

CORRELATION OF A HIERARCHY OF CYCLES
FORCED BY ECCENTRICITY AND PRECESSION:
MIDDLE WILLS CREEK FORMATION,
CENTRAL APPALACHIAN BASIN

A Thesis

Submitted to

the Temple University Board

in Partial Fulfillment

of the Requirements for the Degree

MASTER OF ARTS

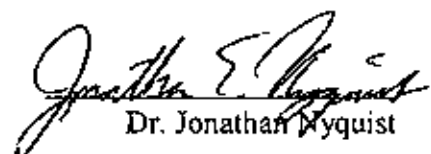
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ABSTRACT

Applying a hierarchic 'Milankovitch' orbital forcing model, a fourth-order (400 ka, long eccentricity) sequence and its internal cyclic structure, in the middle part of the Wills Creek Formation, can be correlated between Pinto, Maryland and Mt. Union, Pennsylvania, a distance of 150 km. This fourth-order sequence comprises four fifth-order (100 ka, short eccentricity) cycles arranged in an asymmetric shallowing-upward pattern, in which the second fifth-order cycle contains a markedly deeper facies or is more carbonate-rich. Fifth-order cycles in the Wills Creek Formation consist of three to five sixth-order (20 ka, precessional) cycles generally arranged in an asymmetric pattern in which the second sixth-order cycle contains the deepest facies. Within sixth-order cycles, the basal deposits (occurring just above surfaces produced by precessionally forced sea-level rises) are carbonate-rich while the upper, shallower parts of cycles are characterized by an abundance of green (or sometimes red) shale. The deepest (most open marine) carbonate facies are oosparites and biosparites. The shallowest facies may be either mudcracked or simply massive (bioturbated?) shale.

Within the studied fourth-order sequence at both localities, symmetry, thickness and fifth-order cyclic structure are similar. The most significant difference between the two localities is that the sequence at Mt. Union contains more onshore and/or nonmarine facies than the correlative sequence at Pinto. The consistency in the pattern of hierarchic cyclic structure between such distant and facies-distinctive localities reinforces an interpretation of Milankovitch orbital forcing as an explanation for Wills Creek cyclic stratigraphy.

ACKNOWLEDGMENTS

Thanks to Dr. Peter Goodwin for his guidance and patience, to Dr. Edwin J. Anderson for his irreplaceable stratigraphic knowledge and to the entire faculty of Temple University's Geology Department for their assistance on my way to becoming a professional.

DEDICATION

I dedicate this thesis to *Martine Comillac* for understanding when I had to go into the field and always being there for me in times of need.

TABLE OF CONTENTS

	Page
ABSTRACT	ii
ACKNOWLEDGMENTS	iii
DEDICATION	iv
LIST OF FIGURES	viii
LIST OF TABLES	x
 CHAPTERS	
1. INTRODUCTION	1
Purpose and Scope	1
General Stratigraphy	3
Methods	5
Objectives	9
 2. MODELS OF ALLOCYCLICITY	10
Punctuated Aggradational Cycles	10
Theory of Orbital Forcing	16
Alloyclic Hierarchy	19

3. FACIES ANALYSIS OF THE WILLS CREEK FORMATION.....	27
Previous Interpretations and Descriptions.....	27
Criteria for Facies Analysis.....	28
Facies Description and Interpretation.....	31
Red/Green Shale Facies.....	31
Laminated and Massive Dolomite Facies.....	31
Laminated Limestone Facies.....	34
Oolitic and Pelletal Calcarenite Facies.....	34
Shelly Calcarenite Facies.....	37
Facies Summary.....	37
4. ALLOCYCLIC INTERPRETATION OF THE	
MIDDLE WILLS CREEK FORMATION.....	40
Introduction.....	40
Large-scale Cyclic Framework.....	41
Anatomy of the Studied Fourth-order Sequence.....	43
Small-scale Allocycles.....	43
Fifth-order Sequences.....	43
<i>Sequence A</i>	47
<i>Sequence B</i>	52
<i>Sequence C</i>	55

<i>Sequence D</i>	55
Conclusion.....	61
5. PALEOENVIRONMENTS, PALEO GEOGRAPHY, BASIN DYNAMICS	65
Paleoenvironments	65
Paleogeography	66
Basin Dynamics	70
REFERENCES CITED	72
APPENDIX: COMPLETE COLUMNAR SECTION AT PINTO, MARYLAND	75

. LIST OF FIGURES

	Page
Figure 1. Silurian Outcrop	2
Figure 2. Upper Silurian Stratigraphy.....	4
Figure 3. Mt. Union, Pennsylvania.....	6
Figure 4. Pinto, Maryland.....	7
Figure 5. Precessional Eustasy and Sixth-order Sequences	15
Figure 6. Elements of the Earth's Orbit.....	18
Figure 7. Orbital Eccentricity.....	20
Figure 8. Hierarchy of Stacking Patterns.....	25
Figure 9. Massive Dolomite Facies.....	32
Figure 10. Laminated Dolomite Facies.....	32
Figure 11. Laminated Dolomite Facies.....	33
Figure 12. Laminated Dolomite Facies.....	33
Figure 13. Laminated Dolomite Facies	35
Figure 14. Oolitic and Pelletal Calcarenite Facies.....	35
Figure 15. Oolitic and Pelletal Calcarenite Facies	36
Figure 16. Shelly Calcarenite Facies.....	36
Figure 17. Shelly Calcarenite Facies.....	39
Figure 18. Shelly Calcarenite Facies.....	39
Figure 19. The Five Third-order Sequences in the Salina Supersequene.....	42

Figure 20.	Orbital Variations Relationship to PACs.....	46
Figure 21.	Stratigraphic Column of Sequence A at Pinto.....	48
Figure 22.	Stratigraphic Column of Sequence A at Mt. Union.....	49
Figure 23.	Fifth-order Sequences A and C at Pinto, Maryland.....	50
Figure 24.	Fifth-order Sequences D and A at Pinto, Maryland.....	51
Figure 25.	Stratigraphic Column of Sequence B at Pinto.....	53
Figure 26.	Stratigraphic Column of Sequence B at Mt. Union.....	54
Figure 27.	Fifth-order Sequences A and B at Mt. Union, PA.....	56
Figure 28.	Fifth-order Sequences B and C at Mt. Union, PA.....	57
Figure 29.	Fifth-order Sequences D at Mt. Union, PA.....	58
Figure 30.	Stratigraphic Column of Sequence C at Pinto.....	59
Figure 31.	Stratigraphic Column of Sequence C at Mt. Union.....	60
Figure 32.	Stratigraphic Column of Sequence D at Pinto.....	62
Figure 33.	Stratigraphic Column of Sequence D at Mt. Union.....	63
Figure 34.	Correlation of Fifth-order Sequences.....	67
Figure 35.	Paleogeographic Reconstruction of the Central Appalachian Basin.....	69

LIST OF TABLES

	Page
Table 1. Genetic Hierarchy of Allocycles.....	23
Table 2. Facies of the Wills Creek Formation.....	29

CHAPTER 1

INTRODUCTION

Purpose and Scope

The purpose of this study is to apply the model of orbital forcing, in conjunction with the Hypothesis of Punctuated Aggradational Cycle (PAC), to analyze the cyclic stratigraphy of a portion of the Wills Creek Formation. Application of these models will determine if precession and eccentricity are reasonable explanations for the cyclic patterns within the formation. Both models are based on the hypothesis that allogenic processes produce a hierarchic stratigraphic record. This study, then, is designed to test the hypothesis of orbital forcing by applying the model of a process-determined allocyclic hierarchy to the analysis of Wills Creek cyclicality.

The scope of this study is limited to a portion of the Upper Silurian Wills Creek Formation at two localities, 150 km apart, at Mt. Union, Pennsylvania and Pinto, Maryland (Figure 1). The measured thicknesses of the study interval at Mt. Union and Pinto sections are 26 and 23 meters, respectively. These measured intervals were used to analyze the lithology, document the cyclic structure, and correlate the hierarchy of cyclic patterns within the formation. Preliminary research in the Wills Creek Formation indicated that a four-tiered allocyclic framework exists within the formation (Zeliznak et al., 1997) and that this cyclic framework is correlative between Pinto and Mt. Union. This study will focus on documenting three tiers in this allocyclic hierarchy within a limited part of the Wills Creek Formation. Description, interpretation and correlation of

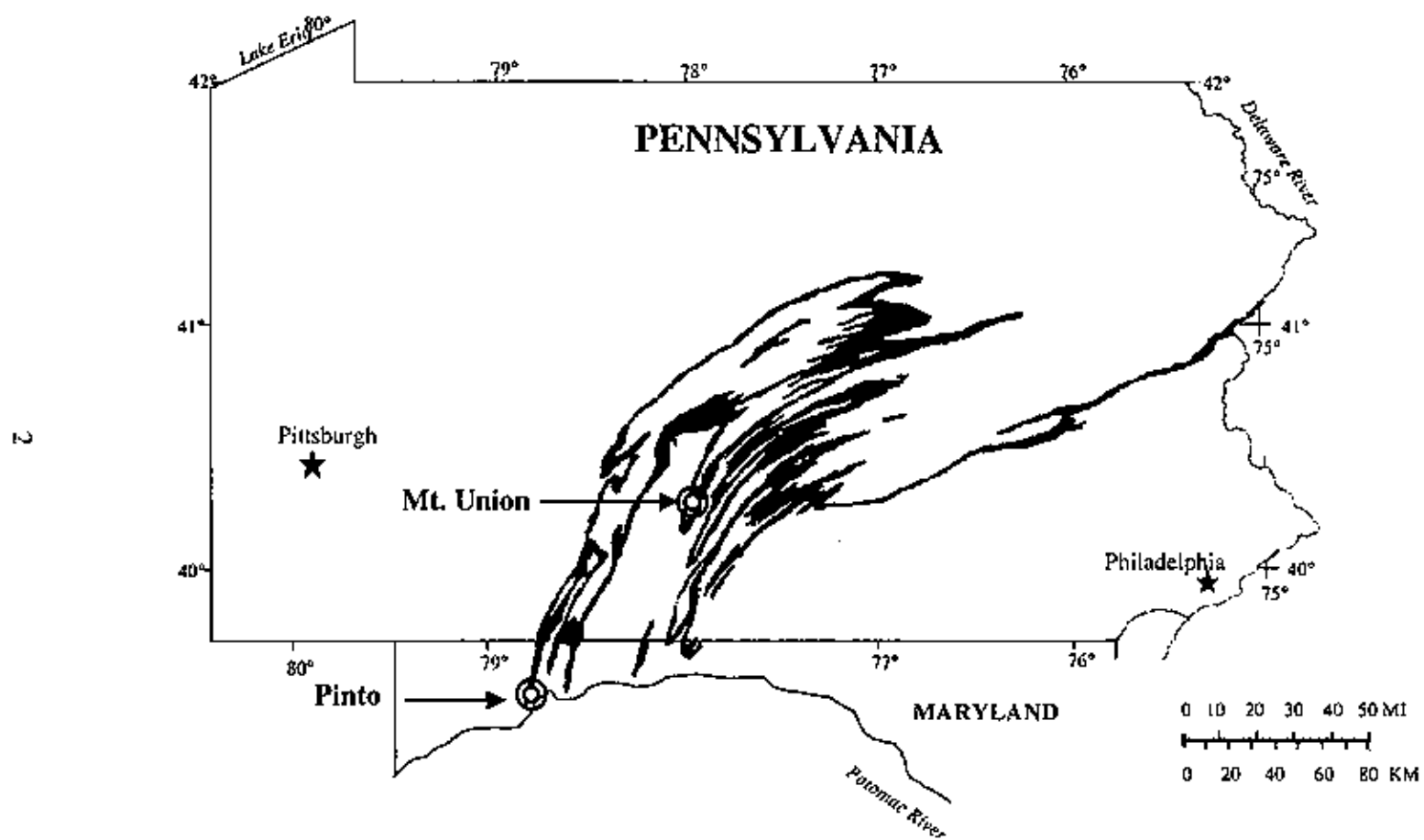


Figure 1. Silurian Outcrop. Location of studied outcrops and general distribution of Silurian outcrops throughout Pennsylvania and Maryland (Modified from Map 7-Geologic Map of Pennsylvania, Pennsylvania Department of Natural Resources).

fourth, fifth and sixth-order cycles in this interval will constitute support for the orbital forcing model of allocyclicality.

