ALLOCYCLIC ANALYSIS OF THE UPPER SILURIAN TONOLOWAY-KEYSER FORMATIONAL CONTACT IN CENTRAL PENNSYLVANIA

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ABSTRACT

Allocyclic analysis of the stratigraphic interval encompassing the Tonoloway-Keyser formation boundary in Central Pennsylvania reveals a complex stratigraphic relationship produced by the superposition of orbitally forced hierarchic eustatic sea-level fluctuations on a differentially subsiding basin. To the north (Tyrone, Pennsylvania) the formation boundary is an unconformable third-order sequence boundary at which open shelf Keyser carbonate facies lie directly on peritidal carbonates of the Tonoloway Formation. Below the unconformity differential subsidence and/or uplift resulted in various amounts of vacuity throughout the study area. To the south (Everett, Pennsylvania) additional Keyser cycles occur above the unconformity, indicating decreasing hiatus in regions of greater subsidence following exposure and erosion. Beneath the unconformity, peritidal Tonoloway facies to the north grade laterally into subtidal Keyser facies to the south within individual sixth- and fifth-order cycles as a result of higher subsidence rates toward the basin axis.

A correlative hierarchic allocyclic fabric of fourth- and fifth-order sequences permits a chronological analysis of these lateral facies changes and of the unconformity. Immediately before accumulation of the study interval, peritidal (Tonoloway) facies existed throughout the study area. Above this datum, over a period of 400,000 years, differential subsidence generally produced Keyser facies to the south and east, a pattern interrupted every 100,000 years by fifth-order lowstands in sea level that produced Tonoloway facies. At localities closest to the basin margin Tonoloway facies persisted throughout the study interval. If the interpretation of the hierarchic cyclic fabric is correct, at least ten fifth-order sequences (1 million years) are lost by erosion at some localities beneath the unconformity (vacuity) and at least five fifth-order sequences (500,000 years) are missing by non-deposition above the unconformity (hiatus). Marked differences in vacuity at Tyrone and the localities immediately to the south and east suggest Upper Silurian movement along a structural lineament. The demonstration of a basinwide correlative allocyclic framework allows quantification of the roles of tectonics and eustasy in the accumulation of stratigraphic sequences.

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DEDICATION

This thesis is dedicated to my mother, Marty Sinclair, who has given more to her family than anyone could ever imagine. Without her support and sacrifice I would not have become who I am or accomplished what I have. Thanks Mommalita.

I would also like to dedicate this work to the memory of my father, Charles Sinclair.

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CHAPTER I

INTRODUCTION

Statement of the Problem

This study focuses on the relationship between the Upper Silurian Keyser and Tonoloway Formations in central Pennsylvania. The Tonoloway-Keyser formational contact lies below the Silurian-Devonian boundary and coincides with the boundary between the Salina and Helderberg Supersequences (figure 1). At the northernmost locality in the study area (Tyrone, Pennsylvania), subtidal shelfal facies of the Keyser Formation lie unconformably on peritidal facies of the Tonoloway Formation. To the south, more stratigraphic section is present between the unique, distinguishable unit that is the base of the Keyser Formation at Tyrone and distinctive Tonoloway facies. The basic issue regarding the relationship between the Tonoloway and Keyser formations is whether there is everywhere an unconformity between the two units or alternatively there is a lateral facies change between the formations in some parts of the basin. Whereas Head (1969, 1972) interpreted the relationship as one of lateral facies change, the stratigraphic relationship between the unconformity at Tyrone and this facies change needs to be resolved. A small-scale allocyclic analysis of the interval including the formational boundary was conducted in order to resolve these issues.

The allocyclic analysis was based on the Hypothesis of Punctuated Aggradational Cycles (PACs). A genetic hierarchy based on principles of Milankovitch orbital forcing was applied to explain the forcing mechanisms involved in stratigraphic accumulation. These models predict a hierarchic framework of small-scale allocycles correlative across facies change and useful in discriminating hiatus (non-deposition) and vacuity (erosion)

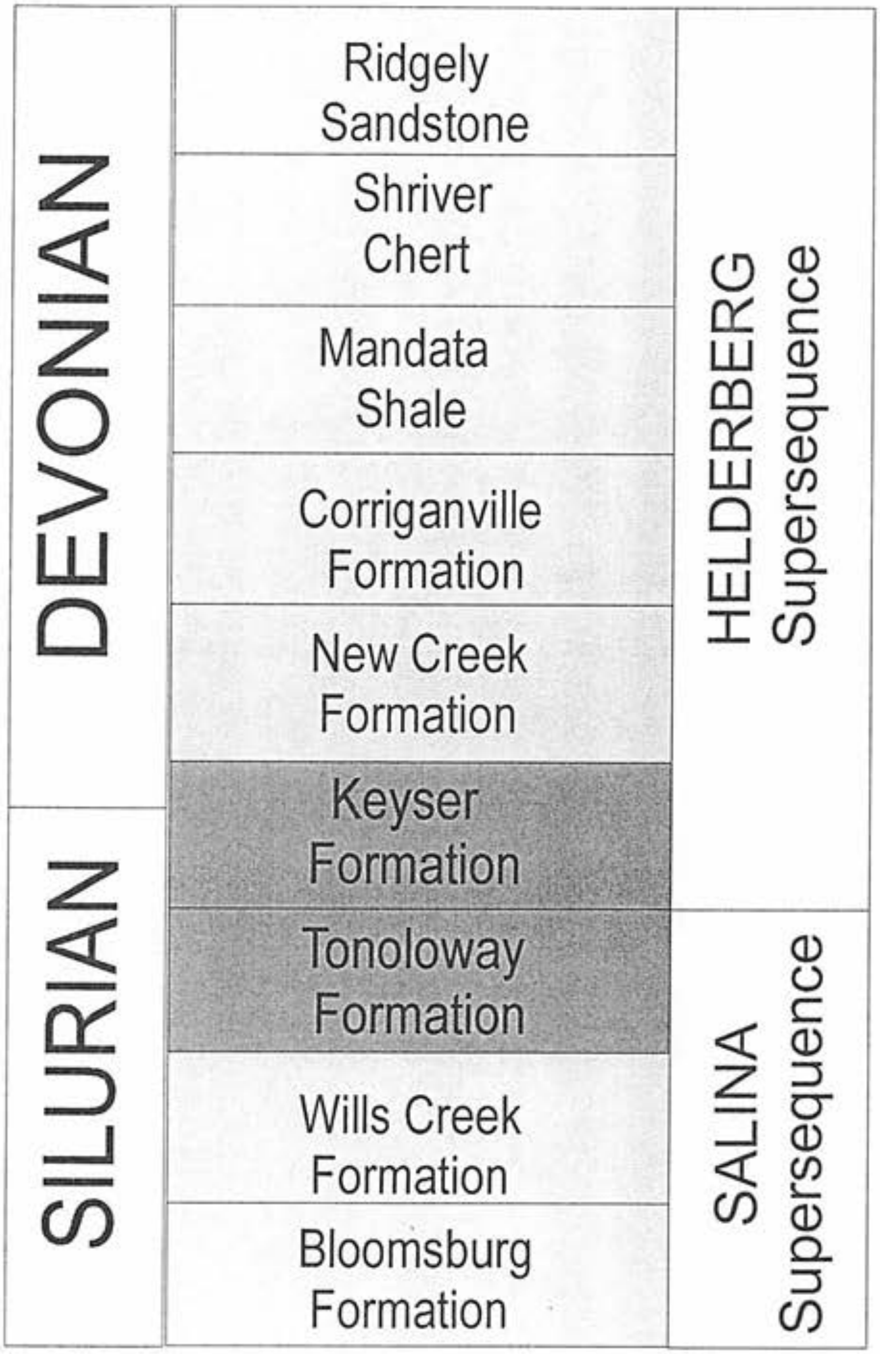

Figure 1: Silurian and Devonian Stratigraphy. The Tonoloway-Keyser formational contact coincides with the boundary between the Salina and Helderberg Supersequences, two second-order sequences representing 10 million years each.

at unconformities (Goodwin and Anderson, 1997). Correlation of allocycles in the interval of the formational boundary should help resolve the relationship between the unconformable contact at Tyrone and the lateral facies change interpreted by Head.

These correlative cyclic patterns provide a framework for interpretation of basin dynamics such as differential subsidence, eustatic sea-level fluctuations, and differential erosion. The results of the study indicate that there is neither a simple unconformable relationship nor a simple lateral facies change occurring between the Tonoloway and Keyser formations, but rather a complex combination of the two end-member models.

