# CORRELATION OF MILANKOVITCH-BAND CYCLICITY IN THE PERITIDAL CARBONATES OF THE TONOLOWAY FORMATION, CENTRAL PENNSYLVANIA AND WESTERN MARYLAND

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A Thesis Submitted
to the Temple University Graduate Board

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in Partial Fullfiment
of the Requirement for the Degree

**MASTER OF ARTS**

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William Chadwick

December 1993

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# ABSTRACT

A hierarchic cyclic pattern consistent with the Milankovitch model of orbital forcing characterizes the Upper Silurian Tonoloway Formation. At three localities in Pennsylvania and Maryland, the Tonoloway Formation is divisible into three Third Order sequences (2 million years duration). The first of these Third Order sequences (44 to 53 meters thick) is an incomplete, shallowing-upward cycle divisible into four shallowing-upward Fourth Order sequences (400 ky eccentricity), averaging 13.2 meters thick defined by the most open facies in the first Fifth Order cycle and the most restricted in the last. Each Fourth Order cycle is divisible into four shallowing-upward Fifth Order sequences (100 ky eccentricity), averaging 3.3 meters thick, defined by the most open facies in the second Sixth Order cycle and the most restricted in the last. Each Fifth Order sequence is divisible into three to five sharply bounded, shallowing-upward, Sixth Order cycles (20 ky precessional) containing a sharp, sea-level-fall surface separating its upper shallower facies from its lower deeper facies.

These asymmetric cyclic patterns can be correlated between Mount Union, Pennsylvania and Pinto, Maryland, a distance of 150 kilometers. The similarity of symmetry and thickness of all cycles over this distance indicates that the principal cause of the stratigraphic fabric of the Tonoloway Formation was eustacy driven by multiple cycles of orbital perturbation. The greater overall thickness of the interval in Pennsylvania indicates greater rates of subsidence in this area.

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# ACKNOWLEDGEMENTS

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# CHAPTER 1

# INTRODUCTION

Cyclic stratigraphic analysis has become a new method of interpreting the stratigraphic record. Beginning with the work of Vail and others (1977) on seismic stratigraphy, the interpretation of the stratigraphic record has moved from an analysis based on facies models and the gradual accumulation of the stratigraphic record to an analysis of cyclic patterns resulting from orbital perturbations that caused global fluctuations in base-level.

Work on stratigraphic cyclicity has led to the recognition of both large-scale and small-scale cyclic patterns. Data on large-scale cycles, attained through seismic reflections and core sampling, make it possible to examine basin-wide patterns of cyclicity resulting from long-term global eustatic sea-level fluctuations (Vail et al., 1977; Posamentier et al., 1988; Posamentier and Vail, 1988). Small-scale cyclic patterns are not recognizable using seismic reflection and core samples, but instead require outcrop data. The investigation of small-scale cyclic patterns in outcrop led to the development of the PAC Hypothesis of Goodwin and Anderson (1985) and the application of the concept of Milankovitch-band orbital forcing as a mechanism for explaining the cyclic patterns observed in the stratigraphic record (Olsen, 1986; Anderson and Goodwin, 1990; Fischer and Bottger, 1991; Goldhammer et al., 1991).

Numerous investigators have identified small-scale, upwardly shallowing (fining) sequences, many exhibiting evidence of exposure at the top, as a basic unit in the stratigraphic record (Busch and Rollins, 1984; Koerschner and Read, 1989; Elrick Read, 1991; Osleger and Read, 1991; Goldhammer et al., 1991). Eustatic sea-level fluctuation is agreed upon as the dominant control on cyclic patterns identified by these investigators and most rely on Milankovitch-band orbital forcing as a mechanism (Busch et al., 1984; Goodwin and Anderson, 1985; Goodwin et al., 1986; Cotter, 1988; Brett et al., 1990; Osleger and Read, 1991; Elrick and Read, 1991; Goldhammer et al., 1991).

This project is an analysis of small-scale cyclic patterns in the Upper Silurian Tonoloway Formation of Central Pennsylvania and Western Maryland. The investigation of the Tonoloway Formation will be conducted using the PAC Hypothesis in conjunction with Milankovitch-band orbital forcing as a possible mechanism for the patterns revealed. Specifically, this study will compare the stratigraphic fabric of the Tonoloway with the predicted genetic hierarchy of allocycles produced by a hierarchy of orbital cycles.

The Upper Silurian Tonoloway Formation of Central Pennsylvania and Western Maryland contains shallow marine to supratidal carbonates. Cyclic patterns have been identified previously in a broad range of similar facies applying the PAC Hypothesis (Anderson et al., 1984; Goodwin and Anderson, 1985; Goodwin et al., 1986; Orzechowski et al., 1992; Mauriello and Ketterer, 1993; Shelton and Anderson, 1993). In the Tonoloway Formation, small-scale cyclic patterns have been described by Cotter and Inners (1989) at Allenport, Pennsylvania, by Smith and Anderson (1992) at the Canoe Creek Quarry in Central Pennsylvania and by Cotter (1993) in the Appalachian Foreland Basin.

Demonstration of the existence and correlation of small-scale cyclic patterns over

150 km, consistent with a hierarchy of cycles based on Milankovitch-band orbital forcing, will support the use of allocyclic patterns in the interpretation of the stratigraphic record. Using Milankovitch-band orbital cyclicity as the driving mechanism of the cyclic patterns will assist in the examination of subsidence and eustacy dynamics during the deposition of the Tonoloway Formation because correlated cycles are time slices in the stratigraphic record.

Criteria for recognizing cyclic patterns are documented with field observations and petrographic analysis of selected samples. Petrographic analysis will be used to identify representative facies and evaluate degree of facies change between cycles at different scales in the hierarchy of cycles in the Tonoloway Formation.

The identification of small-scale cyclic patterns, consistent with the genetic hierarchy demanded by Milankovitch-band orbital forcing, within the Tonoloway Formation by Smith and Anderson (1992) and Chadwick and Goodwin (1993) has directed the path of this investigation. Systematic study of a major portion of the Tonoloway will build on these initial efforts and place Tonoloway cyclicity in the context of a Milankovitch hierarchy.

# CHAPTER 2

# STRATIGRAPHIC FRAMEWORK

## Tonoloway Formation

The Tonoloway Formation encompasses approximately 3/5 of the Upper Silurian Salina Group, a 10 million year Second Order sequence (Figure 1). Although the Tonoloway Formation received its name from Tonoloway Ridge, west of Hancock, Maryland, the true type locality is the exposure along the Chessie System Railroad at Pinto, Maryland (Swartz,1923; Smosna and Warshauer, 1979) present limits of the Tonoloway Formation were first defined at Pinto by Swartz (1923). Swartz (1923) identified a massive limestone bed, 9 feet 6 inches in thickness, as the base of the formation. Below the Tonoloway Formation lies the Wills Creek Formation, the lower-half of the Salina Group (Figure 1), in which a prominent sandstone bed occurs in Maryland approximately 80 feet below the Tonoloway-Wills Creek boundary. This sandstone bed within the Wills Creek was used in the correlation and placement of the formation boundary in Maryland (Swartz, 1923). The Keyser Formation of the Silurian-Devonian Helderberg Group lies above the Tonoloway Formation in both Pennsylvania and Maryland (Figure 1).

Facies contained within the Tonoloway Formation range from shallow subtidal to supratidal. Subtidal facies are represented by calcarenites, oolitic limestone, and fossiliferous limestones. Intertidal environments are represented by flat laminated to domal stromatolites. Typical supratidal facies are indicated by massive, sometimes

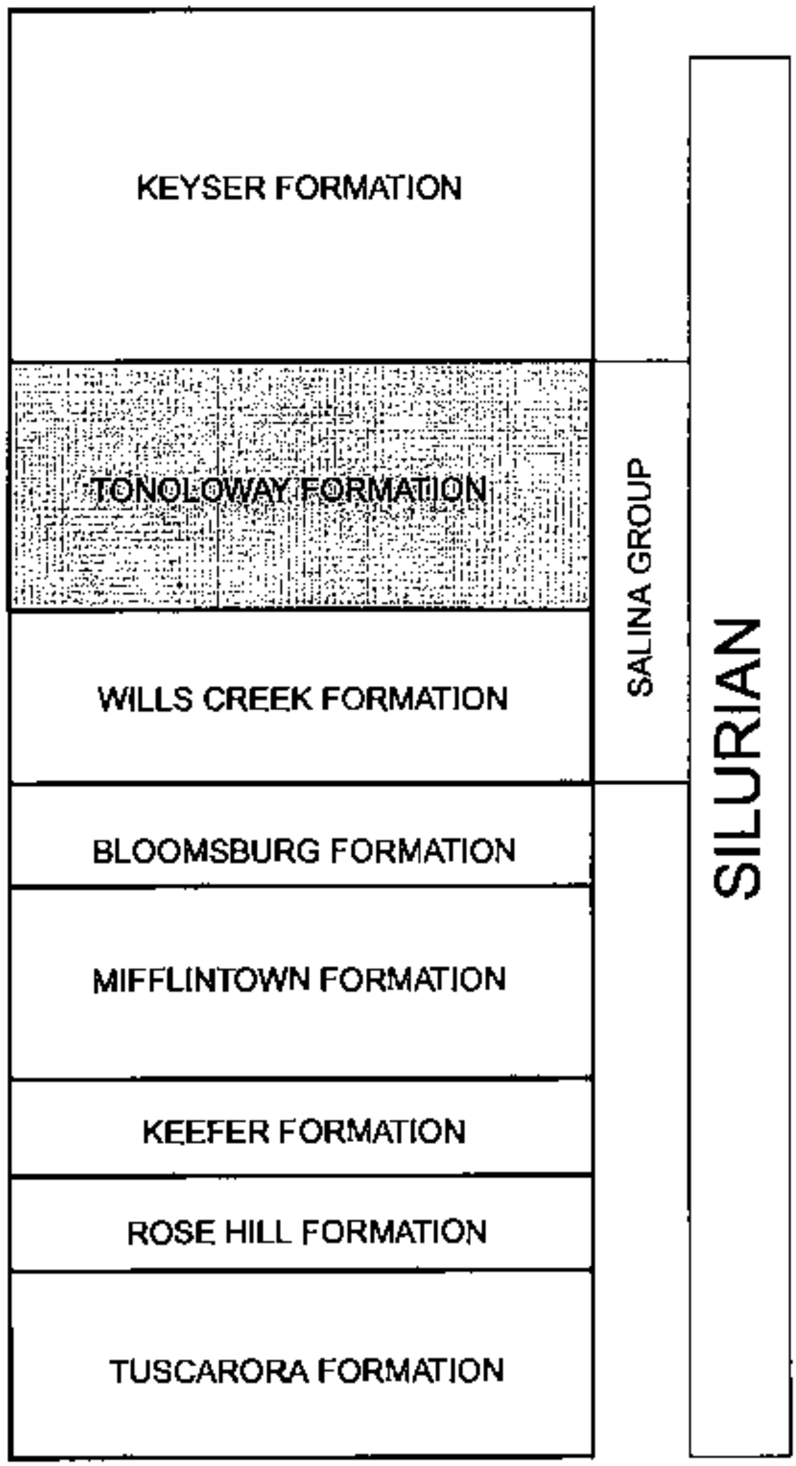


**Figure 1**. Silurian Stratigraphy. Silurian stratigraphy based on Commonwelth of Pennsylvania Department of Environmental Resources 1983 Stratigraphic Correlation Chart of Pennsylvania.

vuggy, dolomite. The peritidal facies of the Tonoloway Formation lie between the near-shore marine to fluvial coastal plain facies of the Upper Silurian Wills Creek Formation and the subtidal facies of the Silurian-Devonian Helderberg Group.

**Localities**

The Tonoloway Formation is exposed in the Valley and Ridge Province of Central Pennsylvania and Western Maryland (Figure 2). Three localities are examined in this region, two in Pennsylvania at Mount Union and Allenport and a third at Pinto, Maryland (the type locality).

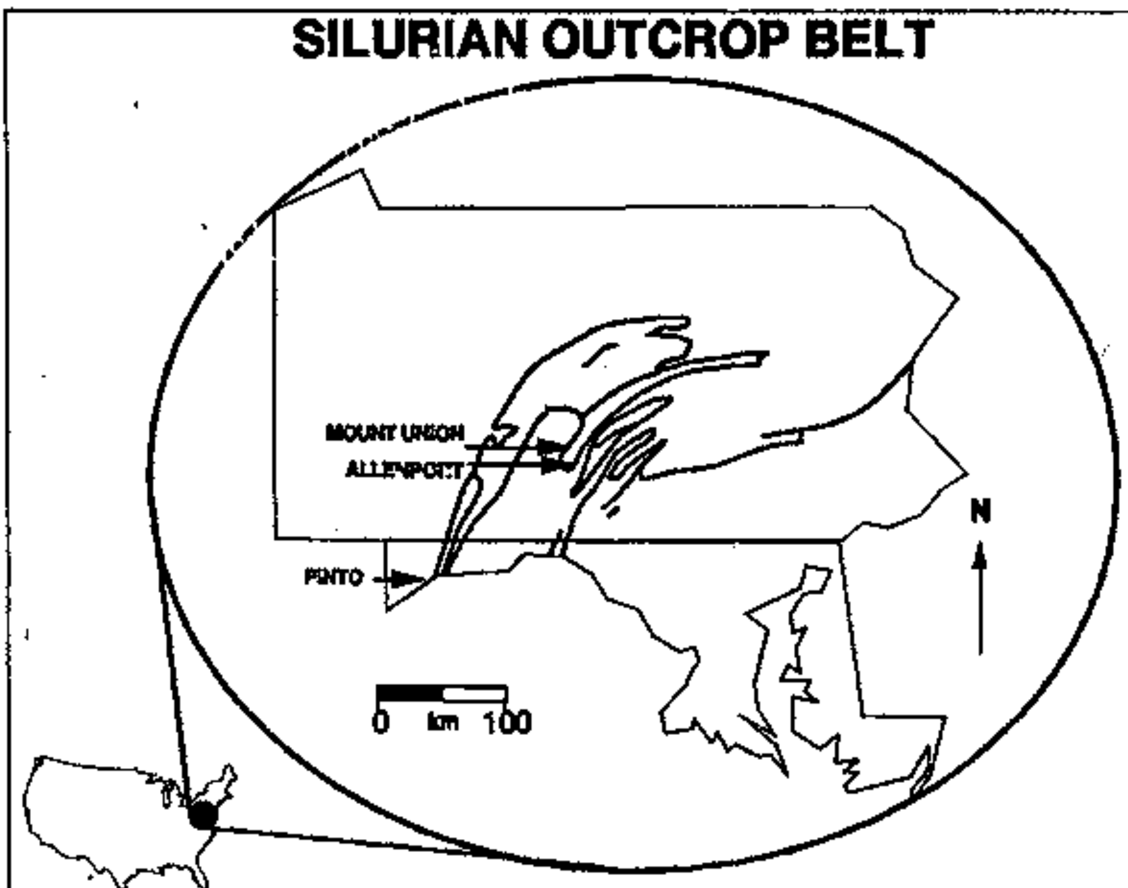


Figure 2. Silurian Outcrop Belt. Map displays the extent of exposure of Silurian strata in Pennsylvania and Maryland

The section at Mount Union, Pennsylvania is exposed north of the Juniata River on State Routes 522/22 approximately 0.25 miles east of the intersection of State Routes 522 and 22 approximately 0.2 miles north of Mount Union (Figure 3). The outcrop is located at 40° 23' 40" North Latitude and 77° 52' 30" West Longitude. At this locality, 295 feet of the lower Tonoloway Formation and its contact with the Wills Creek Formation are exposed. The upper half of the formation and its contact with the Keyser Formation are covered. The strike of the strata is toward N45°E and dip is at 25° to 30°.

The section 3.1 miles east of the village of Allenport is along County Route 103 on the southern side of the Juniata River (Figure 4). The latitude and longitude of this locality are 40° 22' 6" North and 77° 49' 26" West respectively. At this locality, 707 feet of Tonoloway Formation were measured. The lower contact with the Wills Creek Formation is exposed as is the upper contact with the Keyser Formation. However, approximately 100 feet of upper Tonoloway strata are covered. The strike of the strata is toward N 41° W at a dip of 45° to 60°.

The type section at Pinto, Maryland is exposed along the Chessie System Railroad tracks on the North side of the North Branch of the Potomac River (Figure 5). At this locality 648 feet of the Tonoloway Formation are exposed. Again, the lower contact with the Wills Creek Formation is exposed but the upper contact and about 100 feet of upper Tonoloway Formation are covered. The strike of the strata is toward N 10° E at a dip of 80° to 90°.

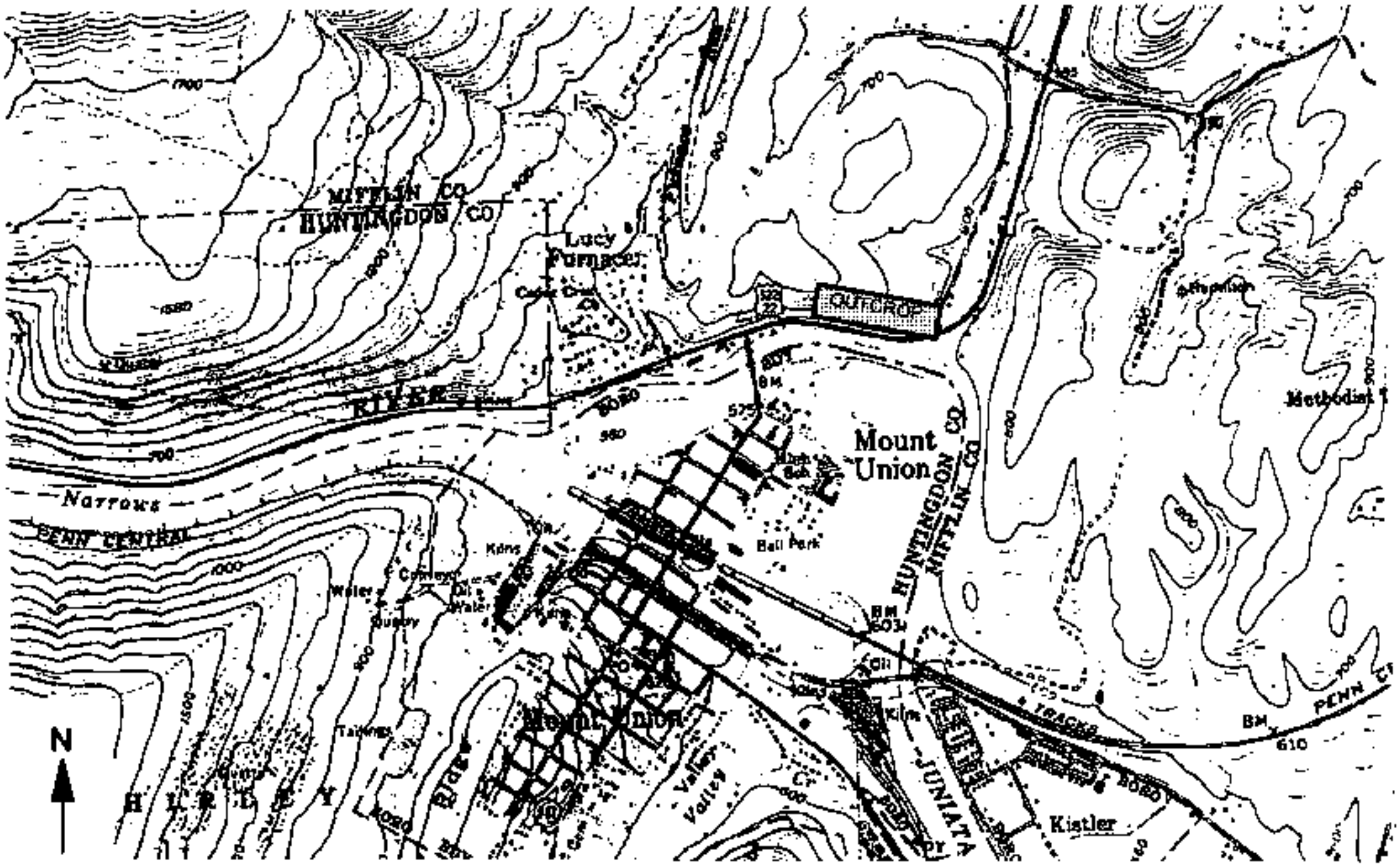


**Figure 3.** Mount Union, PA. Topographic map of the area surrounding theMount Union locality. Shaded area is locality of outcrop.

