SEQUENCE STRATIGRAPHY OF THE TYPE NIAGARAN SERIES (SILURIAN) OF WESTERN NEW YORK AND ONTARIO

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INTRODUCTION

Recent advances in sequence stratigraphy resulting from seismic profiling of continental shelf sedimentary prisms (Vail et al., 1977; Wilgus et al., 1988), combined with a renewed interest in cyclicity and periodicity in the sedimentary record (see, for example, Bayer and Seilacher, 1985; Einsele, 1985; Fischer et al., 1985; House, 1985) have had a revolutionary impact on the field of stratigraphy. Subdivision of sedimentary prisms into unconformity-bound, genetic stratal packages, or sequences, (sensu Vail et al., 1977; Fig. 1) has permitted seismic stratigraphers to make rather detailed intercontinental correlations and has provided a new genetic model of stratigraphic dynamics on continental shelves (see, for example, Van Wagoner et al., 1988; Posamentier et al., 1988a, b; Sarg, 1988; Galloway, 1989). If depositional sequences are produced, at least in part, by eustatic sea level fluctuations, then the principles of sequence stratigraphy should be equally applicable to epicontinental sea and foreland basin strata which appear to be highly influenced by high frequency, low magnitude sea-level oscillations (see, for example, Goodwin and Anderson, 1985; Busch and Rollins, 1984). However, to date, relatively few studies have attempted to discern unconformity-bound sequences in settings other than passive continental margins (notable exceptions include Nummedal and Swift, 1988; Cross, 1988). In order to test the applicability of sequence concepts to epicontinental strata, field geologists must begin to apply the model at an outcrop scale to a broad array of sedimentary environments. Only in this way can the generality of the sequence model be tested and peculiarities of continental interior and foreland basin sequences be distinguished from those characteristics specific to continental shelf deposition.

The Silurian strata of western New York and adjacent Ontario provide an excellent test case for the application of the principles of sequence stratigraphy in a foreland basin setting. The Silurian rocks of the northern Appalachian foreland basin region in New York State, Pennsylvania and adjacent to Ontario are a classic succession in the history of North American geology (Hall, 1839, 1852). Indeed, they include some of the first formally designated stratigraphic units in North America. These rocks, representing marine and paralic, mixed siliciclastic and carbonate facies, have recently been studied in detail both at the surface and in the subsurface of the Niagara region. Extensive drilling for USGS/EPA and industry supported groundwater studies have provided the impetus for a major revision of the classic Niagaran Series (Early and medial Silurian). Extensive regional correlation of outcrop and subsurface data is providing a broader overview of facies patterns in the northern Appalachian basin.

The Niagaran Series records diverse litho- and biofacies, ranging from nonmarine sandstones to deep-water shales and reefal carbonates. These strata span the early Llandoverian through the Ludlovian, an interval of about 10 to 15 m.y. Furthermore, the Niagaran series is internally divided by multiple regional unconformities that provide a basis for tentative subdivision of these strata into genetic depositional sequences (Fig. 4).

In this report we discuss the sequence stratigraphy of the Silurian Medina, Clinton, and Lockport Groups of westernmost New York and Ontario with emphasis on the following: 1) positions of major sequence bounding erosion surfaces; 2) positions of internal discontinuities associated with transgressions and offshore sediment starvation (i.e., marine flooding or downlap surfaces); 3) internal structure of sequences into component systems tracts (facies representing lowstand, transgressive, and highstand portions of large-scale cycles); 4) fine-scale subsequence and parasequence subdivisions and their bounding surfaces; and, finally, 5) lateral changes of facies within sequences and their implications for basin geometry and dynamics.

The Silurian strata of the Niagara region demonstrate the feasibility and utility of a sequence stratigraphic approach. Although these rocks do not perfectly fit all the details of the original sequence model, many constructs and concepts are applicable. Furthermore, detailed studies of foreland basin successions, such as this, should aid in refining the original sequence model and making it more broadly applicable.

GENERAL CONCEPTS OF SEQUENCE STRATIGRAPHY

As underscored repeatedly by the Exxon seismic stratigraphy group (see Wilgus et al., 1988), depositional sequences consist of genetically related packages of relatively conformable strata bounded by subaerial unconformities and their correlative submarine conformities. Sequences are comprised of internal subdivisions of smaller-scale units termed parasequences which commonly form genetic groupings referred to as parasequence sets (see, for example, Vail et al., 1977; Van Wagoner et al., 1988; Figs. 1, 2, herein). We introduce the term sub-sequence to refer to small scale sequence-like divisions that lack evidence for major erosion at their boundaries. The subsequences are composed of two or more parasequence sets and correspond approximately to the concept of systems tracts, proposed by Vail et al. (1977)(Van

Wagoner et al., 1988). Sequences can be subdivided into systems tracts, representing deposition during three phases of a major sea level cycle, lowstand (major sea level fall or regression), transgressive (initial sea level rise or transgressional, and highstand (still stand to early sea level fall). Systems tracts are identified by their position in the sequence and the stacking order of component parasequences (Figs. 1, 2).

Lowstand or continental margin systems tracts accumulate during periods of relative sea level lowstand when much of the continental shelf is subjected to erosion. Consequently, lowstand systems tracts are generally confined to deep sea fans and wedges or erosional valleys on the continental shelf (Fig. 1). Lowstand deposits are bounded at their base by the sequence bounding unconformity, a major erosional surface produced when the rate of sealevel far exceeds local subsidence rates, resulting in rapid sealevel drop.