Scope and Methods

This study consists of eight localities throughout central Pennsylvania where the Tonoloway-Keyser contact is exposed (figure 2). The northernmost locality, Tyrone, is closest to the basin margin while localities to the south and east are basinward and therefore consist of more stratigraphic section. The base of the study interval is a conformable sequence boundary; the interval is everywhere overlain by a unique cycle in the Keyser Formation that is correlative at each locality throughout the study. At Tyrone, Pennsylvania, the Tonoloway-Keyser formational contact is an unconformable third-order sequence boundary at which subtidal shelfal facies of the Keyser Formation directly overlie peritidal cryptalgal laminites of the Tonoloway Formation. At localities to the south and east the formational contact does not coincide with the unconformable sequence boundary but rather is a conformable contact placed at different stratigraphic levels below the unconformity.

In order to conduct the allocyclic analysis, stratigraphic columns were constructed at the eight localities in the study. The columns, drawn at the scale of five feet to the

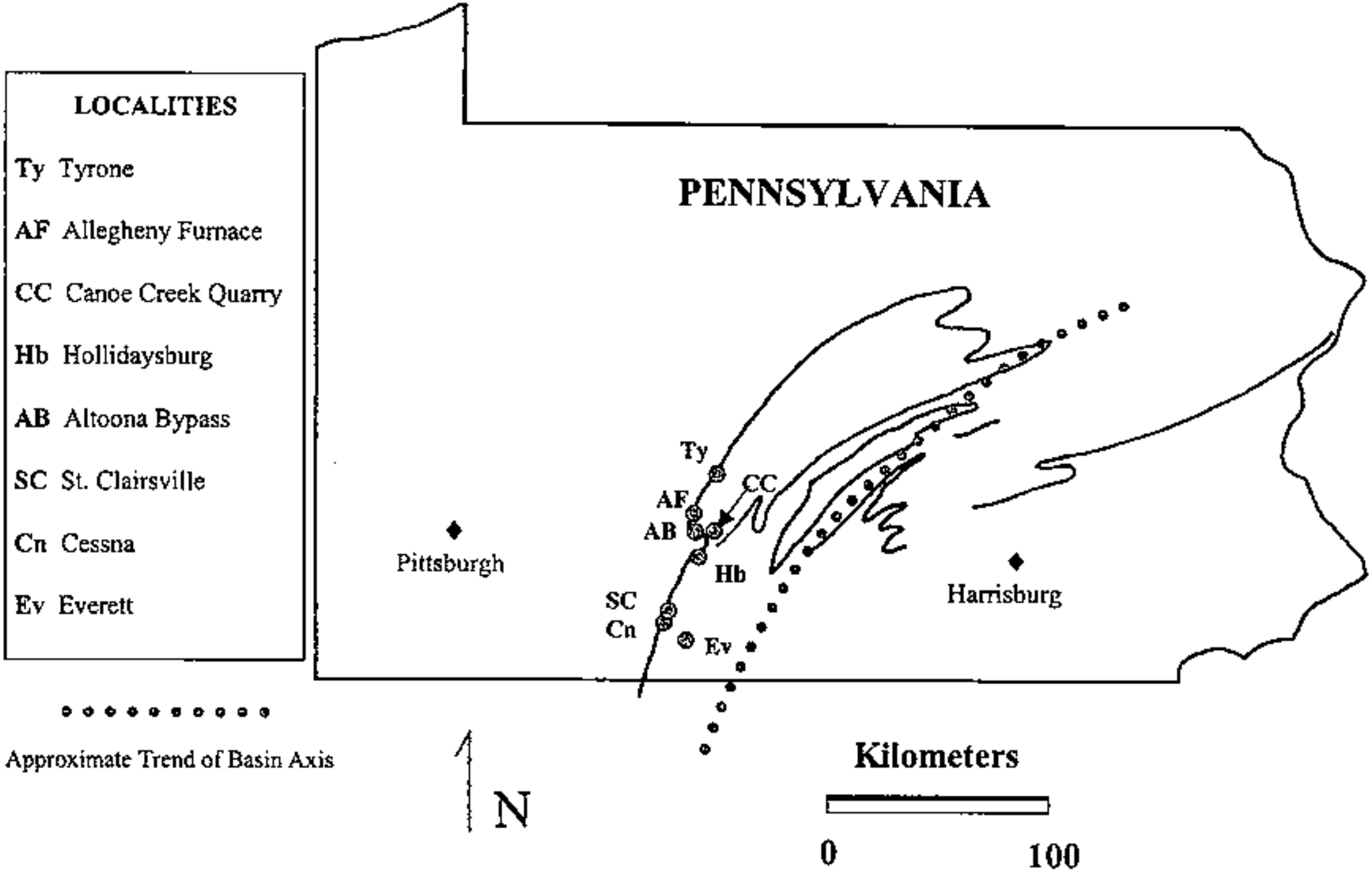

Figure 2: Study Localities. The Silurian outcrop belt of Pennsylvania is represented by the solid lines. Large dots indicate location of outcrops analyzed in this study. Detailed descriptions of outcrop localities as well as complete stratigraphic sections are in Appendices A and B.

inch, included observations made in thin section as well as at the outcrop. Cyclic patterns within the study interval were established on fundamental criteria described in the PAC hypothesis (Goodwin and Anderson, 1985), particularly by the recognition of disjunct facies relationships at cycle boundaries. Correlation among localities was accomplished by matching hierarchic patterns of facies change.

The stratigraphic columns were photocopied, then scanned using Adobe Photoshop LE. Microsoft Paint was used to add color for discrimination of cyclic sequences. All text and titles of figures were added in Microsoft Word.

Field samples were collected above and below most cycle boundaries throughout the stratigraphic study interval. The samples were used for petrographic study in order to examine composition, texture and faunal content in detail. Approximately one hundred samples were cut and mounted on 3 x 2 inch and 3 x 1.5 inch petrographic slides. Rock slabs were helpful in the determination of larger-scale sedimentary structures. Samples proved essential in making ultimate decisions regarding correlation.

Significance

This project was undertaken not to provide evidence that small-scale allocycles exist, but to illustrate their use for analysis of an unconformable sequence boundary at a formational contact. Establishing detailed allocyclic correlation (using Punctuated Aggradational Cycles—PACs) above and below the unconformity allows for quantification of vacuity and hiatus. Details of erosional history (vacuity) can be determined by numbers of cycles missing below the unconformity while onlap history (hiatus) can be interpreted by correlation of cycles above the unconformity. While the formational contact is unconformable at some localities in this study, at other localities the contact is clearly conformable giving rise to the possibility of lateral facies change as suggested by Head (1969, 1972). If there is lateral facies change between the two formations then the allocyclic framework in the Tonoloway Formation should be traceable into Keyser facies. Clarification of the relationship between these two formations using a correlative hierarchic framework should help bridge the gap between large-scale sequence stratigraphy and small-scale allostratigraphy as produced by orbital forcing. This study examined the relationship between sequence-bounding unconformities and a Milankovitch hierarchy of allocycles.

CHAPTER 2

STRATIGRAPHIC MODELS

Introduction

Before the late 1970s, stratigraphic analysis utilized traditional formations and members as the fundamental units of description and interpretation. The common model for stratigraphic study was gradualism (e.g., Rickard, 1962; Laporte, 1969) in which formations were time-transgressive units representing migrating major environments. Traditional use of formations and members was adequate when the general consensus was that broad environmental bands migrated laterally to produce generally diachronous rock units. Walther's Law could explain vertical successions of laterally contiguous environments, but the sharp boundaries between generally conformable units defied explanation in traditional models (Anderson et al., 1984). Also, the common occurrence of correlative intra-formational cyclic patterns indicating episodic accumulation could not be explained. For example, pervasive shallowing-upward cycles at different scales indicated that "transgressive" sequences were not continuously deepening as predicted by stratigraphic gradualism (Goodwin et al., 1986).

In the late 1970s and early 1980s, a new school of stratigraphy, allostratigraphy (Goodwin et al., 1986; Anderson and Goodwin, 1990), recognized that time-stratigraphic sequences, or cycles, bounded by discontinuities, might be more useful than the formation in stratigraphic analysis. Two branches of allostratigraphy were rooted in the basic idea that accumulation of sedimentary rock was episodic: large-scale sequence stratigraphy (e.g., Vail et al., 1977); and small-scale allocyclic stratigraphy, represented by the Hypothesis of Punctuated Aggradational Cycles (Goodwin and Anderson, 1985).