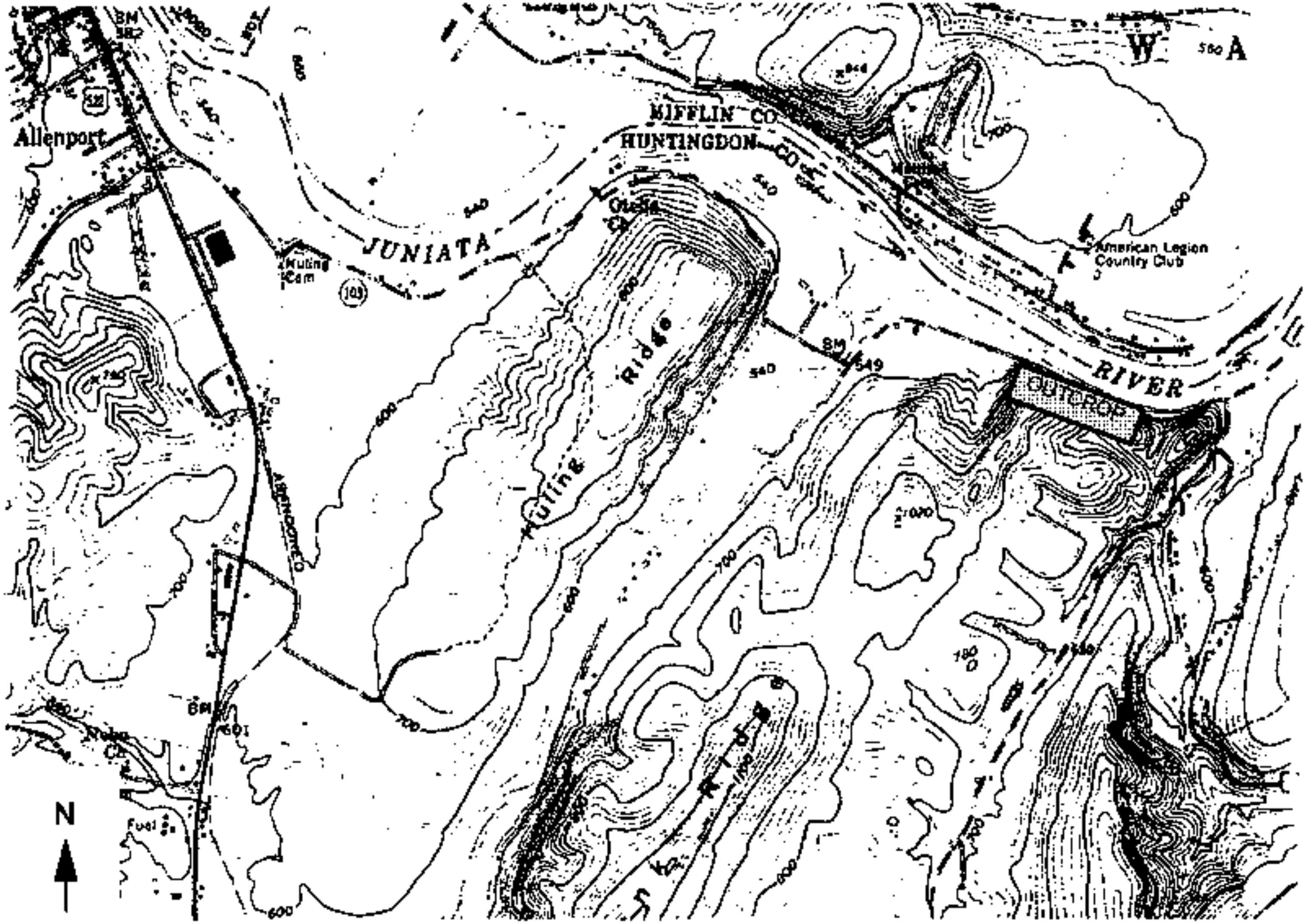


**Figure 4.** Allenport, PA. Topographic map of area surrounding Allenport locality. Shaded area is outcrop locality.

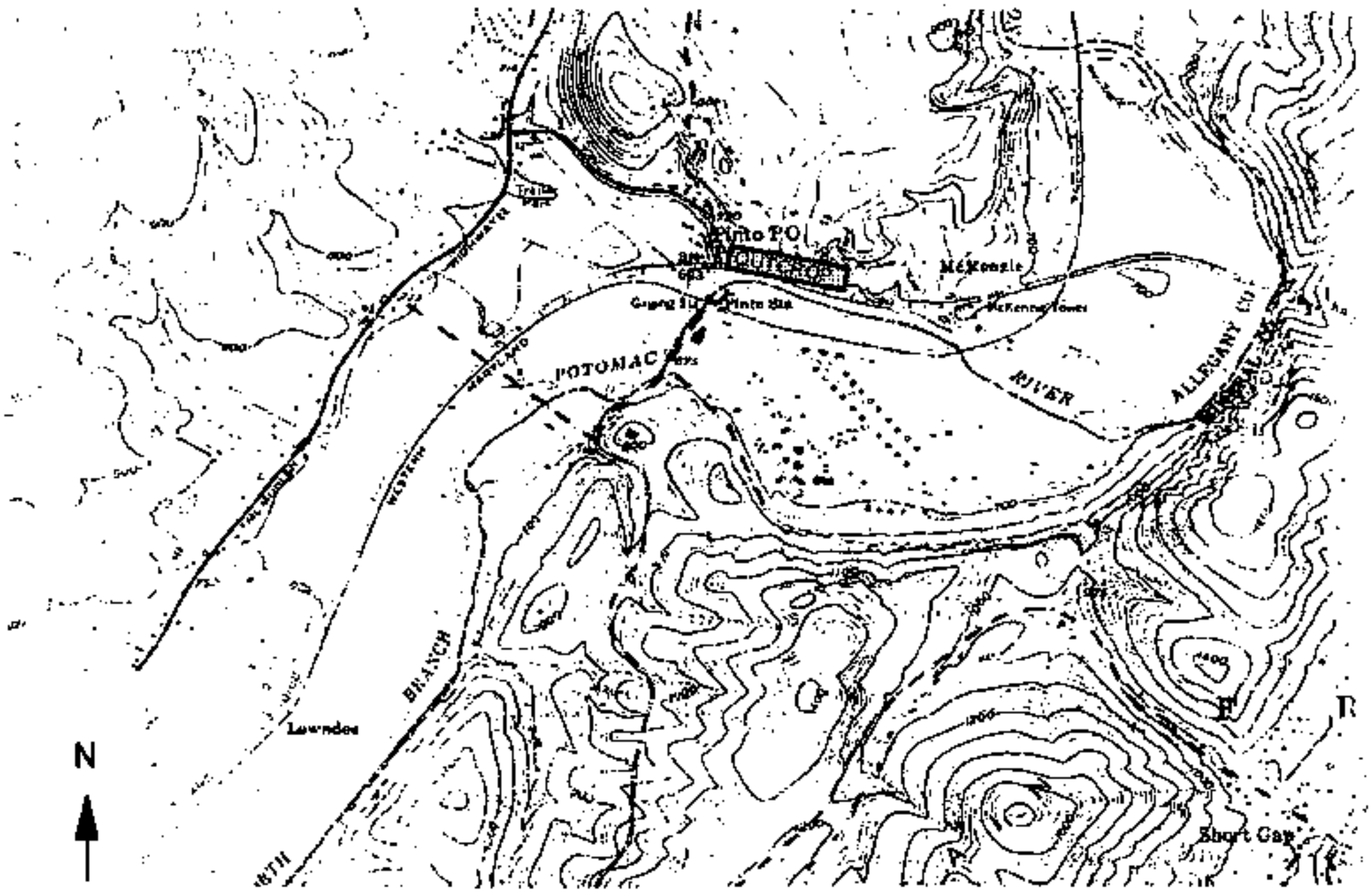


**Figure 5.** Pinto, MD. Topographic map showing Pinto locality in relation to area landmarks. Shaded area is outcrop locality.

## Previous Work

The general stratigraphy, basic facies description and analysis and some work on Tonoloway cyclicity precede the current study. After C.K. Swartz defined the formation in 1923, F.M. Swartz (1934) followed with the description of the Tonoloway Formation in Central Pennsylvania. Swartz's (1934) zones of diagnostic fossils in Pennsylvania sections provided the means for correlation between Silurian sections in New York State and Maryland. Smosna and Warshauer (1979) performed a multivariate facies analysis on the Tonoloway section at Pinto, Maryland to test its use as a method for paleoenvironmental interpretation of the Tonoloway Formation and its applicability to typical geological data. They concluded that there was a gradual pattern of peritidal facies change in the Tonoloway Formation and that a multivariate method of analysis is useful in interpreting trends in geological data. Smosna and others (1993) later determined that the Tonoloway Formation was deposited during modest tectonic activity. This modest tectonic activity was determined, from average subsidence rates attained through the use of shallowing-upward cycles in the Milankovitch-band, to have changed the basin axis over time, thus suggesting that the plate margin during the Silurian was not as stable as previously thought.

Cyclicity in the Tonoloway Formation was first identified by Cotter and Inners (1989) at the Allenport, Pennsylvania locality. Cotter and Inners identified "3 to 8 meter sabka-type cycles capped with vuggy, probably evaporite-bearing, dolostone" (Cotter and Inners, 1989, p.166). Within the Tonoloway Formation, Cotter and Inners (1989) identified 34 such cycles with no specific process nor periodicity.

Smith and Anderson (1992) described stacking patterns of cycles consistent with the Milankovitch model of eustatic sea-level change at the Canoe Creek Quarry in Central Pennsylvania. In 40 meters of section, 50 Sixth-Order (20 ky) cycles (PACs) were identified. These Sixth-Order cycles were grouped into 11 Fifth-Order (100 ky) cycles which were in turn grouped into 3 Fourth-Order (400 ky) cycles. The Fifth and Sixth Order cycles identified were asymmetric in facies distribution as predicted by the PAC Hypothesis.

Cotter (1993) stated that Silurian strata of the central foreland basin in Pennsylvania, including the Tonoloway Formation, were deposited in 1-10 meter shallowing-upward sequences superimposed on large-scale facies patterns. Although he concluded that the deposition of the sequences was driven by Milankovitch-scale eustacy, no effort was made to discriminate the eccentricity (100 ky and 400 ky) signals from the precessional (20 ky) signal and no attempt was made to correlate cycles between localities. Without a discrimination of mechanisms for each scale of cyclicity preserved, the genetic hierarchy forced by these mechanisms is forfeited and correlation of cycles is impossible.

In the preliminary stages of this study, Chadwick and Goodwin (1993), described the pattern and symmetry of cycles at Pinto, Maryland at four levels within a genetic hierarchic model of cycles. The genetic hierarchic model used was that predicted by the Milankovitch model of orbital forcing and was found to be consistent with the cyclicity observed in the Tonoloway Formation. Approximately 230 meters of section were measured at Pinto, Maryland and divided into 3 Third Order (2 my) sequences. Each of these Third Order cycles could be divided into five Fourth Order cycles, twenty Fifth Order cycles, and up to 120 Sixth Order cycles (Chadwick and Goodwin, 1993).

Building on these initial studies of Tonoloway cyclicity, the objective of the current study is to establish a correlative allocyclic framework and compare it to the predictions of the Milankovitch model.

# CHAPTER 3

## PAC HYPOTHESIS

The Punctuated Aggradational Cycle (PAC) Hypothesis (Goodwin and Anderson, 1985) is a current model for the episodic accumulation of the stratigraphic record (Figure 6). The PAC Hypothesis states that the stratigraphic record consists of meter-scale shallowing-upward cycles separated by sharp non-depositional surfaces produced by geologically instantaneous base-level rise. Each PAC boundary is at an abrupt facies change, from relatively shallow facies below to markedly deeper facies above ( Goodwin and Anderson, 1985). Orbital perturbations of the Earth, dominantly the precessional and the eccentricity signals, is favored by Goodwin and Anderson (1985) as the driving mechanism for the global eustatic sea-level fluctuations which have produced the cyclic surfaces observed in the stratigraphic record.

Seismic stratigraphy demonstrated the existance of allogenic surfaces by tracing such surfaces basin-wide and establishing correlations on a global scale (Vail et al., 1977, Van Wagoner et al., 1988). The sharp bounding allogenic surfaces of PACs separate distinct "disjunct" facies representing noncontiguous paleoenvironments (Anderson et al., 1984). This discontinuity of paleoenvironments is produced by rapid rise of relative base level (Anderson et al., 1984). Helderberg correlations between New York and Pennsylvania demonstrate that PACs are "pervasive in time and environment [and are] produced by relatively long periods (tens of thousands of years) of base-level stability punctuated by geologically instantaneous relative base-level rises of ... basin

**Punctuated Aggradational Cycle**

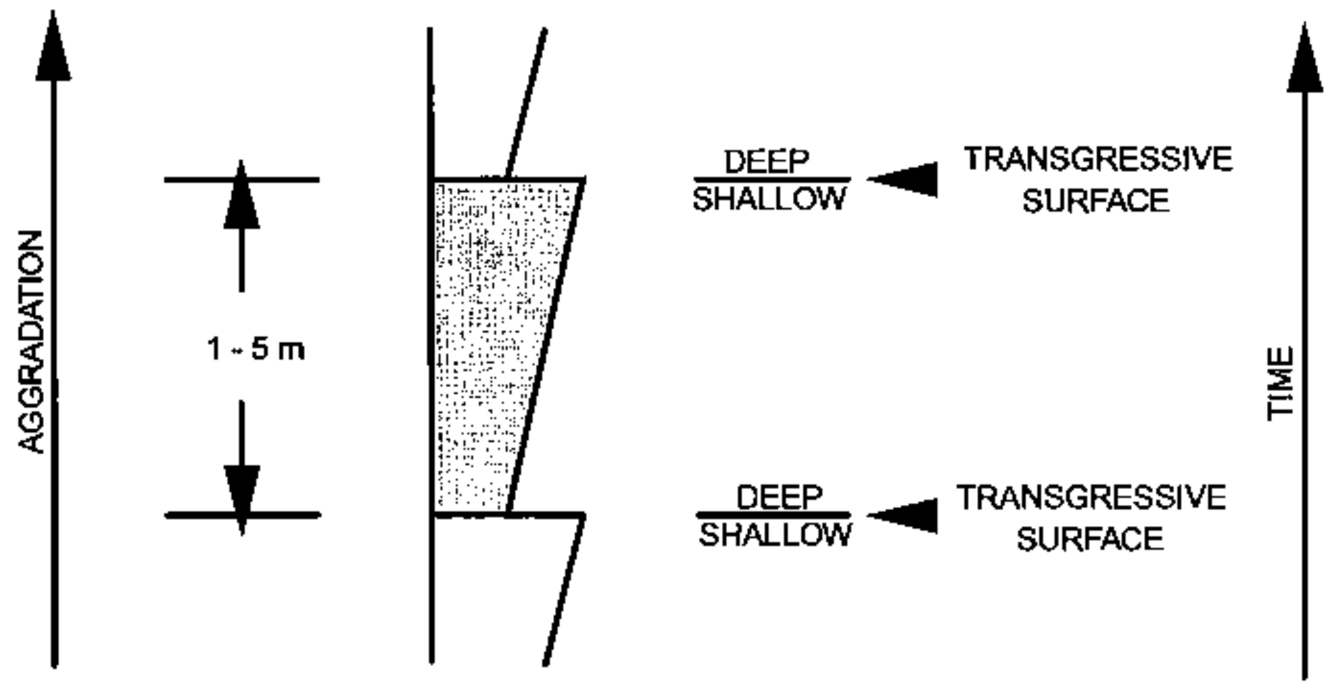


**Figure 6.** Punctuated Aggradational Cycle. Diagram displays PAC Hypotheses as shallowing upwerd cycle punctuated by trangressive surfaces separating disjunct facies.
(From Goodwin and Anderson, 1985)

wide extent" (Goodwin and Anderson, 1985, p.515).

Because facies below and above PAC boundaries do not represent laterally adjacent paleoenvironments (Anderson et al., 1984), Walther's Law can be applied within a PAC but not across PAC boundaries, which separate environmentally disjunct facies (Goodwin et al., 1986). Walther's Law may be applied internal to a PAC because "lateral facies changes within a PAC represent gradations between contiguous environments [and] vertical facies changes within a PAC reflect evolving paleoenvironments as a function of aggradation during periods of base-level stability" (Goodwin and Anderson, 1985, p.525). Even within a PAC, the application of Walther's Law can be negated by the presence of a sea-level-fall surface (Touchberry et al., 1991; Orzechowski et al., 1992). This intra-cycle discontinuity is produced at the inflection point of the precessional sea-level-fall. Such surfaces are common in the Tonoloway Formation (Chadwick and Goodwin, 1993).

Each PAC is thus a genetic unit defined on patterns of facies change, not a unit of particular facies lithology (Goodwin et al., 1986). Each PAC boundary is an actual surface potentially mappable wherever precessional eustacy occurred in a sedimentary environment. Because each PAC is the product of a synchronous allogenic origin, it must be correlative throughout its lateral extent. There are three methods of correlation identified by Goodwin and Anderson (1985, p.524-525). These methods are: 1) "tracing of individual PACs between closely spaced sections", 2) "matching PAC sequences between widely spaced sections", and 3) "correlation of large punctuated events." The ability to correlate PAC and PAC sequence boundaries supports the conclusion that PACs are time-stratigraphic units.

Goodwin and Anderson (1985) concluded that the PAC-producing mechanism was allogenic, repetitive on short time scale (tens of thousands of years), episodic, and persistent throughout geologic time. Glacial eustacy, driven by cyclic perturbations of the Earth's orbit, was favored as the driving mechanism to form the stratigraphic surfaces. Orbital perturbations of the earth was the mechanism favored by Goodwin and Anderson (1985) to produce these eustatic sea-level fluctuations because they have been persistent throughout time and relatively constant in periodicity.

