STRATIGRAPHIC ANALYSIS OF THE LOWER NEW SCOTLAND FORMATION: AN EPISODIC PERSPECTIVE

A Thesis Submitted to the

Temple University Graduate Board in Partial Fulfillment

of the Requirements for the Degree

Master of Arts

by

David M. Side

November 1987

Dr. Edwin J. Anderson
Thesis Advisor

Dr. Peter W. Goodwin

DEPARTMENT COPY

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A Thesis Submitted in Partial Fulfillment
of the Requirements for the Masters Degree
in Geology, College of Arts and Sciences
Temple University
Philadelphia, Pennsylvania
November, 1987

Principal Thesis Advisor: ______________________ ______________
Dr. Edwin J. Anderson Date

Thesis Advisor: ______________________ ______________
Dr. Peter W. Goodwin Date

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I would like to offer a very special thanks to my family, to whom I dedicate this thesis.

ABSTRACT

Application of the PAC Hypothesis to the deep shelf carbonate facies of the lower New Scotland Formation (Lower Devonian) results in the complete division of this interval into 10 PACs that may be correlated throughout the Hudson Valley of Eastern New York State. These deep water PACs primarily consist of terrigenous black shale alternating with limestone beds, the black shale being concentrated at the bases of PACs. Sedimentological analysis suggests that the shales represent "background" deposition of fine suspended sediment and the limestones are event deposits, possibly turbidites and/or tempestites. In contrast to PACs recognized in much shallower facies, a shallowing-upward motif is absent in lower New Scotland PACs. The absence of a shallowing facies pattern suggests that abrupt base-level rises had little direct depth related impact on the deep lower New Scotland shelf. Instead facies change within these PACs was an indirect response related to the supply of transported carbonate sediment into the deep shelf. Comparative analysis of the magnitude of facies change at the base of each lower New Scotland PAC indicates that the sequence of PACs in the study interval is the result of 1 major punctuation event followed by 10 minor punctuation events. General vertical patterns of facies change from PAC to PAC suggest that the deepest point in the lower New Scotland is reached at the base of PAC 7. Lateral facies analysis within PACs leads to the recognition of a proximal to distal trend from Kingston to Callanan Quarry (south to north), a distance of approximately 50 miles. Lower New Scotland PACs at Kingston are characterized by relatively shallower facies, while at Callanan Quarry, these PACs are characterized by deeper, more basinal facies. The lateral persistence of the

10 New Scotland deep water PACs over 50 miles precludes an autogenic origin of these cycles. Rather, accumulation of the deep shelf facies of the lower New Scotland, like the shallower facies of the Kalkberg, Coeymans, and Manlius Formations was principally controlled by small-scale base-level fluctuations as predicted by the PAC hypothesis.

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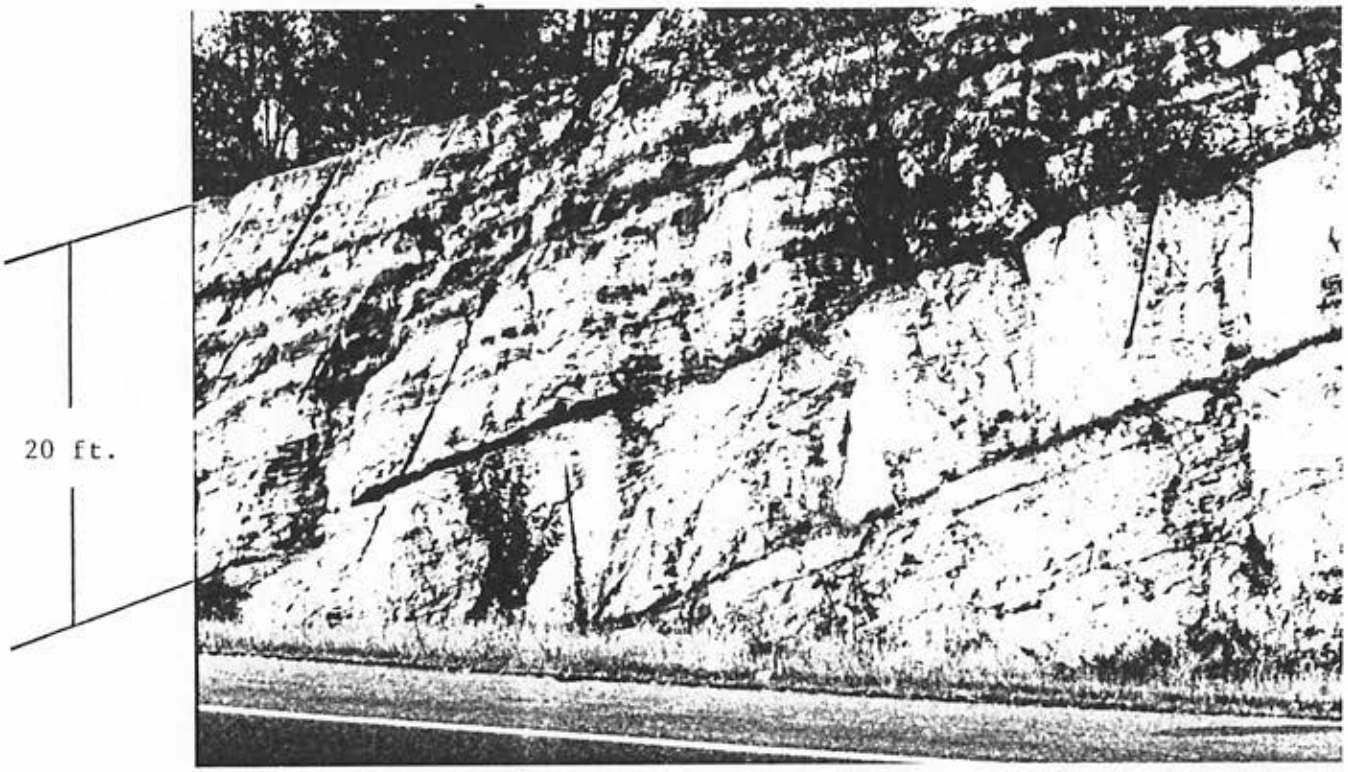
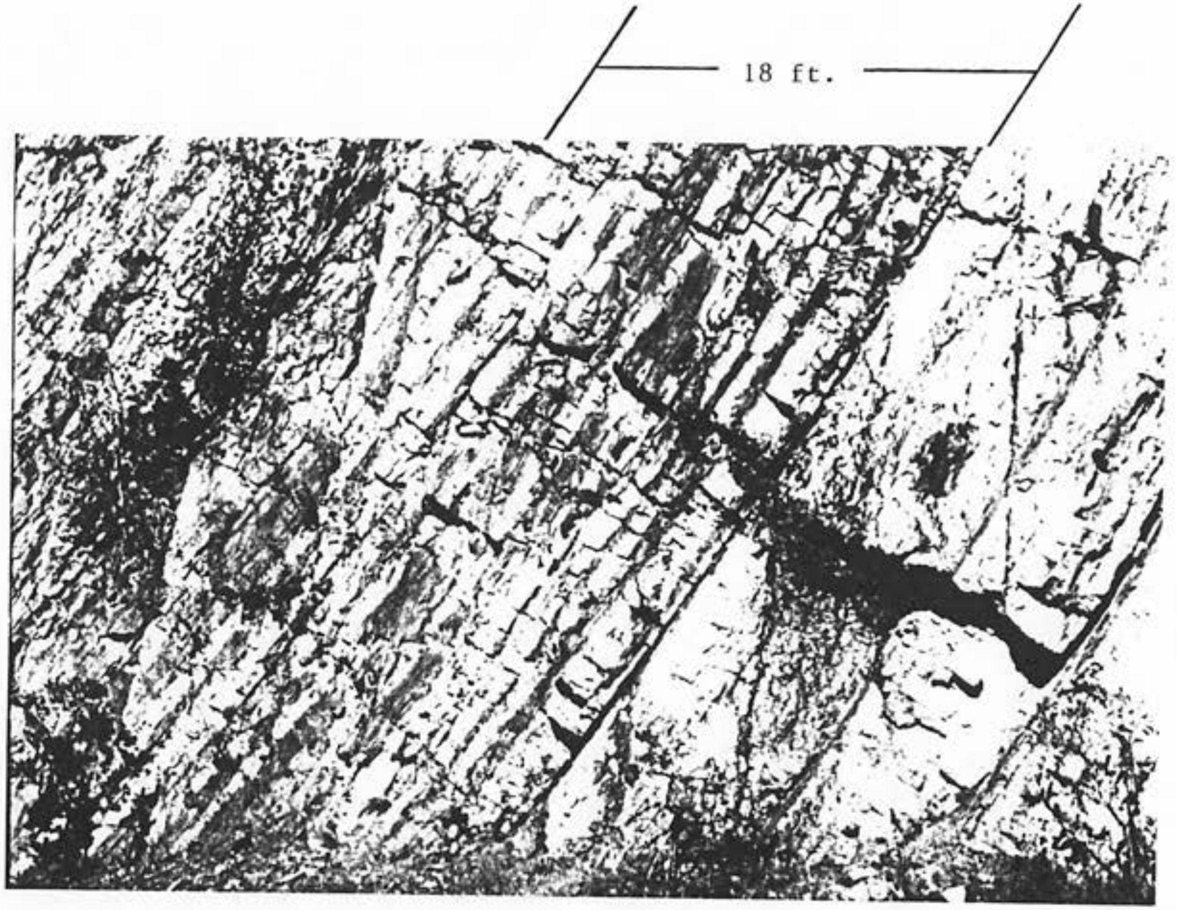
INTRODUCTION

In recent years, cyclicity in peritidal facies (James, 1984) and shallow shelf facies (Aigner, 1985) has been extensively documented and interpreted. Cyclicity in deeper shelf facies is less clearly understood (Einsele and Seilacher, eds., 1982; Hallam, 1986). The Hypothesis of Punctuated Aggradational Cycles (PACs) of Goodwin and Anderson (1985), a general theory of episodic stratigraphic accumulation, argues that cyclicity exists ubiquitously in both nearshore and offshore facies and is related to a common causal mechanism. Goodwin and Anderson and their students have presented numerous papers in which the PAC Hypothesis has been applied to nearshore facies. In this thesis, the PAC hypothesis is applied, and thereby tested, in deep shelf facies of the lower New Scotland Formation in the Hudson Valley of Eastern New York State. This stratigraphic interval is characterized, in part, by limestone-shale couplets (Figures 1a, 1b, 1c, and 1d). The purpose of this study is to develop new field evidence to help explain the origin of these deep shelf carbonate cycles through application of the PAC model.

According to the Hypothesis of Punctuated Aggradational Cycles, most stratigraphic accumulation occurs as 1 to 5 meter thick shallowing-upward cycles (PACs) bounded by sharp non-depositional surfaces (Figure 2). These surfaces and cycles result from relative base-level rises (punctuation events) that are hypothesized to be geologically instantaneous and of at least basinwide extent. Thus, as a comprehensive model, the PAC hypothesis states that the basic units of stratigraphic accumulation are thin and widespread, laterally continuous time-stratigraphic cycles bounded by synchronous surfaces (Figure 3).

Figures 1a, 1b, 1c, and 1d: As these outcrop photographs illustrate, the light-gray to buff weathering limestones strikingly contrast with the drab olive-green weathering shales to give the lower section of the New Scotland Formation a distinctive appearance. The lines in each photograph denote the lower limit (corresponding to the Kalkberg - New Scotland boundary) and the upper limit of the study interval. Figure 1a, page 2, corresponds to the New Scotland at Kingston; Figure 1b, page 3, to the New Scotland at Catskill; Figure 1c, page 4, to the New Scotland at Broncks Lake, and; Figure 1d, page 5, to the New Scotland at Callanan Quarry.