General Stratigraphy

In the Appalachian Basin, Silurian strata are divided into the Niagaran and Cayugan Series; this study focuses on the Upper Silurian Cayugan Series (Berg et al., 1983). In Pennsylvania and Maryland, the Bloomsburg, Wills Creek and Tonoloway Formations and the majority of the Keyser Formation are subdivisions of the Cayugan Series (Figure 2). The lower half of the Cayugan Series is represented by the Salina Group. The Salina Group is comprised of the Wills Creek Formation, named by Stose (1912) from exposures along the Wills Creek in Cumberland, Maryland, and the Tonoloway Formation. The duration of the Salina Group is approximately 10 million years and is considered a 2nd order supersequence by Goodwin and Anderson (1997). Swartz (1923) proposed a general correlation of the Salina Group among localities in Pennsylvania and Maryland. Later work by Swartz (1934) and Hoskins (1961) confirmed the initial correlation. Rickard (1962) correlated a portion of the Salina Group, the Wills Creek Formation, in Pennsylvania and Maryland with the Vernon Formation of New York.

In Western Maryland, the Wills Creek Formation begins at the base of an eight-foot-thick, massive, fine-grained sandstone named the Williamsport Sandstone Member (Hoskins, 1961). Eastward, red fluvial deposits of the Bloomsburg Formation (as described by Hoskins) underlie and laterally replace rocks of the lower part of the Wills Creek Formation. The color change delineating the boundary between the Bloomsburg

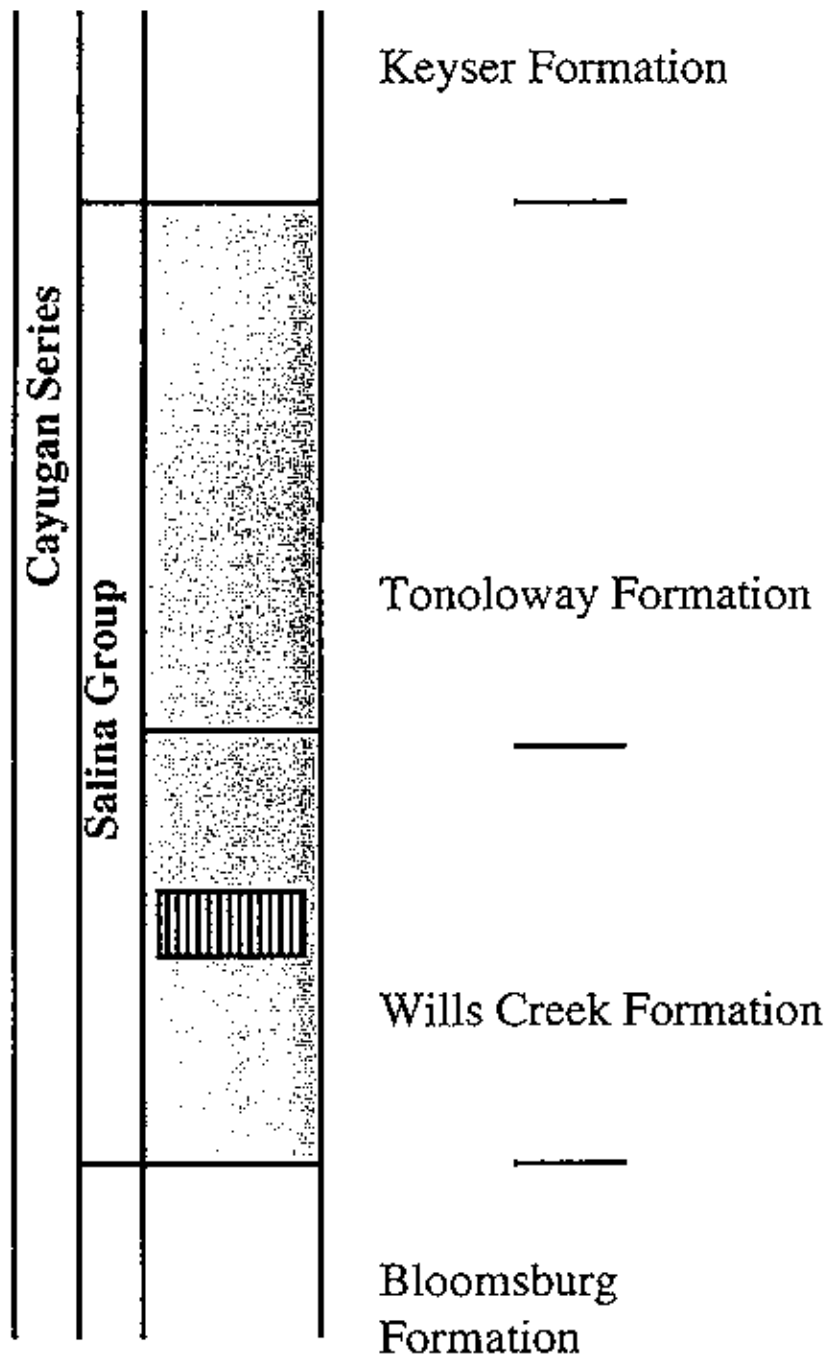


Figure 2. Upper Silurian Stratigraphy. Highlighted section represents the Salina Group. Vertical bars represent approximate study interval in the Wills Creek Formation. Column not drawn to scale.

and Wills Creek Formations occurs stratigraphically some 80-90 feet higher in the section at Mt. Union, Pennsylvania than at Pinto in Western Maryland where it corresponds closely to the defined base of the Wills Creek Formation (below a red massive sandstone). At Mt. Union the contact between the formations is placed at the bed below which the rock is predominantly red and above which the rocks are predominantly of mixed colors (Hoskins, 1961). Overlying the Wills Creek Formation at both localities (Pinto, Md. and Mt. Union, Pa.) is the Tonoloway Formation, which begins at the base of a massive three-meter-thick, dark-blue limestone (Swartz, 1923). The overall thickness of the Wills Creek Formation, as measured by Anderson and Goodwin (personal communication, 1988), is 130 meters at Mt. Union and 138 meters at Pinto, when measured from the same stratigraphic horizons employed by Swartz (1923) and Hoskins (1961).

The dominant lithologies of the Wills Creek Formation are sandstone and shale in the lower part of formation, and limestone and shale throughout the middle and top. The quartz sandstone near the base of the formation has an iron-rich matrix and is interbedded with green shale. Argillaceous limestone, interbedded with green or gray shale, dominates the middle and upper section. The formation varies in color, ranging from red and pale-green at the base to gray-green and buff in the middle and upper portions.

Methods

My study involved portions of two complete exposures of the Wills Creek Formation at Mt. Union, Pennsylvania and Pinto, Maryland (Figure 3 and 4). The Mt. Union section is located along a roadcut for U.S. Routes 522 and 22, on the north side of

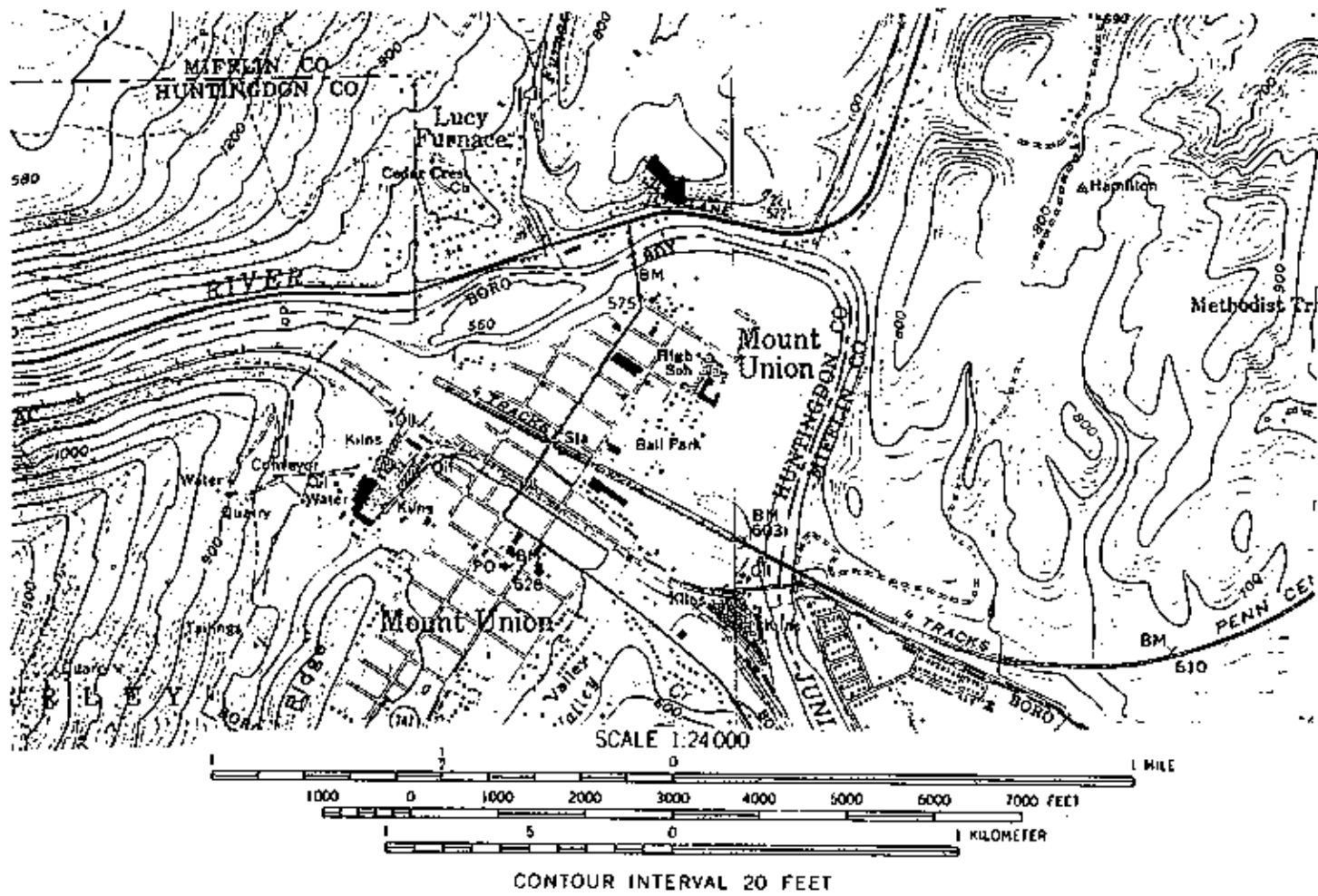


Figure 3. Mt Union, Pennsylvania. Topographic map showing the surrounding area of the Mt. Union locality. The arrow points to the location of the outcrop (Modified from U.S.G.S. Mt. Union and Newton Hamilton Quadrangles, Pennsylvania-7.5 minute series).