The main sequence stratigraphers of the time (e.g., Vail, Mitchum) defined a set of fundamental concepts describing and explaining the unconformity-bounded depositional sequence (Vail et al., 1977). The proponents of small-scale allocyclicity (e.g., Goodwin and Anderson) developed their own set of basic concepts describing and interpreting sharply bounded shallowing-upward cycles (Goodwin and Anderson, 1980; Goodwin and Anderson, 1985). Though based on a shared view that stratigraphic accumulation was episodic and allogenic, these two schools approached stratigraphic analysis in different ways.

Sequence Stratigraphy

Sequence stratigraphy, according to Van Wagoner et al. (1988, p. 39), is "the study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or non-deposition, or their correlative conformities". Sequence stratigraphers use seismic data in conjunction with well log and outcrop data to recognize and correlate allogenic packages of strata (sequences) on a global basis. Mitchum et al. (1977, p. 53) defined the depositional sequence as a "stratigraphic unit composed of a relatively conformable succession of genetically related strata, bounded at its top and base by an unconformity or its correlative conformity" and proposed use of the sequence as a basic unit for stratigraphic analysis (figure 3). A sequence boundary was recognized as an unconformable surface that, if traced laterally, may become a concordant surface of non-deposition exhibiting evidence of less significant hiatus (Mitchum et al., 1977). Onlap of coastal deposits within depositional sequences was used to determine relative changes in sea level (Vail et al., 1977, part 3). A global sea-level curve was generated through correlation of sequence

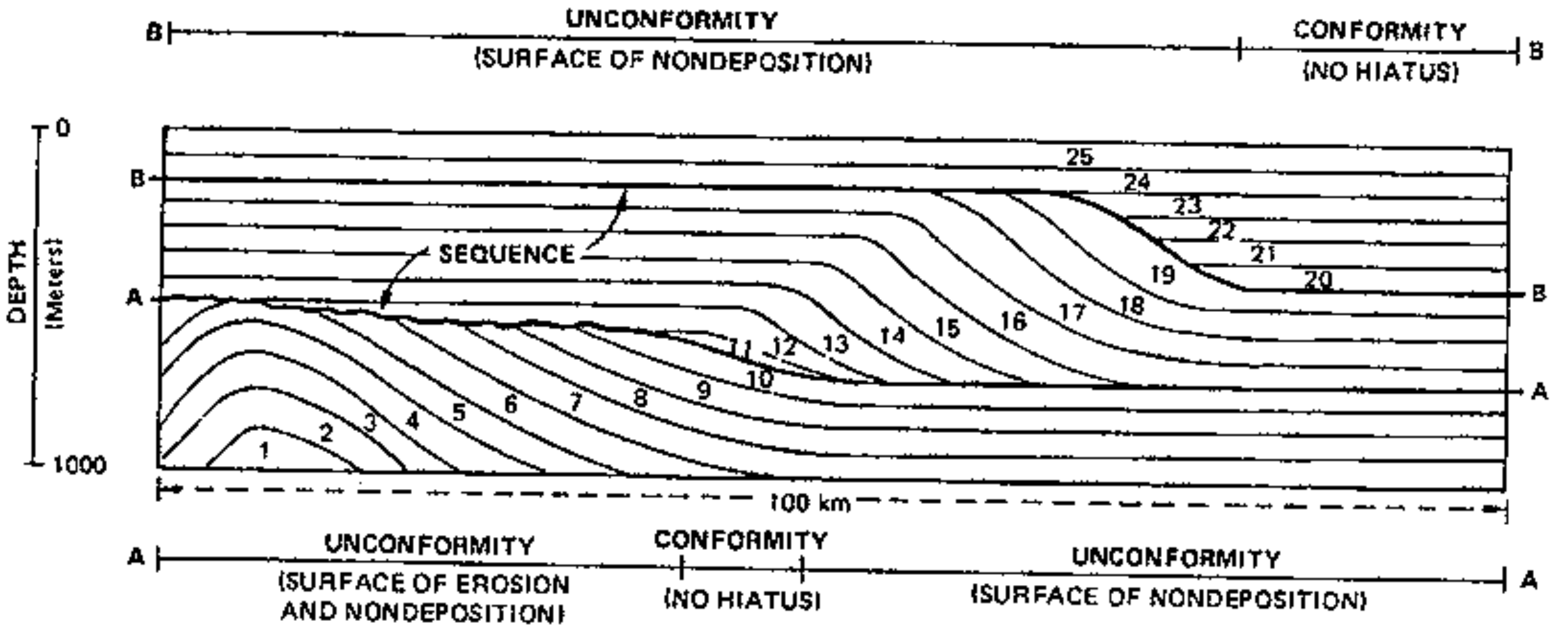

Figure 3: Generalized Stratigraphic Section of a Sequence. Stratigraphic boundaries (A and B) pass laterally from unconformities to correlative conformities. Individual units of strata (numbered 1 through 25) are traced by following stratigraphic surfaces. These surfaces are assumed to be conformable where successive strata are present; hiatuses where units of strata are missing (From Mitchum et al., 1977).

boundaries on different continental margins and the matching of similar relative magnitudes of sea-level changes (Vail et al., 1977, part 4). In this early stage of development the fundamental cycle of relative change in sea level was the third-order cycle, which had a duration of 1-10 million years and represented one rise and fall in sea level.

More recent refinements to sequence stratigraphy have led to a hierarchy of stratal units that consists of parasequences, parasequence sets and sequences (Van Wagoner et al., 1990). A parasequence is a relatively conformable, genetically related succession of beds or bedsets bounded by marine flooding surfaces or their correlative surfaces (Van Wagoner et al., 1988). A parasequence represents hundreds to tens of thousands of years of stratigraphic accumulation. Vertical facies associations within parasequences record a gradual decrease in water depth followed by an abrupt deepening at the marine-flooding surface at the parasequence boundary (figure 4). A parasequence set, representing thousands to hundreds of thousands of years, is a succession of genetically related parasequences that form a distinctive stacking pattern (Van Wagoner et al., 1988). Parasequence sets consist of groups of parasequences that are stacked into retrogradational, progradational and aggradational patterns, each corresponding approximately to a systems tract within a sequence (figure 5 and figure 6). The depositional sequence, bounded by unconformities and their correlative conformities, represents one hundred thousand to millions of years of stratigraphic accumulation. A depositional sequence is characterized by a predictable stacking pattern of parasequence sets.

Identification of a hierarchic stratigraphic record by sequence stratigraphers allowed more detailed analysis of the internal anatomy of depositional sequences.