Transgressive systems tracts are made up of retrograding (upward deepening) parasequences and form during times of relatively rapid sea level rise. Transgressive systems tracts are composed of relatively shallow water sediments, and typically are relatively thin and tend to become increasingly starved of siliclastic sediments upward. They are typically bounded at their bases by a sharp transgressive surface that represents a rapid increase in the rate of sea level rise and separates the transgressive systems tract from the underlying lowstand systems tract (Figs. 1, 2). This surface may be marked by erosional clasts from the underlying lowstand deposits as well as phosphatic and resistant skeletal material in some instances (see Baum and Vail, 1988). The base of the transgressive systems tract is often a very sharply demarcated surface in outcrops as noted by Baum and Vail (1988); it is commonly coextensive with a ravinement surface produced by erosional shore face retreat in a high energy environment. Consequently, the base of the transgressive systems tract typically displays shallow shelf sand sharply overlying non-marine or paralic sediments of the lowstand systems tract. The upper boundary of the transgressive deposits is sharply overlain by deeper water sediments at the base of the highstand systems tract. Transgressive systems tracts are generally relatively condensed near their upper boundaries.

The transgressive systems tract is bounded at its top by another discontinuity surface referred to variously as the downlap surface or surface of maximum sediment starvation (Figs. 1, 2). This surface is commonly associated with (overlain by) a highly condensed horizon containing phosphatic nodules, glauconite, conodonts and other chemically resistant allochems. The condensed section records an extended period of non-deposition or exceedingly low sedimentation rates. A point not usually emphasized, but one brought out by Baum and Vail (1988), is that the base of the highstand systems tract is typically recorded by relatively condensed sediments representing deeper water environments than those underlying the surface of maximum starvation or the downlap surface. Hence, the time of maximum relative water depth, and probably of maximum coastal flooding, actually occurs above the surface of maximum starvation and in the basal portions of the highstand systems tracts (Fig. 2). In many instances, this represents an anoxic basinal sediment which may be highly enriched in organic matter (e.g., condensed black shale facies).

As noted by Baum and Vail (1988) and others, the sediments near the top of the transgressive systems tract and those near the base of the highstand systems tracts are relatively "time rich" and, therefore, are often grouped together as the condensed section. Condensed sections are of extreme importance in that they are very widespread in deeper water areas, often commonly show a concentration of biostratigraphically important fossils (e.g., foraminifera or conodonts), and typically can be traced into marine flooding or transgressive surfaces in shallow marine and nonmarine environments high on the continental shelf. The condensed section and, particularly, the surface of maximum starvation correspond to the time of maximum rate of sea level rise.

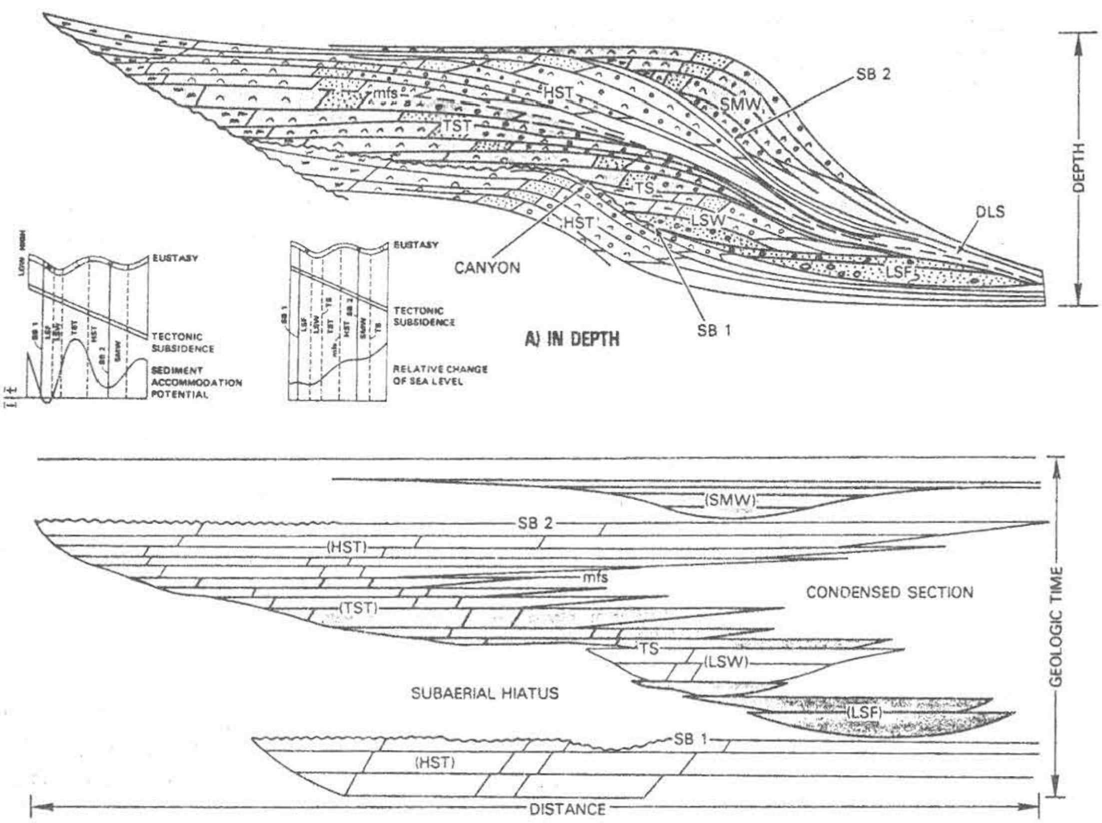
A point not brought out by most sequence stratigraphers is that the surface of maximum starvation (downlap surface) can also be a surface of extensive submarine erosion. This results both from the very low sedimentation rates associated with maximum rate of sea level rise, and from turbulent processes that apparently occur along water mass boundaries at the pycnocline (Ettensohn, 1987; Woodrow, 1985; Baird and Brett, 1986, 1988, and in press).