20 ft.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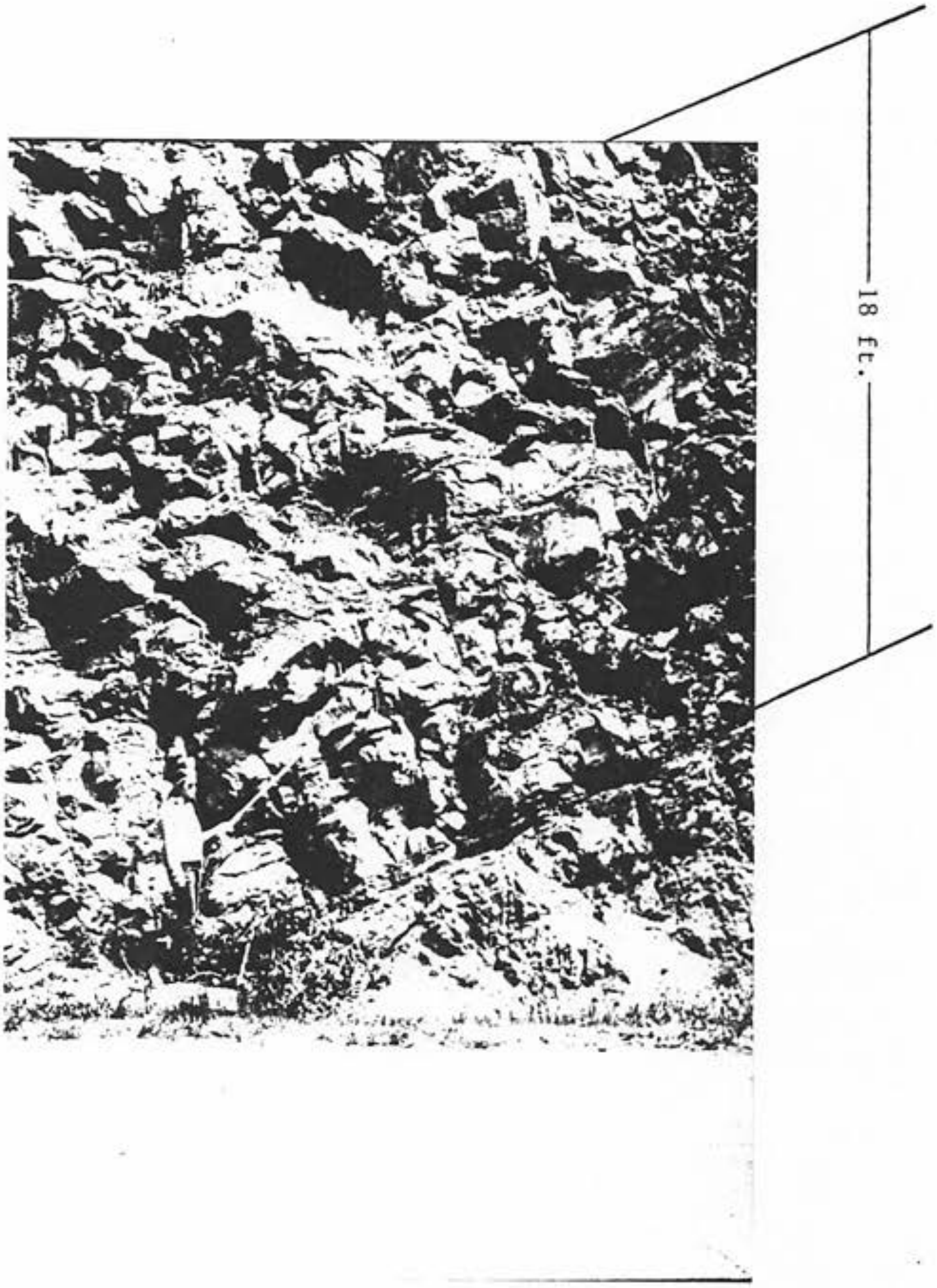
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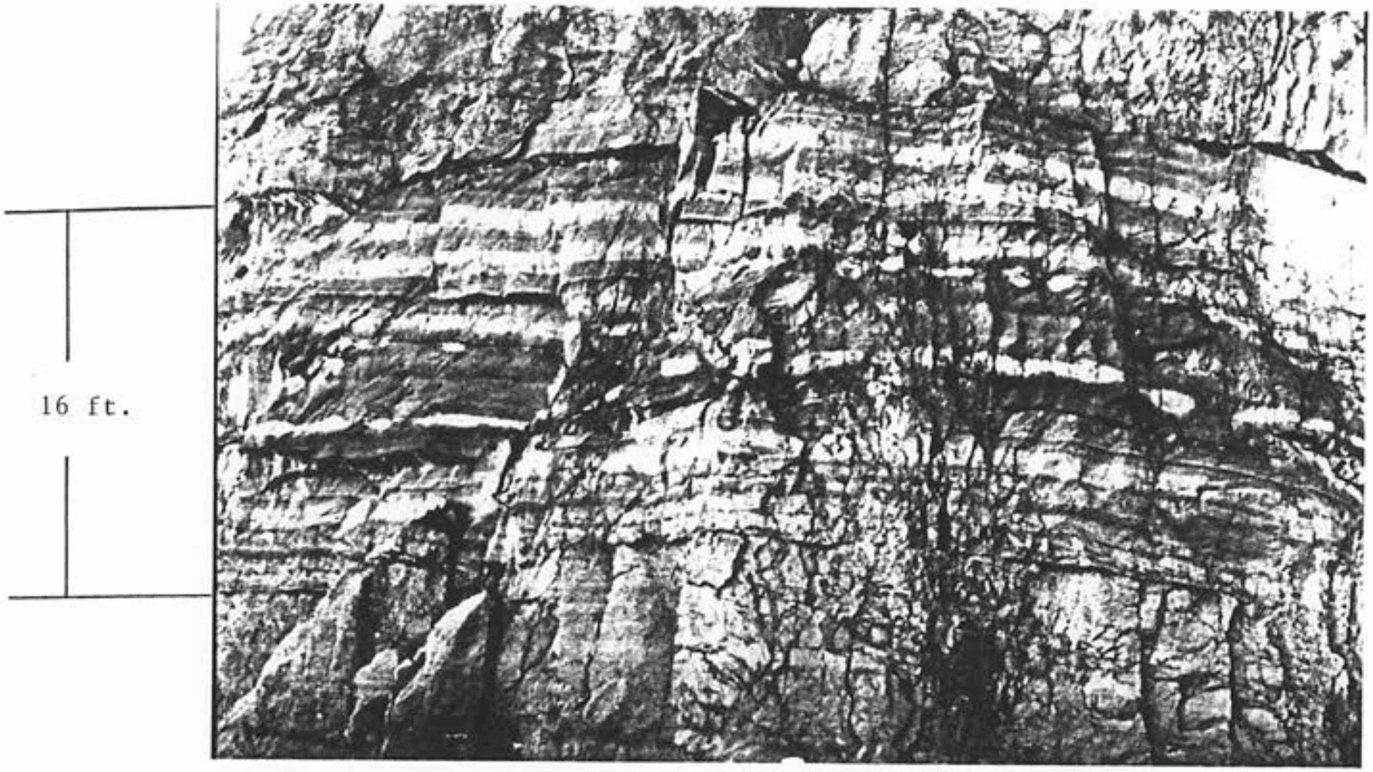
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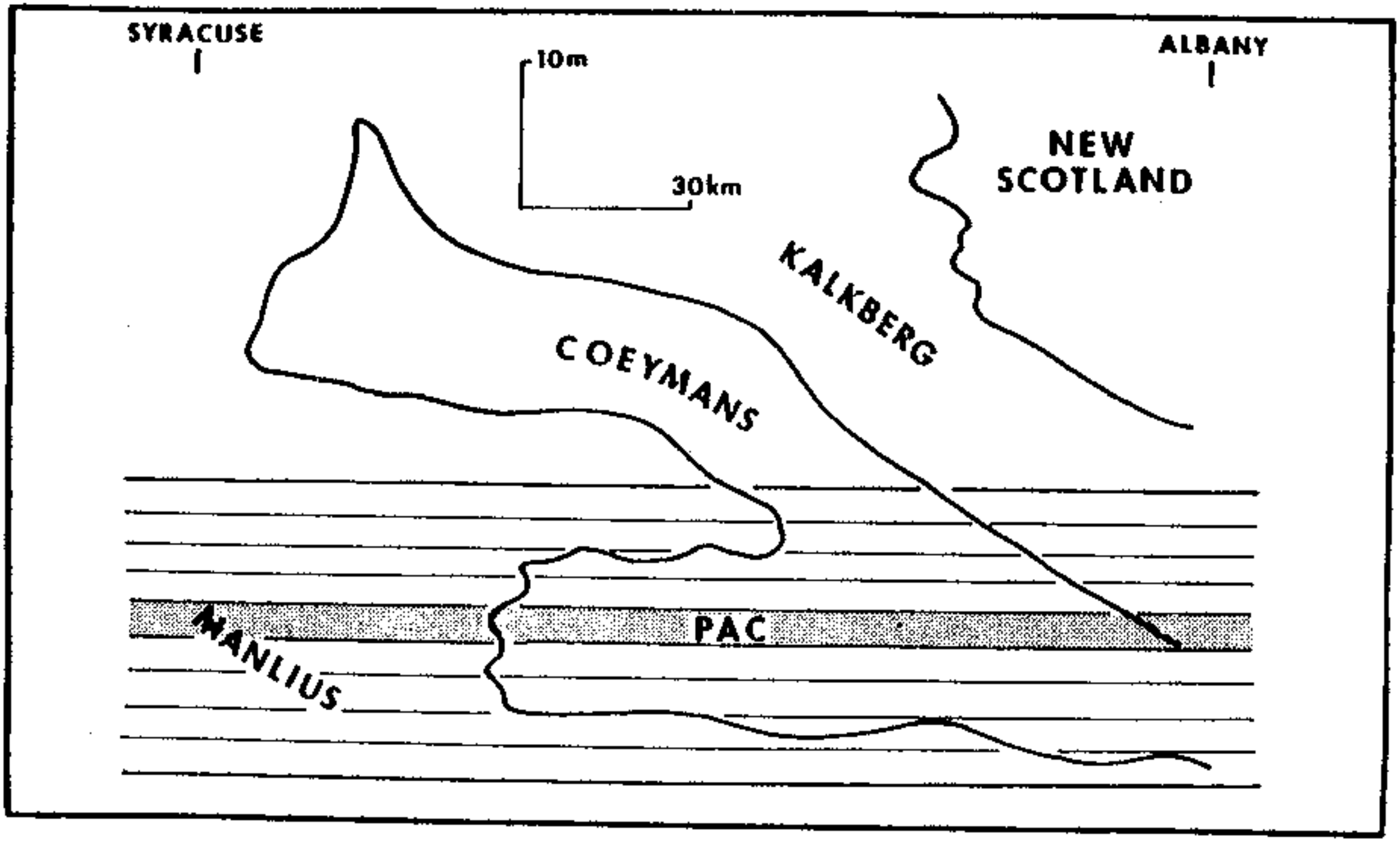

SYRACUSE
ALBANY
10m
30km
NEW SCOTLAND
KALKBERG
COEYMANS
PAC
MANLIUS

The PAC hypothesis predicts that small-scale cyclicity exists in sedimentary facies that are representative of all environments in which an abrupt base-level rise can directly or indirectly affect depositional processes. Thus, a full spectrum of marine carbonate environments (from nearshore to deeper, more basinal environments) should produce deposits with a pervasive PAC-like motif. Sedimentological criteria that define a PAC in a particular environment, however, may be different. In shallow marine facies, Goodwin and Anderson have observed a cyclic motif defined by shallowing-upward criteria and surfaces of deepening. In these environments, facies were directly controlled by base-level rises (1985, p. 516, 517). In deeper marine facies, where the response to base-level rises may be indirect because an increase in water depth had little direct impact on depositional processes, different criteria may define a cycle (Goodwin and Anderson, 1985, p 517).

Previously, the New Scotland Formation of the Lower Devonian Helderberg Group (Figure 4) has been interpretated as the deepest facies in a sequence of facies that were deposited through the combined effects of a slowly transgressing sea and regional subsidence (Rickard, 1962; Laporte, 1969; Epstein, 1971). When viewed from this perspective, small-scale facies alternations within the lower New Scotland might appear to be the result of autocyclic processes coupled with gradual base-level rises, rather than the result of allogenic events as predicted by the PAC hypothesis.