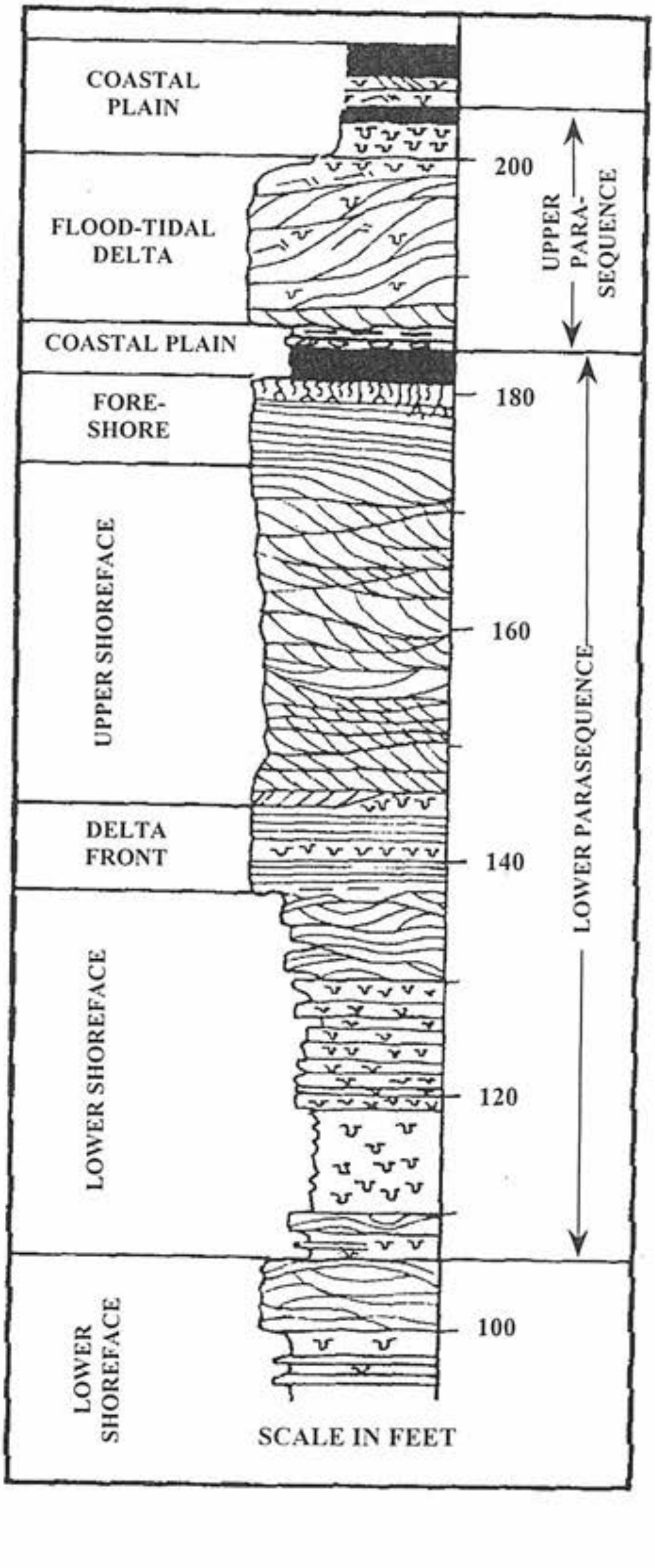

Figure 4: Parasequence Set. Example of a parasequence set containing two parasequences. The boundaries of each parasequence are erosional surfaces. (From Van Wagoner et al., 1990)

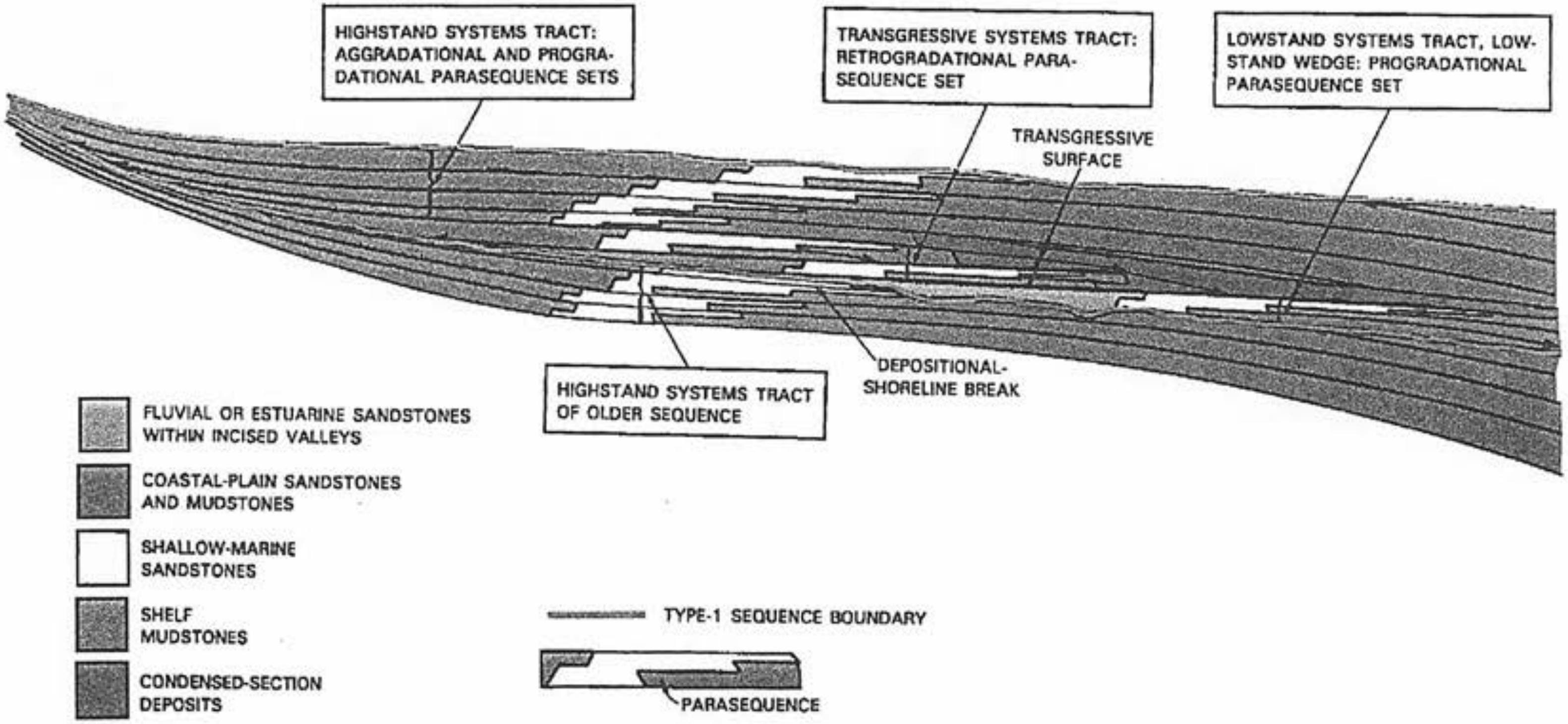

Figure 5: Type 1 Unconformity. The depositional sequence, bounded by unconformities and their correlative conformities, consists of a predictable pattern of parasequence sets. The pattern above represents a type-1 sequence boundary (from Van Wagoner et al., 1990).

Sequence stratigraphers were able to determine that a typical depositional sequence contains lowstand, transgressive and highstand systems tracts, each tract consisting of predictable patterns of parasequence sets. The three-tiered hierarchy did not, however, provide greater resolution of the boundary conditions of any given parasequence or sequence. While this hierarchy fits the patterns observed at many scales (outcrops, well logs and seismic surfaces) and is thus useful for stratigraphic study, it is not scale-specific; consequently there can be no direct connection between a specific process and the accumulation of any given tier in the hierarchy. For example, the recurrence interval for a parasequence or a parasequence set encompasses the periods of more than one orbital process. Owing to that lack of a link between a specific process and the stratigraphic response to that process, sequence stratigraphy is an inadequate approach to stratigraphic analysis. A sequence stratigraphic analysis of a third-order sequence (the fundamental cycle of relative change of sea level) and its boundaries, for example, can reveal the components of the sequence, but fails to adequately explain the origin of these components in terms of specific processes and time.

The limitations of the sequence stratigraphic hierarchy are particularly important in interpreting sequence boundaries. The general geometric relationships of sequence boundaries can be identified and their causes partially explained by the three-tiered model. However the lack of a temporal context and of a connection between each rank in the hierarchy and a specific process renders sequence stratigraphy inadequate for the detailed analysis of a sequence boundary. Two types of sequence boundaries (figures 5 and 6) are identified by vertical changes in parasequence stacking patterns. The unconformable part of a sequence boundary "can be traced seaward into a conformable surface on the shelf or slope, commonly occurring at or near the base of a marine parasequence " (Van Wagoner et al., 1990, p. 30). The two types of unconformities are recognized, but the sequence stratigraphic model does not explain their characteristics or specifically why stratigraphic section is missing at these surfaces. In order to conduct a detailed analysis of the missing section at a sequence boundary in terms of vacuity (erosion) and hiatus (non-deposition), a more effective method of stratigraphic analysis, involving a process-determined hierarchy linking mechanism to response, is required. This study involves the analysis of a sequence boundary using a more refined model that includes a hierarchy of stratigraphic sequences linking process to response.

The Hypothesis of Punctuated Aggradational Cycles

In the early 1980s, Goodwin and Anderson observed that the stratigraphic record consists of thin, sharply bounded, time-stratigraphic units and that the pervasiveness of these units may make them useful for basin-wide correlation (Goodwin and Anderson, 1980; Anderson et al., 1984; Goodwin and Anderson, 1985). These thin shallowing-upward cycles record punctuation events followed by aggradation of sediment. The sharp bounding surfaces of these Punctuated Aggradational Cycles (PACs) were thought by Goodwin and Anderson to be products of geologically instantaneous sea-level rises followed by aggradation at high sea-level stands (Goodwin and Anderson, 1985). These attributes make the PAC a strong candidate to replace the formation as the fundamental unit of stratigraphic analysis (Goodwin, et. al, 1986).