The remaining portions of the highstand systems tract, above the condensed section, consist of a generally static to upward shallowing (aggradational to progradational) set of parasequences culminating at the top in shallow water deposits (Figs. 1, 2). The upward shallowing may result either from sedimentary processes (e.g., progradation of sediment wedges) or more probably from initial lowering of relative sea level or at least diminishing rate of sea level rise. This results in a reduction of accomodation space and consequent progradation of strandline deposits. The highstand systems tract is typically bounded at its top by an erosional unconformity marking the lower boundary of the overlying sequence.

Figure 1. Idealized sequence stratigraphy model showing key surfaces and systems tracts. Sequence boundary 1 (SB-1) is a type 1 (incised) boundary, SB-2 is a type 2 sequence boundary. Note that the sequences are separated by an unconformity representing exposure during times of maximum rate of sea level fall - this unconformity can be traced to continuity offshore. This correlative conformity is a time boundary. From Baum and Vail (1988).

SEQUENCE STRATIGRAPHY DEPOSITIONAL MODEL

SHOWING SURFACES, SYSTEMS TRACTS AND LITHOFACIES



B) IN GEOLOGIC TIME

LEGEND

SURFACES

(SB) SEQUENCE BOUNDARIES
(SB 1) = TYPE-1
(SB 2) = TYPE-2
(DLS) DOWNLAP SURFACES
(mfs) = maximum flooding surface
(TS) TRANSGRESSIVE SURFACE
(First flooding surface above maximum regression)

SYSTEMS TRACTS

HST = HIGHSTAND SYSTEMS TRACT
TST = TRANSGRESSIVE SYSTEMS TRACT
LST = LOWSTAND SYSTEMS TRACT
LSF = LOWSTAND FAN
LSW = LOWSTAND WEDGE
SMW = SHELF MARGIN WEDGE SYSTEMS TRACT