Specific objectives of this thesis, therefore, are: 1) to develop criteria for the recognition of small-scale cycles in the deep shelf carbonate facies of the lower New Scotland assuming an allogenic model of stratigraphic accumulation; 2) to attempt to demonstrate the correlation of these cycles over a sufficient distance to preclude an autogenic origin; 3) to analyze the

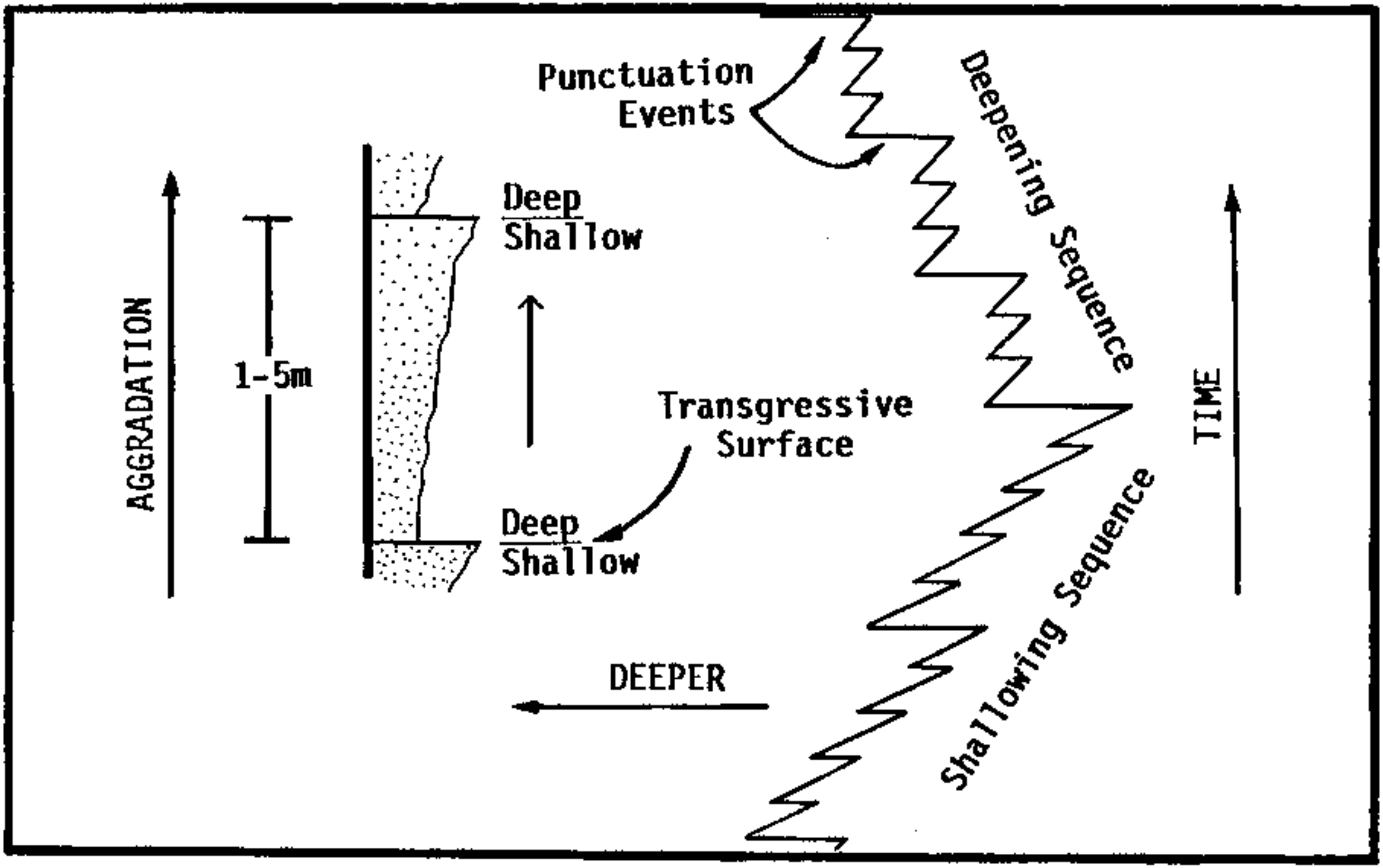
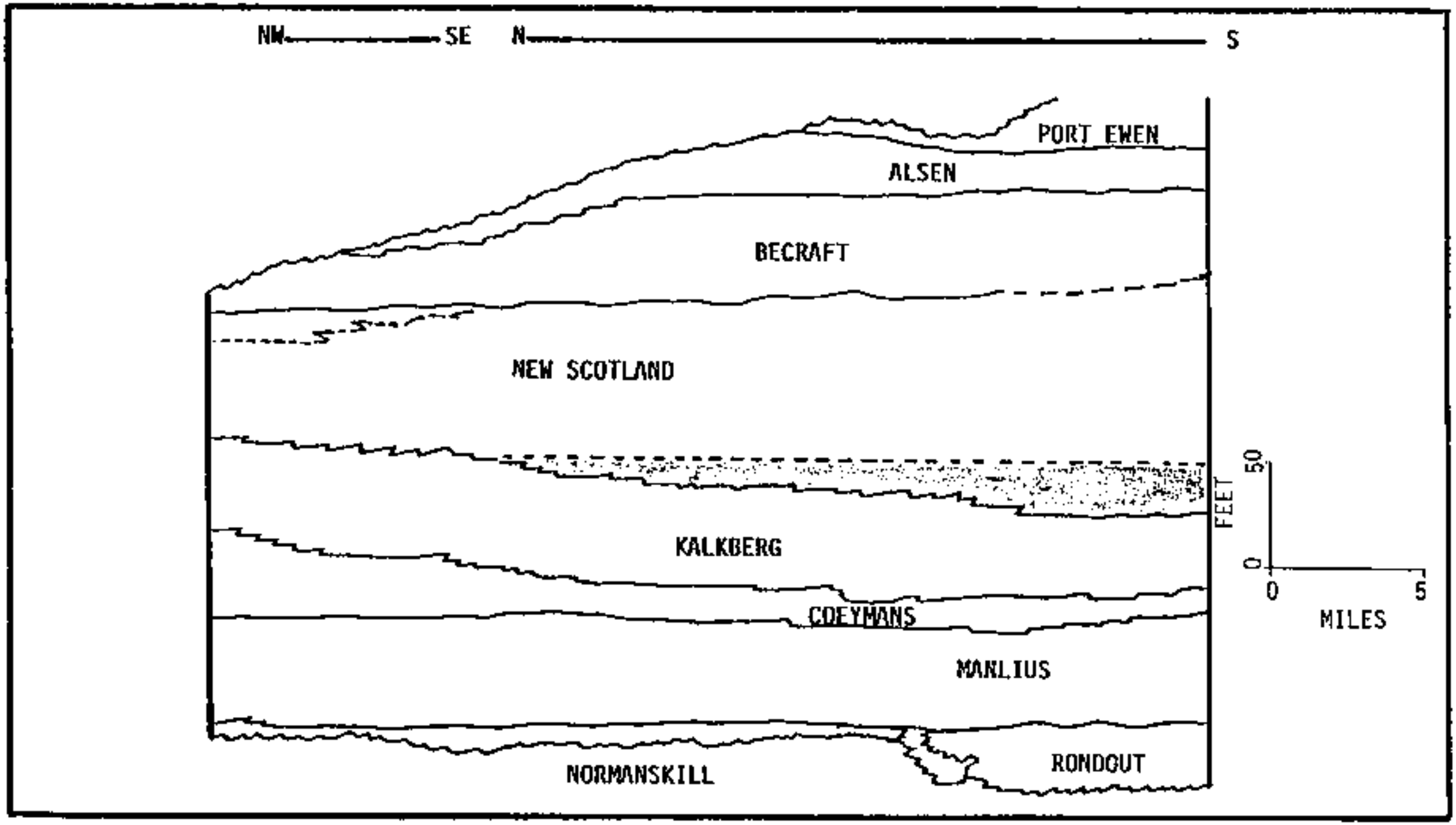

Punctuation Events
Deepening Sequence
Deep
Shallow
AGGRADATION
1-5m
Transgressive Surface
TIME
Deep
Shallow
Shallowing Sequence
DEEPER

Figure 3:
Diagrammatic representation of PACs as widespread time-stratigraphic units. note the relationship of PACs to the formational boundaries of the Helderberg Group (from Anderson, Goodwin, and Sobieski, 1984).

Figure 4:
The stratigraphic relationships of the Helderberg Group in the Hudson Valley from a gradualistic perspective. The shaded area is the study interval (modified from Rickard, 1962).


NW
SE
N
S
PORT EWEN
ALSEN
BECRAFT
NEW SCOTLAND
KALKBERG
COEYMANS
MANLIUS
NORMANSKILL
RONDOUT
FEET
50
0
0
5
MILES

vertical changes that occur between cycles and the lateral changes within cycles in order to interpret the sedimentologic and stratigraphic dynamics responsible for the deposition of the study interval; and, 4) to interpret the local paleogeographic patterns related to the deposition of the study interval.

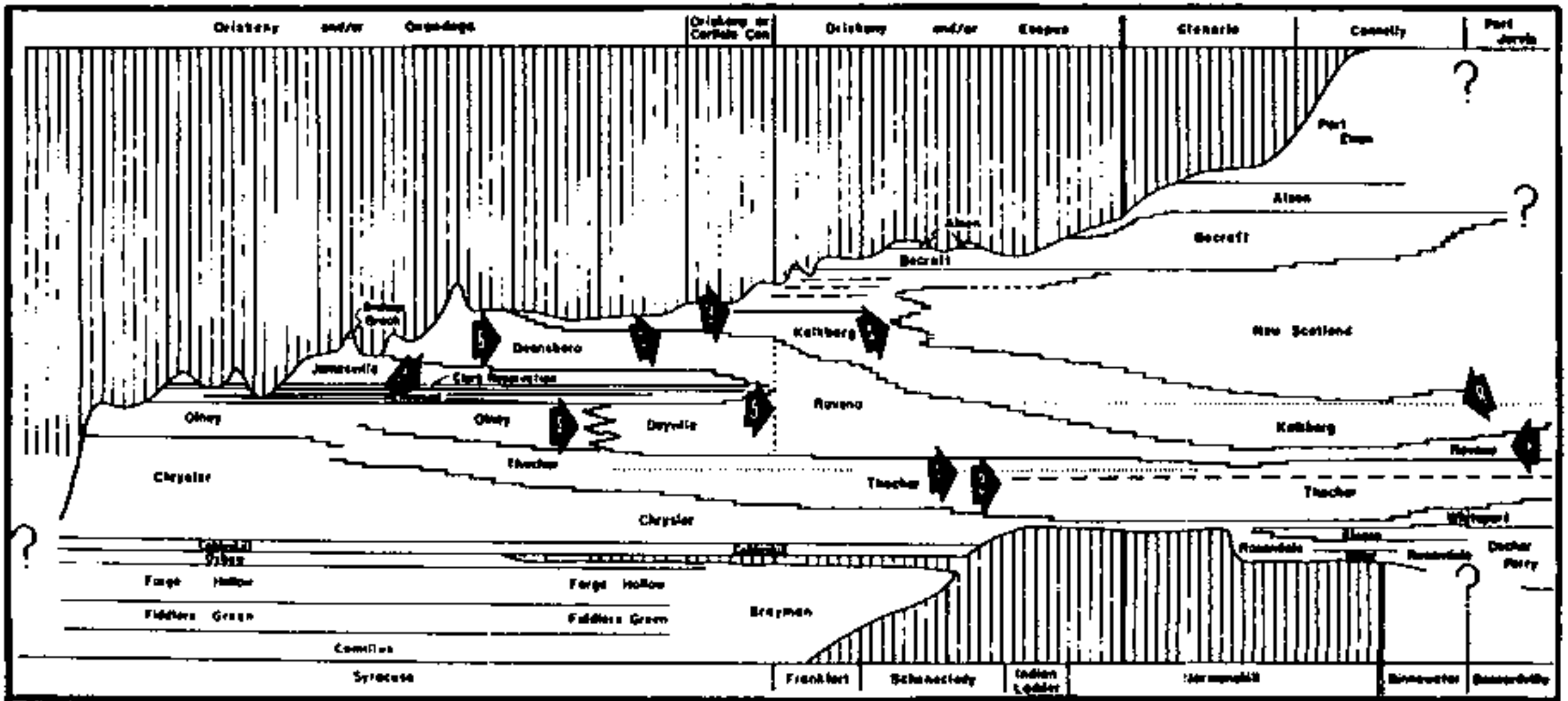
PREVIOUS WORK

Helderberg Stratigraphy

Previous stratigraphic and paleoenvironmental investigations of the Helderberg Group have provided a foundation for the application of the PAC Hypothesis to the New Scotland Formation. Rickard (1962), through his study of the Manlius, Coeymans, Kalkberg, and New Scotland Formations, developed a coherent stratigraphic framework for the lower part of the Lower Devonian Helderberg Group. This framework was based on a general analysis of facies present within this stratigraphic sequence and an interpretation of the stratigraphic and environmental interrelationships of these facies based on the recognition of 8 time planes (Figure 5). Subsequent stratigraphic analysis by Laporte (1967, 1969), Anderson (1967), Head (1969), and Epstein (1971), conducted on the basis of Rickard's stratigraphy, led to an even greater understanding of the formations of the lower Helderberg Group. Inherent to these previous interpretations is the assumption that stratigraphic accumulation in the Helderberg Group was through gradual relative base-level rises superimposed upon the continuous lateral migration of co-existing environments.