Traditional use of the formation as the primary unit of stratigraphic interpretation is a relic of a gradualistic model of stratigraphic accumulation. In the gradualistic view, the formation is considered to be the "stratigraphic expression of a migrating depositional environment or environmental mosaic" (Anderson et al., 1984, p 120). However, because at most formational boundaries there is a sharp contact between two distinct facies, the disjunct nature of formation boundaries precludes the idea that facies below and above the surface were from laterally contiguous environments (Anderson et al., 1984). In contrast to a gradualistic model in which formations develop contemporaneously and are superposed by lateral migration and gradual base-level change (Laporte, 1969), the Hypothesis of Punctuated Aggradational Cycles is a model that predicts facies changes at stratigraphic discontinuities caused by rapid sea-level fluctuations (Goodwin and Anderson, 1980).

The pervasiveness of Punctuated Aggradational Cycles in the stratigraphic record coupled with the fact that PACs, and patterns within PAC bundles, are highly correlative on a basin-wide scale, suggested that there was allogenic control over stratigraphic accumulation (Goodwin and Anderson, 1985). The early model of the Hypothesis of Punctuated Aggradational Cycles (figure 7), demonstrated that stratigraphic accumulation was episodic and allogenic but did not fully explain the hierarchic nature of sequences and their causal mechanisms. The search for a mechanism that met the observational characteristics of PACs and bundles of PACs led to the most recent development in the PAC hypothesis: the incorporation of a genetic hierarchy of allocycles based on "Milankovitch principles" of orbital forcing (e.g., Goodwin and Anderson, 1997). These mechanisms control glacial advance and retreat and in turn directly affect sea-level fluctuations at time intervals that are consistent with the recurrence intervals of PACs and bundles of PACs. In this most recent expression of the PAC Hypothesis (Goodwin and

PUNCTUATED AGGRADATIONAL CYCLES

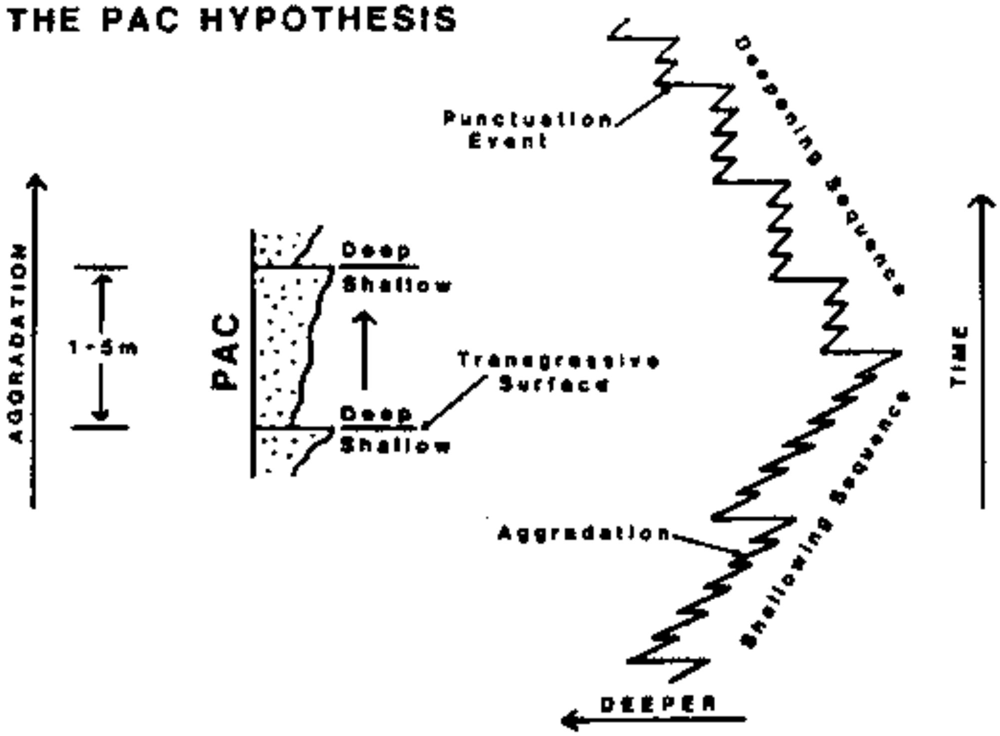

Figure 7: The Early PAC Hypothesis.

Anderson, 1997), PACs are linked directly to the precessional cycle and each level in the hierarchy of bundles of PACs is specifically linked to another orbital process.

The process-determined hierarchy linking PACs and Milankovitch orbital forcing mechanisms (figure 8) is based on the fundamental cycle-producing mechanism, precession. Gravitational effects of the Sun and Moon on the Earth (figure 9) cause precession, the change in orientation of the earth's axis of rotation. The earth's axis migrates through a cone in a period of about twenty thousand years (relative to the long axis of the Earth's eccentric orbit). Changes in the direction of tilt of the earth's axis (precession) alter high latitude summer insolation values when the Earth's orbit is eccentric. Thus, when combined with, or modulated by, the degree of eccentricity of the earth's orbit (which varies with major periods of 100ky and 400ky) precession can cause significant fluctuations in the earth's climate (figure 10).

The precessional cycle is preserved in the rock record as a Punctuated Aggradational Cycle (figure 11) where fluctuations in the precessional sea-level curve are shown to correspond to PAC anatomy. The sharp bounding surfaces of PACs are produced by non-deposition (due to sea level rising at its maximum rate) followed by deposition during sea-level highstand and lowstand when rates of sea-level change are low (Goodwin and Anderson, 1997). Within PACs, sharp surfaces separating highstand facies from overlying lowstand facies can be produced by rapid sea-level falls. Thus, fluctuations in sea level are attributed to glacial eustasy, which is controlled by orbital forcing mechanisms.

RANK	PERIOD	MECHANISM
2nd Order (supersequence)	10 million years	Tectono-Eustasy
3rd Order (sequence)	2 million years	Eccentricity
4th Order	400,000 years	Long Eccentricity
5th Order	100,000 years	Short Eccentricity
6th Order (PAC)	20,000 years	Precession

Figure 8: The Genetic Hierarchy of Allocycles. A process-determined hierarchy of allocycles in which each rank is linked to a specific periodic process causing eustatic fluctuations of sea level (From Goodwin and Anderson, 1997)