Recently, Goodwin and Anderson (1992b) have refined the PAC Hypothesis by currently relating PACs to a strictly periodic process-determined hierarchy of allocycles. Application and testing of the PAC Hypothesis by Goodwin and Anderson and their students have resulted in the identification of cyclic patterns that closely match the hierarchy of cycles predicted by the Milankovitch model of orbital forcing in carbonate formations of the Late Silurian and Early Devonian (Orzechowski et al., 1992; Smith and Anderson, 1992; Chadwick and Goodwin, 1993; Mauriello and Ketterer, 1993; Shelton and Anderson, 1993). They therefore have concluded that Milankovitch-band orbital forcing is the driving force that explains cyclicity in these parts of the stratigraphic record. "As basin wide lithologic time-stratigraphic units, PACs are fundamental to all aspects of stratigraphic analysis, including correlation, paleoenvironmental interpretation, and paleogeographic reconstructions" (Goodwin and Anderson, 1985, p.515).

# CHAPTER 4

# MILANKOVITCH ORBITAL FORCING AND A HIERARCHY OF ALLOCYCLES

## Milankovitch Theory

Orbital forcing (Milankovitch, 1941; Berger, 1988) is an astronomical theory of paleoclimates that provides a mechanism for the cyclic stacking patterns of the stratigraphic record. The theory relates cyclic changes in the Earths orbit to long-term global climatic changes. The "heart of [Milankovitch's] argument is that under those astronomical conditions in which the heat budget around the summer solstice falls below average, so will summer melt, with uncompensated glacial advance being the result" (Berger, 1988, p.630). Thus with melt not equaling the amount of snow deposited, increasing accumulation of snow on the continents would lead to continental glaciation and the lowering of sea-level. When the astronomical conditions in which the heat budget around the summer solstice rises above average, increased melt will result in the deglaciation of the continents and an ensuing rise in sea-level. Milankovitch identified several cyclic orbital fluctuations which have a high degree of predictability, including the 20,000 year precessional and 100,000 year eccentricity signals. The orbital fluctuations most strongly associated with cyclic patterns in the stratigraphic record are the precessional and eccentricity signals (Olsen, 1986; Fischer and Bottger, 1991; Goldhammer et al.,1991; Anderson and Goodwin, 1992b; Goodwin and Anderson, 1992a; Smith and Anderson, 1992; Orzechowski et al.,1992; Mauriello and Ketterer, 1993; Cotter, 1993; Smosna et al., 1993).

The precessional signal of the Earth is produced by the migration of the Earth's axis through 360°, describing a cone (Figure 7). The period of the precessional signal averages approximately 20,000 years (Milankovitch, 1941; Mitchel, 1976; Berger, 1988). Today, when the Earth is near aphelion, high latitudes of the earth receive increased insolation when the northern hemisphere is closer to the sun. In contrast, insolation at high latitudes is low in the northern hemisphere when the Earth is near perihelion. The heat budget in northern hemisphere high latitudes is important because continental glaciation on the Earth today can only occur in these regions. The heat budget thus controls the glaciation and deglaciation and the resulting eustatic sea-level rises and falls on the Earth. These eustatic sea-level rises and falls are the mechanisms which create stratigraphic surfaces (Goodwin and Anderson, 1985; Anderson and Goodwin, 1990). Thus, the precessional signal is the only orbital signal which creates stratigraphic surfaces (Anderson and Goodwin, 1992a; Anderson and Goodwin, 1992b; Goodwin and Anderson, 1992b).

The eccentricity signal defines the shape of the elliptical path of the Earth's orbit around the sun. The eccentricity of the Earth fluctuates at two separate periodicities of approximately 100,000 years and 400,000 years (Mitchell, 1976; Berger, 1988; Fischer and Bottjer, 1991). Eccentricity is associated with change in shape of the Earth's orbit. Change in the Earth's eccentricity thus introduces variations in the seasonal changes. When the Earth's eccentricity is low, it receives more uniform solar radiation throughout the precessional cycle and the effect of precessional signal is at its minimum. The sun occurs at one focus of the Earth's elliptical orbit. As the amount of eccentricity

PRECESSIONAL SIGNAL
20 ky

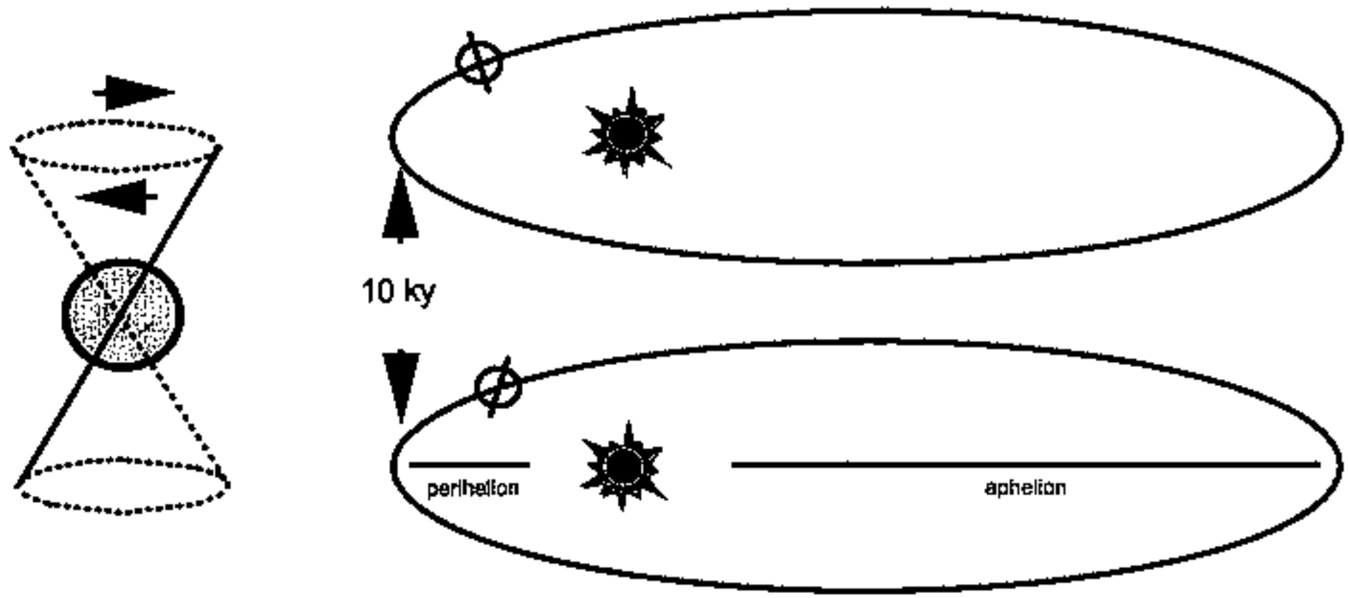


**Figure 7**. Precessional Cycle. The precessional cycle, having a periodicity of 20,000 years, produces small-scale rock cycles through eustatic sea-level fluctuations. These sea-level fluctuations are produced by changing continental glacial mass by changing solar radiation on the Earth.

increases, the distance of the Earth from the sun at perihelion decreases and at aphelion increases.

The 100,000 year eccentricity signal is the direct modifier of the effects of the precessional signal (Anderson and Goodwin, 1992a). This modification is directly related to the relative distance of the Earth from the sun (Figure 8). When eccentricity is low, the effect of the precessional signal is at its minimum because perihelion is at its greatest and aphelion is at its lowest. When eccentricity is high, the effect of the precessional signal is at its maximum at perihelion because the distance of the Earth from the sun is at its closest. Today the Earth's orbit is at low eccentricity (Fischer and Bottjer, 1991,p.1066); thus the fluctuation in glacial mass of the last glaciation was not as great as it was 100,000 years ago and 200,000 years ago. However, melting coincided with maximum tilt resulting in a large sea-level rise.

The 400,000 year eccentricity signal is a direct modifier of the 100,000 year eccentricity signal (Fischer and Bottjer, 1991). Over a 400,000 year period, the 100,000 year eccentricity signal is more or less pronounced dependent upon the distance of the Earth from the sun at perihelion and aphelion.

These cyclic perturbations have been identified in stratigraphic sections in the Silurian and Devonian rocks of Central Pennsylvania and Western Maryland. Orzechowski et al. (1992) identified the precessional signal in Devonian subtidal carbonate rocks of Central Pennsylvania. Smith and Goodwin (1992) and Chadwick and Goodwin (1993) identified the precessional signal in the peritidal carbonates of the Upper Silurian Tonoloway Formation of Central Pennsylvania and Western Maryland.

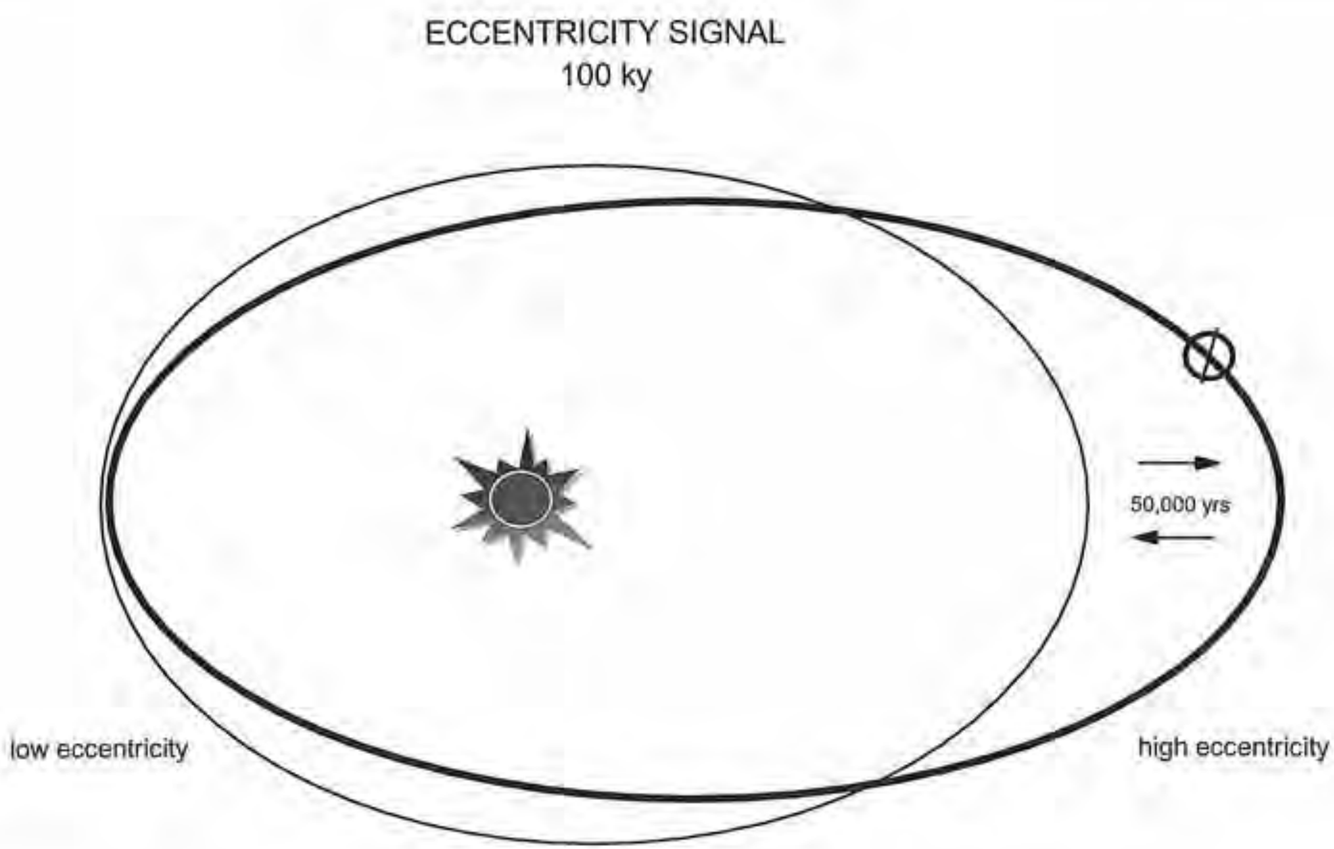


**Figure 8**. Eccentricity Cycle. The Eccentricity cycle modulates the precessional signal by changing the 20,000 year variable solar radiation which the Earth recieves over a 100,000 year period.

Mauriello and Ketterer (1993) identified the precessional signal in the near-shore marine to fluvial coastal plain facies of the Upper Silurian Wills Creek Formation in Central Pennsylvania and Western Maryland. In addition, Shelton and Anderson (1993) identified the precessional signal in the Upper Silurian Williamsport Sandstone of Central Pennsylvania and Western Maryland. The identification of cyclic orbital perturbations in the stratigraphic record implies cyclic, process-driven, accumulation of the stratigraphic record.

## Hierarchy of Allocycles

The Milankovitch model of orbital forcing predicts a genetic hierarchy of cycles within the stratigraphic record (Figure 9). This genetic hierarchy is process-determined and is based on the cumulative effects of the periodicity of each mechanism. The genetic hierarchy begins with the Sixth Order (PAC) with a periodicity of approximately 20,000 years and a driving mechanism of precession. The Fifth Order has a periodicity of 100,000 years and is forced by the short-term eccentricity cycle. The Fourth Order is also driven by an eccentricity signal at a periodicity of 400,000 years. The Third Order (Sequence) has a periodicity of 2 million years with a debated mechanism thought to be related to eccentricity (Olsen, Kent, and Cornet, 1992).

The genetic hierarchy demanded by Milankovitch-band cyclicity mandates a strict stacking pattern of cycles. Under ideal conditions of complete preservation, this strict pattern begins with five Sixth Order, 20,000 year, precessional cycles always internal to each Fifth Order, 100,000 year, eccentricity cycle. The hierarchy then demands that four Fifth Order cycles are to be contained in each Fourth Order eccentricity cycle. This

| ORDER | PERIODICITY | MECHANISM |
| --- | --- | --- |
| THIRD (Sequence) | 2 Million Yrs. | Eccentricity (?) |
| FOURTH | 400,000 Yrs. | Eccentricity |
| FIFTH | 100,000 Yrs. | Eccentricity |
| SIXTH (PAC) | 20,000 Yrs. | Precessional |

**Figure 9**. Genetic Hierarchy. A genetic hierarchy of allocycles based on Milankovitch-Band orbital forcing

hierarchy finally demands that each Third Order, 2 million year, cycle will contain five Fourth Order, 400,000 year, eccentricity cycles (Figure 10). If this hierarchy is valid, the stacking pattern of cycles in the stratigraphic record should approximate the model. Departures from ideal stacking patterns indicate missing cycles, potentially at any level in the hierarchy. Interpretation of stratigraphic dynamics is thus supported by explaining patterns of incompleteness produced by variations in tectonics and eustacy. This project is an effort to apply and test this model in Tonoloway facies.

STACKING PATTERN OF MILANKOVITCH-BAND CYCLICITY

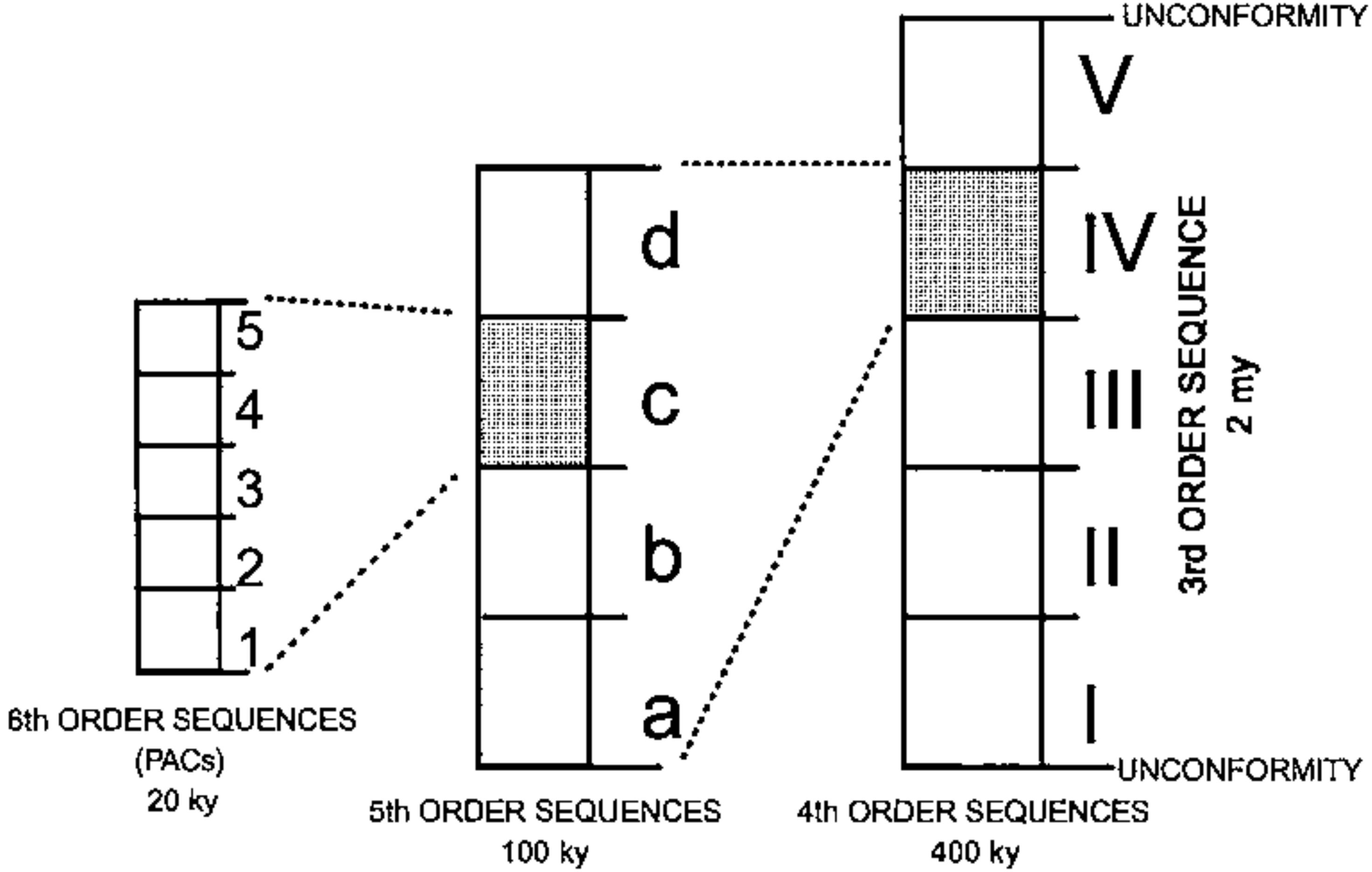


**Figure 10**. Stacking Pattern. Stacking pattern of cycles based upon the genetic hierarchy of cycles demanded by Milankovitch-Band orbital forcing.