Rickard (1962) and some earlier workers (Hartnagel, 1912; Goldring, 1935, 1943), recognized the Kalkberg as a separate formation and restricted the name New Scotland to the lithologically distinct strata above. The New Scotland Formation was termed the "argilli-calcisiltite facies" by Rickard, this formation being predominantly composed of calcareous and argillaceous shales. Like the "cherty calcisiltite facies" of the Kalkberg Formation, the "argilli-

Figure 5:
General stratigraphic correlation of the Helderberg Group as developed by Rickard (1962). The numbered arrows indicate key criteria, which served as a basis for the correlation of this sequence (modified after Rickard, 1962).



1. Thin and persistent lithologic units (e.g. CR, algal laminites)
2. Stromatoporoid biostrome horizons
3. Bentonite, chert beds
4. Lateral interfingering of lithologies
5. A three fold zonation of the Coeymans Formation at Cherry Valley
6. Two varieties of Gypidula
7. Meristella zone
8. Dicoelosia zone

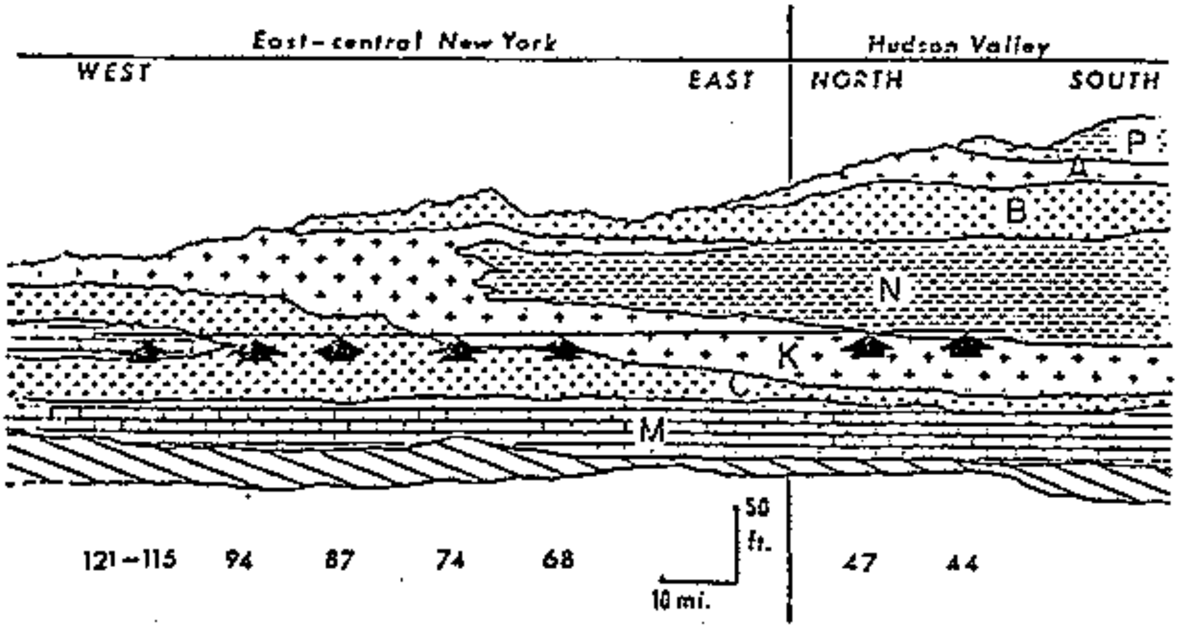
calcisiltite facies" was characterized by an abundant and diverse benthonic fauna. With these criteria, Rickard interpreted the facies of the New Scotland as a neritic environment similar to that of the Kalkberg, but farther offshore and therefore deeper.

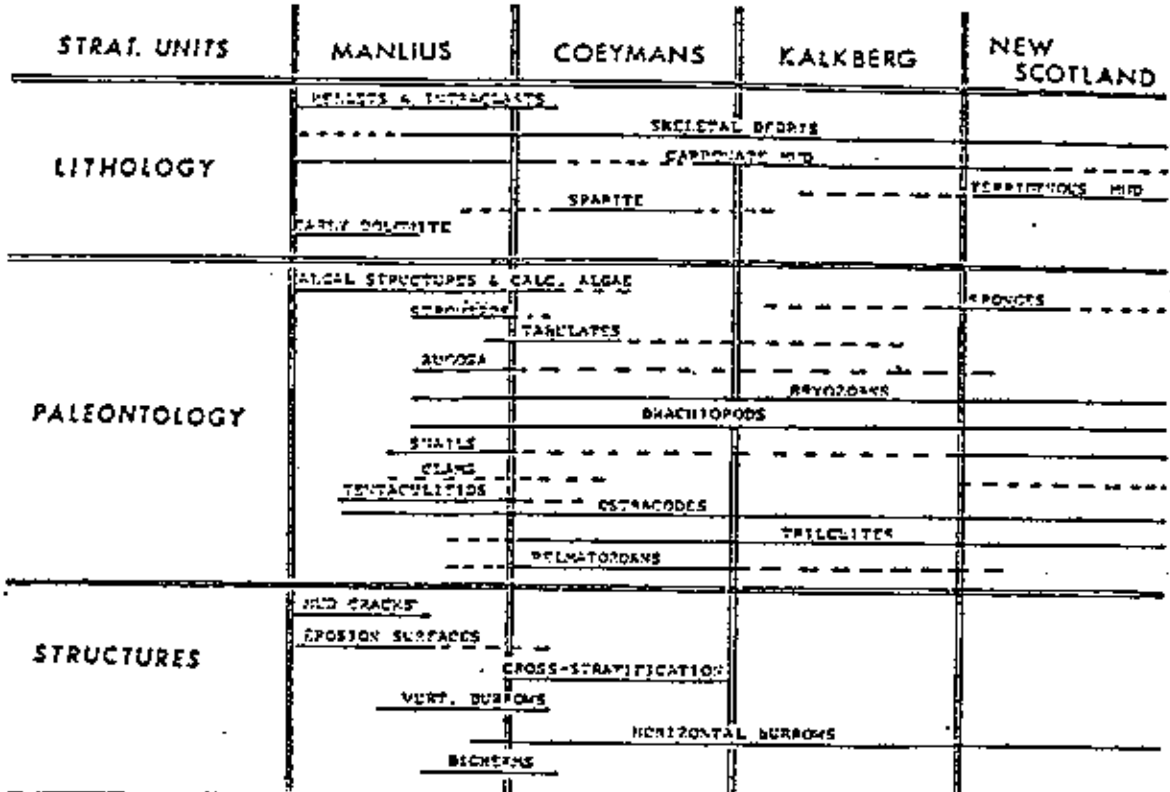
In addition to the 2 shelf facies of the Kalkberg and New Scotland Formations, Rickard distinguished 3 other main facies (lagoon, reef, shallow neritic) in the lower Helderberg Group. Rickard concluded that these facies, which comprised a vertical section, could be demonstrated by correlation to be lateral to one another. The key to Rickard's correlation of the Kalkberg and New Scotland Formations was recognition of the Dicoelosia Zone (Figure 5). Rickard interpretated this epibole as being a chronostratigraphic horizon, and based his correlation of the Kalkberg - New Scotland interval upon it.

In an attempt to refine Rickard's interpretation of the lateral and vertical facies relationships of the Manlius-Coeymans-Kalkberg-New Scotland interval, Laporte (1969) applied the theoretical and predictive models of Shaw (1964) and Irwin (1965) for shallow, clear-water sedimentation in an epeiric sea to the Helderberg Group. Utilizing Rickard's correlation diagram, Laporte projected a hypothetical time plane across these four formations. This datum was drawn near the base of the Clark Reservation Member of the Manlius Formation in the west and a few feet above the Kalkberg-New Scotland boundary in the east (Figure 6). Laporte sampled 3 feet on either side of this datum to document the major faunal and lithological elements of each of the main facies (formations) through which this datum cut (Tables 1 and 2). Based upon the results of this analysis, Laporte maintained that the vertical sequence of facies and their lateral relationships record the migration of once co-existing environments within a slowly transgressing sea.

Figure 6:
Diagram of the hypothetical time plane Laporte (1969) used to sample "co-existing" facies (from Laporte, 1969).

Table 1:
The results of Laport's (1969) facies analysis along the time plane depicted above in figure 6 (from Laporte, 1969).





ENVIRONMENT	TIDAL FLAT-LAGOON; POOR CIRCULATION, HIGHLY VARIABLE ENVIRONMENT.	HIGH AND LOW ENERGY SUBTIDAL; GOOD CIRCULATION, STABLE ENVIRONMENT EXCEPT FOR VARYING WATER AGITATION.	OPEN, SHALLOW SHELF; LOW ENERGY: HIGHLY STABLE ENVIRONMENT WITH GOOD CIRCULATION, LOW TERRIGENOUS INFLUX.	OPEN, SHALLOW SHELF; LOW ENERGY. VARIATIONS CAUSED BY PERIODIC TERRIGENOUS INFLUX.

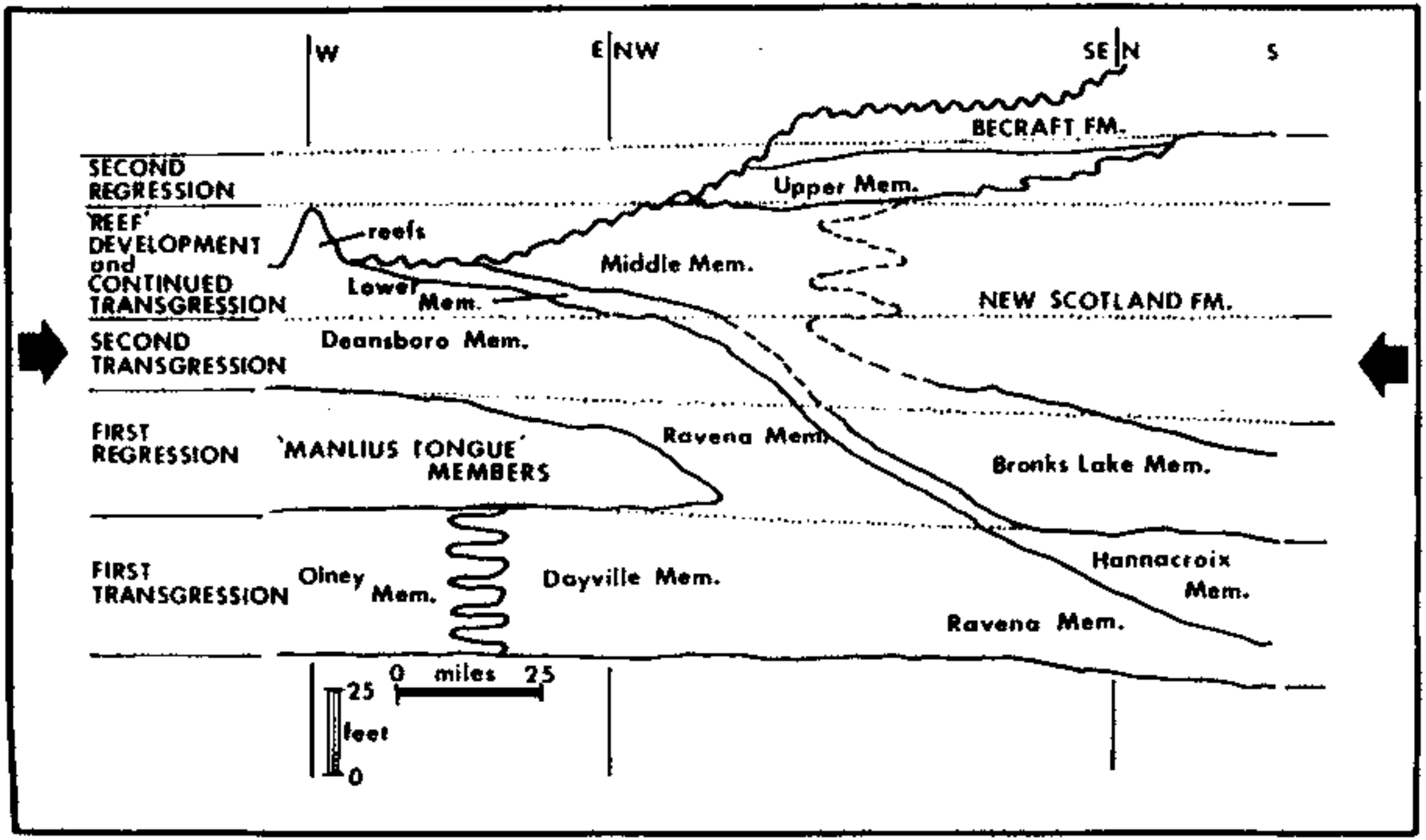
Table 2:
This table lists the brachiopod species of the Coeymans, Kalkberg, and New Scotland shelf facies. X denotes a commonly occurring species; - denotes a somewhat less common species or else restricted to certain portions of the unit (modified from Laporte, 1969).