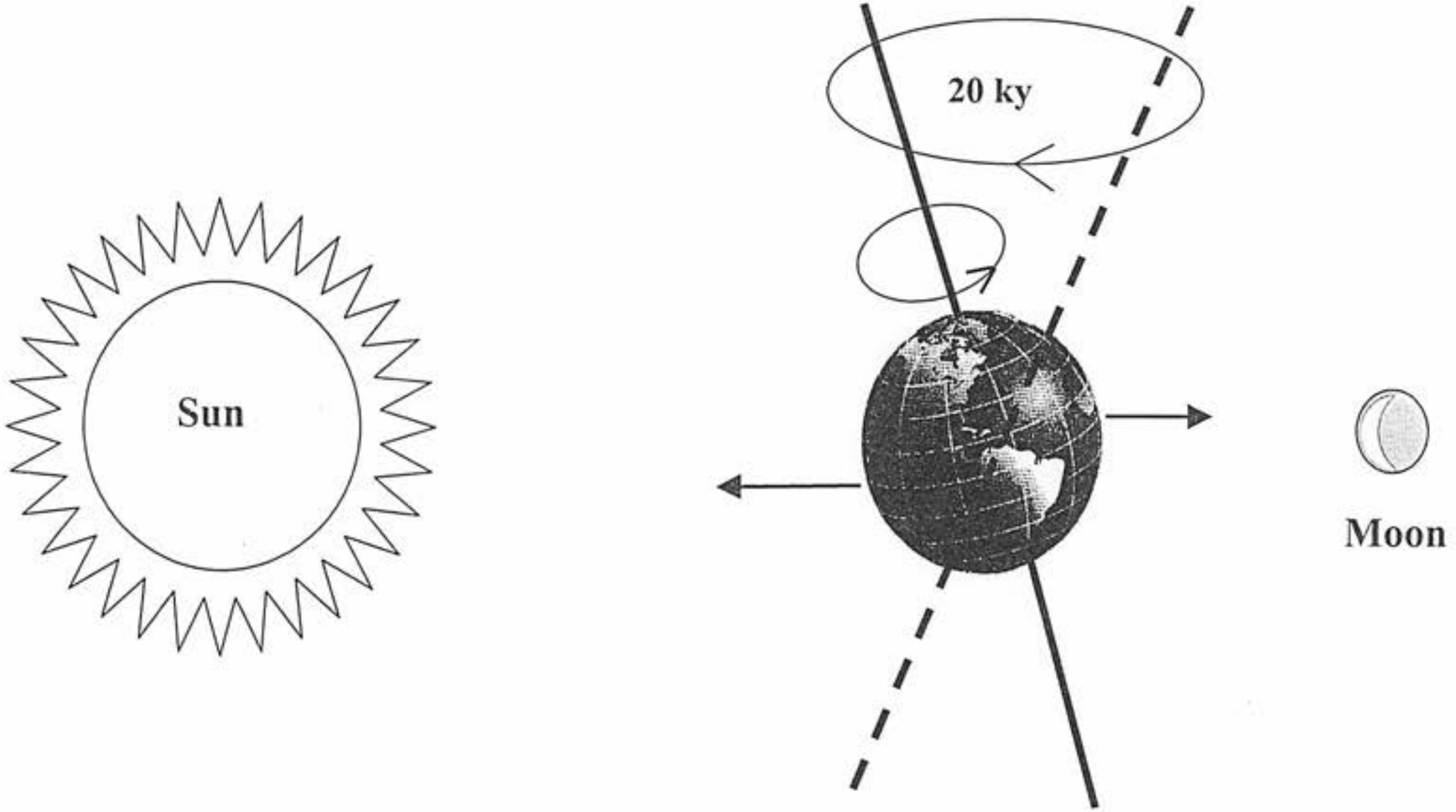

Figure 9: Earth's Precession. Gravitational pulls of the Sun and Moon on the Earth cause the Earth to precess. As the Earth precesses, its axis of rotation traces out a circle that has an approximate period of 26 thousand years (20ky when viewed with reference to the long axis of the Earth's eccentric orbit which itself rotates. This precessional motion resembles a spinning top.

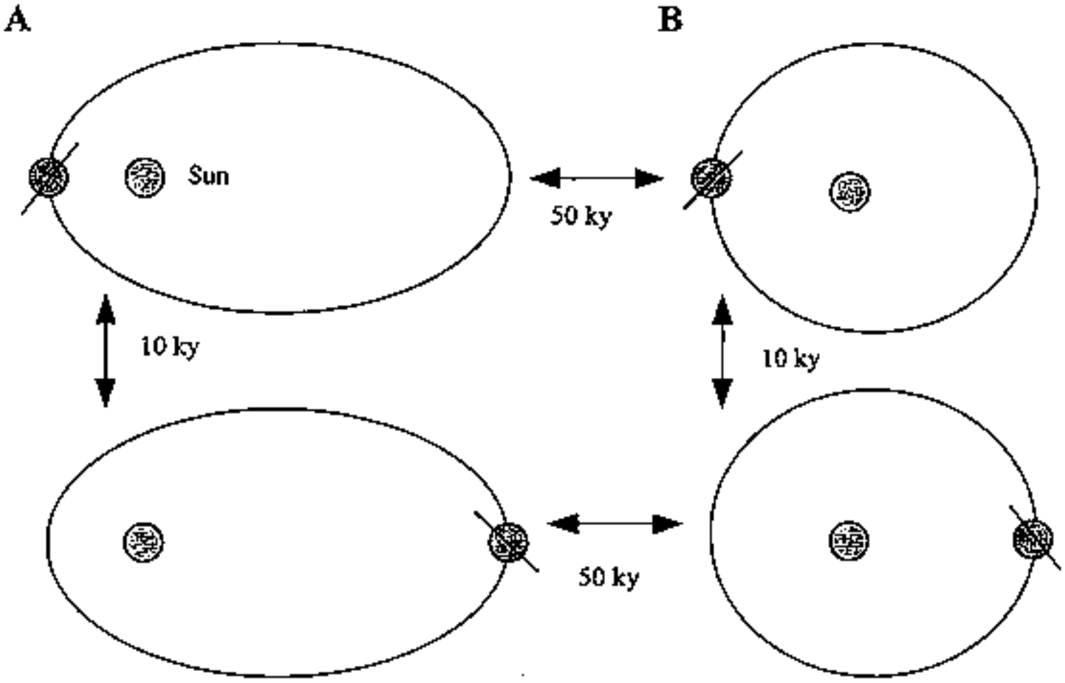

Figure 10: Seasonal Variation with Changing Orbital Parameters. Eccentricity modulates the precessional signal because the degree of eccentricity determines (influences) the amount of high latitude, summer insolation in the Northern Hemisphere. A. When the Earth is at perihelion in the summer and eccentricity is high, the result is a long series of hot summers. High eccentricity when the Earth is at aphelion results in cold summers. Differences in summer insolation are greatest when eccentricity is high. B. When eccentricity is low, the differences in summer insolation between perihelion and aphelion are low. Therefore the effects of the precessional signal are muted.

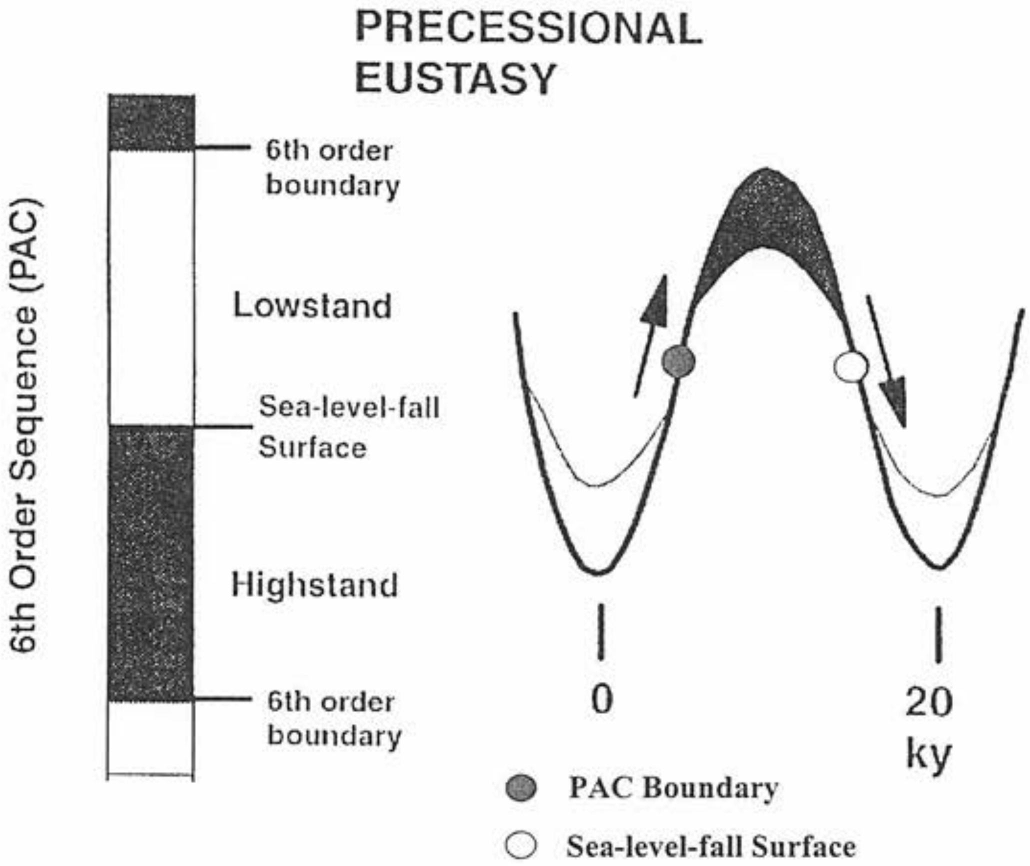

Figure 11: Relationship Between Precessional Eustasy and PACs. PAC boundaries (sixth-order boundaries) are produced at times of non-deposition associated with the maximum rate of sea-level rise (near the inflection point of the rising precessional curve). Sea-level-fall surfaces, when present, are produced in a similar manner at times of rapid sea-level fall (From Goodwin and Anderson, 1997).