# CHAPTER 5

# CYCLICITY IN THE TONOLOWAY FORMATION

Meter-scale cyclicity in the Tonoloway Formation is documented in both Central Pennsylvania and Western Maryland (Cotter and Inners, 1989; Smith and Anderson, 1992; Chadwick and Goodwin, 1993). The meter-scale cycles identified by these workers have all been asymmetric with the most open facies in each cycle represented at the bottom and the most restricted facies at the top.

## Facies

The facies which are present in the Tonoloway have been identified as peritidal carbonates and include subtidal, intertidal, and supratidal facies (Swartz, 1923; Swartz, 1934; Smosna and Warshauer, 1979; Cotter and Inners, 1989; Smith and Anderson, 1992; Chadwick and Goodwin, 1993). Facies in this study will be identified using the Folk Classification of carbonate rocks.

The subtidal facies are represented by micritic ribbon limestones (Figure 11) and calcarenites (Figure 12), some that may be bioturbated and contain ostracods. These calcarenite and micritic ribbon limestone strata are representative of open marine or lagoon environments (James, 1979). Intertidal facies in the Tonoloway Formation are represented by cryptalgal limestone which varies from flat laminated (Figure 13) to domal stromatolites. Some flat cryptalgal laminites exhibit desiccation cracks (Figure 14). These rocks represent a range of paleoenvironments from lower intertidal, domal stramatolites, to high intertidal, mud cracked flat stromatolites (James, 1979).

A.

B.

**Figure 11**. Ribbon limestone. (A) View of typical ribbon limestone facies in outcrop of the Tonoloway Formation. 35mm film-vial cap in lower center is for scale and left is stratigraphic up. (B) Thin section of typical ribbon limestone. This sample is a packed bio-micrite with an average matrix grain size of 0.062mm and bioclast size of 1.5mm. Bioclasts in this sample are ostracods.

A.


B.

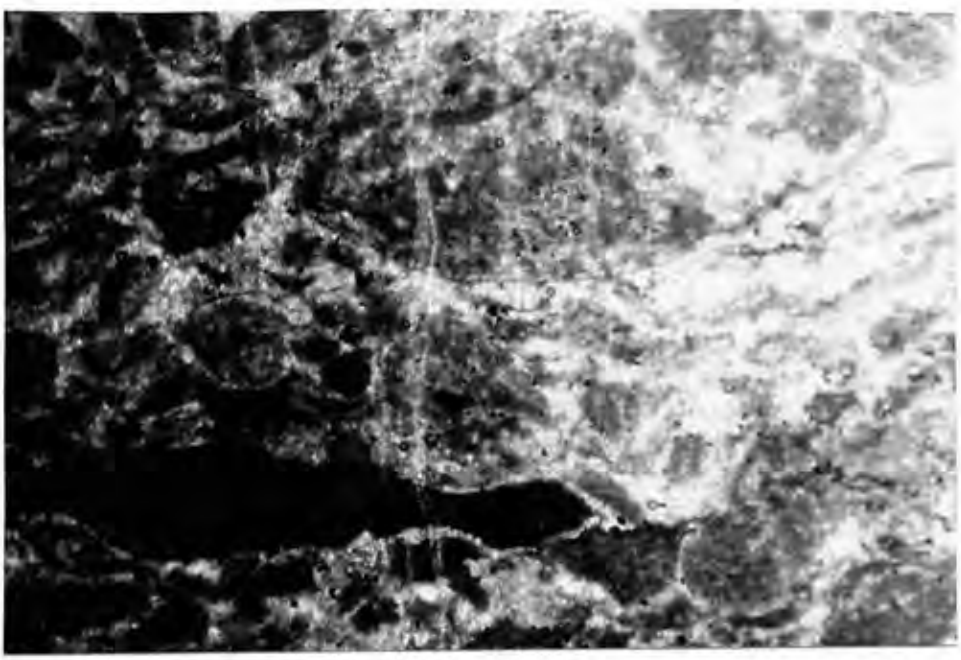

**Figure 12.** Calcarenite. (A) View of typical calcarenite, in hand sample, in the Tonoloway Formation. (B) Thin section of typical calcarenite. This sample is a packed intra-micrite with some oölites and ostracods. Average matrix grain size is <.25mm and intraclast grain size is 2mm. Intraclasts are mictritic and laminated.

A.

B.

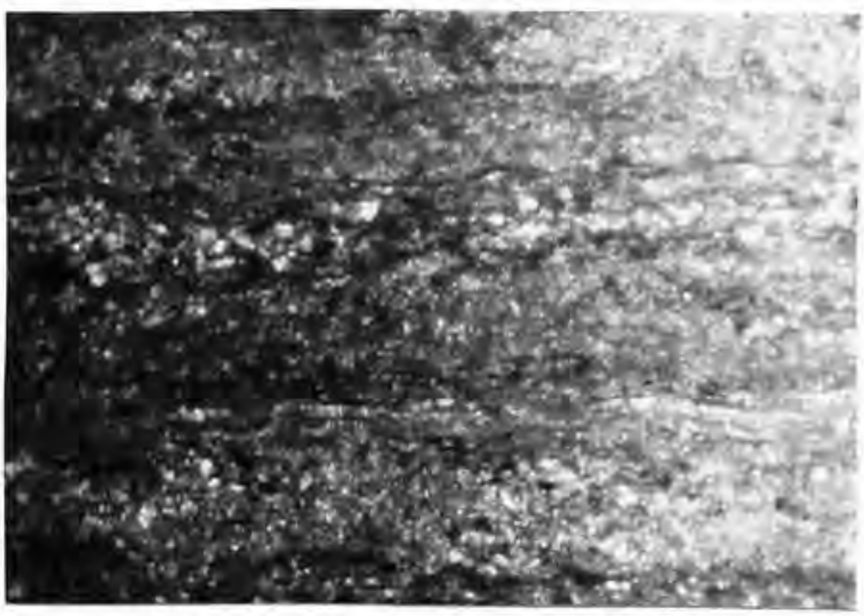

**Figure 13.** Cryptalgal Laminites. (A)View of typical cryptalgal laminites in the Tonoloway Formation. 35mm film-vial in center is for scale and stratigraphic up is to the left. (B) Thin section of typical cryptalgal laminites. This sample is a mudcracked biolithite with an average grain size of less than 0.1mm. Laminites in this sample average .5mm thick.

**Figure 14.** Cryptalgal Laminites with Dessication Cracks. View of the top of typical cryptalgal laminites with dessication cracks in the Tonoloway Formation. 35mm film-vial is for scale.

Massive to laminated dolomite (Figure 15) in the Tonoloway Formation is representative of supratidal facies. Dolomite strata is characteristic of an environment which is characterized by long periods of exposure (James, 1979).

**Third Order Cycle A**

Third Order Cycle A, which begins at the base of the Tonoloway Formation (Figure 16), is 192 feet thick at Mount Union, 187 feet at Allenport, 139.25 feet at Pinto. It contains facies ranging from shallow subtidal to supratidal. Third Order A is asymmetric with the most open subtidal facies dominating smaller-scale cycles towards its base while the most restricted facies, containing dolomite, characterize smaller-scale cycles near its top (Figure 16). Boundaries at the top and bottom of Third Order A are surfaces which separate markedly different facies.

Not only is there marked facies change across the Third Order boundaries, but the degree of facies openness or restriction is markedly different for the entire Fifth Order sequence above and below each boundary. For example, at the base of this Third Order sequence, Fifth Order cycle **AIIa** contains a thick sequence (2.5 - 4.75 feet) of shallow subtidal bioturbated calcarenite with ostracods. This unit shallows through calcarenitic to micritic ribbon limestone, and ends in intertidal crypt-algal laminites (Figure 17). The 2.5 - 4.75 feet of calcarenite in this cycle is the equivalent to the massive, 9.5 feet thick, limestone Swartz (1923) identified as the base of the Tonoloway Formation at the Pinto, Maryland locality. The discrepancy in thickness is the result of a cryptic fault which increased the stratigraphic thickness of the massive calcarenite at each of the three localities. The strata of the Fifth Order cycle below the Third Order

A.

B.

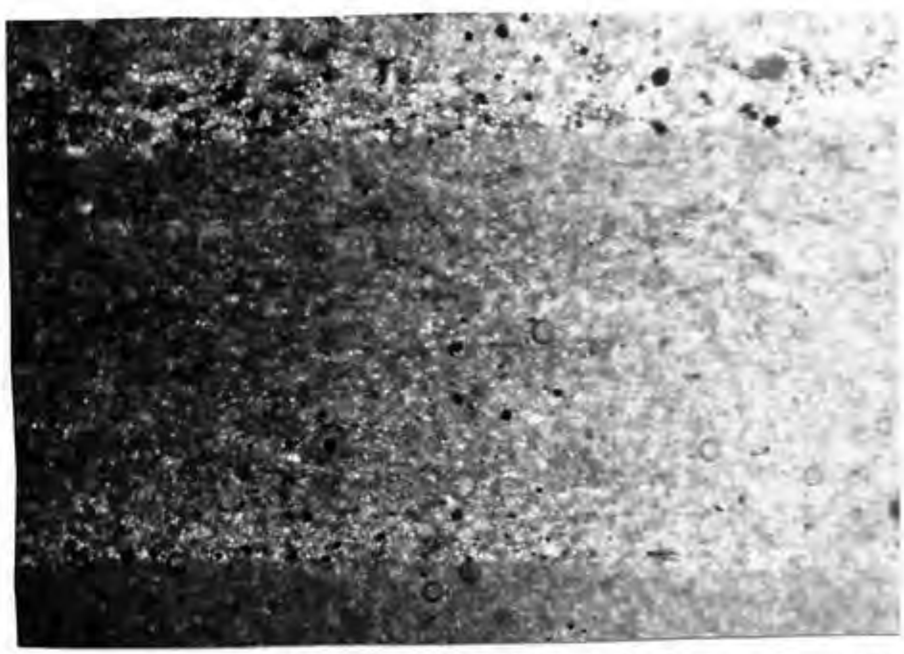

**Figure 15.** <u>Dolomite</u>. (A) View of a typical dolomite in the Tonoloway Formation in hand sample. (B) Thin section of sample of typical dolomite. This sample is a dolomitized micrite with an average grain size of less than 0.062mm. This sample exhibits very-fine lamination averaging .2mm thick.

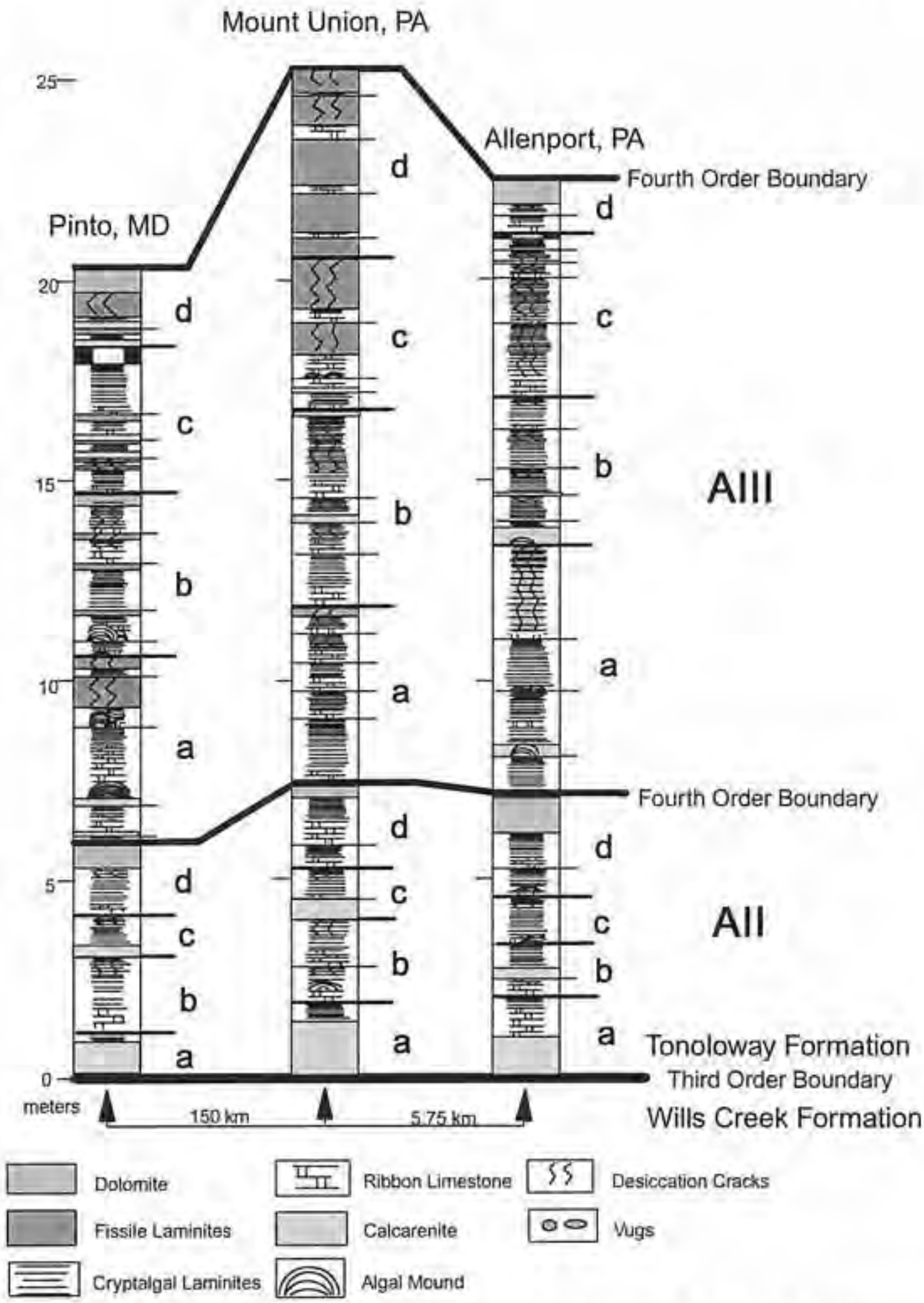


**Figure 16**. Third Order **A**. Columnar sections of Third Order **A** of the Tonoloway Formation of Central Pennsylvania and Western Maryland. Roman numerals designate Fourth Order cycles and lower case letters designate Fifth Order cycles.

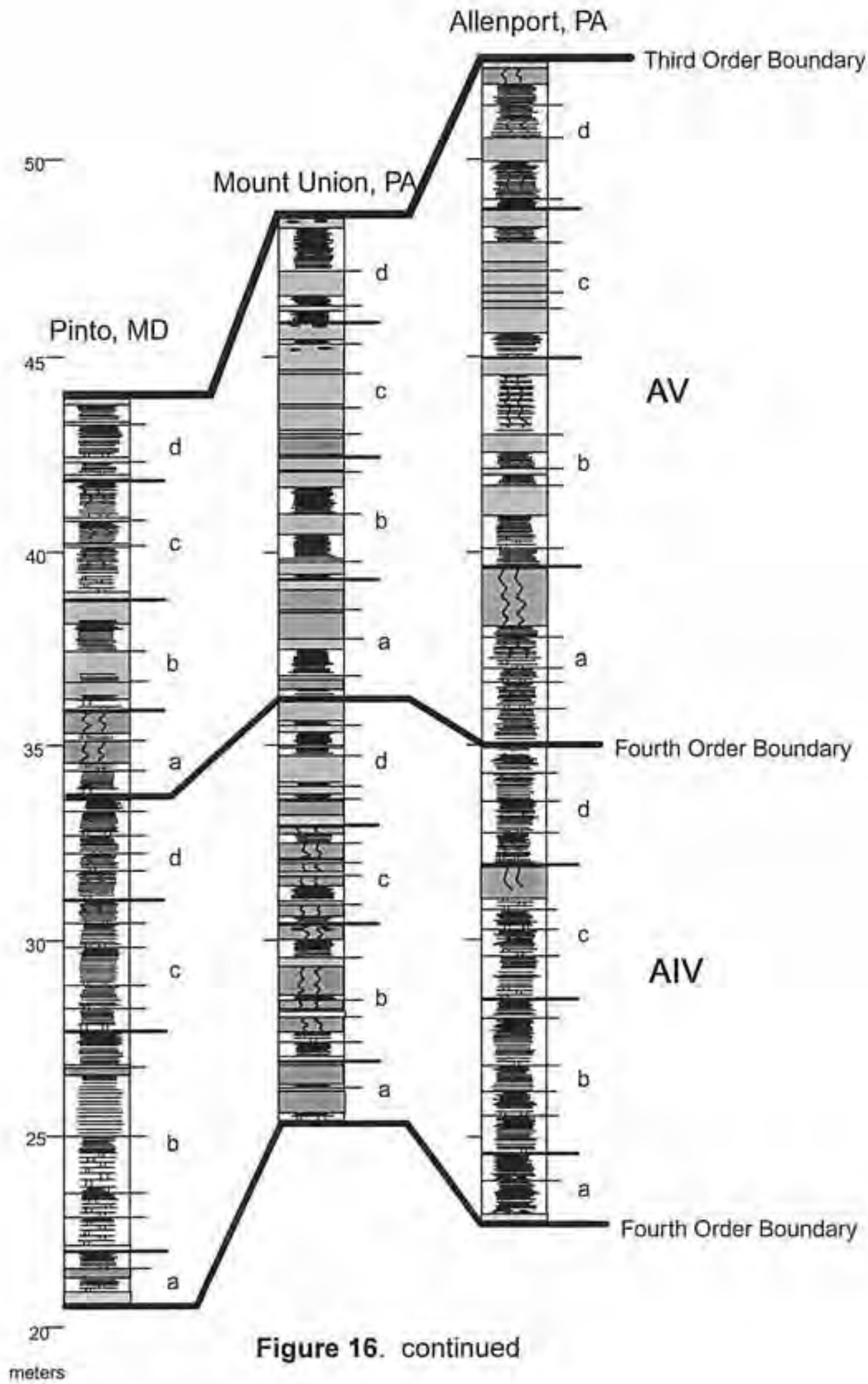


**Figure 16**. continued

A basal boundary is capped by supratidal facies in the Wills Creek Formation (Figure 17). These supratidal facies are illustrated by crypt-algal laminites with desiccation cracks and a dolomite cap (Figure 18).

At the upper boundary, the last Fifth Order eycle (AVd) of Third Order A consists predominantly of supratidal facies. These include intertidal facies, represented by crypt-algal laminites, some with desiccation cracks, and supratidal facies, represented by dolomite, which may be vuggy (Figure 19). The Fifth Order cycle directly above the upper Third Order A boundary contains shallow subtidal to intertidal facies. The shallow subtidal facies contained in this Fifth Order include calcarenite, with ostracods, and fine grained ribbon limestone. The intertidal facies are represented by crypt-algal laminites, which contain desiccation cracks at the Allenport and Mount Union localities. The shallow subtidal ribbon limestone facies is the dominant lithology in this eycle (Figure 20).

Thus, these Third Order boundaries are recognized on the basis of two criteria. First, the degree of facies disjunctness is most extreme across each boundary. Designating this boundary as a Third Order boundary is a function of surveying the relative change in facies across the stratigraphic surface as compared to the changes encountered at other surfaces within the section examined. Secondly, the last Fourth Order cycle in the underlying Third Order sequence is significantly more restricted than the first Fourth Order sequence above the Third Order boundary.

