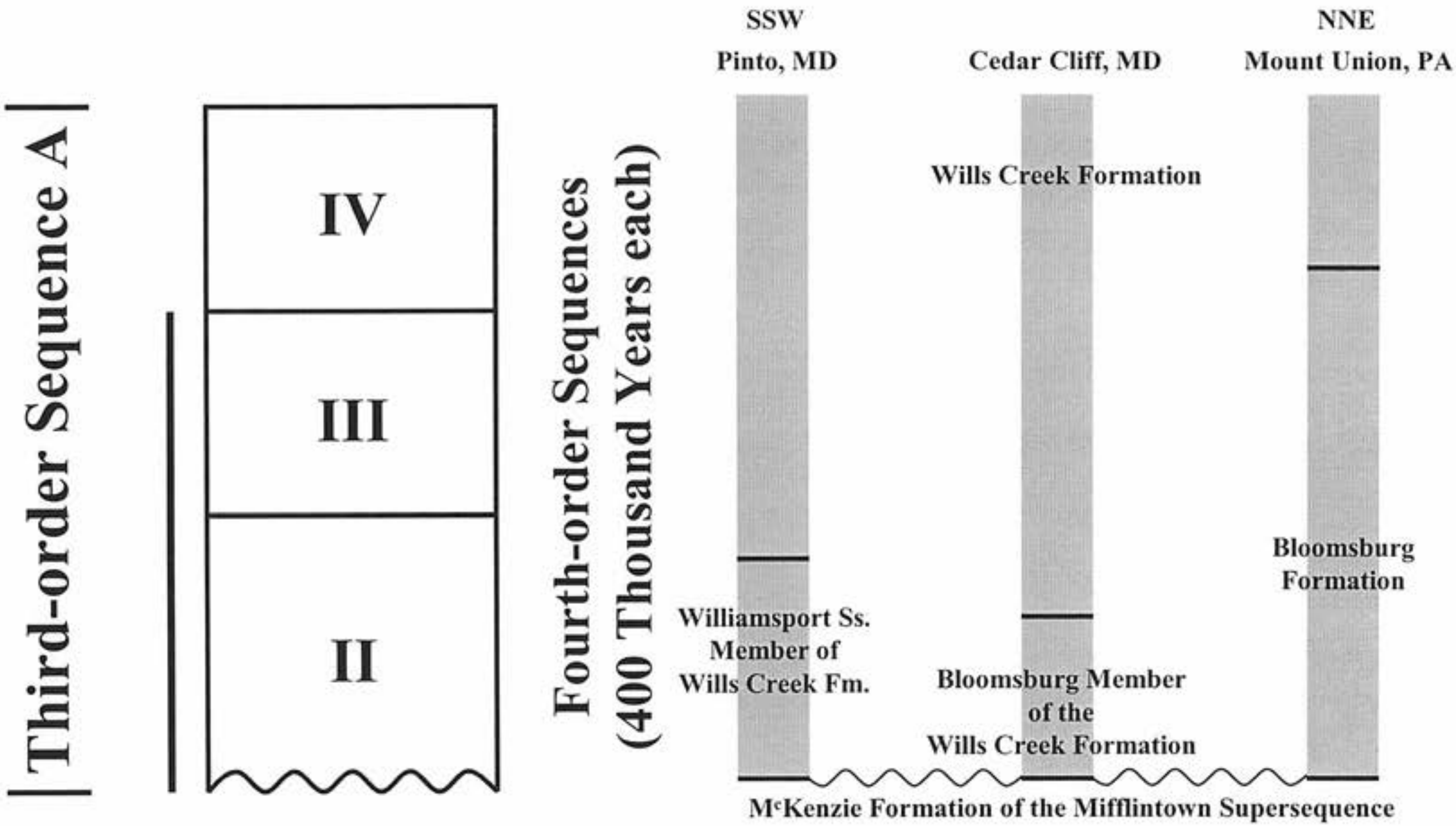


Figure 11. Third-order Sequence A. In Third-order Sequence A of the Salina Supersequence, three fourth-order sequences (II, III, and IV) are preserved. The base of Sequence A rests unconformably on the Mifflintown Supersequence. The study interval (denoted by the black bar) includes the first two preserved fourth-order sequences. Formational names and boundaries at each locality are included to indicate the relationship of member and formation boundaries to the fourth-order sequences. Thickness not drawn to scale.