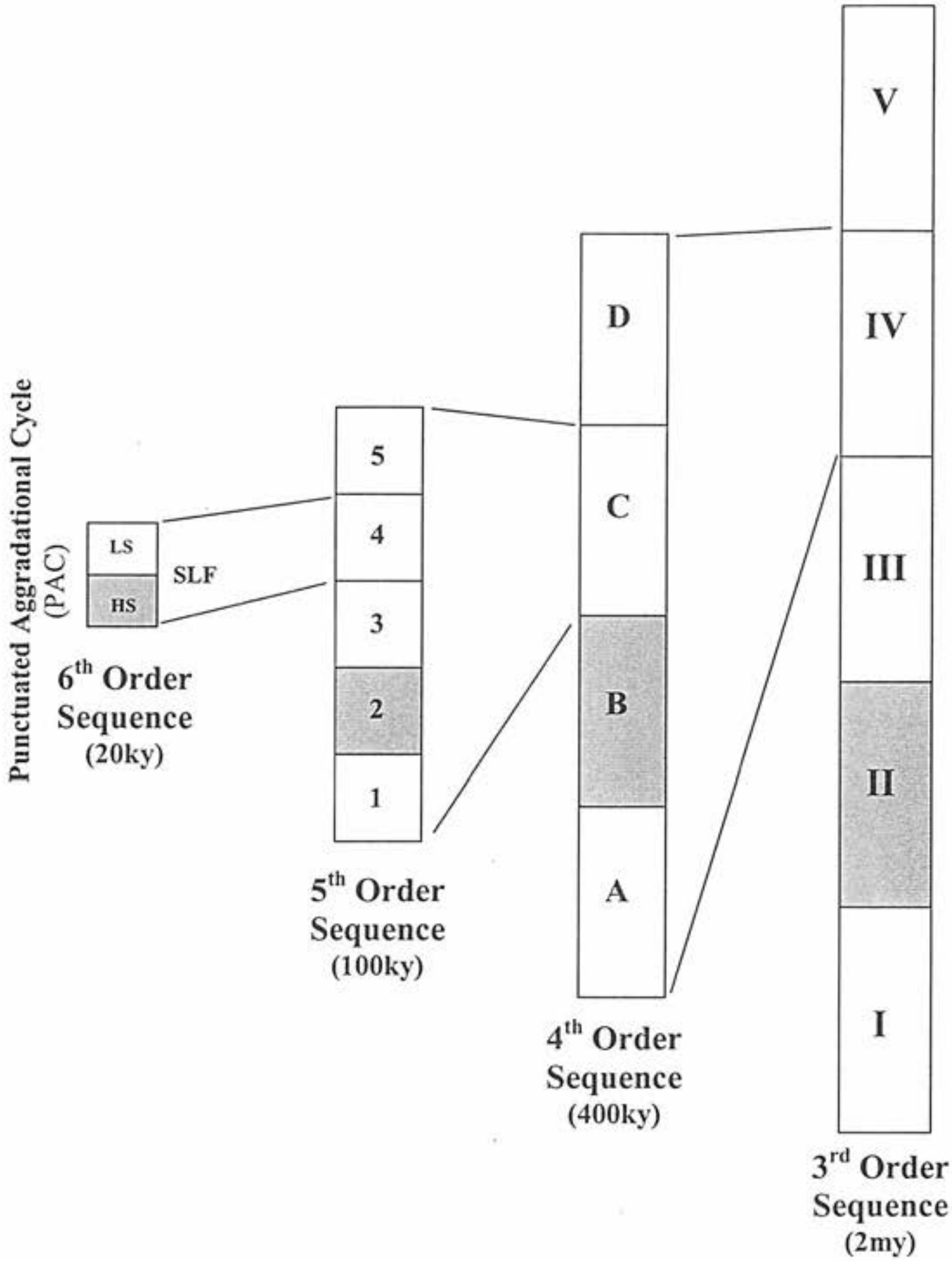

Figure 12: Stacking Patterns of Punctuated Aggradational Cycles. In this model, the fundamental cycle-producing mechanism is precession; eccentricity functions as a modulator of the precessional signal by enhancing or dampening its effect. Modulation of the precessional signal by eccentricity produces fifth-order bundles of sixth-order precessional sequences and fourth-order bundles of fifth-order sequences. The third-order sequence is a bundle of fourth-order sequences. The shaded areas represent the deepest interval within each sequence. SLF=Sea-Level Fall Surface, HS=Highstand, LS=Lowstand.

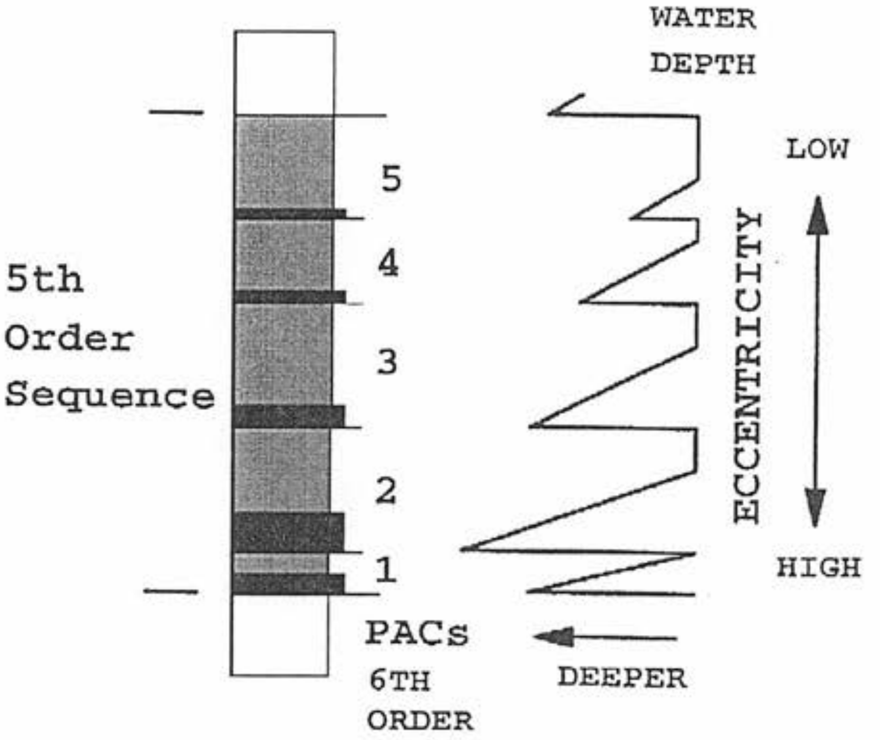

Figure 13: Fifth-order Sequence. The fifth-order sequence is an asymmetric bundle of sixth-order sequences. Enhanced precessional sea-level rises produce major facies changes at fifth-order boundaries; dampened rises produce the generally shallowing-upward trend in the upper portion of the fifth-order sequence. Deepest facies commonly occur at the base of the second PAC (From Goodwin and Anderson, 1997).

Eccentricity modulates the precessional signal by enhancing or dampening its effect (figure 10). Bundling of PACs into predictable stacking patterns (figure 12) is produced by variation in the degree of eccentricity at two scales. The short eccentricity (100ky) cycle produces a fifth-order sequence (figure 13), an asymmetric bundle of five or fewer sixth-order (20ky) cycles (PACs). Generally the second PAC in the fifth-order sequence contains the deepest facies. The long eccentricity cycle (400ky) produces a fourth-order sequence, which consists of four fifth-order sequences (100ky each) arranged in a predictable pattern (figure 12). For example, the second fifth-order sequence generally contains the deepest facies within a fourth-order sequence. Third-order sequences (possibly controlled by eccentricity) are composed of five fourth-order sequences (400ky each); five third-order sequences (2my each) comprise a second-order sequence (10my). Formation of second-order sequences is attributed to tectono-eustasy, for example, long-term sea-level fluctuations caused by swelling of mid-ocean ridge systems.

Because Punctuated Aggradational Cycles represent time-stratigraphic units that can be traced across an entire basin, the degree of facies change from one PAC to the next provides one criterion for correlation between two or more localities. "Correlation of stratigraphic section is accomplished by matching patterns of facies change, particularly the abrupt changes at the synchronous surfaces that mark PAC boundaries" (Goodwin et al., 1986, p. 417). Because processes creating the patterns are allogenic, the patterns should be traceable across the entire basin.