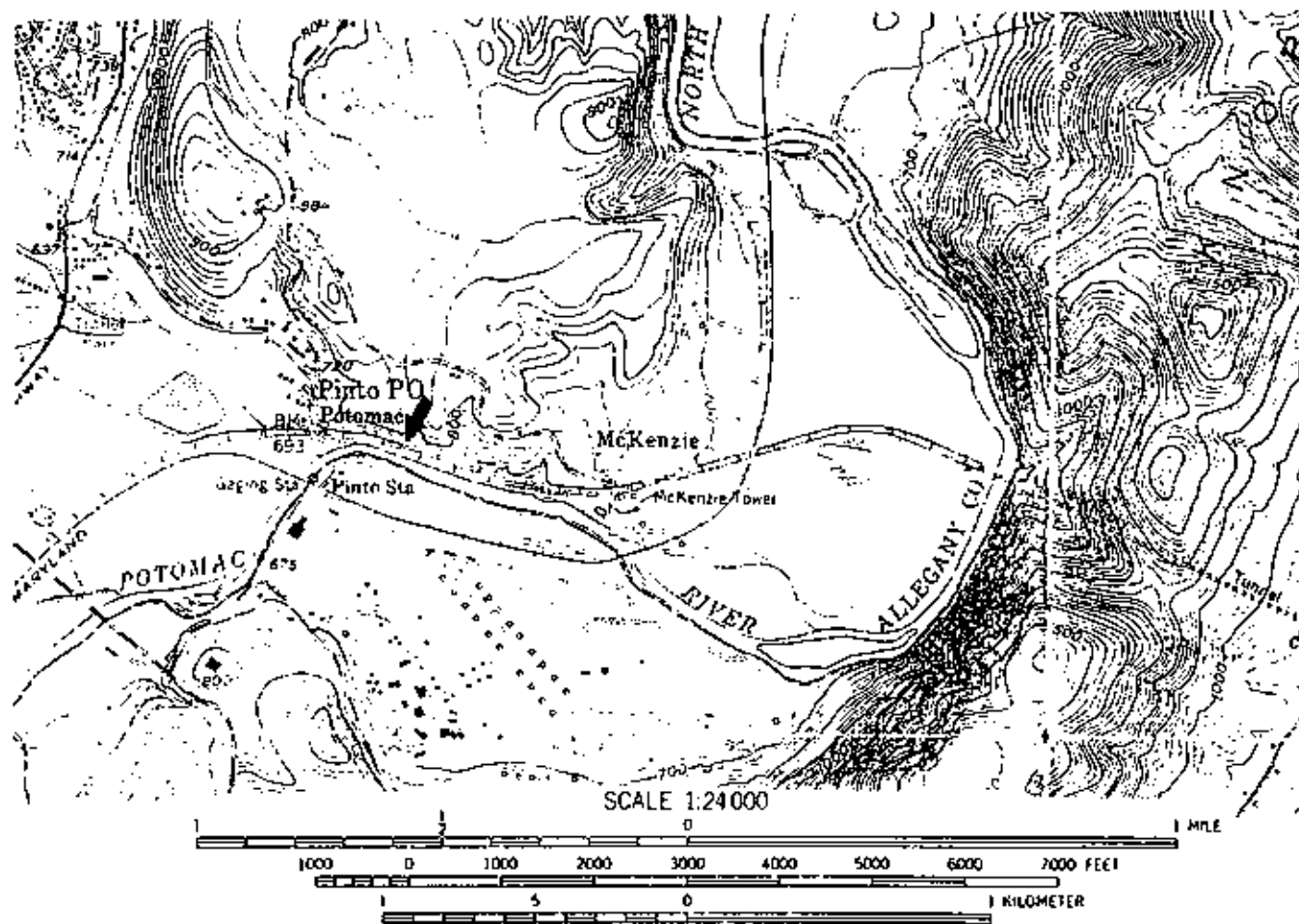


Figure 4. Pinto, Maryland. Topographic map showing the surrounding area of the Pinto locality. The arrow points to the location of the outcrop (Modified from U.S.G.S. Cresaptown, West Virginia-Maryland Quadrangle, 7.5 minute series).

the road, at the bridge that crosses the Juniata River near the town of Mt. Union. The exposure is on the southeastern limb of the Jacks Mountain anticline; strata exposed in the roadcut strike approximately N 16° and dips 27° SE (Lacey, 1960). The exposure at Pinto is located in the town of Pinto, Maryland, 7.4 miles south of Cumberland, Maryland, along the Conrail tracks next to the North Branch of the Potomac River. Access to the outcrop is from the end of Pinto Road, 0.5 miles east of Route 220.

Measurements and descriptions of approximately 80 feet of stratigraphic section in the middle part of the Wills Creek Formation (Figure 2) were recorded at both localities as columnar sections drawn at the scale of five feet to one inch, allowing for high resolution of the observed strata. The columns depict sedimentary textures, sedimentary structures, grain types, faunal content, bedding patterns and cyclic structure.

Cycle boundaries were delineated from field observations based on patterns of disjunct facies change across a surface. Degree of facies change at cycle boundaries and relative thickness of the cycles helped define the ranks of the cycle boundaries. The most prominent cycles in the formation are composite cycles, which average five meters in thickness and are defined by a sharp lithologic change from thick green shale to carbonate. In this study, these cycles bounded by major facies changes are interpreted as fifth-order, 100ky rock cycles or sequences. Similarly, smaller-scale disjunct facies changes are used to divide these fifth-order cycles into sixth-order cycles. The relative amount of shale below a cycle's basal carbonate bed and the sequential pattern of meter-scale cycles allow for the discrimination of fifth and sixth-order cycle boundaries.

Oriented hand-samples were collected from carbonate units occurring just above all fifth and most sixth-order cycle boundaries. Standard thin-sections were prepared

from the hand-samples to provide lithologic and faunal detail. Microscopic analysis of the degree of facies change at each cycle boundary aided in the verification of a disjunct facies relationship.

Hand-drawn stratigraphic columns were scanned into Adobe Photo Shop LE[®] at 150 dots per inch (DPI) using 24-bit color. All other manipulation of the figures was done in Microsoft PowerPoint[®]. Scanning of the columns allowed hand-drawn qualities to be combined with precise computer graphics.

Objectives

The study has four primary objectives:

1. Documentation of the studied interval as a hierarchic sequence of cycles, based on degree of facies change, at three scales (4th, 5th and 6th order).
2. Correlation of stratigraphic sections matching the patterns of facies change and sequences of change over a distance of 150 km.
3. Reconstruction of the Wills Creek Formation paleoenvironment and paleogeography.
4. Interpretation of basin dynamics in the Appalachian Foreland Basin during deposition of the Wills Creek Formation.

Accomplishment these four objectives will lend support to the hypothesis of orbital forcing as the principal cause of small-scale cyclicity in the Wills Creek Formation.

CHAPTER 2

MODELS OF ALLOCYCLICITY

Punctuated Aggradational Cycles

In 1980, Goodwin and Anderson presented the Punctuated Aggradational Cycle (PAC) Hypothesis, a fundamentally new model of stratigraphic accumulation. This comprehensive model, presented as an alternative to the gradualistic model of stratigraphic accumulation, introduced evidence that stratigraphic accumulation is episodic and is a function of allogenic mechanisms. Gradualism is based on gradual base-level fluctuations, autocyclicality and continuous accumulation throughout the stratigraphic record. In contrast, the PAC model suggests that the primary control of stratigraphic accumulation is high-frequency, rapid base-level rises (Goodwin and Anderson, 1985). Over time, the PAC hypothesis has been refined to its present form as a process-determined hierarchy of allocycles fully integrated with the model of orbital forcing.

Conceptually, the model states that the PAC, rather the formation or member, is the intrinsic unit of stratigraphic accumulation. A PAC is defined as a time-stratigraphic, meter-scale, shallowing-upward cycle bounded by synchronous surfaces marking abrupt changes in facies from shallow to deep. The PAC boundary was originally thought of as a surface of non-deposition produced by geologically instantaneous base-level rises of at least basin-wide extent (Goodwin and Anderson, 1985). Since PAC boundaries are laterally traceable over tens of kilometers, they can be considered synchronous surfaces

(Goodwin and Anderson, 1985). Shallowing of a PAC is caused by aggradation that continues until the next base-level rise or until accommodation space is filled.

The mechanism used to explain the episodic nature of the stratigraphic record must account for several observations (Goodwin and Anderson, 1985):

1. PACs occur throughout the geologic record.
2. PACs appear to be the result of rapid base-level rises.
3. PACs are found in most depositional environments and are correlative between facies. Therefore, the mechanism must be allogenic.
4. PACs show evidence of differential subsidence and gradual base-level rise. Therefore, the mechanism that produced the punctuated event must contain or be superimposed on these processes.
5. Because PACs contain little or no transgressive deposits, the rate of base-level rise during punctuation events must exceed the rate of deposition.
6. PACs have a recurrence interval of tens of thousands of years. This rhythm is superimposed on a larger-scale cyclic structure of hundreds of thousand of years represented by sequences of PACs.

The most appropriate mechanism to explain these observations is one based on glacial eustasy superimposed on gradual subsidence (Goodwin and Anderson, 1985). The relationship between glacial eustasy and sedimentary cycles is caused by variations in the Earth's orbital properties, which occur as a hierarchic set of periodic processes. Because the periodic variations in precession (20 ky) and eccentricity (100 ky) can control sea-level fluctuations, and because they recur in the same time-range as PACs and PAC

sequences, Goodwin and Anderson (1985) considered them to be the best candidates for cycle-forming mechanisms.

Adoption of the PAC model implies that the formation and member are no longer suitable for interpreting stratigraphic accumulation. The model requires that the gradualistic interpretation of stratigraphic accumulation be modified or replaced. Gradualism uses formations and members as the fundamental units of stratigraphic description and interpretation. Anderson et al. (1984) summarized the gradualistic concept of the formational boundary by stating that the formational boundary at any given locality represents the passage of an environmental boundary through that geographic point. In contrast, the PAC Hypothesis predicts that the sharp contact between distinctively different facies (observed as a formational boundary) is produced by rapid base-level rise. The contact forms when the rate of sea-level rise is rapid enough to prevent sediment from being deposited. Therefore, the disjunct relationship in facies at formational boundaries is not caused by gradual migration of once contiguous environments combined with a gradual base-level rise. Since a formational boundary at any one locality was caused by a geologically rapid rise in sea-level, a diachronous formational boundary actually must be a series of synchronous surfaces, not as a single environmental boundary which migrated laterally through time (Anderson et al., 1984)

Using the PAC as a template to analyze small-scale cyclic changes permits accurate correlation of time stratigraphic units, more refined paleoenvironmental interpretations and paleogeographic reconstructions, as well as a different interpretation of basin dynamics. In addition, application of the PAC as a fundamental unit of description and analysis permits detailed chronologic correlation because PAC

boundaries are synchronous surfaces that represent rapid base-level fluctuations (Goodwin et al., 1986).

A combination of techniques is used for correlation of PACs. These techniques include recognition of PACs with locally unique facies, boundaries marked by major facies changes, and shallowing or deepening patterns in sequences of PACs. Furthermore, it is possible to correlate at two scales, at the level of PACs and at a larger scale marked by major punctuation events recognized at several localities as the same events. In both cases, correlation is accomplished by matching patterns of facies change, not on the basis of particular facies or lithology (Goodwin et al., 1986).

Internally, each PAC represents a lateral pattern of once-coexisting environments and in vertical sequence records gradual paleoenvironmental evolution (Goodwin and Anderson, 1988). Therefore, a unique paleoenvironmental interpretation is feasible for each PAC as a 20 ky time-slice. Examples of interpretation include determination of the paleotopography at the beginning and end of each PAC, water depths during accumulation of the PAC and the magnitude of sea-level rise at a PAC boundary. Furthermore, correlation of PACs among localities allows for the detailed reconstruction of paleogeographic patterns at the scale of individual cycles (Goodwin and Anderson, 1988).

The degree of facies change at each PAC boundary is such that these surfaces separate environmentally disjunct facies. Therefore, facies above and below PAC boundaries represent paleoenvironments that were not laterally contiguous (Anderson et al., 1984). Each PAC boundary delineates an abrupt small-scale change in paleoenvironmental conditions. The approximate magnitude of each punctuation event

can be determined by analysis of the magnitude of the facies change across the lower PAC boundary. Determining a more exact figure for the magnitude of the deepening event at a locality requires assigning values to compaction, subsidence, and lag time. Punctuation events abruptly modify the paleoenvironmental spectrum but do not modify the basic paleogeography (Goodwin and Anderson, 1988). Large-scale modifications of paleogeography occur at cryptic unconformities, surfaces at which PACs are missing as a function of both tectonism and eustasy. Determination of missing PACs is accomplished by correlation above and below a cryptic unconformity. On a basin-wide scale, the thin time-stratigraphic units make it possible to interpret high-frequency patterns of sea-level fluctuations, erosion and subsidence.

The PAC model further provides a method of determining and quantifying differential subsidence within short time intervals in the stratigraphic record. Correlation of PACs establishes basin-wide synchronous surfaces between which time can be calculated by counting cycles at 20 ky each. Moreover, if the interval is bounded by sea-level surfaces, difference in thickness is totally the result of differential subsidence (Anderson et al., 1986). Finally, since the duration of each cycle is known and the thickness can be measured for each PAC, rate of subsidence can be calculated and compared for each locality.