In other words, Third Order cycle A is asymmetric, episodically shallowing upward from dominantly subtidal to intertidal and supratidal facies. However, it must

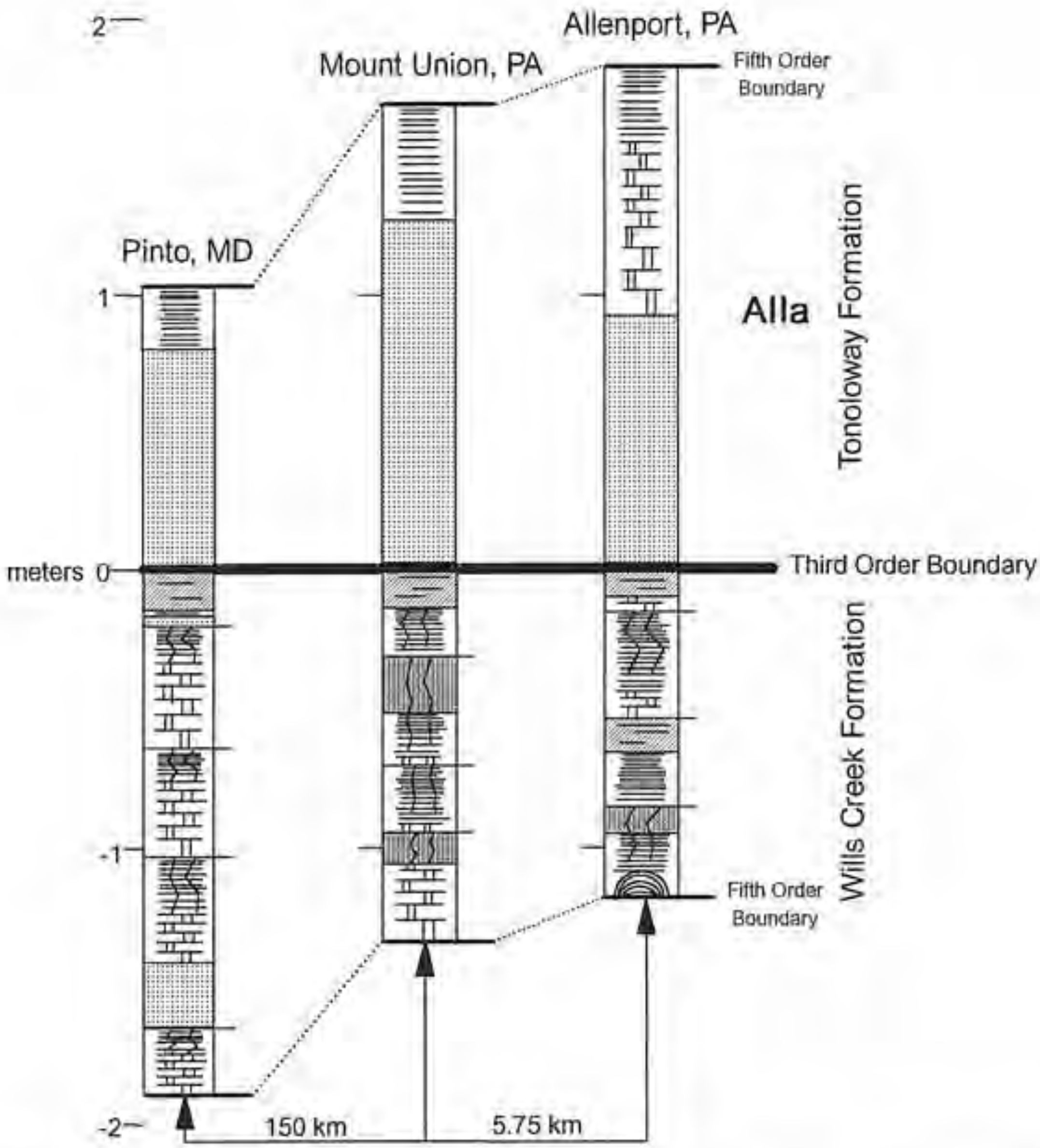


**Figure 17**. Basal Boundary of Third Order **A**. Columnar section of Fifth Order cycles above and below basal boundary of Third Order **A**.

A.

B.

**Figure 18**. Third Order A Basal Boundary. (A) View of Mount Union locality showing abrupt change in facies from predominantly supratidal laminated facies in the Wills Creek to predominantly shallow subtidal calcarenite facies in the Tonoloway Formation. (B) View of Pinto locality showing abrupt change in facies from predominantly supratidal laminated facies in the Wills Creek to predominantly shallow subtidal calcarenite facies in the Tonoloway Formation. Four foot stick is for scale. Arrows point to boundary and in the direction of stratigraphic up.

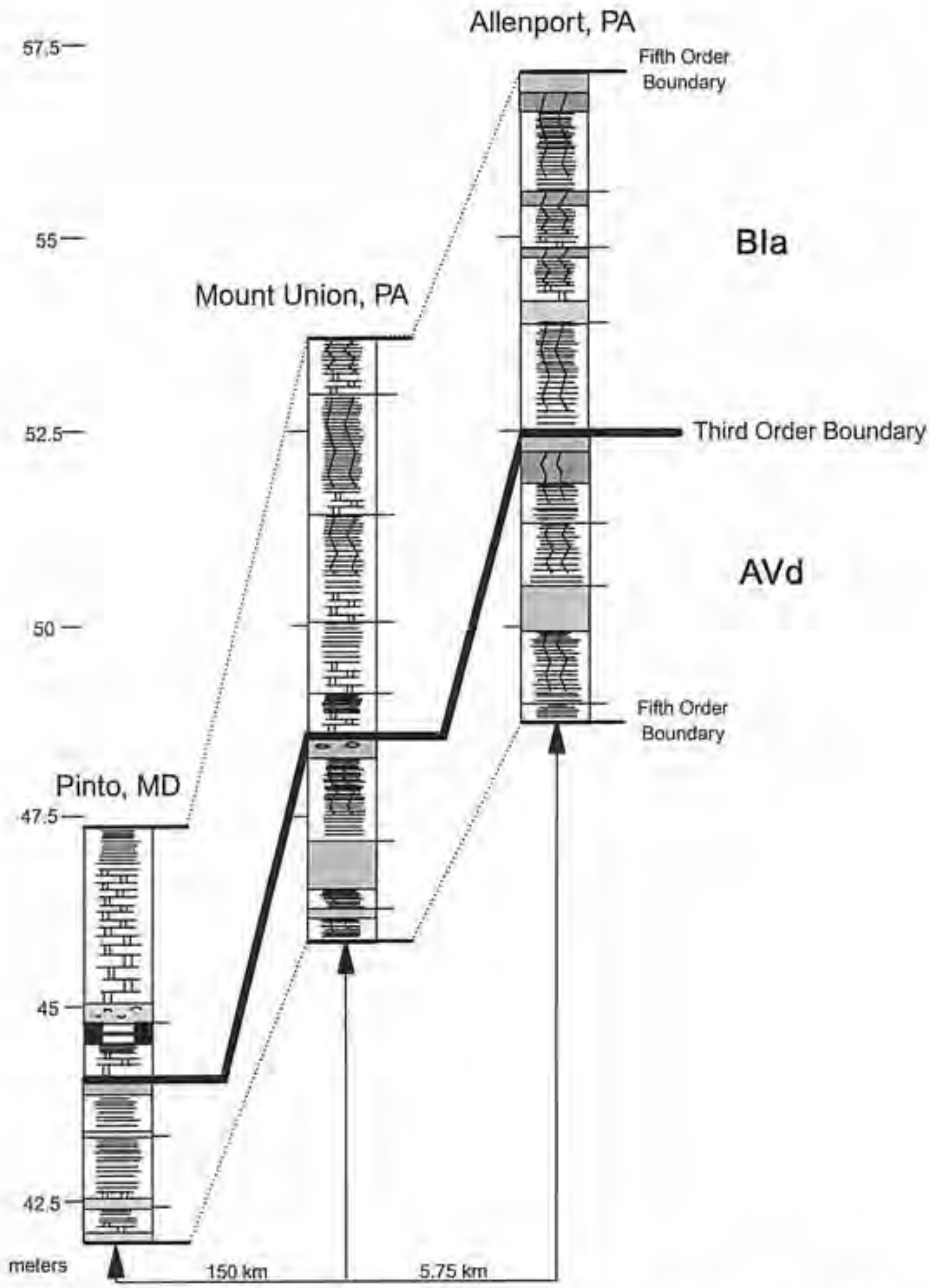


**Figure 19**. Upper Boundary of Third Order **A**. Columnar section of Fifth Order cycles above and below upper boundary of Third Order **A**.

A.

B.

**Figure 20**. Third Order A Upper Boundary. (A) View of Mount Union locality showing abrupt change in facies from predominantly supratidal laminated dolomitic facies in the upper part of Third Order **A** to predominantly shallow subtidal ribbon limestone facies of the next Third Order cycle. (B) View of Pinto locality showing an abrupt change in facies, one foot below the crevice, from predominantly supratidal laminated facies in Third Order **A** to predominantly shallow subtidal ribbon limestone facies in the next Third Order cycle. Four foot stick is for scale and arrows point towards stratigraphic up and the boundary.

be noted that this Third Order sequence is incomplete according to the prediction of the genetic hierarchy (Figure 9); it contains only four Fourth Order cycles instead of the predicted five. More regional work is needed to establish, through correlation, whether the missing Fourth Order cycle exists elsewhere at the base of the sequence or at the top of the sequence. For purposes of this project I hypothesize that the fifth Fourth Order cycle is missing in an unconformity at the base of the Third Order sequence; hence I have numbered my Fourth Order cycles II through V.

## Fourth Order Cycles

The Fourth Order cycles are distinguished from other cycles by relative facies changes across stratigraphic surfaces and by the facies patterns of Fifth Order cycles within them. Fourth Order AII, which ranges in thickness from 19.5 feet to 25.5 feet, is an example of a typical Fourth Order Cycle (Figure 21).

Although Fourth Order AII contains a broad range of facies, shallow subtidal facies dominate the base of the sequence and supratidal facies dominate the top. The relative change in facies across the surface which separates this Fourth Order cycle from those above and below is the first criterion for placing the boundaries in their respective points. The base of Fourth Order AII has previously been identified as a Third Order boundary and is therefore also a Fourth Order boundary when using a strict stacking pattern based on the Milankovitch hierarchy.

The upper boundary of AII is defined by the relatively large facies change across the stratigraphic surface separating AII from AIII (Figures 21 and 22). At all three localities, the capping facies of Fourth Order AII are supratidal, primarily dolomite.

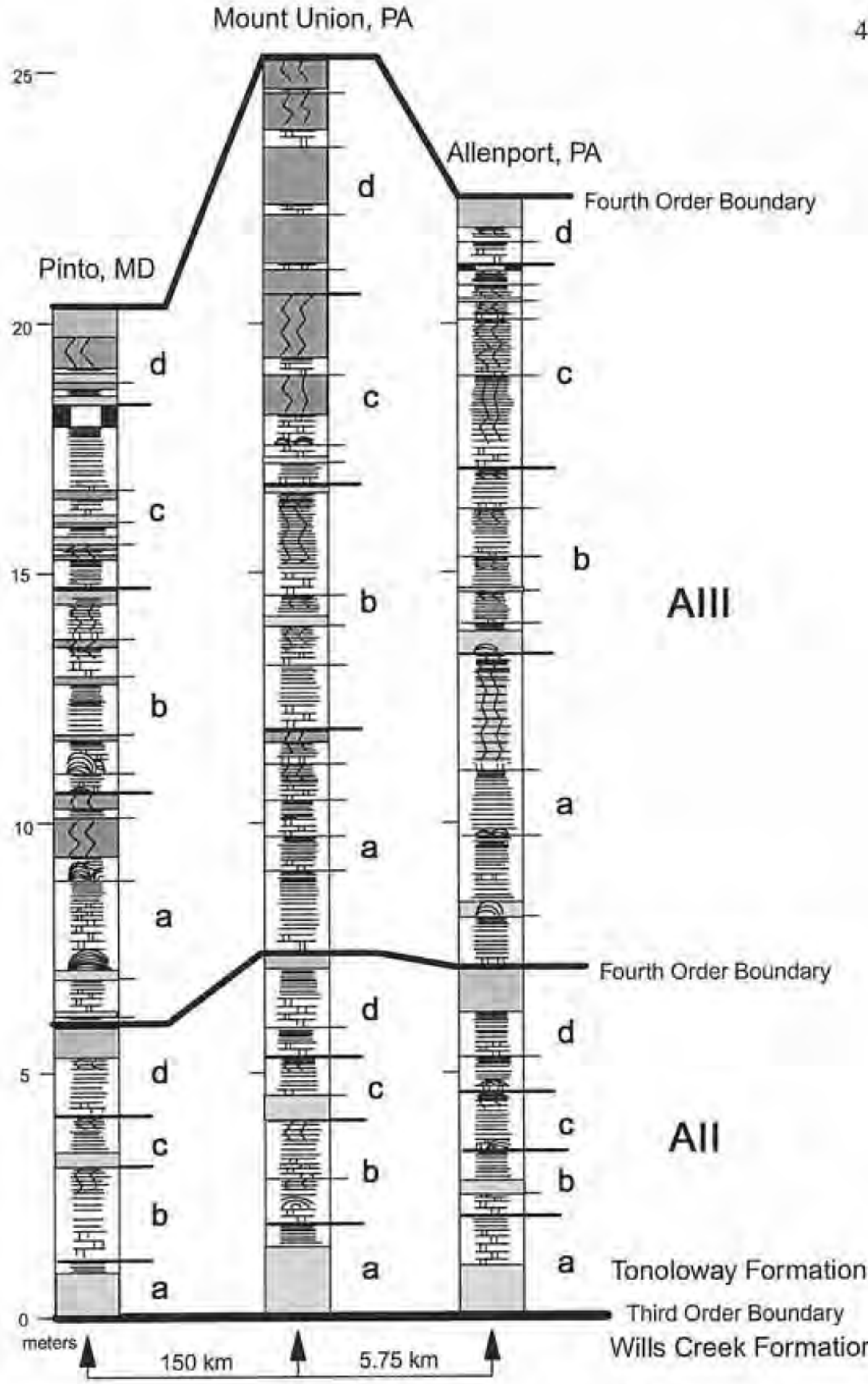


**Figure 21**. Fourth Order Boundary. Columnar sections of Fourth Orders **AI** and **AII.**

A.

B.

**Figure 22.** Fourth Order **AII** - **AIII** Boundary. (A) View of Mount Union locality showing abrupt change in facies from predominantly supratidal dolomitic facies of upper Fourth Order **AII** to predominantly intertidal laminated facies in the base of Fourth Order **AIII**. (B) View of Allenport locality showing abrupt change in facies from predominantly supratidal dolomitic facies of upper Fourth Order **AII** to predominantly intertidal laminated facies in the base of Fourth Order **AIII**. Four foot stick is for scale and the arrows are pointing at the boundary and stratigraphic up.

In contrast, the stratum above the surface separating AII and AIII are dominated by shallow subtidal ribbon limestone at Mount Union, PA and Pinto, MD, and intertidal cryptalgal laminites with no desiccation cracks at Allenport, PA. Although the change in facies is not a dramatic one, the degree of facies change across this surface is large compared to facies changes at Fifth Order boundaries in the Third Order sequence; similar changes are found at only two other surfaces internal to Third Order A. These three boundaries internal to Third Order A, define four Fourth Order boundaries.

Once the Fourth Order boundaries are identified in this manner, the symmetry of Fourth Order cycles is revealed. Fourth Order cycles have a general symmetry analogous to that of the Third Order cycle. Each Fourth Order cycle identified in this research is an overall shallowing-upward sequence of cycles sharply bounded above and below by a stratigraphic surface. A departure from this general upwardly shallowing symmetry occurs internally to the Fourth Order cycle by the third Fifth Order cycle having less restrictive facies than the second Fifth Order cycle in the sequence (Figure 16).

## Fifth Order Cycles

The boundaries of Fifth Order cycles are delineated by the relatively large facies changes across these stratigraphic surfaces compared to the facies changes at most Sixth Order boundaries. This method is the same used to delineate the Fourth Order and the Third Order boundaries, but the degree of facies change is less. In addition, work in other intervals (Goodwin and Anderson, 1985; Anderson and Goodwin, 1990; Mauriello and Ketterer, 1993) predicts that Fifth Order sequences should be 3 or 4 meters thick and be represented by a shallowing upward sequence of Sixth Order cycles with their deepest facies in the second Sixth Order cycle. Using these criteria, sixteen Fifth Order cycles are defined within Third Order A.

Fourth Order AII at Pinto, MD is used as a typical Fourth Order in Third Order A to show the relative facies change across stratigraphic surfaces identified as Fifth Order cycle boundaries (Figures 23 and 24). Facies in these Fifth Order cycles range from shallow subtidal to supratidal facies. Fifth Order AIIa begins at the basal boundary of Third Order A with 2.5 feet of shallow subtidal calcarenite grading upward to intertidal cryptalgal laminites and terminating at a stratigraphic surface which separates this Fifth Order cycle from Fifth Order AIIb. Fifth Order AIIb then begins with shallow subtidal ribbon limestone, grades into intertidal cryptalgal laminites, and is capped by 1.75 feet of supratidal cryptalgal laminites with desiccation cracks. Above the cryptalgal laminites with desiccation cracks of Fifth Order AIIb, the base of Fifth Order AIIc is a shallow subtidal calcarenite with intraclasts. A sharp surface separates the cryptalgal laminates of Fifth Order AIIb from the overlying calcarenite of Fifth Order AIIc. Fifth Order AIIc grades upward from the 1 foot calcarenite to intertidalcryptalgal laminites and is capped with 1 foot of supratidal cryptalgal laminites with desiccation cracks. Above the cryptalgal laminites with desiccation cracks in Fifth Order AIIc, separated by a stratigraphic surface, is 0.5 feet of shallow subtidal ribbon limestone at the base of Fifth Order AIId. Fifth Order AIId then grades upward from the ribbon limestone to intertidal cryptalgal laminites, that become dolomitized towards

**Figure 23**. Fifth Orders **AIIb** and **AIIc**. View of strata representing the facies of Fifth Orders **AIIb** and **AIIc** at Pinto locality. Fourth Order **AIIb** begins with shallow subtidal ribbon limestone, moves through intertidal laminated facies and is capped by supratidal laminated facies. Upon the supratidal laminated facies of Fifth Order **AIIb** lies the shallow subtidal calcarenite facies of Fifth Order **AIIc**. Fifth Order **AIIc** shallows upward through intertidal laminited facies and is capped by supratidal laminated facies. refer to Figure 15 for stratigraphic thicknesses. Stratigraphic up is to the left and the Arrows point to the base of each cycle.