Correlation of Punctuated Aggradational Cycles allows for interpretation of detailed basin processes because each PAC represents a unique paleoenvironmental pattern initiated and terminated by rapid sea-level fluctuations. Since PAC boundaries signify abrupt changes to deeper and environmentally disjunct facies, each PAC contains its own paleoenvironmental patterns produced by aggradation within the sequence (Goodwin and Anderson, 1988). The facies above and below PAC boundaries represent paleoenvironments that were not laterally contiguous; therefore the resulting vertical sequences were not produced by lateral migration (Goodwin and Anderson, 1988). Interpretation of patterns of sea-level fluctuations, erosion and subsidence discernible through the correlation of PACs allows greater understanding of detailed basin dynamics (Goodwin et al., 1986). Identifying missing cycles using PAC correlations (Goodwin and Anderson, 1988) also more easily reveals small-scale cryptic unconformities (such as the Tonoloway-Keyser formational contact).

This study was conducted using the process-determined hierarchy to investigate the cyclic patterns at a sequence boundary within a specific temporal context. The combined use of small-scale allocycles and the process-determined hierarchy allowed quantification of non-deposition (hiatus) and erosion (vacuity) surrounding the sequence boundary.

CHAPTER 3

GEOLOGIC BACKGROUND

Introduction

The Upper Silurian Tonoloway and Keyser Formations have been extensively studied both by workers using a gradualistic model (C.K. Swartz, 1913; Head 1969, 1972; Makurath, 1977) and by workers using an allocyclic model (Goodmann, 1986; Dorobek and Read, 1986; Chadwick, 1993). While the formations themselves have been well studied, the contact between the Tonoloway and Keyser Formations has not been the primary focus of any stratigraphic analysis. Although the contact has not received particular attention, many workers have addressed the issue of the relationship between the Tonoloway and Keyser Formations (C.K. Swartz, 1913; F.M. Swartz, 1939; Head, 1972; Dorobek and Read, 1986; and Goodwin et al., 1986). The interpretation of the nature of the Tonoloway-Keyser contact differs with the method of study employed in the stratigraphic analysis.

Geologic Setting

The Upper Silurian—Lower Devonian central Appalachian Basin consists of an accumulation of largely carbonate strata deposited during a time of tectonic inactivity. The carbonates of this time are "sandwiched" between the Silurian and Devonian terrigenous clastic wedges (Head, 1972). During this period of low subsidence, carbonate ramps developed on "both the eastern and western (cratonic) side of the Appalachian Basin" (Dorobek and Read, 1986, p. 601). During the Silurian and Devonian Periods, the Appalachian Basin was an elliptical basin extending from Alabama to New York and possibly further northeastward (Dennison and Head, 1975).

The depositional axis of the basin had a northeastward trend (figure 2) with maximum subsidence occurring near the southwestern corner of Pennsylvania (Dennison and Head, 1975). Unconformities along the entire basin margin, as well as sedimentologic and faunal patterns, record changes in water depth and provide evidence for sea-level changes (Dennison and Head, 1975).

Restriction of the Late Silurian epeiric sea was greatest during deposition of the Salina Group (Bloomsburg-Wills Creek-Tonoloway Formations) when both the eastern and western margins of the basin were shallow-water shelves and evaporite facies were being deposited in the central basin in West Virginia (Smosna and Patchen, 1978). Following deposition of the intertidal and supratidal facies of the Tonoloway Formation, deposition of the Keyser Formation of the Helderberg Group (Keyser-New Creek-Corriganville-Mandata-Shriver-Ridgely Formations) marks the beginning of a complex of marginal and shallow marine facies deposited during the transgression of a broad shallow sea (Makurath, 1977).

The Keyser Formation (named after its type locality of Keyser, WV), in contrast to the Tonoloway Formation, is highly fossiliferous (containing Cnidaria, Brachiopoda, Echinodermata, Arthropoda, Mollusca, Bryozoa and Ammonoidea) and consists of massive, nodular subtidal shelfal facies (C. K. Swartz, 1913). At its type locality of Keyser, WV, the Keyser Formation is over 280 feet thick. C. K. Swartz (1913) recognized the Keyser as a member of the Helderberg Formation but F. M. Swartz (1929) considered the Keyser to be of a formation in the Helderberg Group. Head (1972) suggested that the Keyser lithologies represent environments located near the shallow subtidal-intertidal-supratidal interface. Because the lower Keyser facies differ markedly from facies of the upper Keyser two distinct lithologic units were recognized by C. K. Swartz (1913). Bowen (1967) recognized a faunal distinction between upper Keyser and lower Keyser facies and defined two faunal zones. The Keyser facies involved in this study are confined to the lower faunal zone, *Eccentricosta jerseyensis* (Bowen, 1967). This zone contains the peak zone of a distinct brachiopod, *Gypidula prognostica*, that marks the upper boundary of the study interval (Bowen, 1967). Bowen (1967) observed that the boundary between the lower and upper faunal zones within the Keyser Formation seems to coincide with the Silurian-Devonian systemic boundary.

Many workers described and studied the Tonoloway and Keyser Formations, using the gradualistic practice of formations and members, in terms of regional transgressions (e.g., Head, 1969; Smosna and Patchen, 1978) and time-transgressive facies (e.g., Makurath, 1977). More recently, these formations have been analyzed from an allocyclic perspective (Dorobek and Read, 1986; Goodmann, 1986; Chadwick, 1993). Dorobek and Read (1986) described the Helderberg Group as a third-order sequence reflecting low sea-level stand during deposition of the Tonoloway Formation followed by a "series of transgressive-regressive sequences developed in response to basinwide changes in relative sea level caused by eustatic sea-level changes and/or basin subsidence." At a smaller scale, Goodmann (1986) recognized the episodic accumulation of the Keyser Formation by correlating Punctuated Aggradational Cycles throughout the formation in Pennsylvania. Chadwick (1993), in a similar study in the Tonoloway Formation, found evidence for hierarchic episodic accumulation expressed as two nearly complete third-order sequences.

The Tonoloway-Keyser Formational Contact

While many workers described the Tonoloway-Keyser Formational contact, traditional methods of stratigraphy were unable to fully explain the nature of the contact. For example, F. M. Swartz described the contact as a distinct boundary that is often sharp enough to suggest an unconformity (1939). According to C. K. Swartz, the massive, nodular limestone of the lower Keyser Formation strongly contrasts with the fissile, thin-bedded limestones of the Tonoloway Formation below (1913). Head (1969) recognized that the lowest member of the Keyser Formation (Byers Island Member) thins toward the basin margin and suggested that this thinning is due to "lateral replacement by the supratidal and shallow subtidal lithofacies of the Tonoloway Limestone."

It is possible that through the adoption of an allocyclic model of stratigraphic analysis, a more detailed description of the contact between the Tonoloway and Keyser Formations can be developed. For example, by looking at the formational contact from a large-scale allocyclic perspective, Dorobek and Read (1986) concluded that the Tonoloway—Helderberg contact is "an erosional disconformity along the basin margin, but is conformable in the basin in West Virginia and western Maryland" (p. 602). This study carries the allocyclic analysis of this formational contact one more step by applying a hierarchic approach based on the small-scale precessional cycle as the fundamental unit of analysis.

End-Member Models for the Formational Contact

Descriptions of the Tonoloway-Keyser Formational contact given by workers using traditional models of stratigraphic analysis provided two basic end-member models for the relationship between the two formations (C. K. Swartz 1913; F. M. Swartz 1929, 1939; and Head 1969, 1972). Is the relationship one in which the two formations are separated by an unconformity or are there lateral facies changes between the Tonoloway and Keyser formations? In order to answer this question, the field investigation would have to provide detail on a finer scale than traditional formations and members allow. The application of a small-scale allocyclic analysis using Punctuated Aggradational Cycles was the preferred method for a study of this kind because it not only allows great detail in field observations, but also furnishes a model that explains the mechanisms involved in accumulation of the stratigraphic record.

Before beginning the investigation, the two end-member models for the possible relationship between the Tonoloway and Keyser formations were considered. The first model suggests a simple unconformable relationship between the two formations (figure 14). In this model, the Tonoloway peritidal carbonates would have been deposited and exposure and erosion would have been followed by deposition of Keyser subtidal carbonates. If there is an unconformable relationship between the two formations, no surface within the Tonoloway Formation should be traceable into the Keyser Formation. A second possibility is a relationship of lateral facies changes where Tonoloway facies toward the basin margin become more Keyser-like toward the basin center (figure 15). In this case, deposition of Tonoloway and Keyser facies may have been contemporaneous. If lateral facies changes take place between the Tonoloway and Keyser Formations, cyclic patterns internal to the Tonoloway should match correlative patterns in the Keyser. In order to resolve the nature of the formational contact, recognition and correlation of fifth-order sequences was used to make conclusions regarding missing stratigraphic