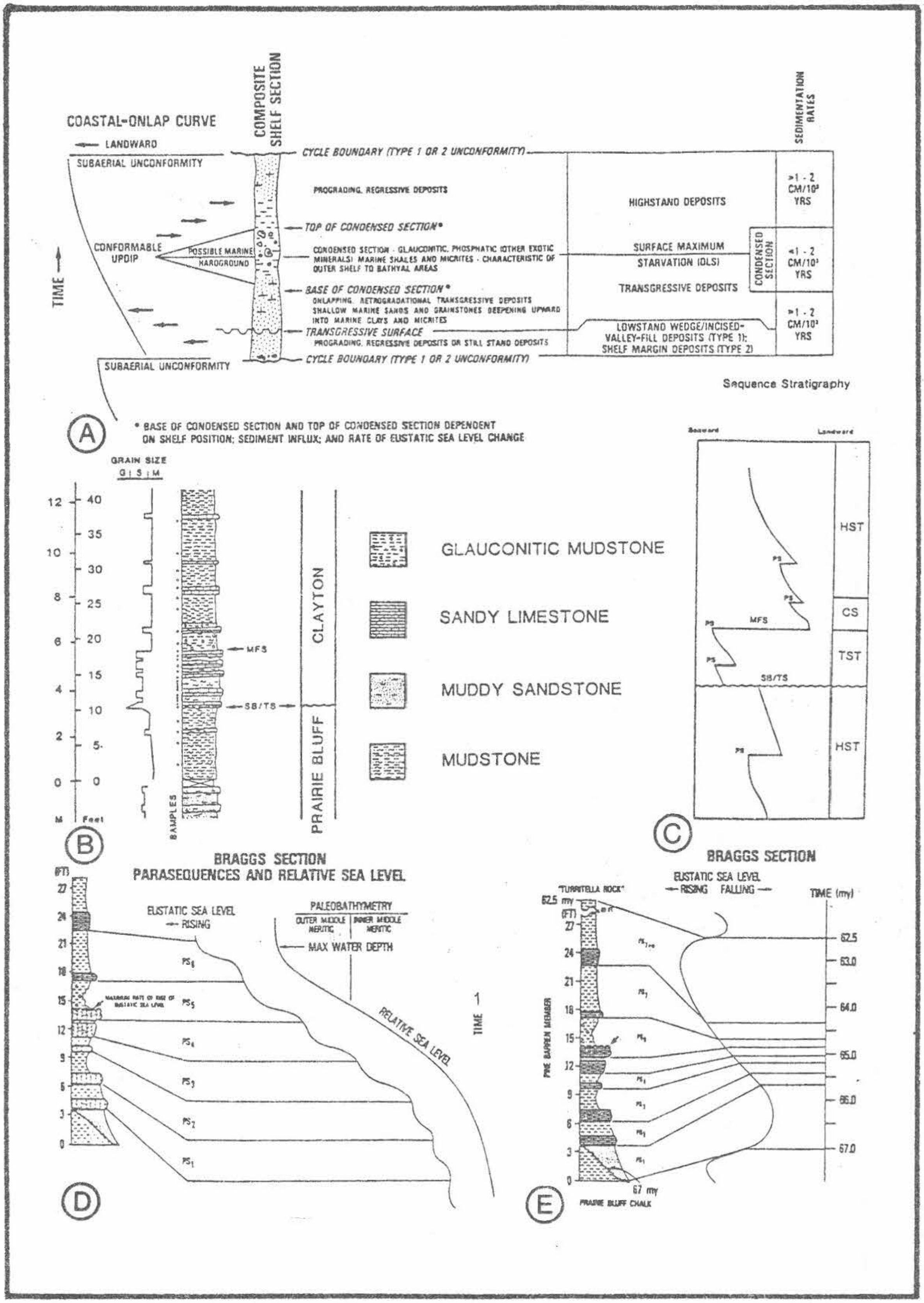
LITHOFACIES

- SUPRATIDAL
- PLATFORM
- PLATFORM-MARGIN GRAINSUPPORTSTONE/REEFS
- MEGABRECCIAS/SAND
- FORESLOPE
- TOE-OF-SLOPE/BASIN

Unconformity bound sedimentary packages have begun to be recognized in epicontinental sea deposits of the Paleozoic (e.g. Ross and Ross, 1985; 1988). Furthermore, a hierarchy of depositional cycles (1st to 6th order), apparently of eustatic origin, has been recognized particulary in Carboniferous deposits of the North American continental interior, but also elsewhere (Bush and Rollins, 1984; Heckel, 1986). Small scale (parasequence-like) features recorded as shallowing upward cycles or puntuated aggradational cycles (PACs) have been recognized in several portions of the stratigraphic column (Goodwin and Anderson, 1985).

How can these differing scales and types of cycles be reconciled with the sequence stratigraphy model of seismic stratigraphers? And how do sequences on epicontintental seas or foreland basins compare with those recognized on continental margins? Can the three primary surfaces of the idealized sequence, i.e. the basal erosion surface, transgressive surface, and surface of maximum starvation (downlap surface), be recognized in foreland basin/epicontinental sea areas? Answers to these questions require thorough re-examination of epicratonic strata. Most epicratonic successions are too thin to be resolved by seismic methods. Therefore application of sequence stratigraphic principles requires detailed field and subsurface correlation of strata in well-studied areas, as in the case study presented herein.

Figure 2. Stratigraphic profiles illustrating outcrop appearance of sequences. (A) Idealized model showing positions of three key surfaces; note that transgressive surface (TS) and cycle boundary tend to merge in shallow shelf areas; also note that condensed section spans late parts of the transgressive deposits and early highstand deposits; it includes the surface of maximum starvation (also referred to as downlap surface), which develops during times of maximum rate of sea level rise. From Baum et al. (1984). (B-E) Lithostratigraphy, sequence stratigraphy and inferred relative (D) and eustatic sea level fluctuations for Cretaceous-Tertiary boundary sediments exposed at Braggs, Alabama. Note that sequence boundary (SB) at Prairie Bluff/Clayton Contact) and first transgressive surface (TS) are merged. Also note condensed section (CS) overlying marine flooding surface (MFS), and separating transgressive (TST) and highstand (HST) systems tracts. PS1-PS6 are parasequences. Maximum relative and eustatic sea level stands occur above the surface of maximum starvation (MFS: noted with arrow) in early highstand; minimum relative sea level coincides with early transgressive deposits. Figures A, D and E from Baum and Vail (1988), figures B and C from Donovon et al. (1988).