Brachiopod species	Coeymans	Kalkberg	New Scotland
Mesodouvillina varistriata	X		
"Uncinulus" mutabilis	X		
"Camarotoechia" semiplicata	X		
Gypidula coeymanensis	X	-	
Dalejina oblata	X	X	
Atrypa "reticularis"	X	X	
Meristella laevis	X	X	
Leptaena "rhomboidalis"	X	X	X
Strophonella punctulifera	X	X	X
Eatonia medialis		X	
Levenea subcarinata		X	
Amsdenella abrupta		X	
Isorthis perelegans		X	-
Iridistrophia woolworthana		X	X
Kozlowskiellina perlamellosa		X	X
Howellella cycloptera		-	X
Hedeina macropleura		-	X
Leptostrophia beckii		-	X
Dicoelosia varica		-	
Meristella arcuata		-	-

Epstein's (1971) paleoenvironmental and sedimentological analysis of lower Helderbergian shelf facies (represented by the Coeymans, Kalkberg, and New Scotland Formations) documented in even greater detail the major lithological and faunal elements present within each facies. His analysis of these facies was based largely upon the measurement of sedimentological characteristics and the degree of bioturbation as seen in thin-section. Through the results of this analysis, Epstein established 3 types of bottom environments; the sandy bottom open shelf of the Coeymans, the silty bottom open shelf of the Kalkberg, and the clayey bottom open shelf of the New Scotland.

The results of this paleoenvironmental investigation, combined with the previous stratigraphic descriptions and correlations of Rickard (1962), Anderson (1967), and Head (1969), enabled Epstein to recognize several transgressive and regressive episodes within the shelf facies of the lower Helderberg Group. From these episodes, Epstein defined 5 basinwide time-stratigraphic intervals (Figure 7). Epstein argued that during the "second transgressive pulse", the deeper water New Scotland and Kalkberg facies migrated from near the basin axis to the northwest over the shallower facies of the Ravena Member of the Coeymans (Figure 7). The time-horizon between the second and third time-stratigraphic intervals was defined by Epstein as occurring near the top of the Manlius "tongue" in the west and near the Kalkberg-New Scotland formational contact in east central New York (Figure 7). During the third and fourth intervals, Epstein recognized that the New Scotland became laterally extensive. Moreover, he recognized that the first terrigenous clastic deposition in the Devonian of New York began with the New Scotland.

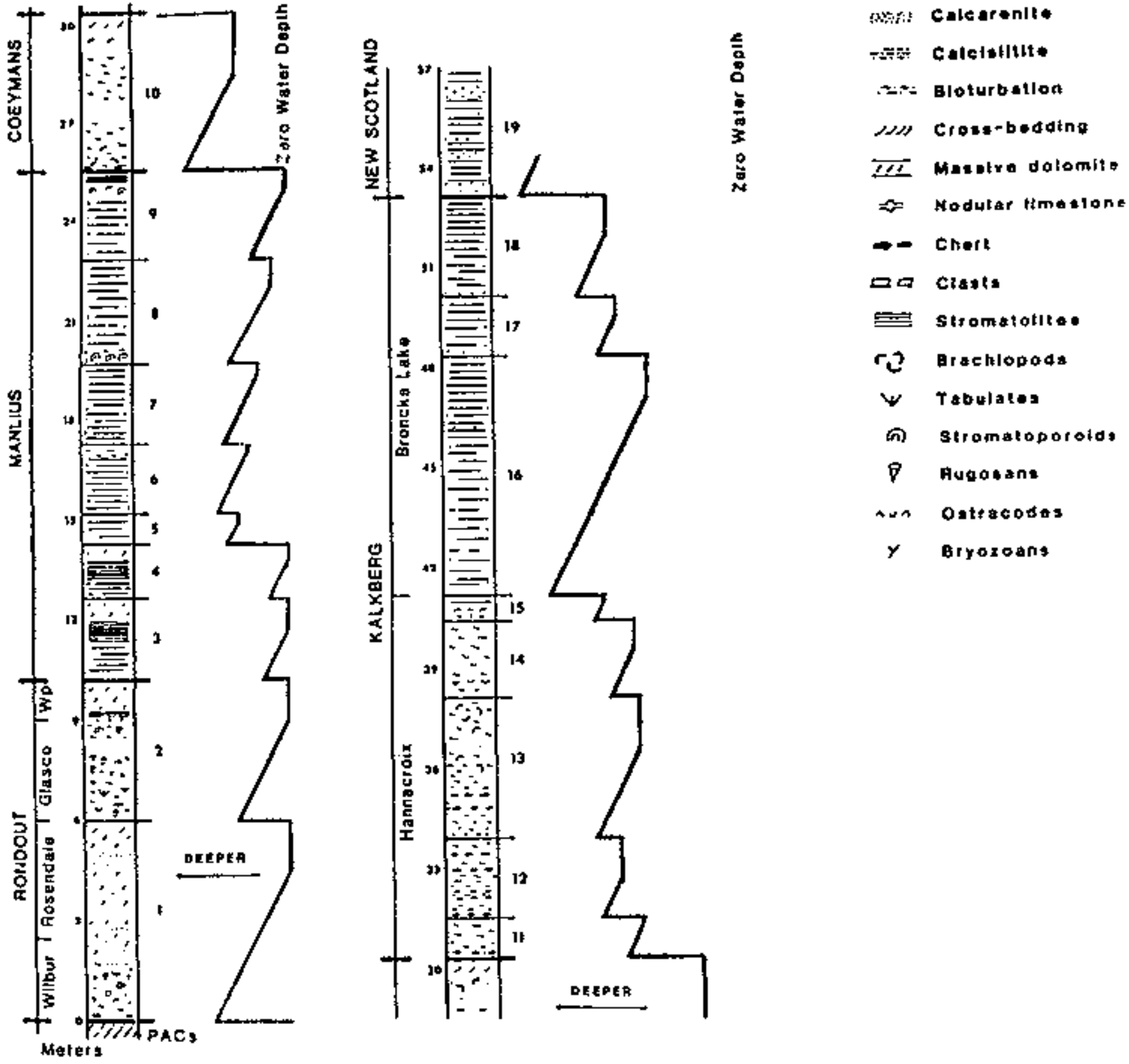
<u>Figure</u> 7:
Epstein's correlation of transgressive and regressive configurations in the Helderberg Group. Each configuration is bounded by dotted lines. The arrows denote the configuration corresponding to the study interval (modified from Epstein, 1971).


W
E
NW
SE
N
S
BECRAFT FM.
SECOND REGRESSION
Upper Mem.
'REEF' DEVELOPMENT and CONTINUED TRANSGRESSION
reefs
Middle Mem.
Lower Mem.
NEW SCOTLAND FM.
SECOND TRANSGRESSION
Deansboro Mem.
FIRST REGRESSION
'MANLIUS TONGUE' MEMBERS
Ravena Mem.
Bronks Lake Mem.
FIRST TRANSGRESSION
Olney Mem.
Dayville Mem.
Hannacroix Mem.
Ravena Mem.
0 miles 25
25 feet 0

In contrast to the traditional and generally accepted methods of facies analysis used by Rickard, Laporte, and Epstein, the hypothesis of Punctuated Aggraditional Cycles of Goodwin and Anderson (1985) offers an episodic approach to stratigraphic analysis. Fundamental to this model is that facies change abruptly at PAC boundaries in response to rapid base-level rises (punctuations events). Within an individual PAC, facies change continuously in response to gradual shallowing-upward through sedimentary aggradation. Application of the PAC hypothesis to the diverse and comparatively nearshore carbonate facies of the Helderberg Group (e.g. Figure 8) has demonstrated that most of this stratigraphic sequence in the Hudson Valley is completely divisible into PACs (Connor, 1983; Sobieski, 1984; Goodwin, Anderson, Goodman, Saraka, 1986). As preducted by the PAC hypothesis, the cycles recognized in these facies are thin (1 to 5 meters thick), bounded by sharp surfaces, and have a shallowing-upward motif (Figures 2 and 9). The identification and correlation of individual PACs between widely separated localities within the Hudson Valley has been accomplished by the recognition of major punctuation events and the matching of similar deepening and shallowing trends in series of PACs (Figure 2). The refined stratigraphic framework of the PAC approach has permitted the analysis of specific facies with respect to depth and lateral position relative to other facies.

Of particular interest to the current study, are the paleoenvironmental studies conducted by Connor (1983) and Sobieski (1984). Connor investigated the uppermost Hannacroix Member of the Kalkberg Formation and the Dicoelosia Zone, the deepest facies to which the PAC approach of facies analysis has been applied prior to the current study. Through detailed field observations and thin-section analyses, Connor defined descriptive criteria for the recognition

Figure 8:
Columnar section of the Helderberg Group at Kingston. The entire section is divisible into PACs. PACs in this diagram are designated by horizontal lines that intersect the column margin. The curve to the right indicates relative water depths (from Anderson, Goodwin, and Sobieski, 1984).


COEYMANS
MANLIUS
RONDOUT
Wilbur
Rosendale
Glasco
Wp
Meters
0
3
6
9
12
15
18
21
24
27
30
1
2
3
4
5
6
7
8
9
10
PACs
DEEPER
Zero Water Depth
NEW SCOTLAND
KALKBERG
Hannacroix
Broncks Lake
30
33
36
39
42
45
48
51
54
57
11
12
13
14
15
16
17
18
19
DEEPER
Zero Water Depth
Calcarenite
Calcisiltite
Bioturbation
Cross-bedding
Massive dolomite
Nodular limestone
Chert
Clasts
Stromatolites
Brachiopods
Tabulates
Stromatoporoids
Rugosans
Ostracodes
Bryozoans

of 3 PACs in these carbonate shelf facies (Figure 10). For the limestone beds in these PACs, Connor proposed a turbiditic origin, the interpretation of which was primarily based on their lateral continuity through the span of an outcrop and their sharp basal contacts. In addition, Connor demonstrated that the Dicoelosia Zone in the Hudson Valley does not occur within the same PAC in this series of PACs. He concluded that the deposition of the Dicoelosia Zone was environmentally controlled, occurred in a sequence of 2 or 3 PACS, and therefore does not represent a single time plane.

Sobieski, in a comprehensive study of the shallow and deeper shelf facies of the Coeymans and Kalkberg Formations, identified 8 PACs between the base of the Coeymans and the base of the Dicoelosia Zone (Figure 11). Sobieski interpreted these PACs as shallowing-upward storm deposit sequences that consisted of distal tempestite facies overlain by proximal tempestite facies. In general, Sobieski characterized PACs in the Coeymans as cycles consisting of proximal tempestite facies, while he characterized PACs in the Hannacroix as cycles consisting of distal tempestite facies. Moreover, Sobieski demonstrated that the seemingly diachronous Coeymans-Kalkberg boundary in the Hudson Valley corresponds to successive PAC boundaries, and that these boundaries are the only correlatable stratigraphic surfaces within the study area (Figures 12a and 12b).