Formation at the base of the Mifflintown Supersequence (Mauriello et al., 1994), suggesting that this pattern may be pervasive in second-order, nearshore supersequences. Initiation of these two supersequences by siliciclastic deposits is an indication of subaerial exposure during lowstands of sea level, possibly coupled with uplift of the tectonically active eastern margin of the Appalachian Basin.

The unusual thickness (about half the thickness of the other sequences) of Third-order Sequence A could be due to either reduced rates of deposition over the duration of the sequence, or to missing section. Preliminary examinations of the study interval indicated that the interval is incomplete, consisting of only three fourth-order sequences (Figure 11). The problem is to determine which three fourth-order sequences (of the predicted five) were preserved (Figure 12).

Comparison of the facies in these three sequences with the allocyclic hierarchic model of Goodwin and Anderson (1997) suggests that the first and fifth fourth-order sequences are missing (Option C, Figure 12). The first preserved fourth-order sequence of the study interval contains the most marine facies of Sequence A. According to the model (Figure 9), the first fourth-order sequence of a third-order sequence will have deeper water (and thus more offshore) facies than the final fourth-order of the third-order sequence below. But the first fourth-order sequence will be a transitional sequence into the deepest water (and deepest facies) of the second fourth-order sequence. The subsequent fourth-order sequences (III, IV, and V) are progressively shallower to the termination of the sequence (Figure 9). The preserved interval of Third-order Sequence A consists of a shallowing sequence of three conformable fourth-order sequences. The