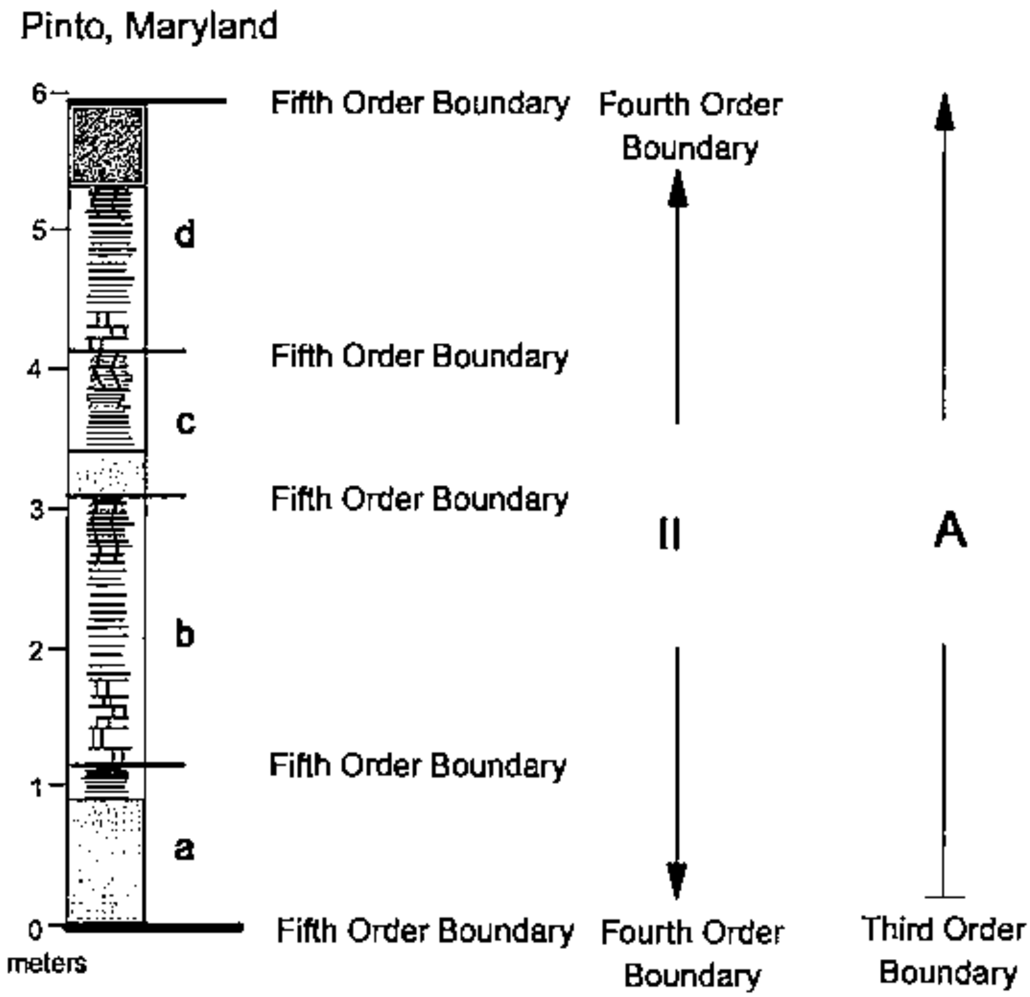


**Figure 24.** Fourth Order AII. Columnar section of Fourth Order **AII** at Pinto, MD with all Fifth Order Cycles defined. General facies of Fifth Order cycles range from predominantly shallow marine facies at the base of Fourth Order **AII** to predominantly supratidal facies **at the top.**

the top. Thes laminites are capped with 2.5 feet of supratidal dolomite exhibiting some lamination.

Thus each Fifth Order boundary is a surface of abrupt facies change relatively greater than changes at Sixth Order boundaries but less than facies changes at Third and Fourth Order boundaries. The symmetry of Tonoloway Fifth Order sequences matches the predictions of earlier work. While the cycles are generally shallowing-upward, the deepest facies are found in the second Sixth Order cycle, not at the basal cycle of each Fifth Order cycle.

## Sixth Order Cycles

Because I have not established correlations at this scale, Sixth Order cycles cannot be delineated in this study with great confidence. Those Sixth Order cycles that are recognized, such as the Sixth Orders of Fifth Order AIIIb (Figure 25), are consistent in symmetry and scale with PACs of Goodwin and Anderson (1985).

These cycles shallow-upward and are bounded by sharp stratigraphic surfaces at the base and top produced by geologically instantaneous base-level rises (Figure 26). For example, the base of Sixth Order AIIIb1 lies on a stratigraphic surface of non-deposition at the Fifth Order boundary. Internally, Sixth Order AIIIb1 grades upward from domal stromatolites, through ribbon limestone, to cryptalgal laminites. Above the capping cryptalgal laminites of Sixth Order AIIIb1 low intertidal domal stromatolites of Sixth Order AIIIb2 rest on a sharp surface. The cryptalgal laminites of Sixth Order AIIIb1 are separated from the domal stromatolites of Sixth Order AIIIb2 by a stratigraphic surface of non-deposition caused by a geologically instantaneous rise in base-level.

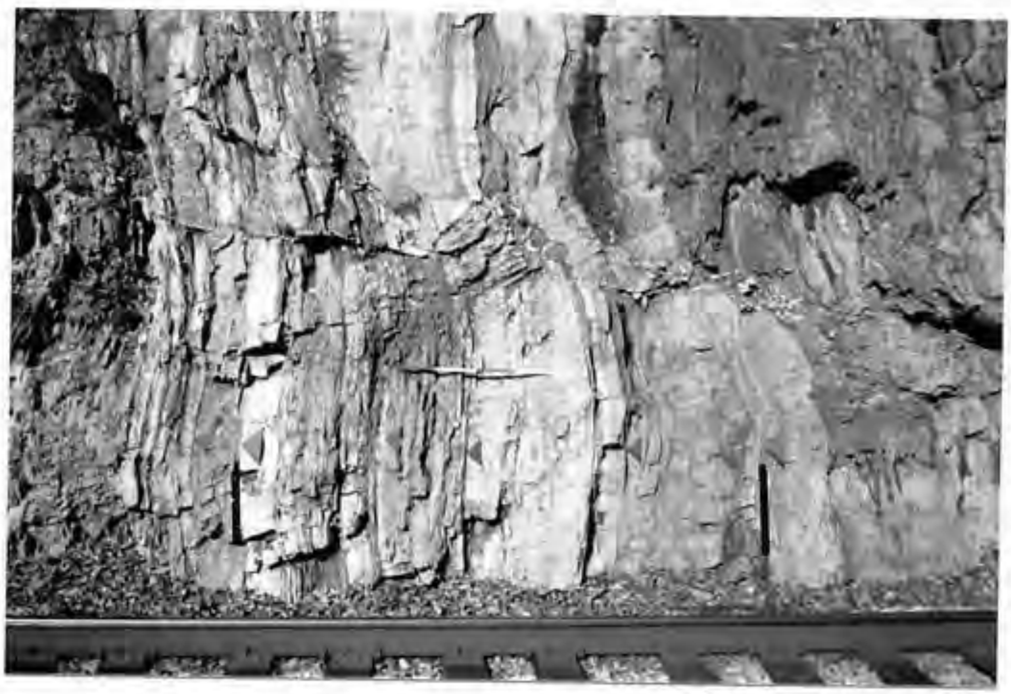

**Figure 25.** Fifth Order AIIIb. Photograph of Fifth Order AIIIb with all Sixth Order cycles delineated by arrows pointing to bases of cycles. Four foot stick is for scale and stratigraphic up is to the left. Black bars mark the base and top of this cycle.

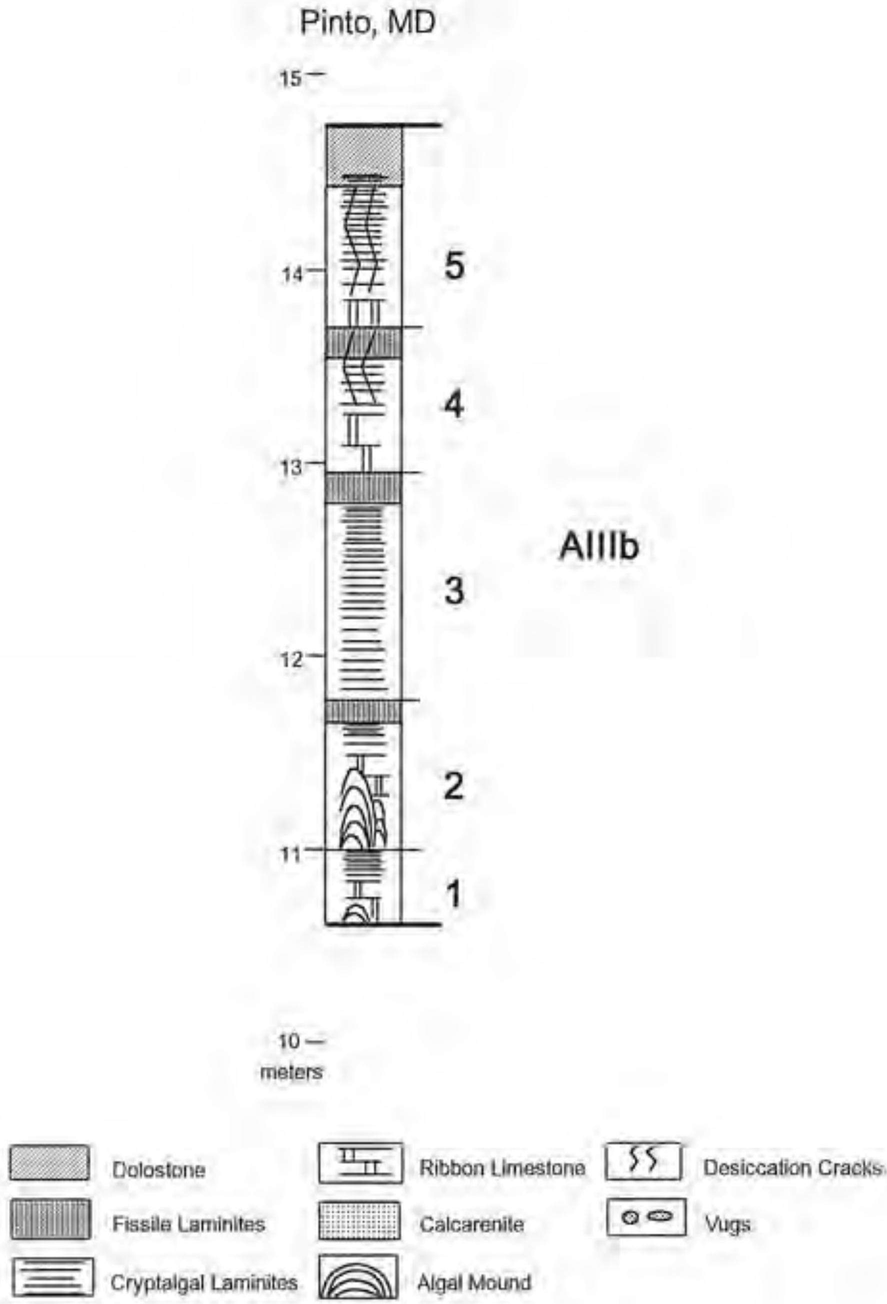


**Figure 26**. Columnar Fifth Order **AIIIb**. Columnar section of Fifth Order AIIIb at Pinto. All Sixth Order cycles in the Fifth Order are present and their respective facies are represented.

**AIIIb2** grades upward from the domal stromatolites, through ribbon limestone, to cryptalgal laminites and is capped by fissile laminites. Another sharp surface separates these laminites from the limey cryptalgal laminites of Sixth Order **AIIIb3**. Sixth Order **AIIIb3** grade upward from the cryptalgal laminates to fissile shaley laminites at the top. These laminites are then overlain by ribbon limestone at the base of Sixth Order **AIIIb4**. Sixth Order **AIIIb4** grades upward from ribbon limestone, through cryptalgal laminites with desiccation cracks, to fissile laminites with desiccation cracks. Sixth Order **AIIIb5** again begins with ribbon limestone atop a sharp surface separating it from Sixth Order **AIIIb4** and grades upward from the ribbon limestone to cryptalgal laminites with desiccation cracks at the top.

Each Sixth Order of Fifth Order **AIIIb** is shallowing-upward and bounded by sharp stratigraphic surfaces separating disjunct facies. This is consistent with the definition of the Punctuated Aggradational Cycle (Goodwin and Anderson,1985). Some Sixth Order cycles in the Tonoloway Formation also exhibit sharp sea-level-fall surfaces which separate the basal high-stand facies from the upper low-stand facies. Sea-level-fall surfaces have previously been identified by other researchers looking at small-scale allocycles (Touchberry et al., 1991; Orzechowski et al., 1992).

# CHAPTER 6

# CORRELATION

By matching patterns of facies change and stacking patterns of cycles between Mount Union, Pennsylvania and Pinto, Maryland, I have confirmed the general correlation of the Wills Creek-Tonoloway formational boundary by F.M. Swartz (1934) and established finer-scale correlations as well. After identifying as many Sixth Order cycles (PACs) as possible, the identification and correlation of larger-scale cyclic patterns of the Fifth Order, Fourth Order, and Third Order was undertaken using cyclic symmetry and major deepening events.

Correlation of Third Order A was based upon the degree of facies change across each stratigraphic surface separating the facies above and below the basal and upper boundaries. Upon assigning an order of cyclicity to each boundary within Third Order A, correlation was a function of relating the facies and symmetry of each cycle and related top and bottom boundary from one locality to its corresponding cycle at each other locality. Figure 27 is a columnar diagram of Third Order A at all three localities examined in this research. Each order of cyclicity, based on the Milankovitch theory of orbital forcing, is represented in the columnar diagram. Bold tie lines mark cycle boundaries correlated with the greatest confidence between the three localities in this study.

Four Fourth Order cycles were identified internally to Third Order A at all three localities and were correlated on the bases of internal symmetry and degree of facies

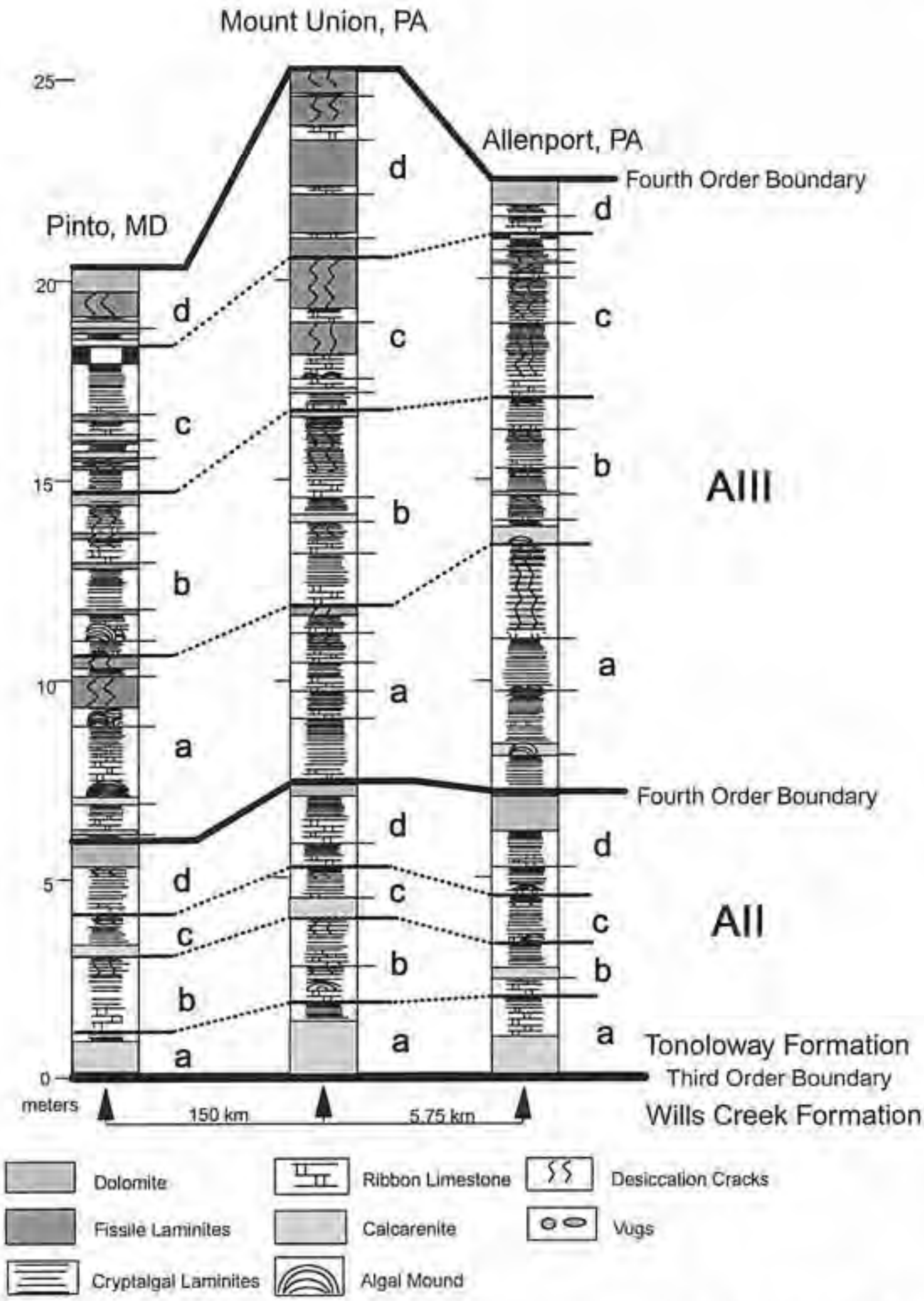


**Figure 27**. <u>Correlation of Third Order **A**</u>. Columnar sections of Third Order **A** at localities in Central Pennsylvania and Western Maryland. Tie lines show correlation of Third Order, Fourth Orders, and all Fifth Orders cycles.