Utilizing the results of these and other PAC studies, Anderson, Goodwin and Sobieski (1984) proposed a descriptive relationship between PACs and formation boundaries. They stated that at any single locality in the Hudson Valley most formation and member boundaries in the lower Helderberg Group coincide with the non-depositional surfaces of PAC boundaries (Figure 13). Consistent with the predictions of the PAC Hypothesis, each surface represents

Figure 9:
Diagram of PAC 3 of the nearshore facies of the Manlius Formation at Thacher Park. At its top and base, PAC 3 is bounded by sharp surfaces. Internally, PAC 3 aggrades from ribbon limestones through stromatolites (modified from Goodwin et al, 1986).

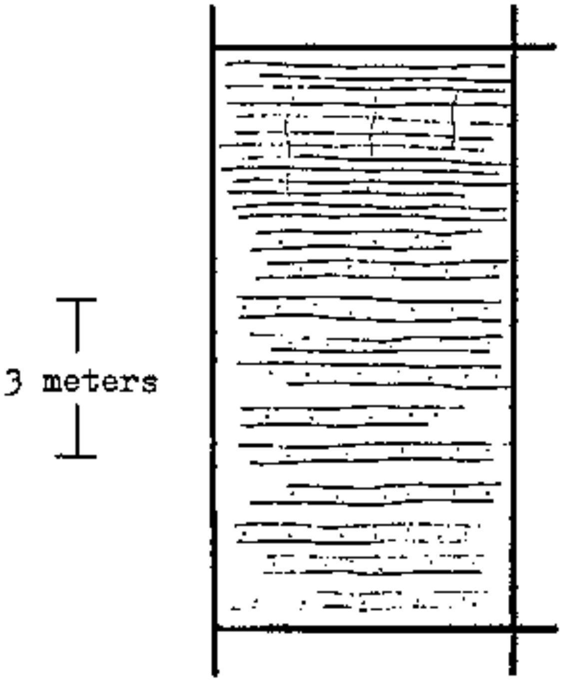

3 meters

Figure 10:
Connor's correlation diagram of three PACs, which encompass the Dicoelosia Zone in the Hudson Valley. The arrows emphasize the Hannacroix-Broncks Lake boundary (from Connor, 1983).

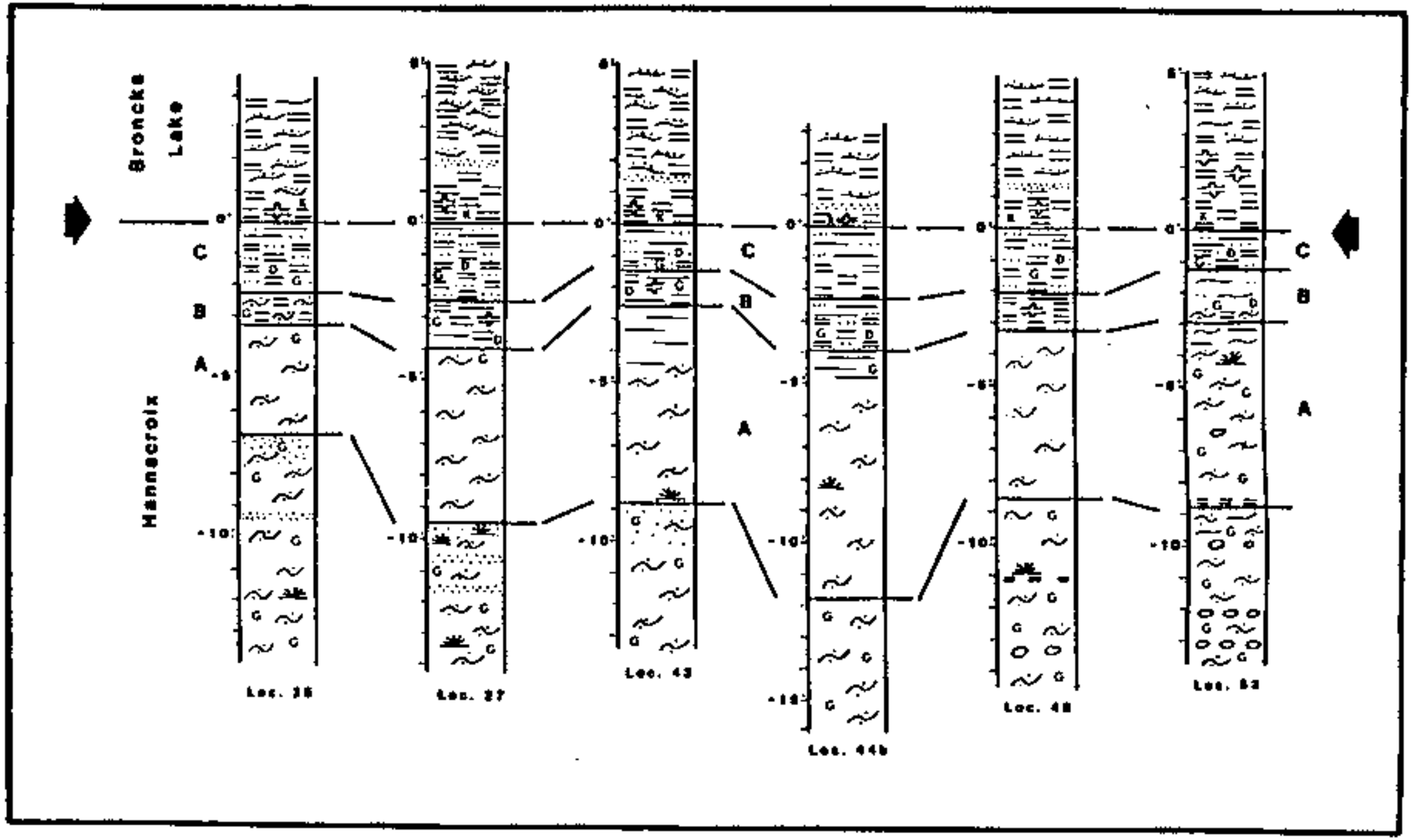
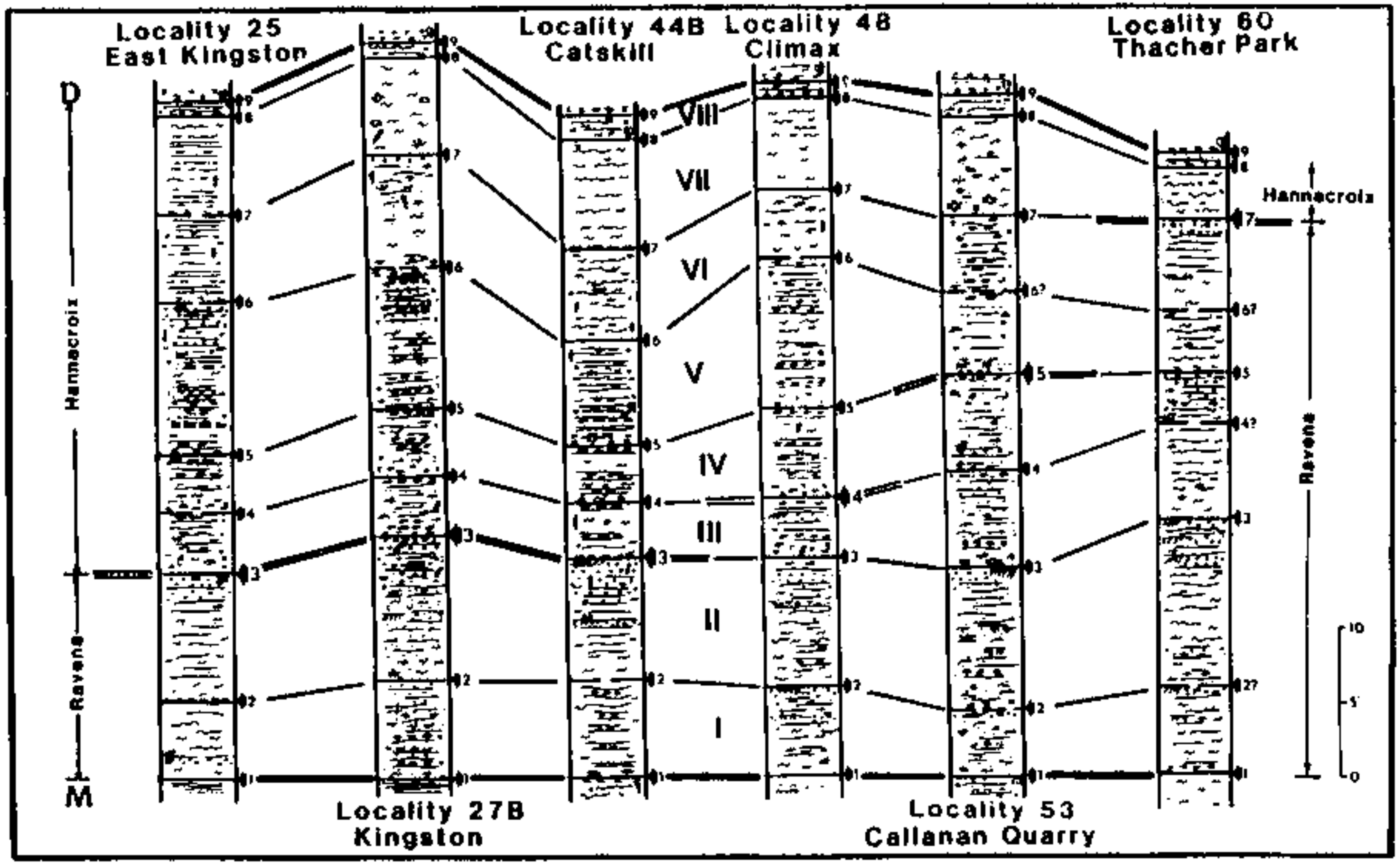
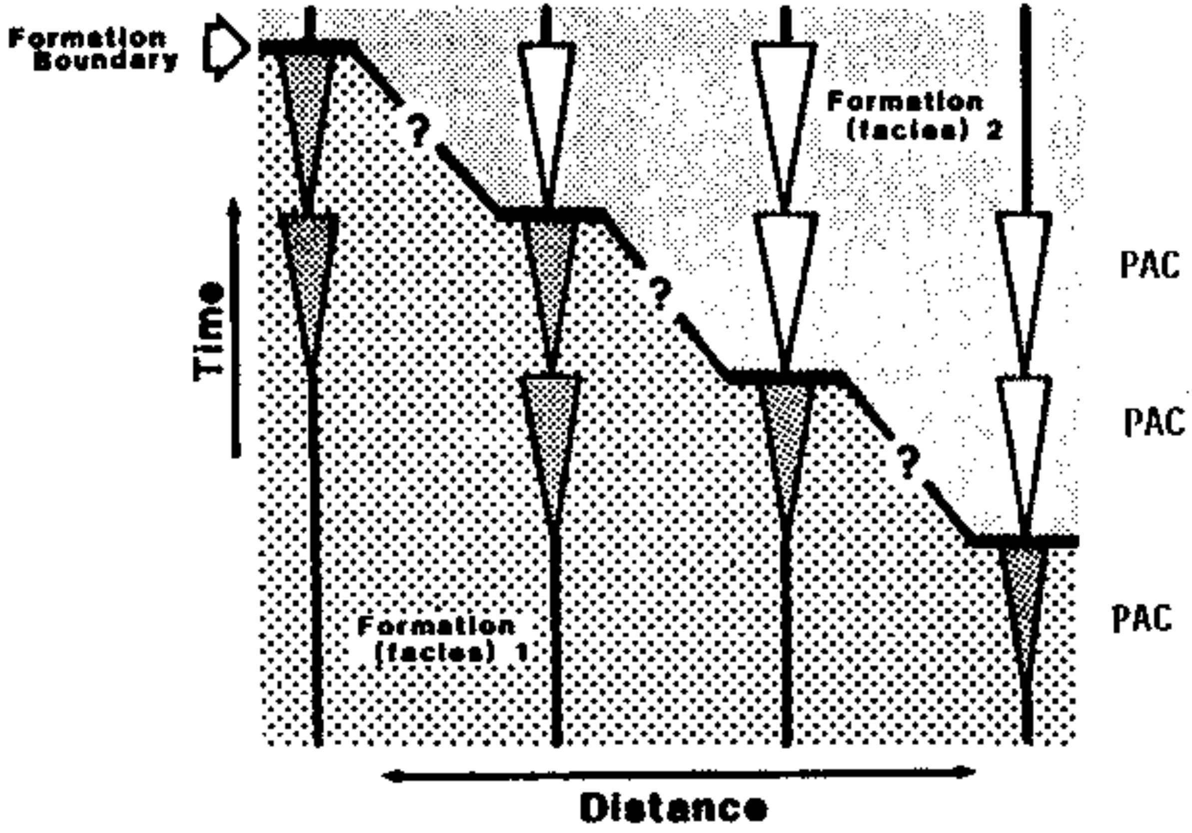

Broncke Lake
Hannacroix
0'
-5'
-10'
-15'
A
B
C
Loc. 35
Loc. 27
Loc. 43
Loc. 44b
Loc. 48
Loc. 53

Figure 11:
Sobieski's correlation of the eight PACs in the Coeymans-Hannacroix interval. The darkened lines emphasize the diachronous boundary between the Ravena Member of the Coeymans and the Hannacroix, and the Hannacroix-Broncks Lake boundary (from Sobieski, 1984).