Currently, Goodwin and Anderson (1997) view PACs in the context of a genetic hierarchy of allocycles based on Milankovitch orbital forcing mechanisms. In this model, precession is the fundamental cycle-producing mechanism; eccentricity functions as a modulator of the precessional signal by enhancing or dampening its effect

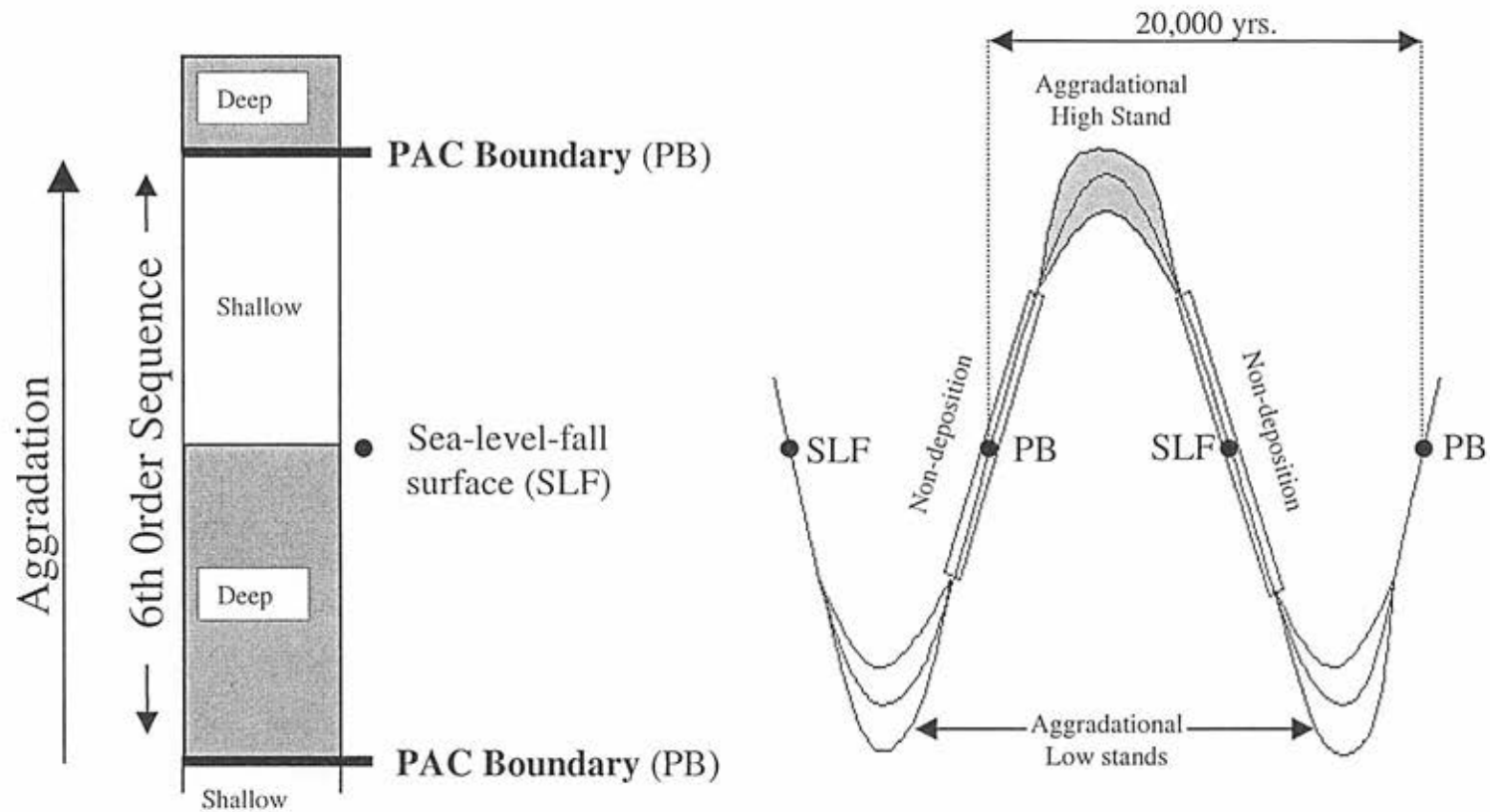


Figure 5. Precessional Eustasy and Sixth-order Sequences. PAC boundaries are formed during times of non-deposition associated with the maximum rate of sea-level rise. Aggradation occurs during times of relative sea-level stability. Sea-level-fall surfaces form during times of rapid sea-level fall. (After Goodwin and Anderson, 1997)

(Goodwin and Anderson, 1997). Dynamics of the precessional cycle produce a sharply bounded, shallowing-upward cycle (PAC) defined by disjunct facies relation at its boundaries (Figure 5). The sharp boundaries formed during times of non-deposition when sea level was rising at a maximum rate (Goodwin and Anderson, 1997). PACs also may preserve an internal non-depositional surface attributed to sea-level fall (Figure 5).

Theory of Orbital Forcing

The model of orbital forcing is based on cyclic perturbations in the Earth's rotational and orbital patterns. The model was originally conceived by Milutin Milankovitch (1941), who calculated variations in insolation values over the last 1.0 Ma and associated minimal insolation values to glacial periods in the Earth's past. Insolation is defined as the amount of solar energy received at the surface of the Earth per unit area. The insolation (Watts/m^2) at critical high latitudes varies at regular predictable intervals as a function of precession, obliquity and eccentricity. The amount of solar radiation used for the calculations was based on the energy received from the Sun at the top of the atmosphere with the assumption that the solar output is constant and the atmosphere is transparent. The theory of orbital forcing is made up of four parts (Berger, 1992):

1. Theoretical computation of long-term variations in the Earth's orbit, axial orientation and the related geometrical insolation (angle of sun light hitting the Earth).
2. Design of climatic models to transform the insolation into climatic change.
3. Collection of geologic data to be interpreted in terms of climate.
4. Comparison of the proxy data to the simulated climatic variables.

The energy available at any latitude (w) on Earth depends on the semi-major axis of the ecliptic (a), eccentricity (e), obliquity (o), and the longitude of the perihelion measured from the moving vernal equinox (φ), which combines with e to define the climatic precession parameter $e \sin \varphi$ (Figure 6).

The eccentricity of the Earth's orbit around the Sun and the precession of the Earth's axis are the two primary constituents of orbital forcing. These astronomical parameters cause variation in the spatial distribution and intensity of solar energy reaching the Earth's surface. The variation in the distribution of solar energy will affect the accumulation of ice. Maximum solar radiation occurs when the summer solstice coincides with perihelion of the orbit, during which times the volume of glacial ice decreases by melting. Minimal solar radiation values occur when the summer solstice coincides with aphelion, during which times glacial ice volume increases (Meselella, 1969).

Precession is the progressive change in the orientation of the Earth's axis through a cone, owing to the combined effects of the solar and lunar attraction to the equatorial bulge, with an absolute period of 26 ky (DeBoer, 1994). From Earth, the precessional cycle is less than this value, varying between 19 ky and 23 ky with a mean of 21.74 ky because of counter rotation of the Earth's elliptical orbit (Bassinot, 1994). Extreme values for the precessional cycle have been calculated to be 14 ky and 28 ky (Berger, 1988). Amplification of the precessional effect occurs during high eccentricity and damping occurs during low eccentricity. Within an eccentricity cycle, the number of precessional cycles could range from a minimum of three to a maximum of seven cycles with an average slightly under five cycles (Fischer, 1991).

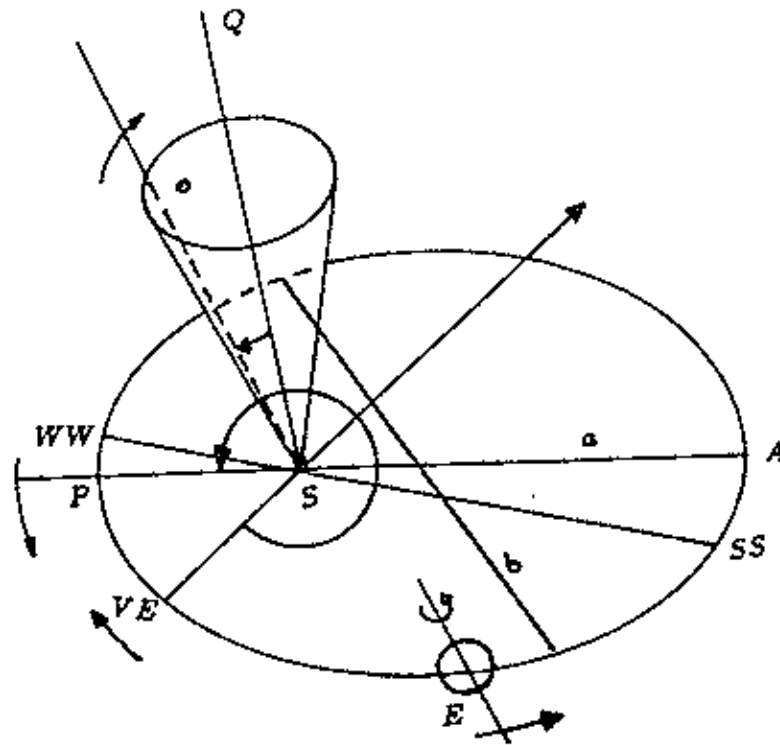


Figure 6. Elements of the Earth's Orbit. The Earth's orbit is defined by the ellipse (P EA). E = Earth, S = Sun, P = perihelion, A = aphelion, e = eccentricity is defined by $\frac{(a^2 - b^2)^{\frac{1}{2}}}{a}$, WW = winter solstice, SS = summer solstice, VE= vernal equinox, SQ = perpendicular to the elliptic, σ = obliquity, a =semi-major axis, b = semi-minor axis (Berger, 1992).

Over geologic time there is some evidence that the precessional period has increased due to the slowing of the Earth's spin (Fischer, 1991). Tidal friction causes the slowing of the Earth's rotation. Therefore, faster rotation early in the geologic record might increase the number of precessional cycles between eccentricity-modulated events.

Degree of eccentricity is given by the relative shape of an ellipse, in this case the path of the Earth around the Sun. Change in ellipticity affects the Earth's distance from the Sun (Figure 7). Orbital eccentricity is equal to the distance between the Sun and the perihelion, divided by the distance between the Sun and the aphelion. Eccentricity of the Earth's path ranges from nearly circular to an orbit that is 3 percent elliptical. The half cycle period, i.e. from minimum eccentricity to maximum eccentricity, is approximately 50 ky (De Boer, 1994). Variations in the eccentric path also occur at periods of 400 ky and 2 Ma, caused by the gravitational interaction of other planets with the Moon-Earth-Sun system (Peltier, 1994).

Allocyclic Hierarchy

Within the past decade the stratigraphic record has increasingly been recognized as a hierarchy of allocycles (Busch and Rollins, 1984, Goodwin and Anderson, 1985, Cotter, 1989, Goldhammer et al., 1990, Osleger and Read, 1991, Cisneros and Vera, 1993, Brett and Goodman, 1994, Strasser, 1994, Olsen, 1995, Elrick, 1996 and Balog et al., 1997). However, approaches to interpreting this hierarchic record vary considerably, both in concepts of hierarchy and in criteria for defining cycles. Most hierarchic models of allocyclicality do not associate particular rock cycles to any one periodic process. For