COASTAL-ONLAP CURVE
COMPOSITE SHELF SECTION
SEDIMENTATION RATES
LANDWARD
SUBAERIAL UNCONFORMITY
CYCLE BOUNDARY (TYPE 1 OR 2 UNCONFORMITY)
PROGRADING, REGRESSIVE DEPOSITS
HIGHSTAND DEPOSITS
>1 - 2 CM/10³ YRS
TOP OF CONDENSED SECTION*
CONFORMABLE UPDIP
POSSIBLE MARINE HARDGROUND
CONDENSED SECTION - GLAUCONITIC, PHOSPHATIC (OTHER EXOTIC MINERALS) MARINE SHALES AND MICRITES - CHARACTERISTIC OF OUTER SHELF TO BATHYAL AREAS
SURFACE MAXIMUM STARVATION (DLS)
CONDENSED SECTION
<1 - 2 CM/10³ YRS
TIME
BASE OF CONDENSED SECTION*
ONLAPPING, RETROGRADATIONAL TRANSGRESSIVE DEPOSITS SHALLOW MARINE SANDS AND GRAINSTONES DEEPENING UPWARD INTO MARINE CLAYS AND MICRITES
TRANSGRESSIVE DEPOSITS
TRANSGRESSIVE SURFACE
PROGRADING, REGRESSIVE DEPOSITS OR STILL STAND DEPOSITS
LOWSTAND WEDGE/INCISED-VALLEY-FILL DEPOSITS (TYPE 1); SHELF MARGIN DEPOSITS (TYPE 2)
>1 - 2 CM/10³ YRS
CYCLE BOUNDARY (TYPE 1 OR 2 UNCONFORMITY)
SUBAERIAL UNCONFORMITY
Sequence Stratigraphy
A
* BASE OF CONDENSED SECTION AND TOP OF CONDENSED SECTION DEPENDENT ON SHELF POSITION; SEDIMENT INFLUX; AND RATE OF EUSTATIC SEA LEVEL CHANGE
GRAIN SIZE
G S M
M Feet
SAMPLES
MFS
SB/TS
CLAYTON
PRAIRIE BLUFF
GLAUCONITIC MUDSTONE
SANDY LIMESTONE
MUDDY SANDSTONE
MUDSTONE
B
Seaward
Landward
HST
PS
MFS
CS
TST
SB/TS
HST
C
BRAGGS SECTION
BRAGGS SECTION PARASEQUENCES AND RELATIVE SEA LEVEL
(FT)
EUSTATIC SEA LEVEL
RISING
PALEOBATHYMETRY
OUTER MIDDLE NERITIC
INNER MIDDLE NERITIC
MAX WATER DEPTH
MAXIMUM RATE OF RISE OF EUSTATIC SEA LEVEL
PS6
PS5
PS4
PS3
PS2
PS1
RELATIVE SEA LEVEL
TIME
D
"TURRITELLA ROCK"
62.5 my
EUSTATIC SEA LEVEL
RISING FALLING
TIME (my)
62.5
63.0
64.0
65.0
66.0
67.0
PINE BARREN MEMBER
67 my
PRAIRIE BLUFF CHALK
E

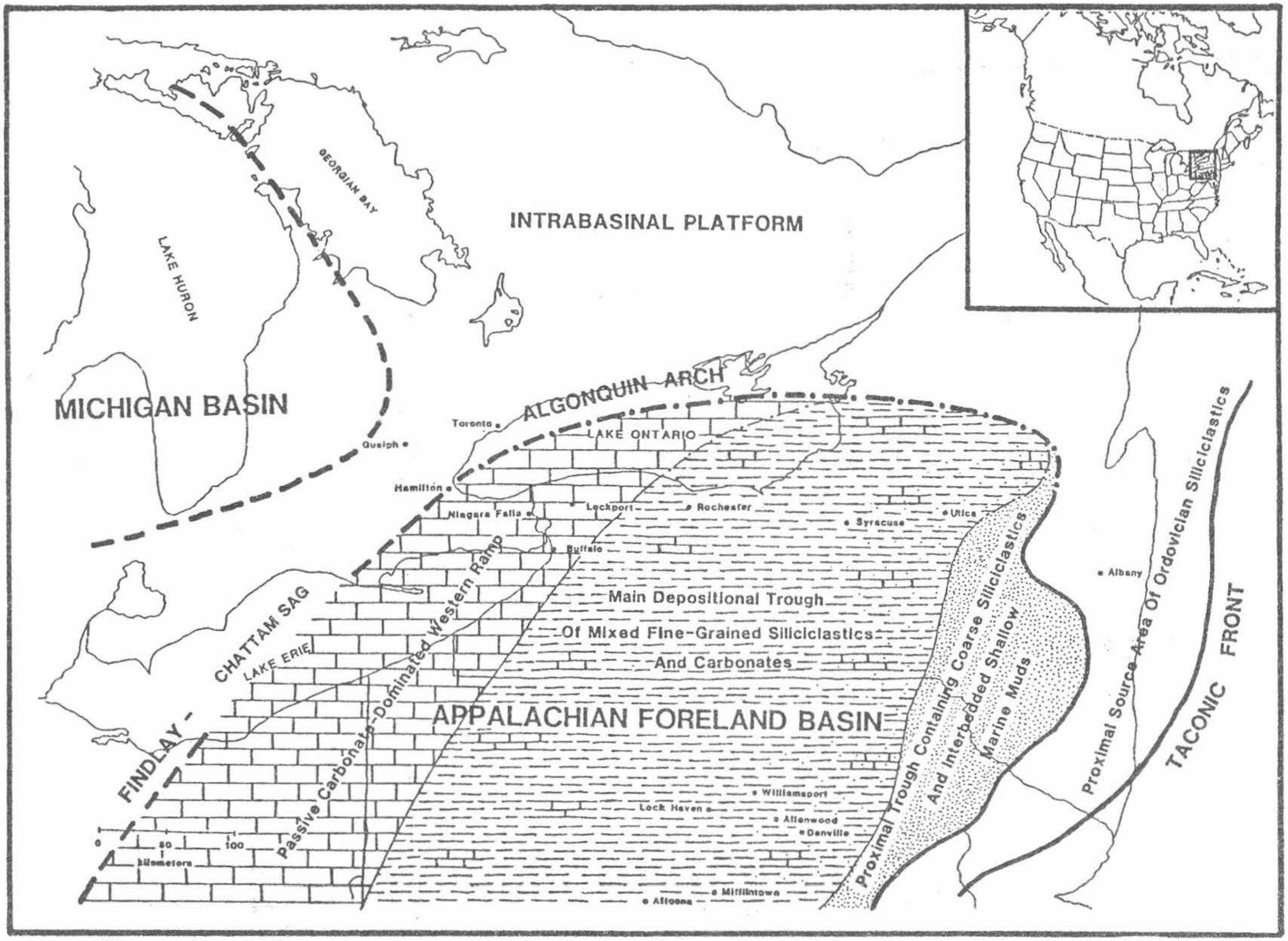


Figure 3. Paleogeographic map of the northern Appalachian foreland basin during medial Silurian time; inset map shows position of the study area within North America. Modified from Brett (1983).