Locality 25
East Kingston
Locality 27B
Kingston
Locality 44B
Catskill
Locality 48
Climax
Locality 53
Callanan Quarry
Locality 60
Thacher Park
D
M
Hannacroix
Ravena
VIII
VII
VI
V
IV
III
II
I
1
2
3
4
5
6
6?
4?
2?
7
8
9
10
5
0

<u>Figures</u> 12a and 12b:
12a: Diagrammatic representation of an apparent diachronous formation boundary divided into PACs. 12b: Diagrammatic representation of the formation boundary corresponding to isochronous surfaces (I.S. 1-4) that are PAC boundaries. The formation boundary actually occurs at different isochronous surfaces at each locality (from Anderson, Goodwin, and Sobieski, 1984).

"DIACHRONOUS" BOUNDARIES



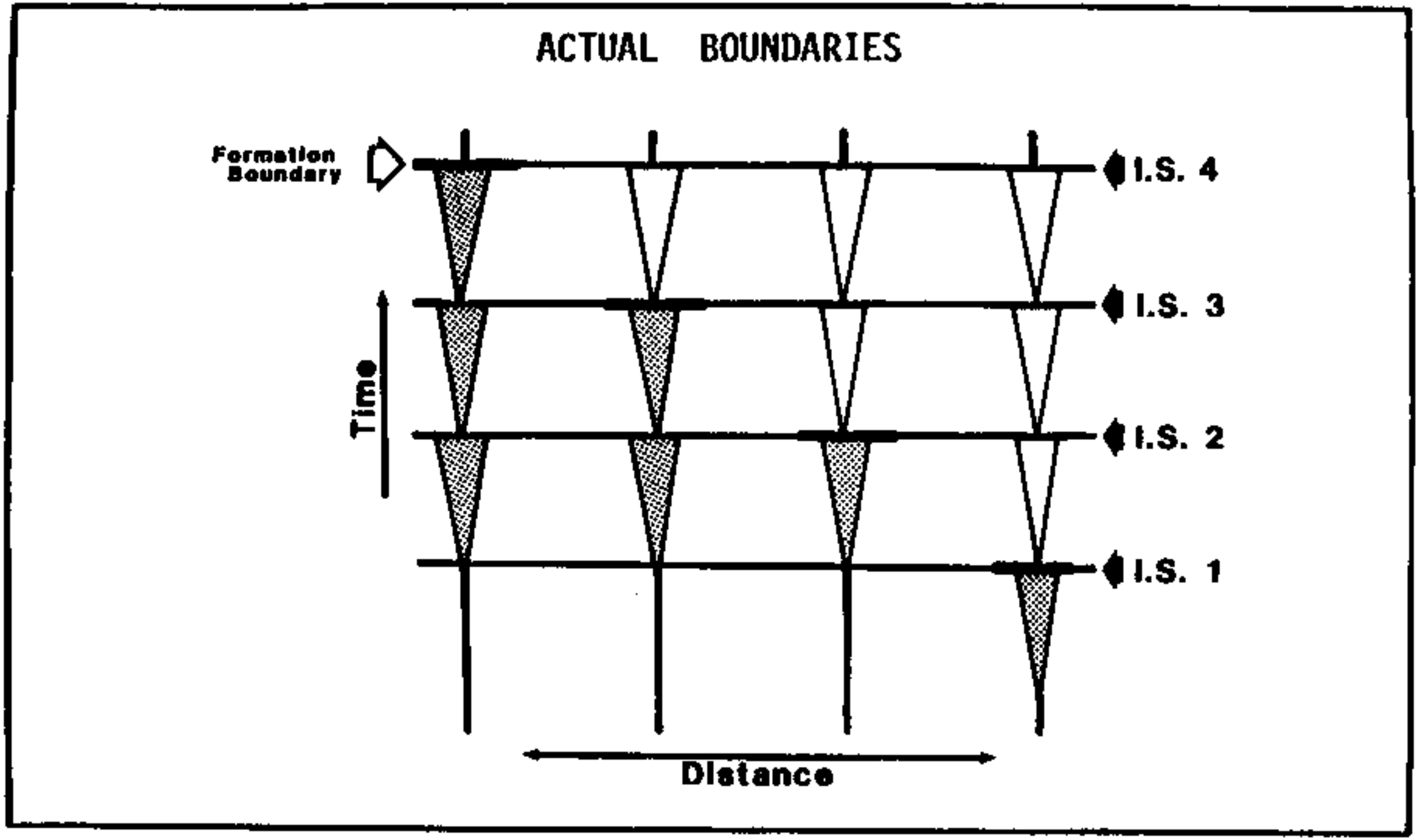
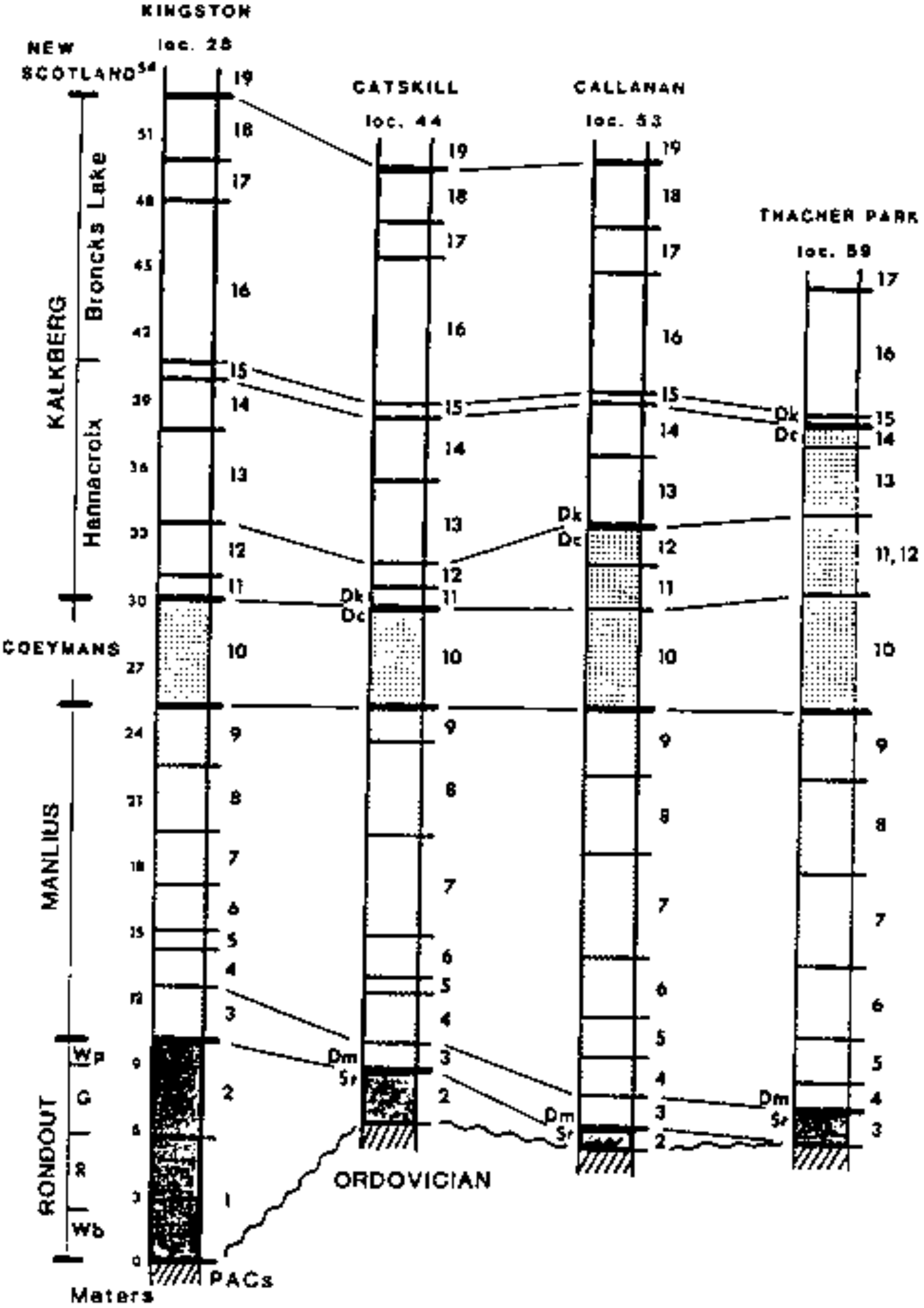

ACTUAL BOUNDARIES
Formation Boundary
I.S. 4
I.S. 3
I.S. 2
I.S. 1
Time
Distance

Figure 13:
Columnar cross section of the Helderberg Group in the Hudson Valley. The formations are indicated by patterns and by the symbols Sr, Dm, Dc, and Dk. The Manlius-Coeymans, Hannacroix-Broncks Lake, and Kalkberg-New Scotland boundaries coincide with single isochronous PAC boundaries. The Coeymans-Kalkberg boundary coincides with three isochronous PAC surfaces (from Anderson, Goodwin, and Sobieski, 1984).


KINGSTON
loc. 28
CATSKILL
loc. 44
CALLANAN
loc. 53
THACHER PARK
loc. 59
NEW SCOTLAND
KALKBERG
Broncks Lake
Hannacroix
COEYMANS
MANLIUS
RONDOUT
Wp
G
R
Wb
Meters
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48
51
54
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
11, 12
Dk
Dc
Dm
Sr
PACs
ORDOVICIAN

a major paleoenvironmental discontinuity that corresponds to significant and widespread facies changes produced by a large punctuation event relative to those responsible for facies changes between PACs within members or formations. These boundaries are either continuous and isochronous and coincide with a single PAC surface, as is the case with the Rondout-Manlius, Manlius-Coeymans, Hannacroix-Broncks Lake, and Kalkberg-New Scotland contacts, or discontinuous and diachronous and coincide with different PAC boundary surfaces, as in the Coeymans-Kalkberg contact.

The recognition of the Kalkberg - New Scotland formational contact as a single PAC boundary surface, and the previous PAC studies of Helderbergian shelf facies establish a basis for the application of the PAC Hypothesis to the deep shelf carbonate facies of the lower New Scotland Formation in the Hudson Valley. The same approach to facies analysis used in these previous PAC studies is used in this thesis to determine the relationship of small-scale facies alternations in the lower New Scotland to punctuated aggradational cycles.

Limestone - Shale Couplets

The deep shelf facies of the lower New Scotland Formation predominantly consists of limestone-shale couplets. Previous studies of stratigraphic sequences of limestone-shale couplets contribute to a better understanding of the development of these facies patterns. Among some workers who have discussed limestone-shale couplets, Richardson (1933), Kent (1936), and Sujkowski (1958) asserted that their origin was solely diagenetic (rhythmic unmixing). According to Einsele (1982), however, current understanding of diagenesis suggests that a complete unmixing of a homogeneous sediment column appears to be unlikely, and that the role of diagenesis in the formation of limestone-shale couplets is probably limited to overprinting original sedimentary structures and textures. Einsele distinguished 2 basic kinds of primary limestone-shale couplets: those that display a cyclic ABAB pattern (of an order of a few decimeters per cycle) of shale or marl and fine-grained argillaceous limestone; and those consisting of successions of distal limestone event beds interbedded with shale. The first kind of sequence consists of cycles that have variously been termed two-phase bedding cycles (Fischer, 1981), short cycles (Schwarzacher, 1975), and periodites (Einsele, 1982). The second kind of sequence consists of limestone turbidites (Thomson and Thomasson, 1969; Davies, 1977; Wright and Wilson, 1984) or limestone tempestites (Markello and Read, 1981; Aigner, 1982, 1984, 1985; Brett, 1983).