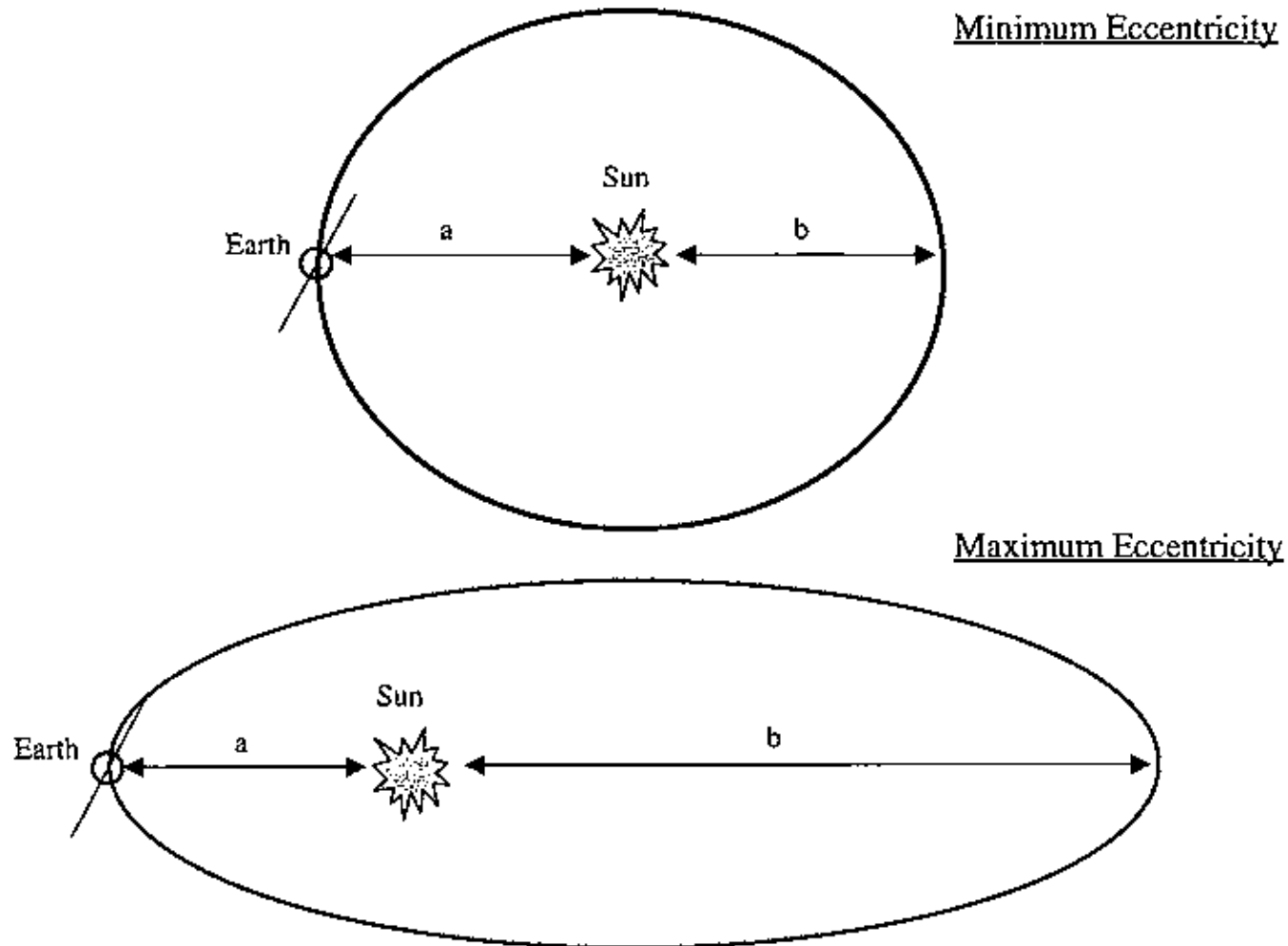


Figure 7. Orbital Eccentricity. From minimum eccentricity to maximum eccentricity is 50,000 years. At minimum eccentricity $a=b$ and at maximum eccentricity $a<b$. (Note: Earth is in the summer position.)

example, the hierarchic model adopted by Goldhammer et al. (1994) was one in which cycles were placed in a range of geological time. These arbitrary temporal compartments are: third-order cycles ranging in time from 1 to 10 Ma.; fourth-order cycles between 100 ky and 1 Ma.; and fifth-order cycles ranging in duration from 10 ky to 100 ky.

Using this approach, Goldhammer et al. (1994) recognized two levels of cyclicity in the Middle Pennsylvanian (Desmoinesian) of SW Paradox Basin, Utah. These levels of cyclicity consisted of a hierarchy fourth-order cycles (1 Ma. to 100 ky) ranging from 55 to 153 feet and fifth-order cycles (100 ky to 10 ky) ranging from 6 to 39 feet. Together, these two kinds of cycles constitute the third-order (10 Ma. to 1 Ma.) Desmoinesian sequence. The fourth-order cycles were grouped into a third-order sequence based on progressive thinning of the fourth-order cycles resulting from a decrease in accommodation space. The fourth-order cycles were subsequently divided into fifth-order cycles. Goldhammer et al. (1994) combined this concept of hierarchy with a definition of cyclicity dependent on repetition of lithology. For example, fourth and fifth-order sequences were bounded by subaerial exposure surfaces, the better-developed caliches occurring at fourth-order sequences boundaries (Goldhammer et al., 1994).

Fifth-order cycles were further defined by the occurrence of black laminated mudstone. In this hierarchy the number of fifth-order cycles contained within fourth-order cycles ranged from three to nine, suggesting either a high degree of incompleteness or inconsistency in recognition of cycles, possibly at both scales. The wide range of thickness in both fourth and fifth-order cycles suggests that Goldhammer et al. (1994) were not consistently discriminating cycles produced by specific processes. Therefore,

this approach in which ranks in a hierarchy are not linked to process and cycles are defined by lithology does not permit determination of the stratigraphic response of each of the orbital processes.

Another hierarchic model introduced by Goodman and Brett (1994) was based on a "nested" hierarchy with seven orders. Applying the model, they divided the Silurian strata of the Appalachian Foreland Basin into approximately eight third-order depositional sequences. Each laterally correlative third-order sequence was bounded by regionally recognized unconformities. The duration of the third-order sequences ranged from 1.5 to 5.0 Ma. Internal to the third-order sequences were two or more fourth-order sub-sequences suggesting a nested hierarchy of allocycles (Goodman and Brett, 1994). Each sub-sequence has a recurrence range of 0.9 to 1.5 Ma. Sub-sequences are defined by less erosive bounding disconformities than those bounding the third-order sequences. Goodman and Brett's (1994) small-scale cycles, fifth-order parasequence sets correspond to highstands and lowstands in relative sea-level (Goodman and Brett, 1994). The parasequence set is defined by facies variations and lateral changes in symmetry as a function of minor fluctuations in sea-level. Parasequence sets range from 400 - 500 ky in duration and range in thickness from 1 to 10 m. Sixth-order parasequences have a recurrence interval that averages 100 ky and range in thickness from 0.5 to over 1.0 m. These parasequences are the smallest unit that is laterally correlative and are caused by minor fluctuations in relative sea-level (Goodman and Brett, 1994). Their seventh-order cycles or rhythmic bedding cycles are found internal to the sixth-order cycles but do not have a specific duration and can not be correlated among localities.

Brett and Goodman's (1994) model suggests that ranks in the stacked hierarchy, consisting of fourth, fifth and sixth-order sequences, all range in both duration and thickness. These extreme variations in thickness and duration may indicate that Goodman and Brett (1994) may have included more than one genetic cycle in each rank. This possible inconsistency in cycle definition would account for the wide range in thickness and duration. A more strictly process-determined approach, starting with the assumption of periodic orbital forcing mechanisms could produce a more consistent interpretation.

In summary both Goodman and Brett (1994) and Goldhammer et al. (1994), while attempting to link cyclicity with an allogenic mechanism, do not adopt approaches which facilitate discrimination of each separate process. Rather, these approaches tend to produce hierarchic ranks that contain more than one genetic cycle.

In contrast, the approach of Goodwin and Anderson (1997) is strictly process determined (Table 1). Each rank in the hierarchy is linked to a specific allocyclic periodic mechanism.

Table 1. Genetic Hierarchy of Allocycles (Goodwin and Anderson, 1997)

Rank	Period	Mechanism
2 nd Order (Supersequence)	10 million years	Tectono-Eustasy
3 rd Order (Sequence)	2 million years	Eccentricity ?
4 th Order	400,000 years	Long Eccentricity
5 th Order	100,000 years	Short Eccentricity
6 th Order (PAC)	20,000 years	Precession

Since these processes are periodic, stacking patterns of resulting cycles are predictable and tightly constrained. In addition, each rank in the hierarchy is characterized by cycles having specific symmetry. Large-scale Supersequences (2nd order), first recognized by seismic stratigraphers (Haq et al., 1987), are packages of strata bounded by major unconformities caused by global sea-level fluctuations. Currently, within the hierarchic PAC model the supersequence has a recurrence interval of 10 Ma., and is thought to form as a function of tectono-eustasy. Internally, second-order sequences are divisible into five third-order sequences, each having a duration of 2 Ma and a forcing mechanism of a long eccentricity cycle (Olsen and Kent, 1996). These also are unconformity-bounded sequences consistent with the usage of Haq et al. (1987)

Small-scale cycles have durations within the Milankovitch-band. The sixth-order sequence (PAC), a function of the precessional cycle (averaging 20 ky), is the fundamental unit in the genetic hierarchy. The boundaries are defined by an abrupt change in facies from shallow to deep. PACs are internally asymmetrical exhibiting deeper facies at the base and shallower facies toward the top. Likewise, each order of the hierarchy has a specified duration, symmetry, stacking pattern and degree of facies change associated with a specific process (Figure 8).

A fifth-order sequence is a function of short eccentricity modifying the precessional cycle by amplifying some sea-level rises and reducing others. Fifth-order boundaries are defined by a significant magnitude of change in facies caused by an amplified precessional event. Internally, fifth-order sequences consist of five 20 ky sixth-order sequences. The second sixth-order sequence generally contains the deepest facies. Following this deepest cycle, successive cycles in a fifth-order sequence each

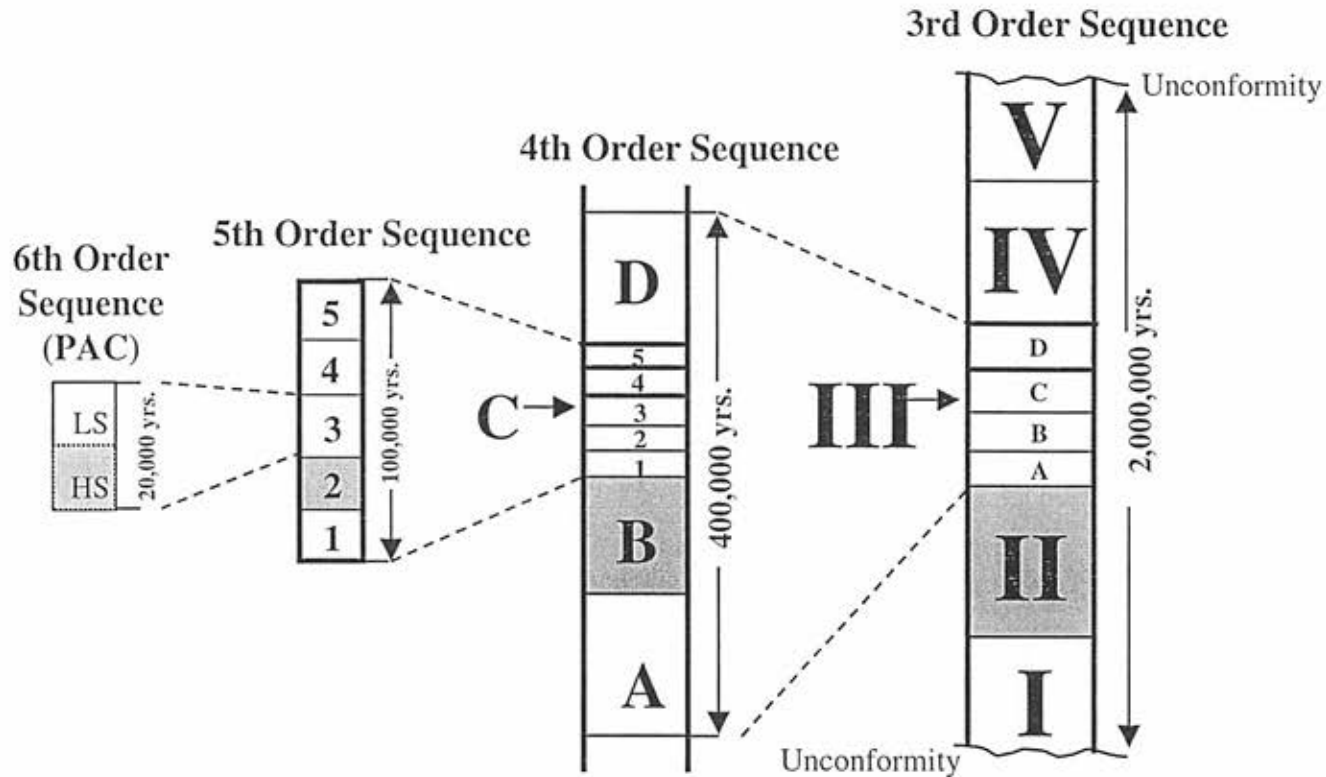


Figure 8. Hierarchy of Stacking Patterns. Genetic hierarchy of allocycles linked to specific periodic orbital cycles. Precession produces the fundamental sixth-order sequence. Eccentricity modulates the bundling of these sequences into fifth-order, fourth-order and third-order sequences. Shaded cycles represent the deepest facies within the respective sequence. (HS = high stand; LS = low stand).

are characterized by progressively shallower facies. The total duration of the fifth-order sequence is 100 ky.