GENERAL GEOLOGICAL SETTING

Paleogeography and Sedimentology

The Medina, Clinton, and Lockport Groups of New York State and Ontario and their correlatives in Pennsylvania and Ohio were deposited in the northern end of the Appalachian Foreland Basin (Fig. 3). Along the southeastern margin, the basin was bordered by a linear belt of uplifted Middle to Upper Ordovician shales and sandstones and, beyond, by the Taconic orogenic belt from which Silurian siliciclastics were derived. The Appalachian Basin was bordered along its northwest margin by the northern extension of the Findlay Arch, locally referred to as the Algonquin Arch (Fig. 3).

During the Silurian Period, the northern reaches of the Appalachian Basin occupied a position approximately 20-25 degrees south latitude (Van der Voo, 1988). Given this position, it is likely that the basin was subjected to tropical storms following southerly paths (Middleton, 1987). Signatures of episodic sedimentation are common in the Llandoverian through Ludlovian Series of western New York.

These strata comprise a 130 meter thick, mixed carbonate-siliciclastic succession representing multiple, small to medium-scale depositional systems (Fig. 3). Near the southeastern strandline, the sequence is dominated by coarse-grained siliciclastics which were deposited on a storm-dominated shallow shelf and shoreface (Zenger, 1971; Cotter, 1983). The middle to outer regions of the eastern basin flank are represented by argillaceous limestones and sandy or silty shales containing coarser-grained, storm event beds with unidirectional (generally NW-directed) current indicators. Across the basin axis and up the western ramp, the succession becomes increasingly carbonate-dominated. Proximal to the Algonquin Arch, the Medina-equivalent Brassfield Formation of Ohio, and the Clinton and Lockport Groups of southwestern Ontario consist nearly entirely of carbonates, mainly dolomitic, crinoid and brachiopod grainstones, representing normal wave base environments.

Basin Tectonics

The Appalachian Foreland Basin developed from compression of a passive, carbonate-dominated, continental margin during collision with an island arc system during the Middle Ordovician. Early phases of the Taconic Orogeny are recorded by thick turbidite sequences of the Martinsburg (PA) and Snake Hill-Frankfort (NY) Formations. The waning phases of the main orogenic pulse during the Late Ordovician (Ashgillian) are recorded by the Bald Eagle-Oswego sandstone wedge and the overlying Juniata-Queenston red bed sequences.

In many parts of the Appalachian Basin there is evidence of a Late Ordovician to Early Silurian tectonic rejuvenation of the Taconic Front (Quinlan and Beaumont, 1984; Tankard, 1986). In New York State and Pennsylvania, evidence for a late Taconic pulse lies in the regionally extensive, low angle unconformity at the Ordovician-Silurian boundary (Cherokee Unconformity) and an overlying thick Early Silurian clastic wedge. Medial Silurian strata become finer grained indicating a period of quiescence between Taconic and Salinic orogenic pulses.

The Salinic Orogeny was a brief and relatively local uplift in eastern New York State which occurred during the Ludlovian Epoch. The signature of the Salinic Disturbance is an unconformity which ultimately separates the Pridolian Syracuse Formation and upper Ordovician strata. Lower and medial Silurian strata are missing completely east of Van Hornesville, New York.

Other evidence for the Salinic may be recorded in the Bloomsburg-Vernon red bed sequence, and, perhaps more definitively, in the overlying "upper Shawangunk Tongue" of southeastern New York and northeastern Pennsylvania (Prave et al., 1989). It appears that the upper Shawangunk Tongue consists of cannibalized middle Silurian sediments (e.g. Herkimer Sands) eroded from the northern Hudson Valley which were transported southward.

There is little sedimentological or stratigraphic evidence for major unconformities in latest Silurian strata. However, Salkind (1979) has argued for Latest Silurian tectonic activity based upon structural relationships in the Hudson Valley.

SILURIAN SEQUENCES AND BASIN HISTORY

The Llandoverian to Ludlovian (Medina through Lockport Group) succession in New York State, Ontario, Ohio, and Pennsylvania is divisible into at least six large-scale, unconformity-bounded stratal packages (Fig. 4) comparable in some respects to depositional sequences of seismic stratigraphers (e.g., Vail et al., 1977; Van Wagoner et al., 1988). For the most part, these sequences correspond to previously recognized group-level stratigraphic units, but in some cases, cut slightly across traditional subdivisions. The first sequence corresponds to the Medina Group, the second and third to the lower and middle portions of the Clinton Group, respectively, the fourth and fifth to parts of the upper Clinton Group, and the sixth to the Lockport Group and the Vernon Formation.