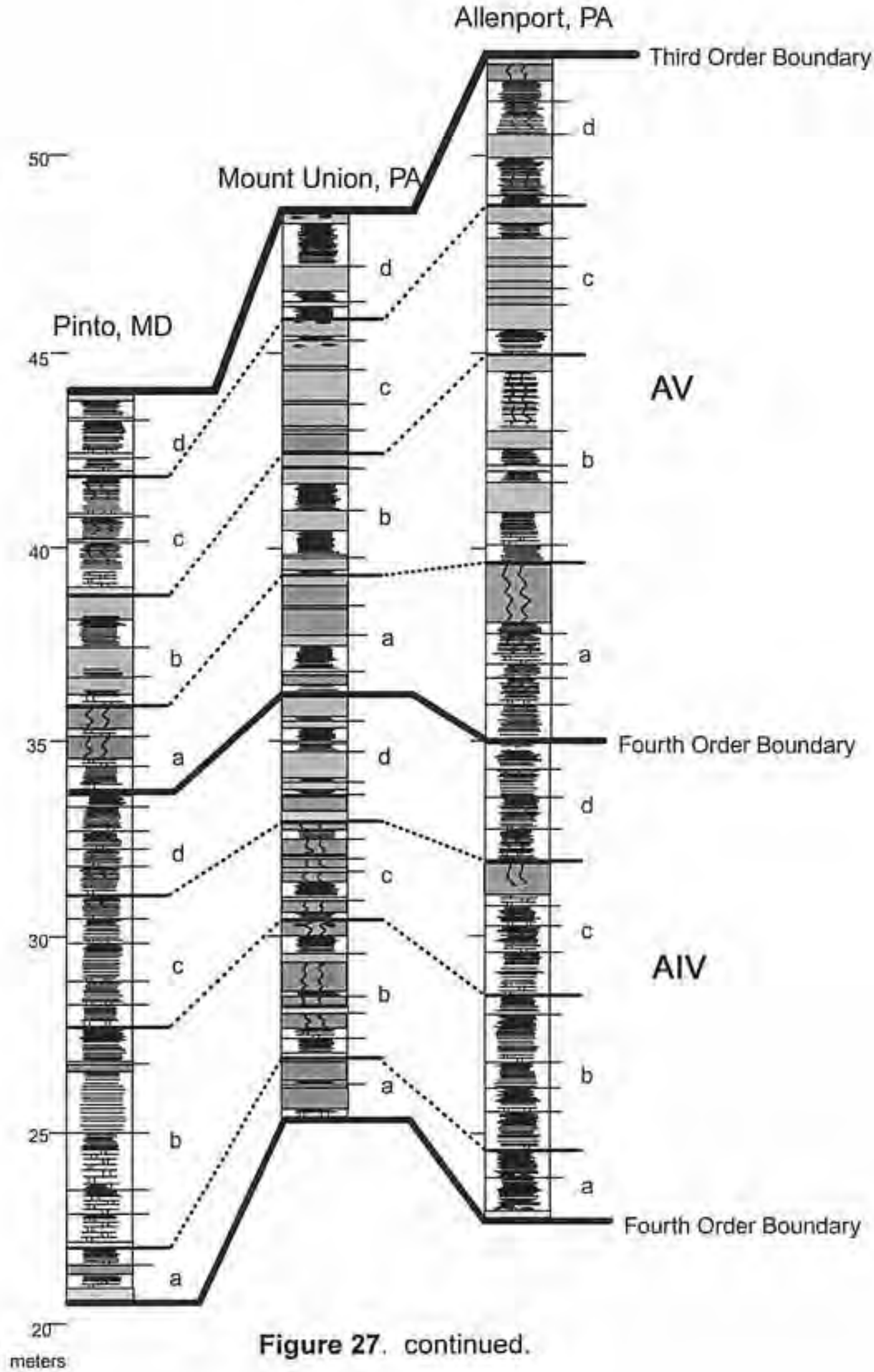


**Figure 27**. continued.

change across the basal and upper boundaries. Internal to the four Fourth Order cycles at each locality, four Fifth Order cycles were identified and correlated. Fifth Order cycles were again correlated on the bases of symmetry and degree of facies change across the basal and upper boundaries. Although Sixth Order cycle boundaries are denoted in the column, correlation of Sixth Order cycles was not undertaken in this study due to the difficulty in identifying these small-scale cycles in the represented facies. Thus, the correlation of Sixth Order cycles would be a misleading venture to undertake without first examining where any of the up to one hundred Sixth Order cycles may be missing in the strata of Third Order A.

Overall, the correlation of a cycle at any scale is based on symmetry, presence of diagnostic facies, and degree of facies change across its cycle boundaries. Correlation of cycles, of different orders, between three localities and over a distance greater than 150 km, then supports the conclusion that each boundary is a surface related to an allogenic, geologically instantaneous, rise in base-level .

# CHAPTER 7

# STRATIGRAPHIC DYNAMICS

## Eustacy

With the correlation of cyclic patterns over 150km, rapid changes in base-level, and the resulting cycle boundaries, are concluded to be directly related to the precessional signal (Figure 28). The stratigraphic surface at the base of each Sixth Order cycle (PAC) is produced by a rapid rise in base-level at the inflection point of precessional rise. At this point the rate of sea-level rise is great enough to cause cessation of sedimentary accumulation, thus producing the basal Sixth Order boundary. Stratigraphic accumulation (aggradation) upon the surface begins when base-level stabilizes. Stratigraphic accumulation persists in open (deep) facies until base-level reaches a critical rate of fall. This fall in base-level produces an identifiable stratigraphic surface (sea-level-fall surface) in many Sixth Order cycles (PACs) (Touchberry et al.,1991; Orzechowski et al., 1992). As base-level stabilizes at a lower level, stratigraphic accumulation (aggradation) commences again in the restricted (shallow) facies. Stratigraphic accumulation then ceases at the inflection point of the next rise, producing another stratigraphic surface (Sixth Order boundary).

Eustatic fluctuations that produce the Sixth Order cycle (PAC) is modulated by the 100,000 year eccentricity signal. Figure 29 is a diagram showing the modulation of the precessional signal, which produces Sixth Order cycles (PACs), by the eccentricity signal, which produces Fifth Order sequences. Change in base-level is greatest in the

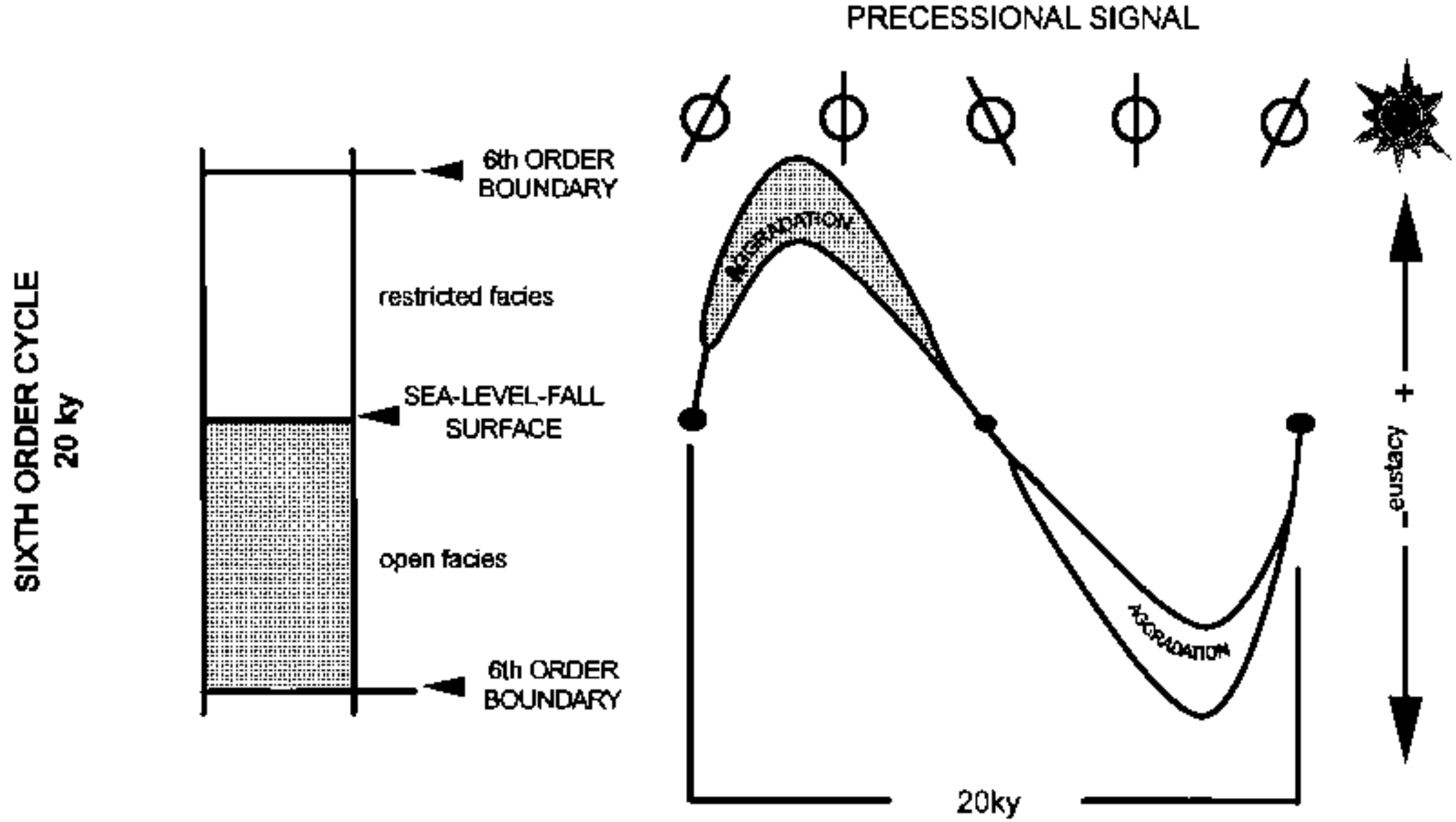


**Figure 28**. Eustacy in the Precessional Signal. Diagram of the typical symmetry of the Sixth Order Cycle (PAC)with its relation to the precessional signal.

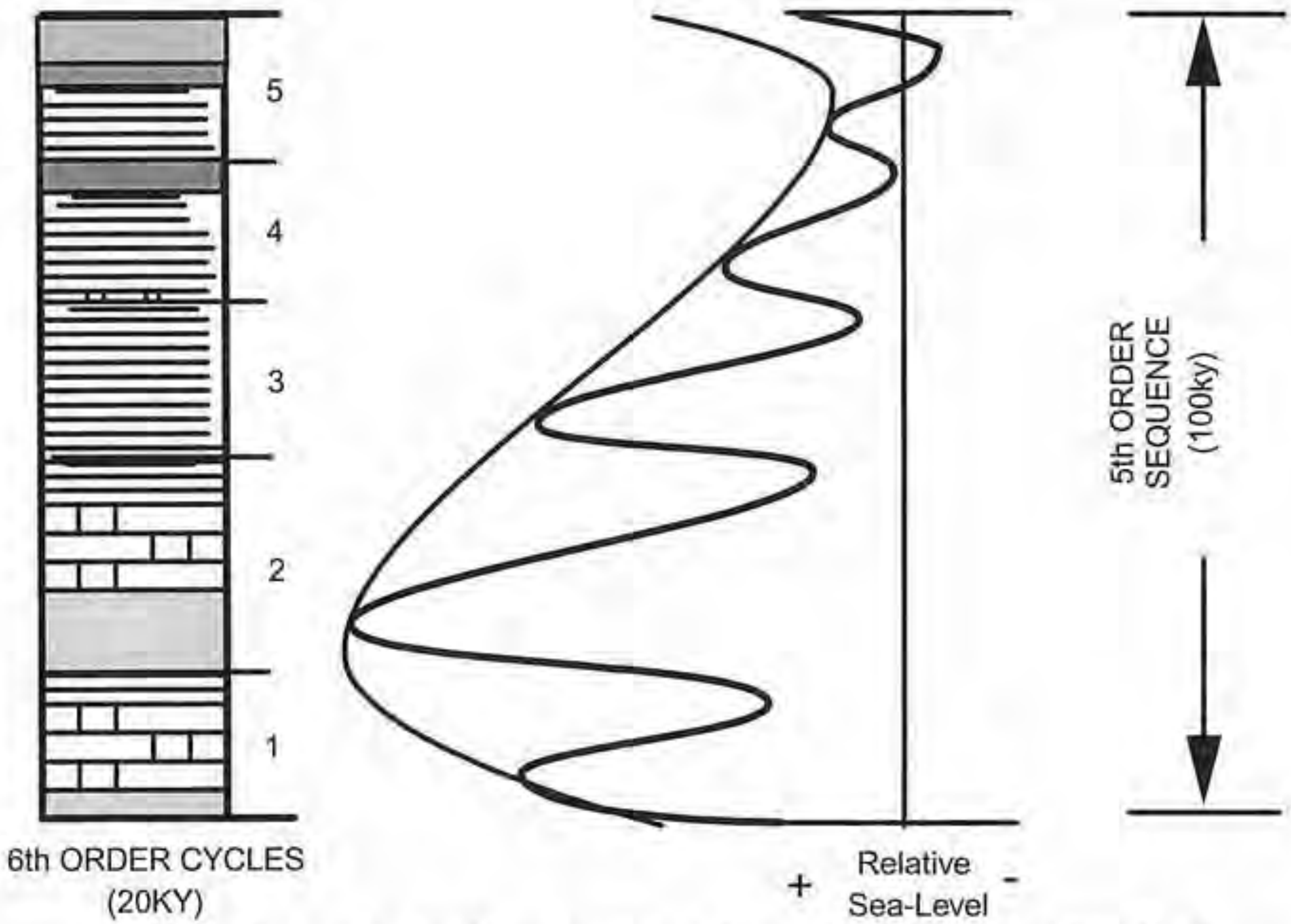


**Figure 29**. Eustacy in the 100ky Eccentricity Signal. Diagram of ideal Fifth Order sequence, with all Sixth Order cycles present, and a relative sea-level curve showing eustacy throughout one eccentricity signal. Note that Sixth Order boundaries occur at inflection point of sea-level rise.

basal two Sixth Order cycles in a Fifth Order sequence. The first two Sixth Order cycles (PACs) exhibit the greatest transgressive flooding in the Fifth Order sequence with the second Sixth Order cycle representing the most open (deep) facies in the Fifth Order sequence. The latter three Sixth Order cycles in the Fifth Order sequence represent a regressive trend in base-level. This regressive trend in base-level is represented by progressively smaller changes in base-level in each Sixth Order cycle towards the top of the Fifth Order sequence. The upper Sixth Order cycle of the Fifth Order sequence represents the most restricted (shallow) facies of the Fifth Order sequence.

The 100,000 year eccentricity signal is then modified by changes in eccentricity with a 400,000 year periodicity. In the study interval, change in base-level, due to the precessional signal is greatest in the first Fifth Order cycle of the Fourth Order cycle (400,000 year eccentricity signal), the second Fifth Order cycle of the Fourth Order exhibits the third greatest changes in base-level, the third Fifth Order cycle has the second greatest changes in base-level, and the fourth Fifth Order cycle shows the least change in base-level internal to the Sixth Order (precessional) cycles (Figure 30). The 2 million year Third Order (eccentricity ?) cycle then modulates the Fourth Order, 400,000 year eccentricity, cycles (Figure 31). The effect of the 2 million year Third Order cycle on each Fourth Order sequence is analogous to the effect of the 100,000 year eccentricity signal on the precessional signal.

Third Order A of The Tonoloway Formation only has four Fourth Order cycles internal to it. Figure 32 is a diagram which displays two scenarios explaining why and where the Fourth Order cycle may be missing in Third Order A. Figure 32B shows a

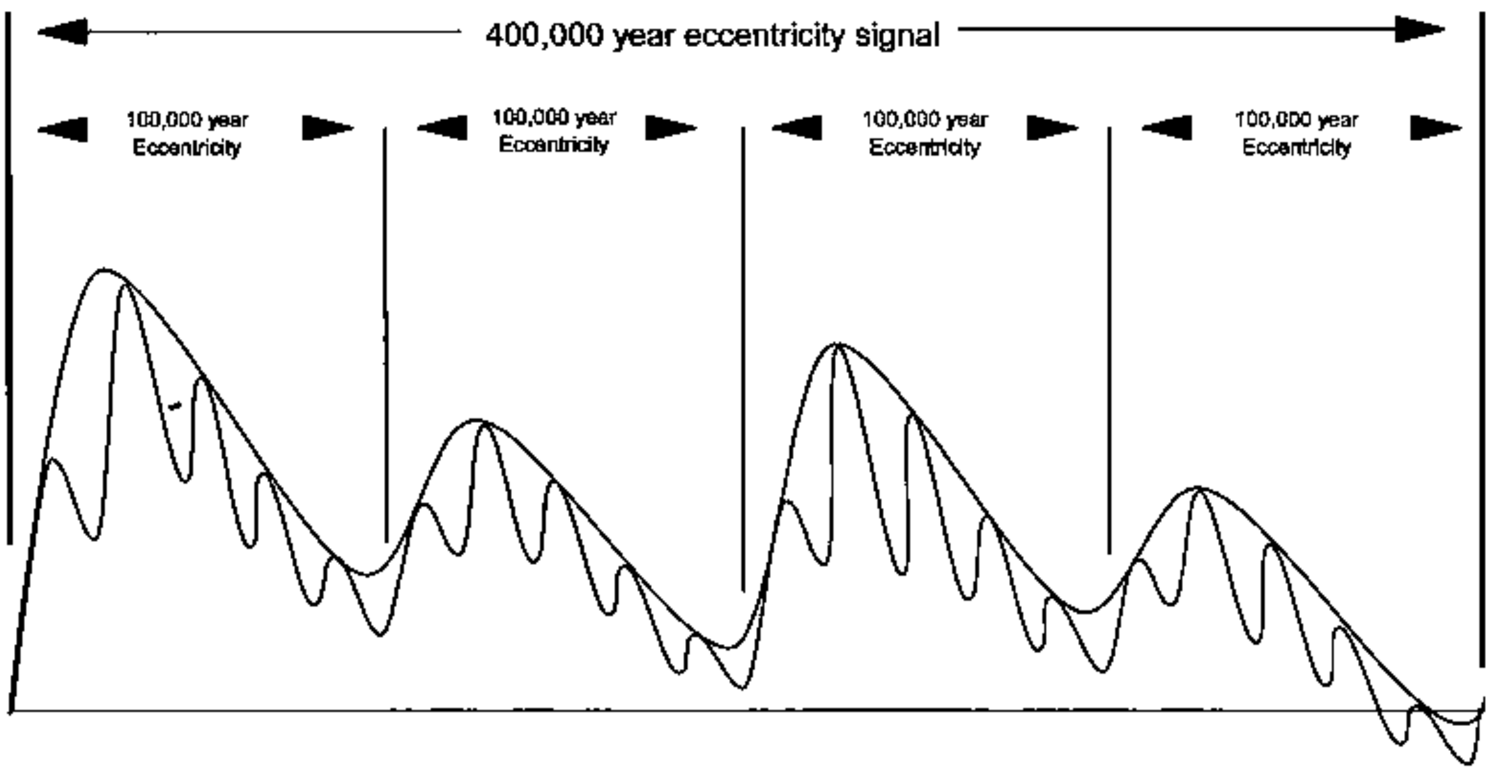


**Figure 30**. Eustacy in the 400,000 Year Eccentricity Signal. Diagram showing the effect of the 400,000 year eccentricity signal on the 100,000 year eccentricity signal and the 20,000 year precessional signal.