A fourth-order sequence is a function of long eccentricity (400 ky) modifying the precessional cycle. Furthermore, the internal structure of the fourth-order sequence shows an asymmetric pattern, in which the first fifth-order sequence contains markedly deeper facies than the underlying fifth-order sequence and the second fifth-order sequence generally contains the deepest facies. The remaining two fifth-order sequences are successively shallower. Thus, a typical fourth-order sequence is initiated by a reversal of the shallowing facies trend in the upper portion of the underlying fourth-order sequence.

Therefore, according to the PAC model every rank is connected to a periodic process, ranks are distinguished by specific patterns of symmetry and types of cycles are discriminated on the degree of facies change at their boundaries. The other two models presented did not specifically connect cycles to periodic processes. In addition, they did not suggest a consistent pattern to the cycles nor were the boundaries of cycles based on a general pattern of facies change. This study incorporates the process-determined hierarchic model in an effort to discriminate the stratigraphic response to each of the orbital cycles.

CHAPTER 3

FACIES ANALYSIS OF THE WILLS CREEK FORMATION

Previous Descriptions and Interpretations

C.K. Swartz (1923), F. M. Swartz (1943), Lacey (1960) and Hoskins (1961) made significant contributions to the description and understanding of Wills Creek facies. In particular, Swartz (1923) detailed description of the Pinto locality was useful in precisely placing the study interval in a traditional stratigraphic context and in providing confirmation of facies descriptions and interpretations (Appendix A). Specifically, the study interval begins 150 feet above the base of the Wills Creek Formation as described by Swartz (1923). In that description, Swartz placed the base of the Wills Creek at the base of a sandstone unit now called the Willamsport Sandstone (Hoskins, 1961).

In his investigation of the stratigraphy and paleontology of the Bloomsburg Formation, Hoskins (1961) included a description of the contact between the Wills Creek and Bloomsburg Formations and a brief description of the Wills Creek Formation at Mt. Union. He placed the boundary between the formations at the bed below which the rock is predominantly red and above which the rocks are predominantly of mixed color. This boundary between the Bloomsburg and Wills Creek Formation is 110 feet above the above the base of the first thick (2 feet and 5 inch) red sandstone bed, above the concealed interval. Furthermore, this point is 20 feet above where Swartz (1943) placed the formational boundary. At Mt. Union, Hoskins (1961) described the Wills Creek Formation as variegated claystone, with some fissile and calcareous sections.

Previous work on the Wills Creek Formation included only minimal facies descriptions by Swartz (1923); Lacey (1960) and Hoskins (1961). Swartz (1923) suggested that the depositional environment of the Wills Creek Formation was shallow quiet water. Lacey (1960) suggested that the cycles formed in response to fluctuating sea-level; the carbonate units formed when sea-level was highest and offshore, and the claystone units when the sea-level was lowest and onshore. Hoskins (1961) in his facies description of the Bloomsburg Formation described units now considered part of the lower Wills Creek Formation at both localities. His interpretation, particularly of those strata containing ostracods, indicated that deposition occurred offshore of a fluvial coastal plain system in shallow brackish lagoons.

Criteria for Facies Analysis

My analysis of cycles in the Wills Creek Formation is based on detailed lithologic and faunal analysis of five facies, which occur in consistent repetitive patterns throughout the studied interval (Table 2). The criteria used for description and analysis of lithofacies were color, texture, sedimentary structures and fauna. The recognized lithofacies, in order of most restricted to most open facies, are:

1. Red or green shale facies- (Supratidal)
2. Massive and laminated dolomite facies- (High intertidal)
3. Laminated limestone and shaley laminated limestone facies- (Intertidal)
4. Oolitic and pelletal calcarenite facies- (Restricted subtidal)
5. Shelly calcarenite facies- (Open subtidal)

Each facies is an indicator of an approximate location within a restricted shallow subtidal to peritidal environment.

Table 2. Facies of the Wills Creek Formation

Facies	Environmental position	Color	Texture	Sedimentary Structures	Fauna
Red/green shale	Supratidal	Light red olive green to light green	Silt and clay sized grains that are well sorted	Mud cracks Bioturbation	No fauna present
Laminated and massive dolomite	High intertidal	Light gray to dark gray and buff/ yellow	Silt-sized grain with coarser grained sparry areas	Millimeter scale laminations, some cross lamination	Algal laminites and thrombolites
Laminated limestone	Intertidal	Light gray to dark gray and	Silt-sized grain with coarser grained sparry areas	Millimeter scale laminations, some cross lamination	Algal laminites and thrombolites
Oolitic and pelletal calcarenite	Restricted subtidal	Dark gray	Coarse-grained with well sorted ooids and pellets	Cross lamination	Ostracod shell fragments
Shelly calcarenite	Open subtidal	Dark gray	Coarse-grained with shell and lithic fragments	Cross lamination	Ostracod shells, fragments of other arthropods, echinoderm fragments and pieces of brachiopod shells

Within the Wills Creek Formation the grain size for the terrigenous material ranges from clay size (0.002 mm) to coarse sand (1.0 mm). These sediments range from well rounded and very well sorted to angular and poorly sorted. Similarly, carbonate grains range from a fine micrite to microspar (0.004-0.016 mm) to coarse allochems (0.25- 2.0 mm). The allochems of the coarser-grained carbonates include intraclasts, ooids, pellets, ostracod shells, trilobite fragments and other skeletal debris. These allochems range from well sorted to poorly sorted. Generally, the ooids and pelletal material are well sorted, but the ostracod shells and other arthropod fragments are not as well sorted.

Several different types of sedimentary structures occur within the Wills Creek Formation. These structures include, at the outcrop scale, mud cracks, cross-stratification and flat laminated to domal stromatolites. At the microscopic scale, the structures include millimeter-scale ripple cross-lamination and millimeter-scale flat laminations. Occasionally, the thin-sections contain evidence of penecontemporaneous sediment deformation including bioturbation and possible water escape structures.

Faunal content was limited primarily to algal material and ostracods. However, fragments of echinoderms, brachiopods and trilobites were present in the most open marine facies. Combining the limited faunal information with textural and sedimentary structural data allows for detailed interpretation and description of the peritidal to restricted subtidal facies present in the Wills Creek Formation.

Facies Description and Interpretation

Red or Green Shale Facies

This facies is lithologically represented by arenaceous red and green shale. The color of the green shale varies from a light green to olive-green. The red shale within the studied section of the Wills Creek Formation is a light red or pink. The red or green shale is predominantly clay and silt size material and varies between massive and fissile. Sedimentary structures include mud cracks and bioturbation. I found no evidence of fauna within this facies. In contrast, Swartz (1923) noted the presence of *Leperditia alta* in the lower 3 feet of a green shale unit that is the second cycle in Sequence A at Pinto (Appendix A); the presence of fauna is a probable indication of a storm deposit. In conclusion I found that the red or green shale facies is the most restricted facies and formed in the highest supratidal zone.

Laminated and Massive Dolomite Facies

Fine-grained laminated dolomite and massive dolomite (Figure 9) lithologically represent this facies. These dolomites range from buff to yellow in color. However, when a fresh surface is exposed these dolomites are dark gray in color. The massive dolomite consists of silt size grains with some coarser grained sparry areas. The laminated dolomite contains millimeter-scale planar to wavy laminations; the upper part of these units may be mud cracked. Some of the dolomitized flat laminated stromatolites have interbedded sediment between them indicating episodic flooding, probably in the high intertidal zone (Figure 10). Some of the thin-sections show low-angle cross-lamination. The fauna is limited to occasional fragments of ostracods. Cryptagal

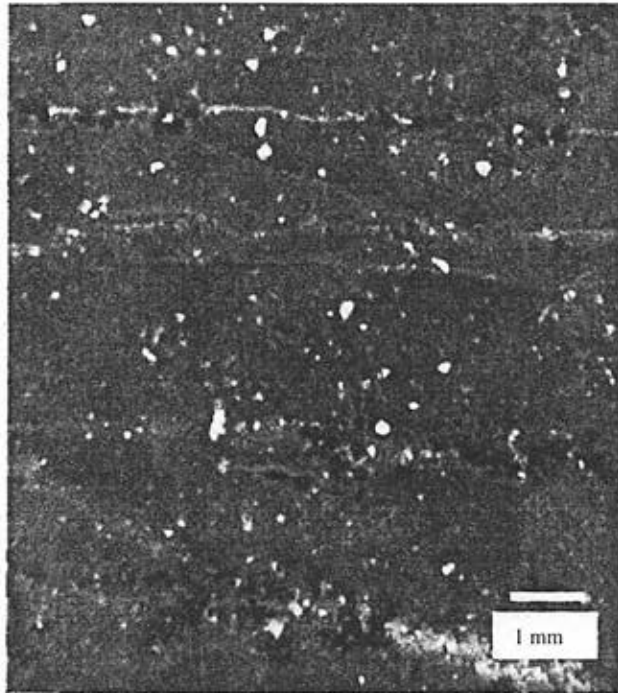


Figure 9. Massive Dolomite Facies. Massive dolomitic mud with limonitic staining. Sample # 912 Cycle D-4, Mt. Union (Figure 32).

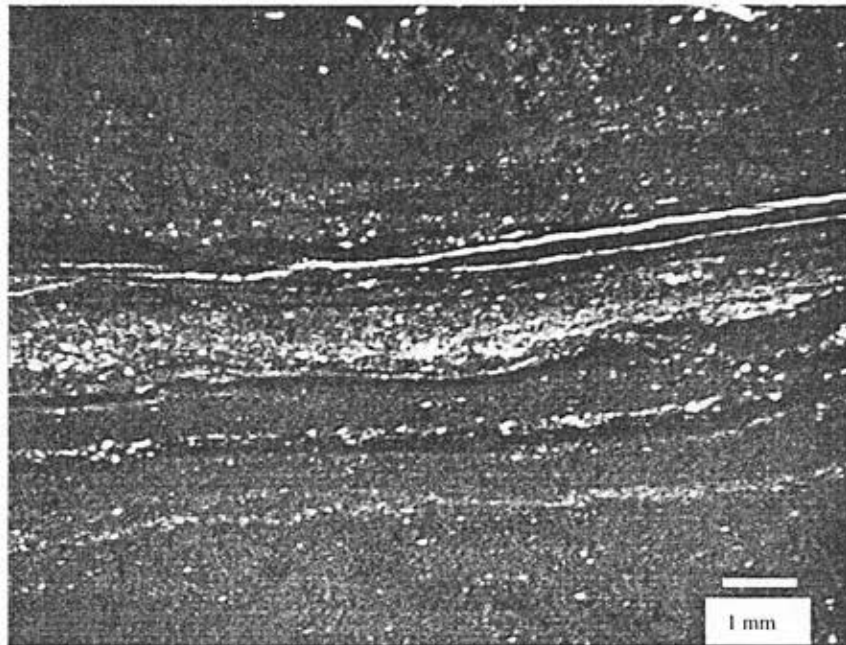


Figure 10. Laminated Dolomite Facies. Dolomitic millimeter-scale, graded cryptalgal lamination. Sample # M8, Mt. Union (Figure 22).

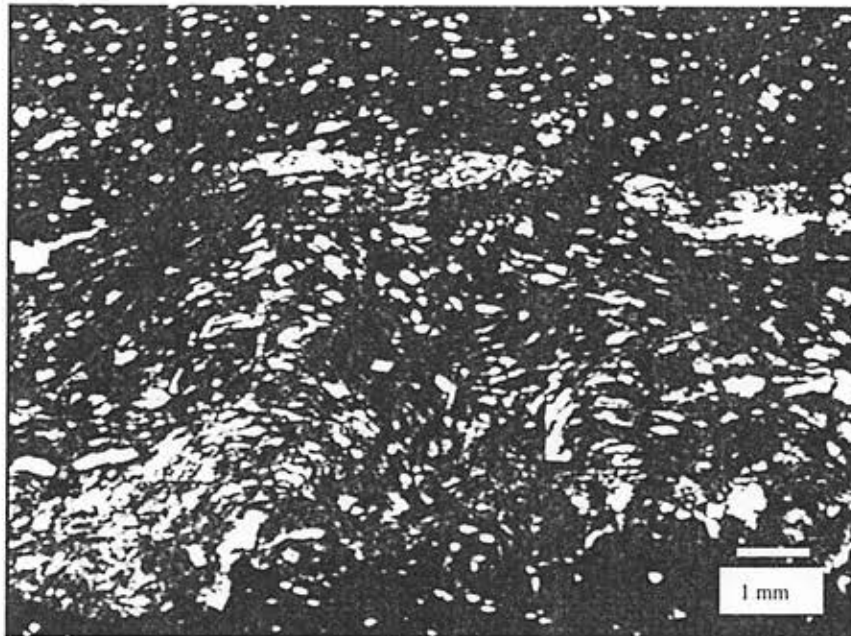


Figure 11. Laminated Limestone Facies. Small-scale domal stromatolites with fenestral fabric. Sample # 96, Pinto (Figure 33).