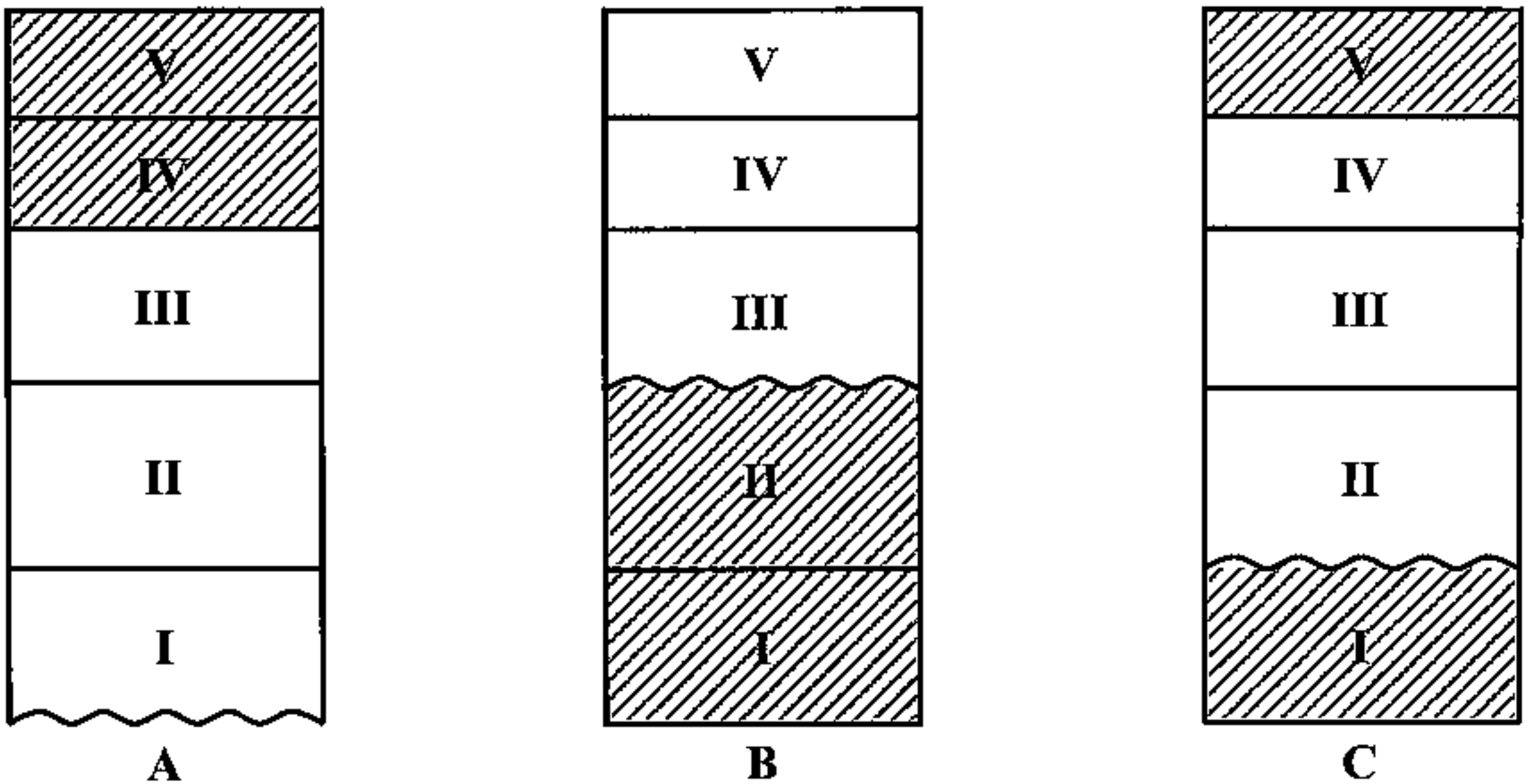


Figure 12. Structure of Fourth-order Sequences in Third-order Sequence A. Three possible configurations of fourth-order sequences within Third-order Sequence A are: **A.** Preservation of Fourth-order Sequences I, II, and III, with non-deposition or erosion of Sequences IV and V; **B.** Non-deposition of Fourth-order Sequences I and II, with deposition of Sequences III, IV, and V; or **C.** Non-deposition of Fourth-order Sequence I, deposition of Sequences II, III, and IV, and non-deposition of Fourth-order Sequence V. Deposited fourth-order sequences are represented by empty boxes, fourth-order sequences not-deposited or eroded are filled with gray lines.

absence of unconformities within the sequence limits the possible preservational options to three (A, B, or C of Figure 12). Option A can be eliminated because it requires deeper facies in the second fourth-order sequence. Therefore, options B and C, which form shallowing sequences, fit the general pattern of the study interval. Option C was chosen because it seems likely that the deepest fourth-order sequence would be preserved as the product of amplified sea-level rises.

Facies distribution (deepest facies at base, followed by successively shallower fourth-order sequences) argues against Option A which would require that the second fourth-order sequence be more marine than the first. Either Option B or C is possible in that successive shallowing either from II to IV or from III to V matches the model. The option of one fourth-order sequence missing by hiatus at the unconformity and one missing by hiatus at the top was chosen as the conservative option.

Fourth-order Sequence II

Fourth-order Sequence II, the first preserved part of the Salina Supersequence, rests unconformably on the M^cKenzie Formation of the Mifflintown Supersequence at the three study localities. This dominantly siliciclastic sequence represents a significant change in facies from the interbedded carbonates and black shales of the M^cKenzie Formation. Sequence II is also distinct from the overlying Sequences III and IV, which consist dominantly of carbonate and shale. Vertically, Fourth-order Sequence II exhibits a pattern of facies change that defines fifth-order sequences as predicted by the allocyclic hierarchic model of Goodwin and Anderson (1997). Fifth-order Sequence *B* contains deeper facies than Fifth-order Sequence *A* within the fourth-order sequence, with

Sequences *C* and *D* becoming progressively shallower. Laterally, Fourth-order Sequence II contains more offshore carbonate and shale at Pinto and Cedar Cliff, MD and mostly onshore red sandstone and shale at Mount Union, PA.

While variable in thickness, Sequence II is stratigraphically complete at the fifth-order scale, consisting of the predicted four fifth-order sequences at all localities. This fourth-order sequence varies in thickness; it is 51 feet at Mount Union, PA, 44 feet at Cedar Cliff, MD, and 48 feet at Pinto MD. Although Fourth-order Sequence II is complete at the fifth-order level at all localities, fifth-order sequences within it display different degrees of completeness.

<u>Fifth-order Sequence II *A*</u>

Fifth-order Sequence II *A*, containing the first preserved sediments of the Salina Supersequence, begins above the unconformity with the interbedded carbonates and gray shales of the M^{c}Kenzie Formation below. At all three localities, this dominantly shaley sequence is incomplete, consisting of four sixth-order sequences (PACs) at the Maryland localities, and one PAC at Mount Union, PA.

At Pinto, MD, Fifth-order Sequence II *A*, which begins above the unconformity 15 feet below the M^{c}Kenzie Formation/Bloomsburg Member contact of Hoskins (1961), consists of 4 PACs, numbered 2, 3, 4, and 5 (Appendix B). Similarly at Cedar Cliff, MD, Sequence II *A* is missing PAC 1. All PACs in Sequence II *A* at the Maryland localities are lithologically similar, consisting of minor sandstone or calcarenite highstand deposits, capped by lowstand shale deposits. These highstand deposits are characterized by small-scale parallel lamination and ripple cross-stratification, structures commonly produced on