The sequences recognized herein are at least crudely divisible into systems tracts analogous to those within previously recognized sequences of seismic stratigraphers (see for example, Vail et al., 1977; Van Wagoner et al., 1988; Posamentier et al., 1988). In terms of temporal magnitude, Silurian sequences, like

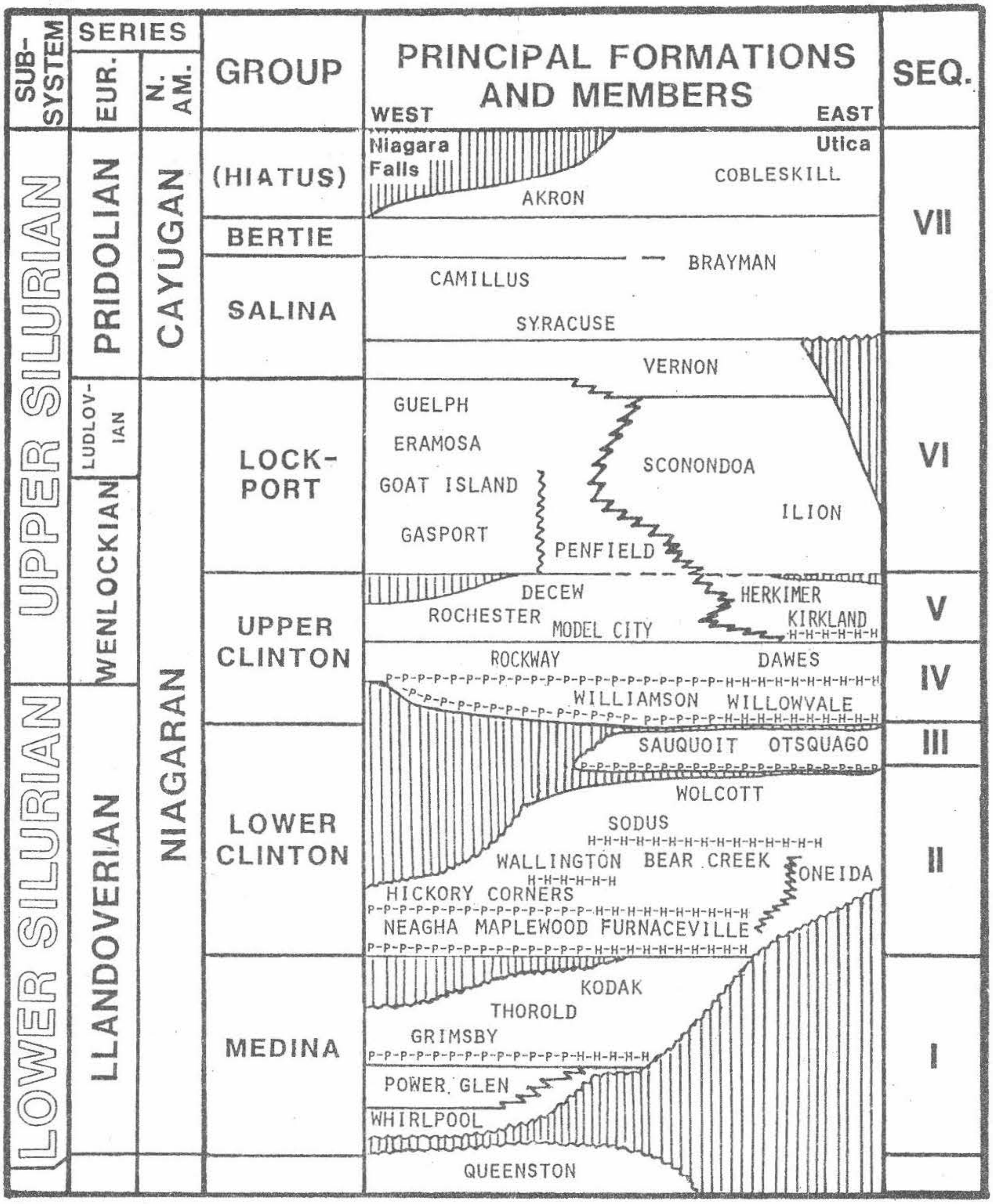


Figure 4. General time stratigraphic chart showing Silurian sequences of New York that are recognized on the basis of major, bounding unconformities.

those of the seismic stratigraphers, encompass about 1 to 5 million years and, therefore, can be classified as <u>3rd order</u> cycles (Vail et al., 1977). The Silurian sequences are divisible internally into very prominent and basin-wide <u>subsequences</u>, which are of lesser temporal magnitude and display sharp, slightly erosive, disconformities. Each sequence contains 2-5 subsequences. We estimate, therefore, a subsequence recurrence interval on the order of 0.8 to 1.5 million years, coinciding with <u>4th order</u> cycles or <u>synthems</u> (see Ramsbottom, 1979; Busch and Rollins, 1984). In a crude sense, the subsequences mark out lowstand, transgressive, early highstand, and late highstand systems tracts (see Van Wagoner et al., 1988). Sequences and subsequences are distinctive in having sharp bases at which typically shallower water deposits are juxtaposed over deeper water sediments of the stratal package. These boundaries may be nearly conformable or may be regionally angular unconformities.

In turn, the subsequences are made up of smaller-scale subdivisions that correspond approximately with submembers or even beds in the lithostratigraphic terminology. Each subsequence is divisible into two to three minor regressive, transgressive or shallowing, deepening cycles that may be nearly symmetrical to markedly asymmetrical nature. These parasequence sets, apparently represent 5th order cycles or cyclothems (Bush and Rollins, 1984; Heckel, 1986).