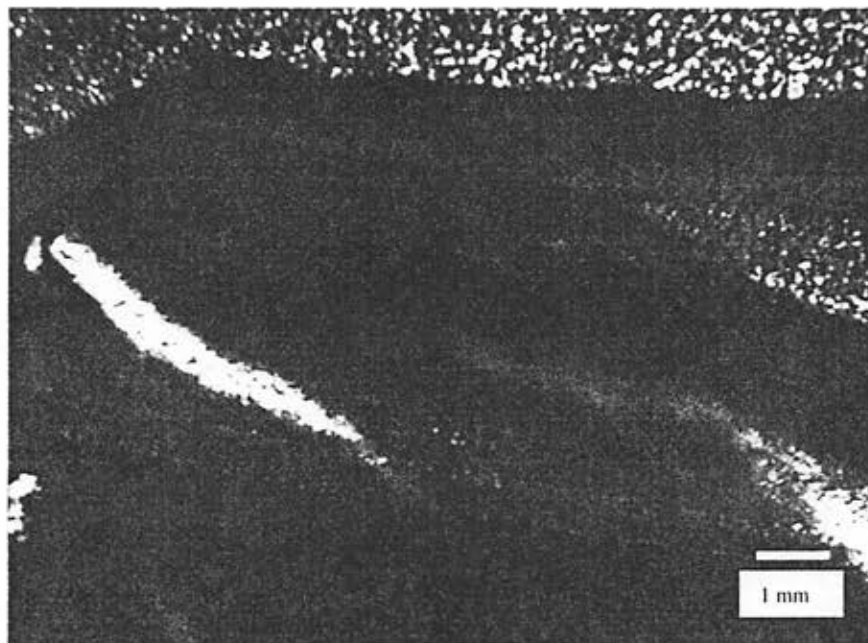


Figure 12. Laminated Limestone Facies. Small-scale, graded, ripple cross-lamination. Sample # 97, Pinto (Figure 33) .

lamination is common. At the time of deposition the area was covered by shallow water at high tide, allowing for saturation of the sediment followed by subaerial exposure causing the formation of mud cracks and growth of algal mats. Penecontemporaneous dolomitization suggests elevated salinities high in the tidal zone.

Laminated Limestone Facies

Flat laminated and domal stromatolitic limestone (Figure 11) is common in this facies, which varies from dark gray to light gray in color. These stromatolitic structures are thought to be produced by the binding of sediment by algal mats. The stromatolitic limestone are in places interbedded with calcisiltite to fine calcarenite beds with bipolar ripple cross-lamination interpreted as the product of tidal current reversals (Figure 12). This facies also contains beds of massive micritic limestone (Figure 13). Throughout this facies mud cracks with shale partings are evident, a function of wetting and drying of the low intertidal zone. Fauna within this facies is limited to an occasional ostracod shell fragment in addition to stromatolitic structures, in both the laminated and massive micritic units (Figure 13).

Oolitic and Pelletal Calcarenite Facies

Oolitic (oosparite) and pelletal calcarenite (pelsparite) facies are lithologically represented by fine-grained ooids and pellets within a sparite matrix (Figure 14). The lithology is dark gray in color when a fresh surface is exposed. However, the rock weathers to a light gray or buff color. The ooids and pellets are well-sorted and range in size from 0.25 to 2 mm. Cross-lamination is present in some beds observed in the field

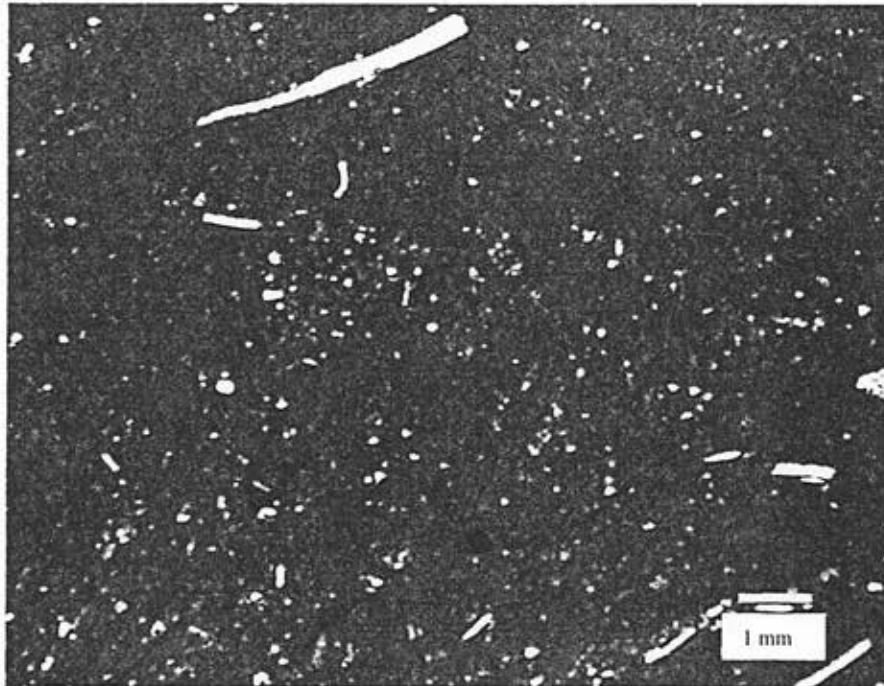


Figure 13. Laminated Limestone Facies. Massive bioturbated micrite with scattered ostracod fragments. Sample # M5, Mt. Union (Figure 32).

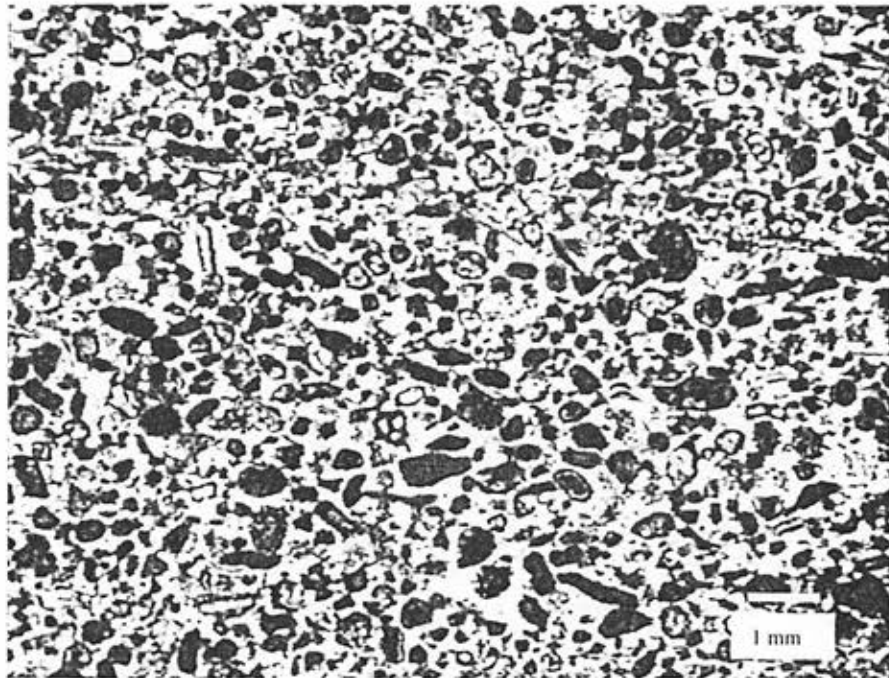


Figure 14. Oolitic and Pelletal Calcarenite Facies. Fine-grained, oolitic, pelletal sparite. Sample # 910, Mt. Union (Figure 27).

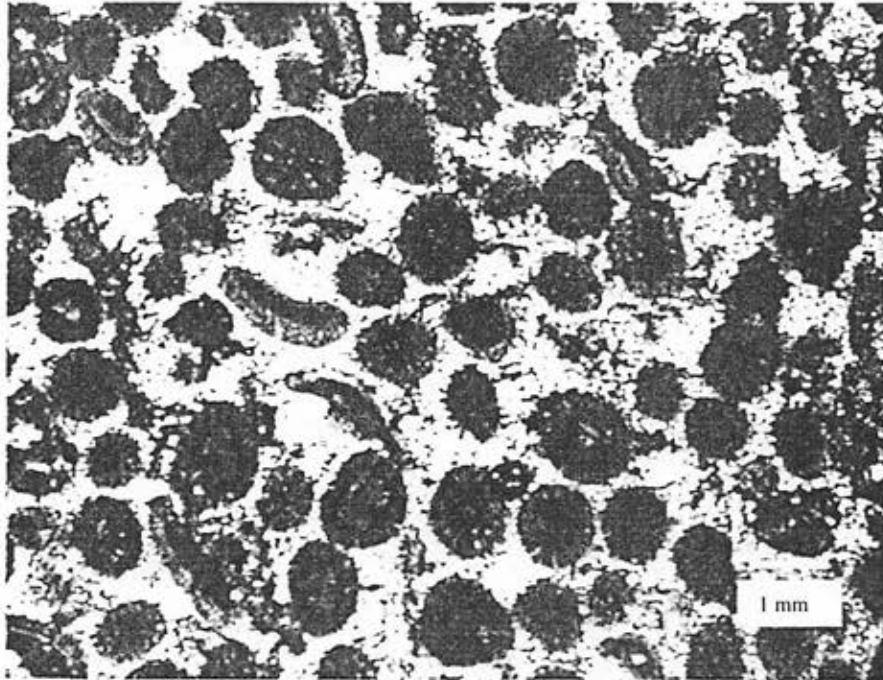


Figure 15. Oolitic and Pelletal Calcareenite Facies. Coarse-grained oosparite with occasional oolitic coating on the ostracod shells. Sample # M1, Mt. Union (Figure 31).

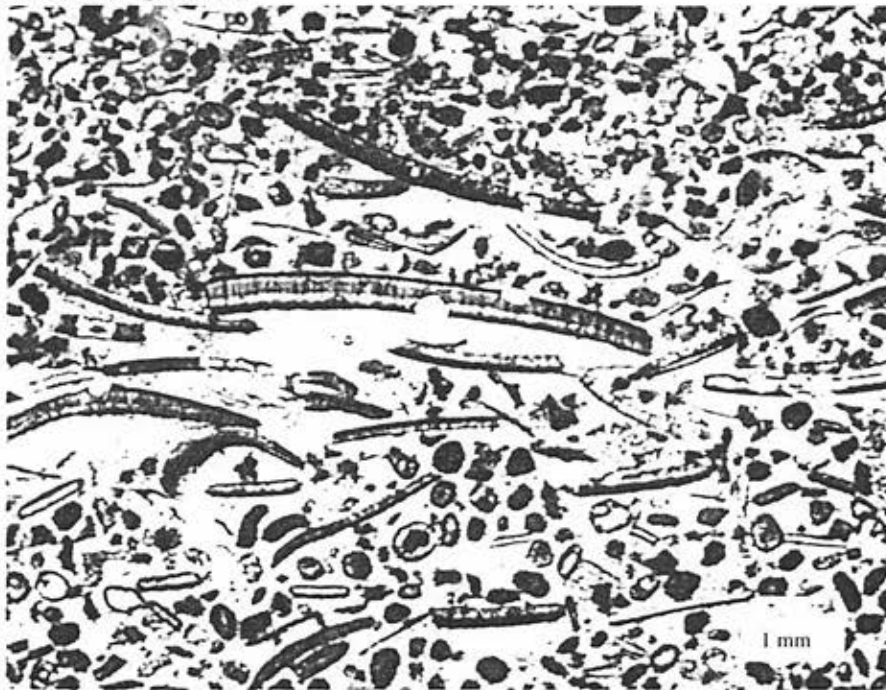


Figure 16. Shelly Calcareenite Facies. Poorly-sorted ostracod and trilobite biosparite with occasional pellets and ooids. Sample # 92, Pinto (Figure 26).

and within some of the thin-sections. Occasionally, shell fragments are present among the fine-grained oosparite and pelsparite facies (Figure 15). This facies formed in a shallow subtidal environment.