Einsele (1982), Fischer (1982), and Schwarzacher (1975) have noted the prevalence of limestone-shale couplets in deep marine stratigraphic sequences. Fischer termed these rhythms two-phase bedding cycles, and described them as a mixture of a biogenic carbonate phase (limestone) and a detrital silicate phase (clay), the ratio of which alternately increased in 1 phase relative to the other over the course of time. Schwarzacher stated that the regularity of these cycles suggests that they contain certain time information, and hence described them as "short cycles". Einsele agreed that these cycles may contain time information when the sequence is due to a mechanism with a statistically constant time period, and hence he referred to these cycles as "periodites".

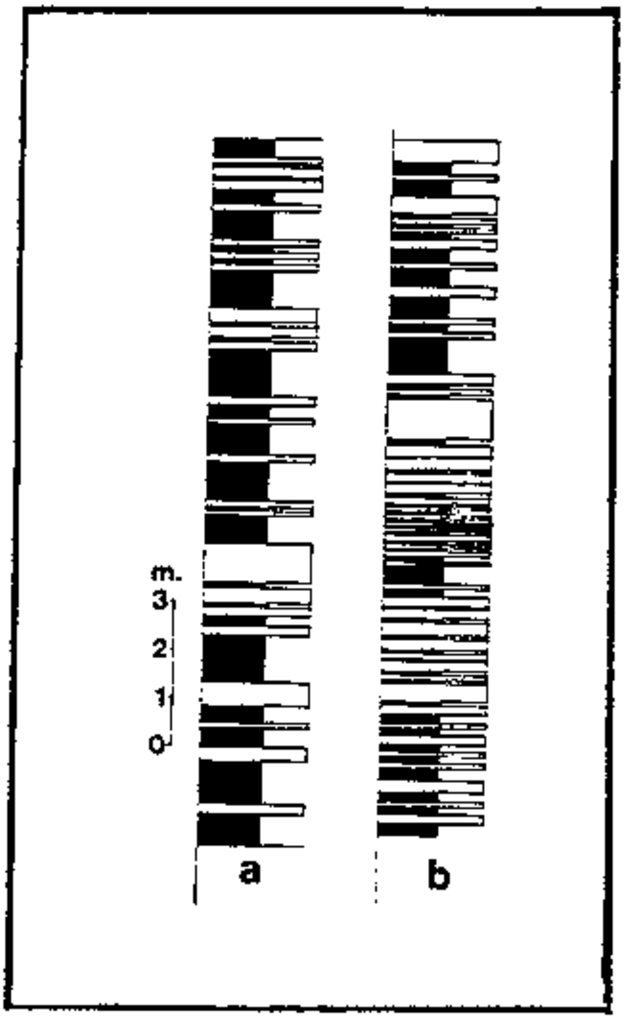
According to Einsele (1982), 3 different types of cycles are recognized, although some cycles may be a combination of 2 or all 3 types. The 3 types are productivity cycles, dilution cycles, and dissolution cycles. Productivity cycles and dilution cycles were described by Einsele as being produced when 1 phase periodically fluctuated during the steady contribution of the other phase. In productivity cycles, carbonate production oscillated while the supply of clay remained constant. In dilution cycles, a relatively constant production of carbonate was diluted by an oscillating supply of clay. The third type of cycle was described by Einsele as being generated when carbonate dissolution fluctuated as the supply of clay and the production of carbonate remained constant. Regardless of the type of cycle, Einsele asserted, cyclicity in limestone-shale sequences composed of these cycles is characterized by periodic changes in sediment parameters, bioturbation, and sedimentation rates, and by continuous vertical accumulation over time (p. 5).

Aigner (1982, 1984, 1985), and others (Thomson and Thomasson, 1969; Brett, 1983; Wright and Wilson, 1984) have revealed the importance of event deposition in the development of facies patterns in stratigraphic sequences of limestone-shale couplets. These deposits, unlike those of limestone-shale rhythms, are characterized by the slow, gradual accumulation of a terrigenous shale component and the intervening rapid deposition of a carbonate component. In each case, distal event facies were interpreted by these authors as having been deposited by downslope sediment flows.

Thomson and Thomasson (1969), in their study of the Dimple Limestone of the Marathon Region, and Wright and Wilson (1984), in their study of the Lower Jurassic Brenha of Portugal, interpreted the occurrence of shelf derived limestones interbedded with hemipelagic shales as turbidites. Thomson and Thomasson proposed a turbiditic origin for the limestones in the basin facies of the Dimple Limestone on the basis of their lateral persistence and internal grading. They concluded that turbidity currents originating on the carbonate shelf flowed along the bottom of the gently sloping shelf into the basin. Wright and Wilson interpreted the limestones of 2 lithostratigraphic units in the Brenha (Units 3 and 4) as turbidites on the basis of internal grading and sharp, grooved bases (Figure 14). Utilizing the current siliclastic submarine fan model, Wright and Wilson concluded that the depositional setting for Unit 3 was an outer fan or basin plain, while Unit 4 was a more proximal part of an outer fan.

Of particular relevance to the current study, are the studies of Brett (1983) and Aigner (1982, 1984, 1986) because they defined cycles in successions of distal limestone event deposits. Brett (1983) described the Rochester Shale (Lewiston, Burleigh Hill, Stoney Creek members) in Western New York as sparsely to richly fossiliferous, gray, shalely mudstone interbedded with carbonates including intrasparrudites, lenticular biosparites and biomicrites (calcarenites), and laminated pelmicrites (calcisiltites). In general, Brett interpreted these interbeds as the result of the concentration and transport of carbonate sediments by storm-wave action on a gently sloping

Figure 14:
Representative logs of Unit 3 (a) and Unit 4 (b) of the Lower Jurassic Brenha of Portugal. The black depicts mudstone and the white depicts peloidal grainstones (from Wright and Wilson, 1984).


m.
3
2
1
0
a
b

shelf. He considered the coarser sediments to be "erosion-lag deposits" formed above storm-wave base and the finer storm generated deposits to have formed from suspension clouds which flowed downslope. Within this interval, Brett distinguished 2 "transgressive-regressive cycles". Brett interpreted the Lewiston Member as a "nearly symmetrical cycle of deepening and shallowing," and the Burleigh Hill and Stoney Creek Members as an "asymmetrical, shallowing-upward hemicycle" (Figure 15). Brett attributed the vertical changes in the Rochester Shale to a shifting of environmental belts due to the migration of the paleoshoreline.

Aigner (1982, 1984, 1986), in a comprehensive study of the Triassic Upper Muschelkalk of Southwest Germany, distinguished (in an offshore direction) a crinoidal or shelly, partly oolitic "shoal" facies followed by a deeper marine facies composed of laterally persistent limestones interbedded with marls. Based on the presence of sharp and often erosional contacts, upward-grading of lithoclasts and bioclasts, and depositional bedforms similar to the Bouma sequence (Figure 16), Aigner interpreted these facies as having been deposited on the gently-inclined shelf of the Upper Muschelkalk basin under high energy conditions produced by storms. He interpreted the deeper facies as distal tempestites consisting of thinner, mud-dominated event beds primarily composed of calcilutite. In discussing the depositional mechanisms responsible for tempestite deposition, Aigner considered 2 main processes, waves and currents. Aigner noted that the action of waves stirred-up and reworked bottom sediments in situ while currents (possibly suspension, bottom, or density currents) accounted for the lateral transport and deposition of allochthonous sediment.

Figure 15:
Correlated columnar sections of the Rochester Shale at 7 localities in Ontario and Western New York State. Brett interpreted the Lewiston Member as a "nearly symmetrical cycle of deepening (Units A-C) and shallowing (Units C-E)". He interpreted the Burleigh Hill and Stoney Creek Members as an "asymmetrical shallowing-upward hemicycle." (from Brett, 1983).

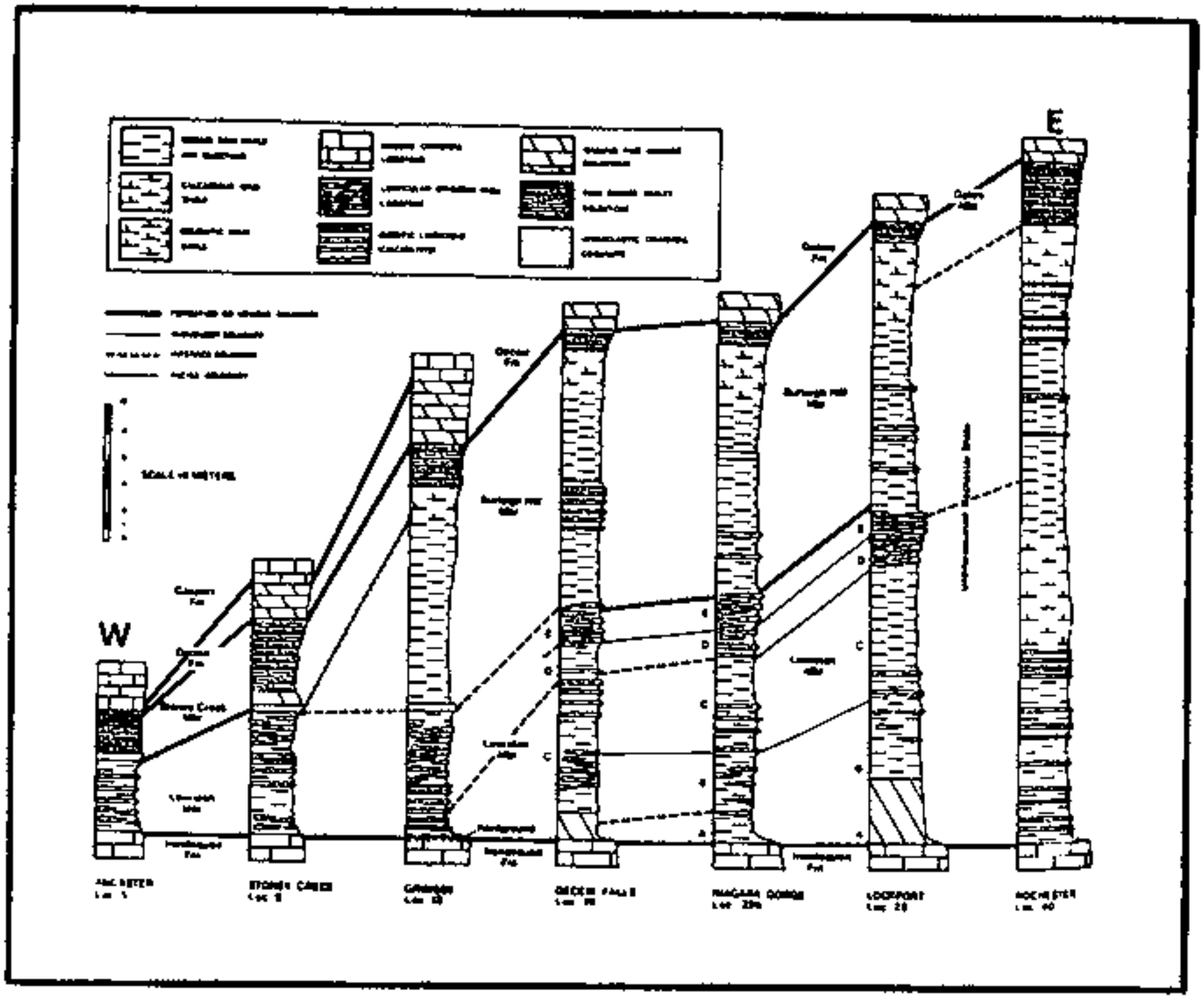
W
E
A
B
C
D
E
SCALE IN METERS
ANCASTER
STONEY CREEK
GRIMSBY
DECEW FALLS
NIAGARA GORGE
LOCKPORT
ROCHESTER

Figure 16:
The Bouma Sequence.