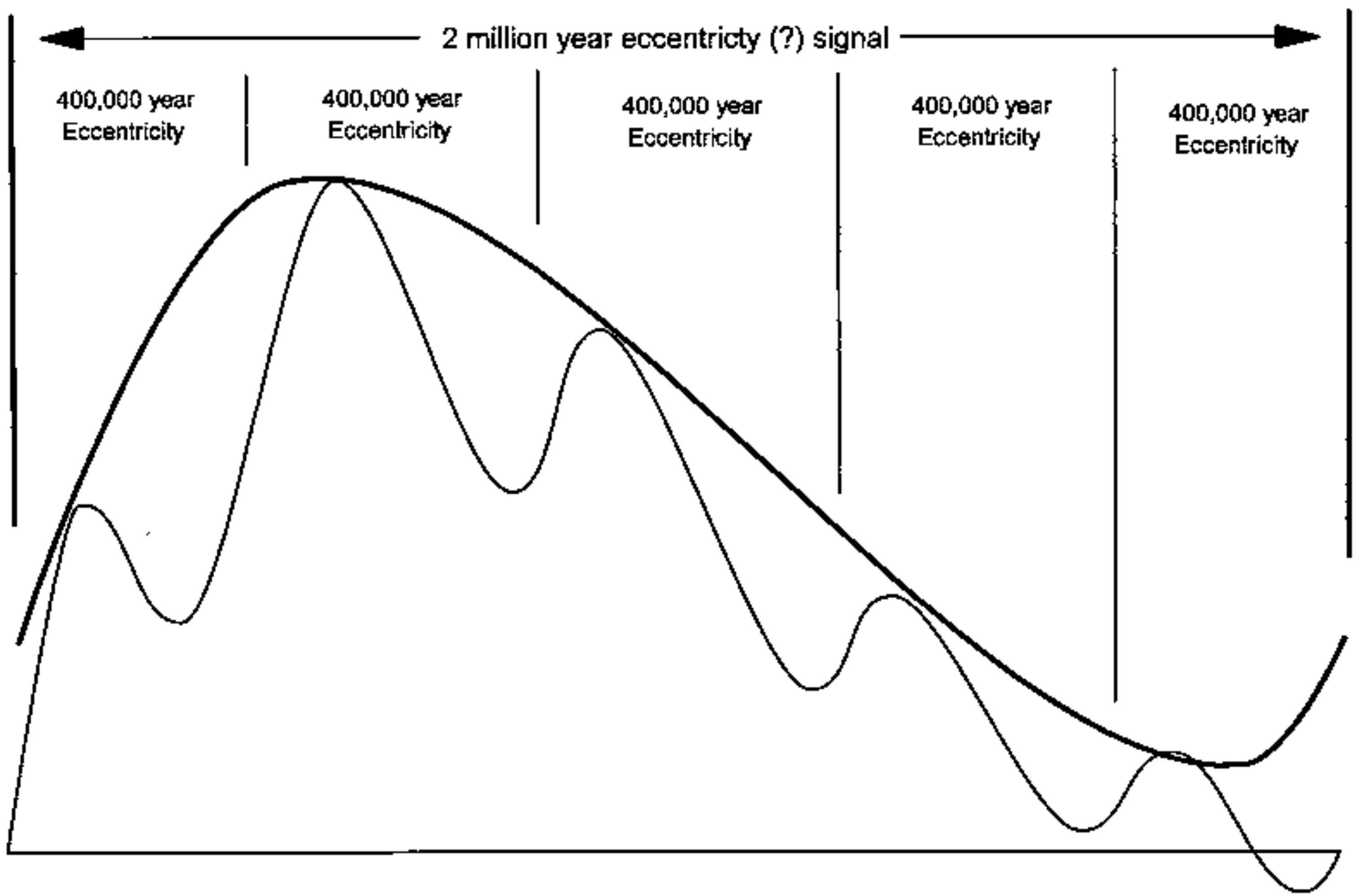


**Figure 31**. Eustacy in the Third Order Eccentricity (?) signal. Diagram of Fourth Order cycles modulated by the Third Order eccentricity (?) signal.

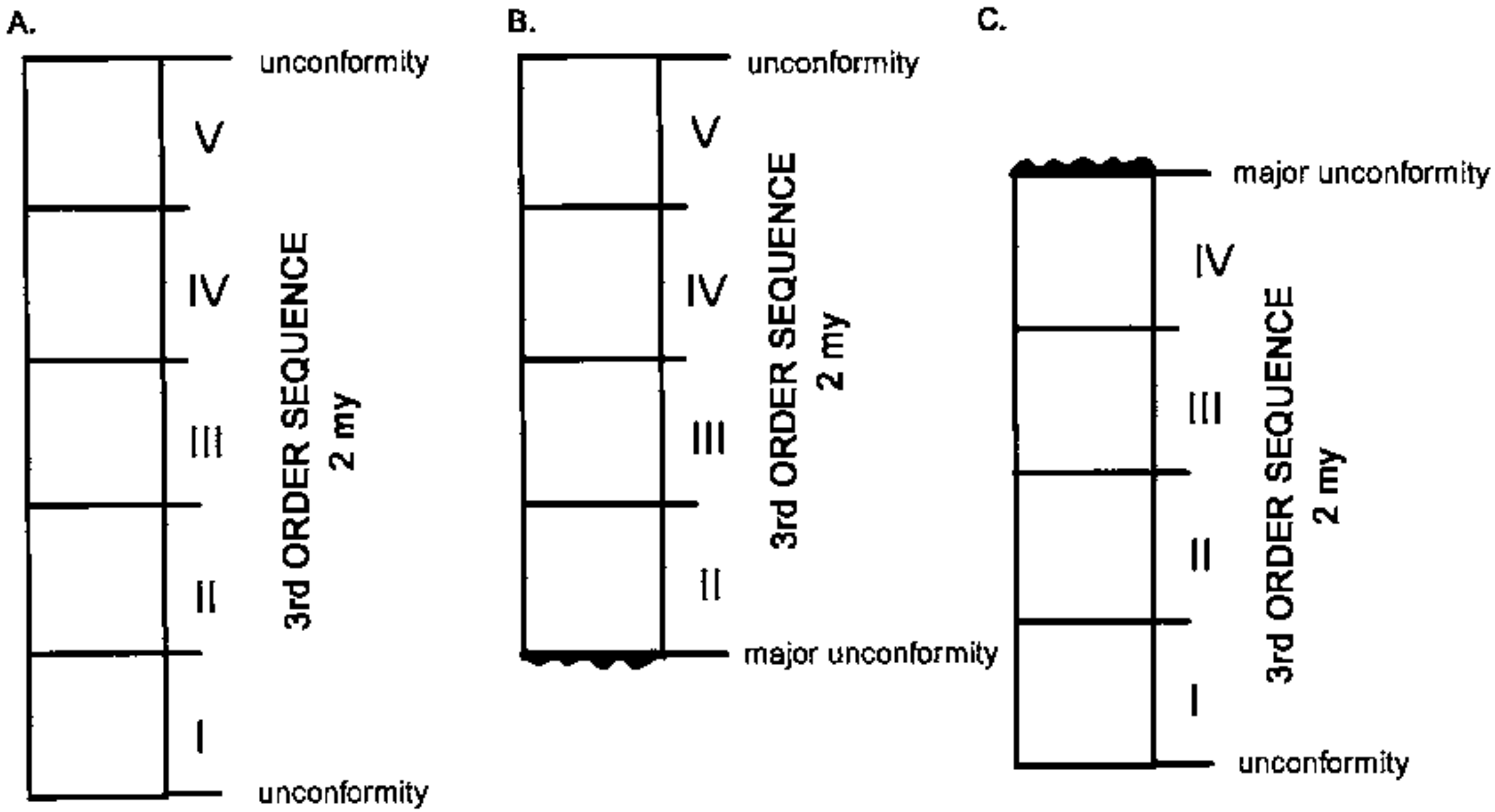


**Figure 32**. Possible Scenario for Missing Fourth Order Cycle in Third Order A. (A) is a diagram of a typical Third Order sequence with five Fourth Orders contained within it. (B) is a Third Order sequence with the basal Fourth Order cycle missing due to nondeposition or erosion. (C) is a Third Order sequence with the upper Fourth Order cycle is missing due to erosion or nondeposition.

major unconformity at the base of the Third Order sequence. This unconformity has Fourth Order I missing through non-deposition or erosion. Figure 32C shows a major unconformity, with Fourth Order V missing, at the top of the Third Order sequence due to non-deposition or erosion. For Third Order A of the Tonoloway Formation, it is proposed that the missing Fourth Order sequence is at the base of the Third Order sequence due to a hiatus in deposition or erosion at the Tonoloway-Wills Creek Boundary. Hiatus is chosen as the probable reason for the missing Fourth Order cycle at the base of Third Order A because there is a major deepening, represented by a massive shallow subtidal calcarenite, which has no analogue throughout the Salina Group. This Third Order boundary is also the surface with the most disjunct facies pattern overall.

## Subsidence

Episodic base-level rises and falls produce stratigraphic surfaces. These stratigraphic surfaces, when correlated, are synchronous surfaces which can be used to examine subsidence rates within a basin (Anderson et al., 1986). Variation in thickness between synchronous stratigraphic surfaces may be influenced by local topography, creating accommodation space for aggradation, and lateral variation of sediment accumulation rates as well as differences in subsidence (Anderson et al., 1986). To isolate subsidence from the other factors controlling stratigraphic thickness, synchronous surfaces that were also horizontal surfaces at sea-level must be utilized. Such paleoisotopographic surfaces eliminate topography as a factor in controlling thickness. Thus, thickness differences between such surfaces are attributable to differential subsidence (Figure 33).

This concept can be applied to Tonoloway cycles at all scales because of the abundance of sea-level surfaces. Fourth Order AII, for example, has a different stratigraphic thickness at all three localities. The strata of Fourth Order AII begins at all localities, with shallow subtidal calcarenite and ends with supratidal dolostone (Figure 34). Thus, this Fourth Order begins on a horizontal surface and ends on a horizontal surface, although the thicknesses are different. The differences in thickness are therefore due to differential subsidence over time.

The stratigraphic thickness of Third Order A is different at the Mount Union locality and the Pinto locality by approximately 5 meters (Figure 27); thus overall subsidence was greater at the Mount Union locality than at the Pinto locality by 5 meters over a 2 million year period. If one looks at the Fourth Order cycles internal to the Third Order sequence, one finds an inconsistency in subsidence. Mount Union locality has greater subsidence for the first two and the last Fourth Order cycle of the sequence while the Pinto locality has greater subsidence than the Mount Union locality during deposition of the third Fourth order cycle of the sequence.

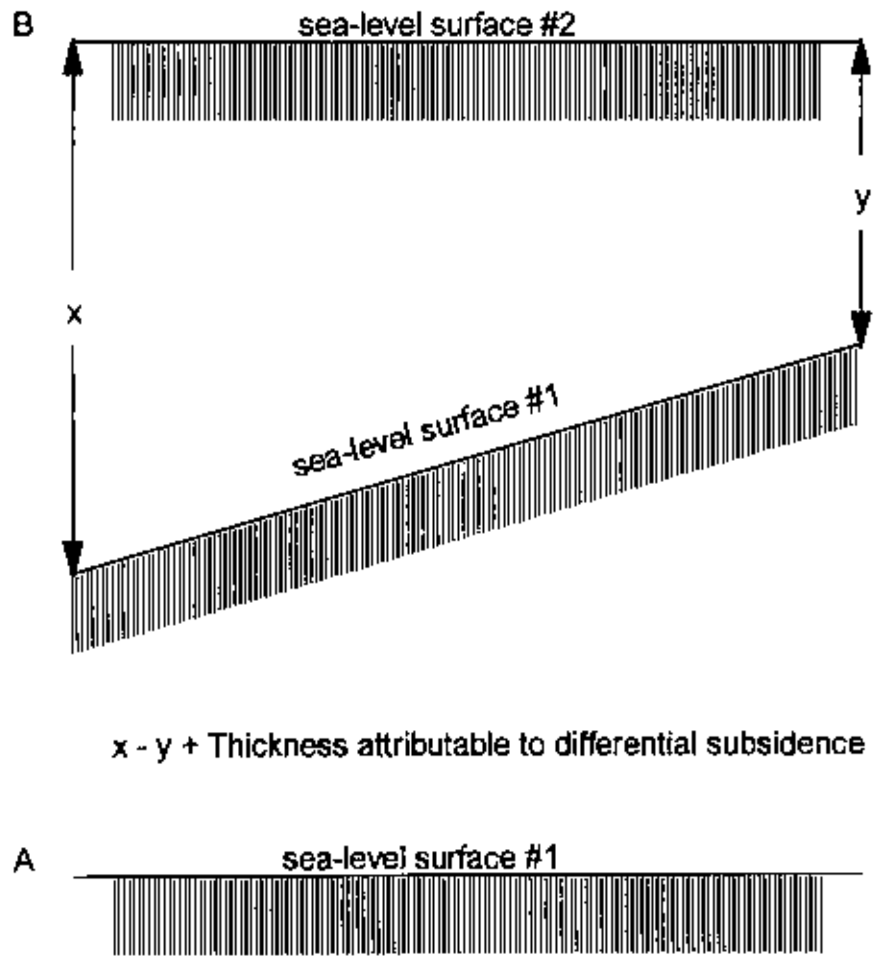


**Figure 33**. Subsidence. Model for calculating differential subsidence based on recognition of once synchronous horizontal surfaces: (A) represents time 1 and (B) a later point in time. (Anderson et al., 1989,Fig. 5)

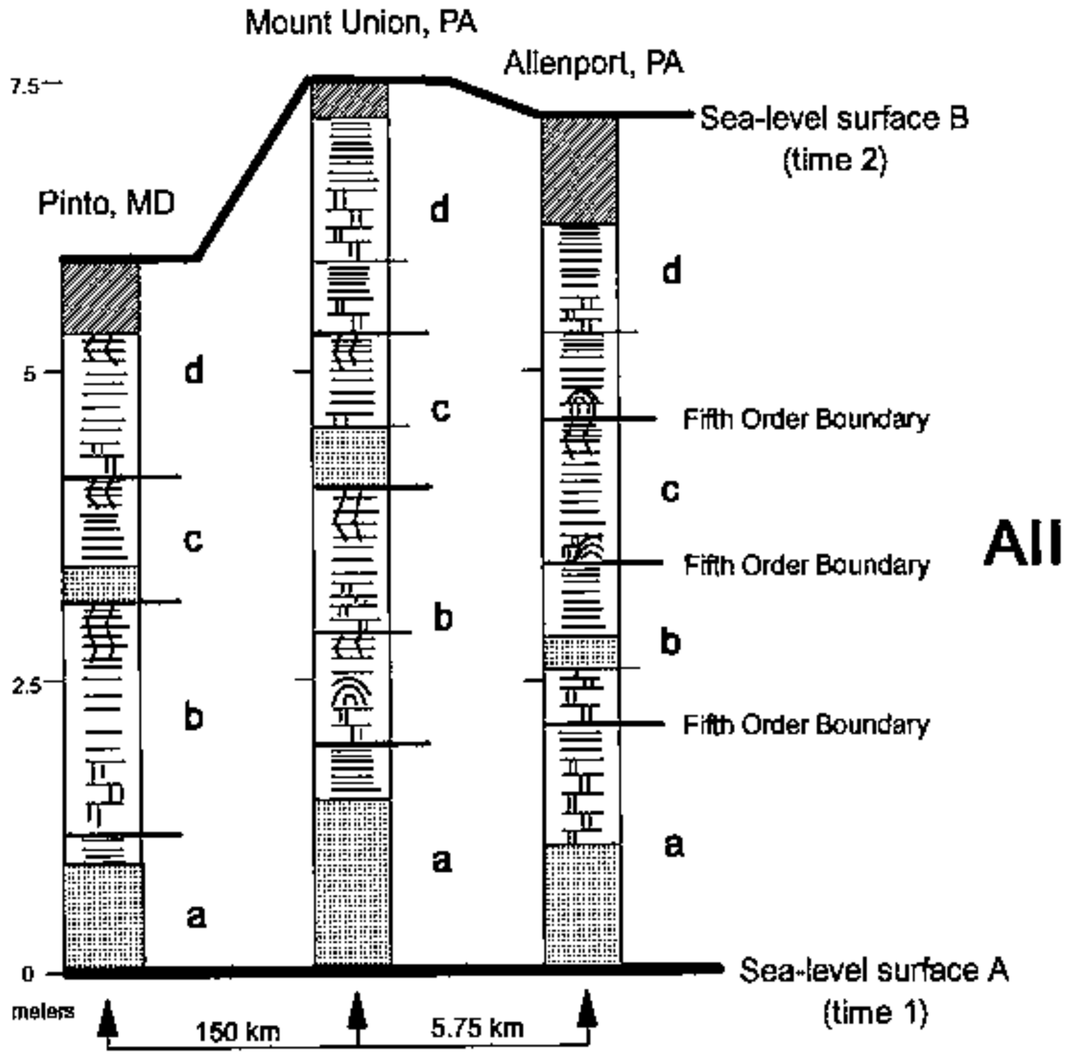


**Figure 34.** Subsidence of Fourth Order **AII**. Columnar sections of Fourth Order **AII** to show differential subsidence between localities and over time. Sea-level surface A is a horizontal synchronous surface at time 1 and Sea-level surface B is a horizontal synchronous surface at a later time (time 2).

# CHAPTER 8

# CONCLUSIONS

The Upper Silurian Tonoloway Formation is made up of small-scale peritidal cycles, with an average cycle thickness of 3.2 feet. These small-scale cycles are upward-shallowing and bounded by abrupt surfaces produced by geologically instantaneous rises in base-level. These surfaces separate markedly disjunct facies. Internal to these small-scale cycles are sea-level-fall surfaces which separate the lower high-stand portion of the cycle from the upper low-stand portion. The general symmetry of these small-scale cycles is comparable to that of PACs (Goodwin and Anderson, 1985). These small-scale cycles were given the designation of Sixth Order (PAC).

The Sixth Order cycles (PACs) identified in Third Order A of the Tonoloway Formation were found to be grouped into larger orders of cyclicity based on symmetry and magnitude of facies change across stratigraphic surfaces. Fifth Order cycles are basically asymmetric (shallowing-upward) with a minor deepening portion in the second Sixth Order. The symmetry of a complete Fifth Order cycle is one in which the first Sixth Order cycle of the Fifth Order cycle has the greatest deepening of the Fifth Order cycle. The second Sixth Order cycle (PAC) of the Fifth Order cycle has the most open facies of the Fifth Order cycle. The last three Sixth Order cycles progressively become more restrictive towards the top of the Fifth Order Cycle.

Fourth Order cycles then contain four Fifth Order Cycles. The symmetry of the Fourth Order cycle is one which has the most open facies in the first Fifth Order cycle and the most restricted in the last Fifth Order. The medial two Fifth Orders, however, do not follow the overall symmetry of the Fourth Order cycle. The first of the two medial Fifth Order cycles is more restricted than both the first and the third Fifth Order cycle in the Fourth Order cycle. The second medial Fifth Order cycle of the Fourth Order cycle is more open than the second and fourth Fifth Order cycles of the Fourth Order cycle but more restrictive than the first Fifth Order cycle of the Fourth Order cycle (Figure 20). Third Order A was found to have a symmetry which is shallowing upward from the first Fourth Order cycle to the last Fourth Order cycle.

The stacking pattern of each order of cyclicity identified in Third Order A of the Tonoloway Formation is consistent with the stacking pattern demanded by the orbital theory of Milankovitch (Figure 10). This consistency in the stacking patterns of cycles in Third Order A with the stacking pattern of Milankovitch-band orbital forcing constitutes evidence for a genetic hierarchy of allocycles.

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