Shelly Calcarenite Facies

Ostracod shells, other arthropod fragments, echinoderm fragments and small pieces of brachiopod shell in a coarse-grained biosparite in a sparite matrix represent the shelly calcarenite facies. The degree of sorting ranges from poorly-sorted (Figure 16) to well sorted (Figure 17), with the poorly sorted facies including lithic fragments (Figure 18). Size of the shell fragments ranges from 1.0 mm to 6.0 mm. The lithology is a dark gray to dark brown in color. This facies is the most open of the restricted environments, which formed in the shallow subtidal environment.

Facies Summary

Based on thin-section and outcrop analysis of the Wills Creek Formation, sediment was deposited in a spectrum of peritidal environments ranging from supratidal marsh to restricted shallow subtidal (lagoonal). The shallowest environment in the Wills Creek Formation is the supratidal marsh, represented by green or red shale facies. Dolomitic laminites and limey laminites represent the intertidal facies. Oolitic calcarenite and shelly calcarenite constitute the deepest environments, current-washed but restricted, shallow subtidal lagoons.

The pattern of facies change is interpreted in relation to relative sea level and degree of restriction from open marine circulation. The environmental position therefore

is a function of eustatic sea level fluctuations in relation to global glacial ice volume. For example, when there is an abrupt change from the red/green shale facies to the shelly-calcarenite facies, the interpretation is that a rapid rise in sea level occurred in relation to the glacial ice melting. Such patterns of facies change repeat themselves in a cyclic manner. These cycles are asymmetric and shallowing upward throughout the formation. The cycles are defined by subtidal facies (shelly-calcarenite and oolitic-calcarenite) at the base and high intertidal to dolomitic laminites to supratidal facies (red or green shale) at the top. Specific cycle definitions with regard to facies are given in the next chapter.

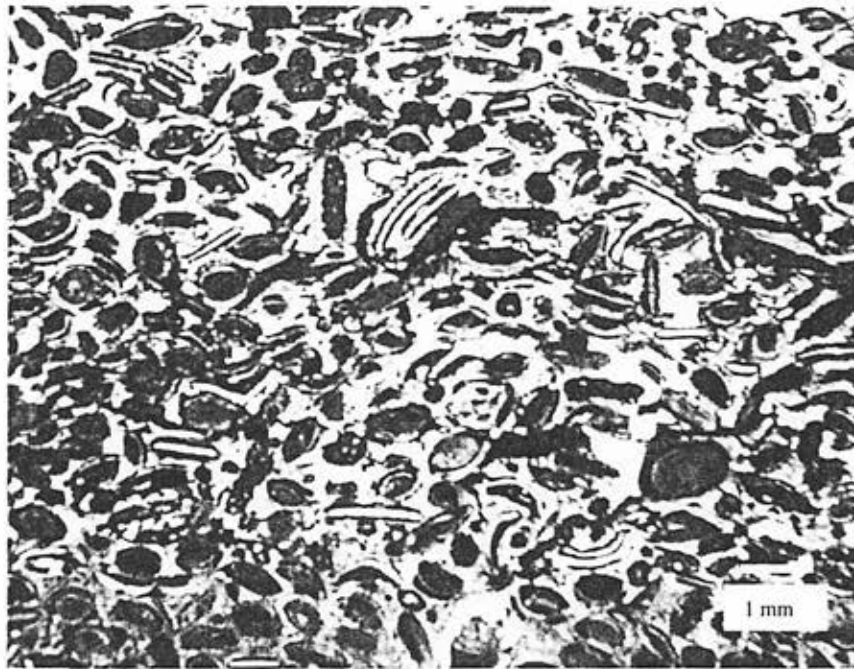


Figure 17. Shelly Calcarenite Facies. Well-sorted ostracod biosparite with occasional pellets. Sample # 911, Mt. Union (Figure 32).

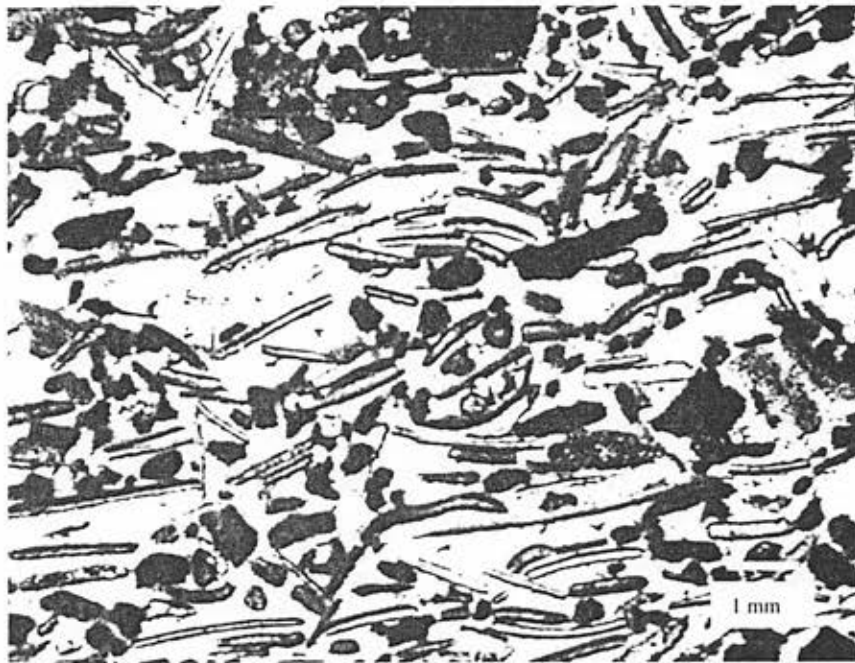


Figure 18. Shelly Calcarenite Facies. Poorly -sorted ostracod and trilobite biosparite with prominent micritic intraclasts. Sample # 93, Pinto (Figure 26).

CHAPTER 4

ALLOCYCLIC INTERPRETATION OF THE MIDDLE WILLS CREEK FORMATION

Introduction

Several studies of the Appalachian Foreland Basin have investigated the cyclic nature of Late Silurian formations throughout Pennsylvania and Maryland (Lacey, 1960; Cotter and Inners, 1986; Cotter, 1988; Chadwick and Goodwin, 1993; Mauriello and Ketterer, 1993; Shelton and Anderson, 1993; Goodman and Brett, 1994; Clark et al., 1996; Zeliznak et al., 1998, and Brown et al., 1998). All of the studies, except that of Lacey (1960), indicate that a cyclic hierarchy exists within the Late Silurian rocks. However, the authors' approaches to this hierarchic record are varied, as are their interpretations. For example, Brett and Goodman (1994) defined their basic cycles (sequences) as unconformity-bound packages correlative throughout the basin. These sequences, in turn, were subdivided into subsequences and parasequences, which had no consistent internal facies pattern (e.g., shallowing-upward or deepening-upward). In contrast, a method introduced by Goodwin and Anderson (1985) discriminated cycles based on consistent patterns of facies change. This study will apply the PAC model (e.g., Goodwin and Anderson, 1985; Anderson and Goodwin, 1990) and the assumption of a Milankovitch hierarchy based on patterns of facies change (Goodwin and Anderson, 1997), to interpret the allocyclic nature of Late Silurian rocks in the Wills Creek Formation in the Appalachian Foreland Basin. This study is part of a continuing effort by

Anderson, Goodwin and their students (e.g. Chadwick, 1994; Shelton, 1995) to link specific ranks in a hierarchic stratigraphic record to individual processes of origin.

Large-scale Cyclic Framework

The Wills Creek and Tonoloway Formations constitute the Salina Supersequence, a probable second-order, 10 Ma. (Haq et al., 1987) allocycle consisting largely of peritidal facies (Table 1). The Wills Creek Formation is lithologically dominated by terrigenous material, while the Tonoloway Formation is dominated by carbonate material. The overall thickness of this supersequence is 326 meters at Pinto, Maryland (Swartz, 1923) and 390 meters at Mt. Union (Swartz, 1934). Within the Salina Supersequence, there are five, 2 Ma. third-order sequences.

In the approach of Goodwin and Anderson (1997), third-order sequences (2 Ma) are large-scale transgressive-regressive sequences consisting of five fourth-order sequences, the second of which contains the deepest facies. The subsequent three fourth-order sequences exhibit a shallowing trend. The next fourth-order sequence reverses this shallowing trend and starts a new third-order sequence (see Figure 8).

The focus of this study is on a single fourth-order sequence, the third fourth-order sequence in the second third-order sequence in the Wills Creek Formation (Figure 19) at two localities in Pennsylvania and Maryland. Analysis of the lithologic composition and internal structure of this fourth-order sequence over a distance of 150 km allows for significant detailed interpretations of Silurian paleogeography and basin dynamics.

Salina Supersequence

2nd Order- 10 Million Years

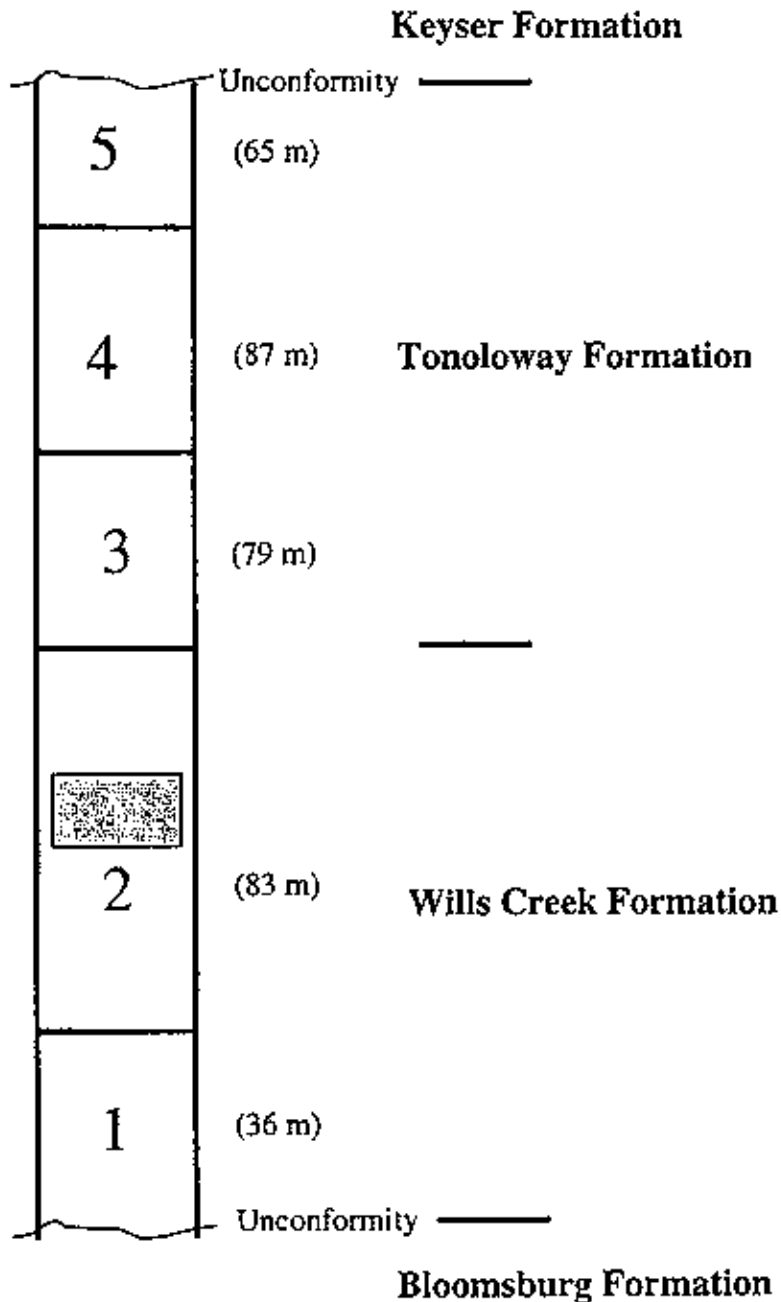


Figure 19. The Five Third -Order Sequences in the Salina Supersequence. Each third-order sequence encompasses 2 million years. Shaded area is the fourth-order sequence studied.