The smallest scale subdivisions of the 5th order cycles tend to be more numerous (typically three to five per cyclothem) and most commonly show an asymmetrical shallowing-upward pattern, in contrast to the larger scales of cyclicity. These correspond to PACs or <u>6th order</u> cycles (Goodwin and Anderson, 1985).

In the following sections we describe the six major sequences and then discuss broader implications of the stratigraphic patterns and processes.

Sequence I: Medina Group

The first sequence nearly overlaps with traditional definitions of the Medina Group in New York State and parts of Ontario and Ohio, and of the Tuscarora Sandstone in Pennsylvania (Cotter, 1982; Duke, 1987; Figs. 4-8). Its lower boundary coincides with the major Hirnantian unconformity that marks the Ordovician-Silurian contact over much of eastern North America. Dennison and Head (1975) labeled this erosion surface the Cherokee Unconformity and used it to subdivide Sloss' (1963) Tippecanoe Sequence into a lower "Creek" (Middle to Upper Ordovician) and an upper "Tutelo" succession (Silurian-Lower Devonian).

The Cherokee Unconformity is a gently north-westward sloping, nearly planar surface (Middleton et al., 1987). In the central Appalachians, the unconformity is manifest by the basal contact of the Tuscarora Formation on the Martinsburg Shale or the Juniata Formation (Cotter, 1983; Fig. 5).

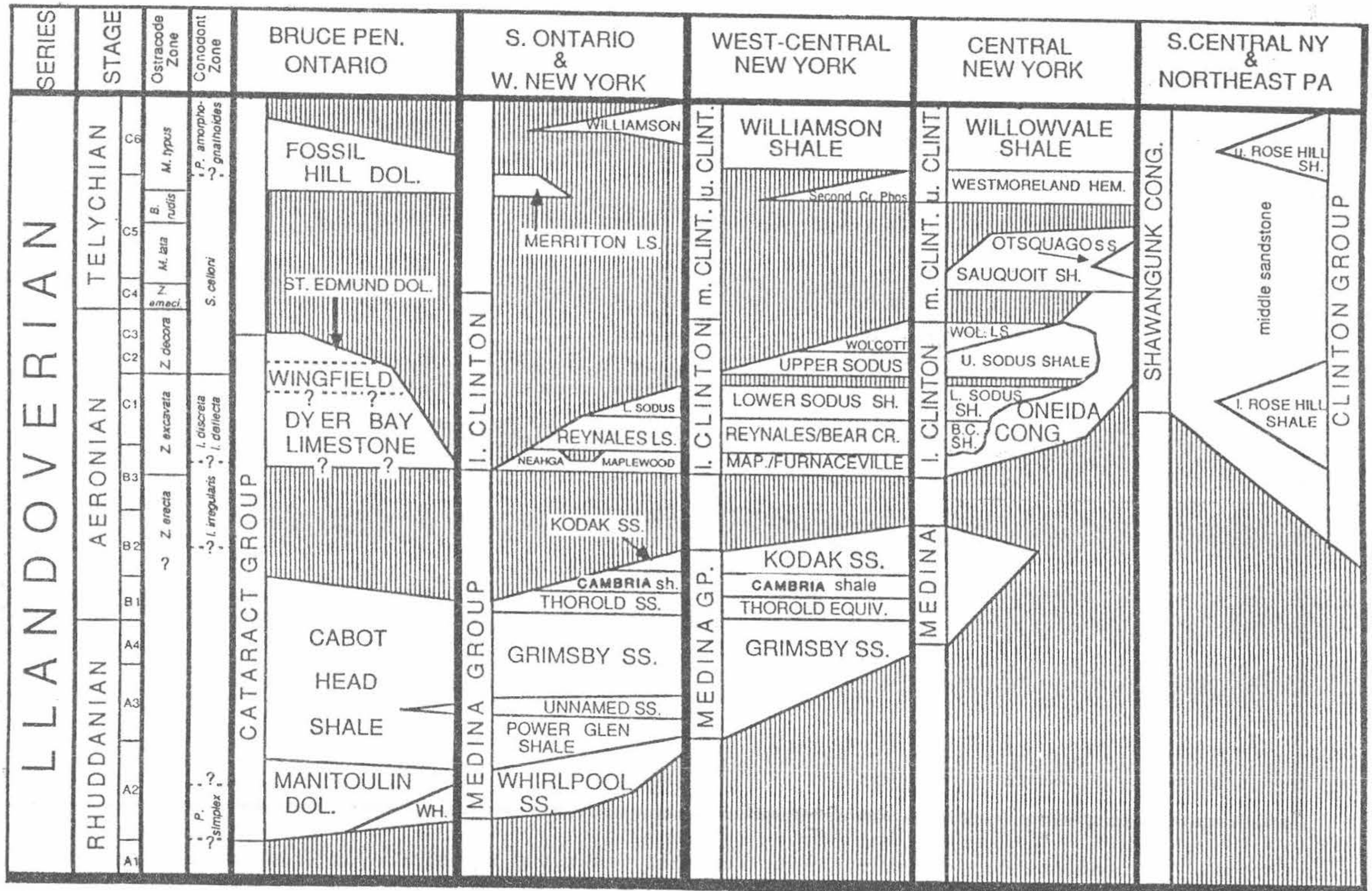


Figure 5. Chronostratigraphic correlations of Lower Silurian (Llandoverian) strata of sequences I and II in Ontario (Bruce Peninsula), western, central and eastern New York State. Vertical ruling indicates unconformities.

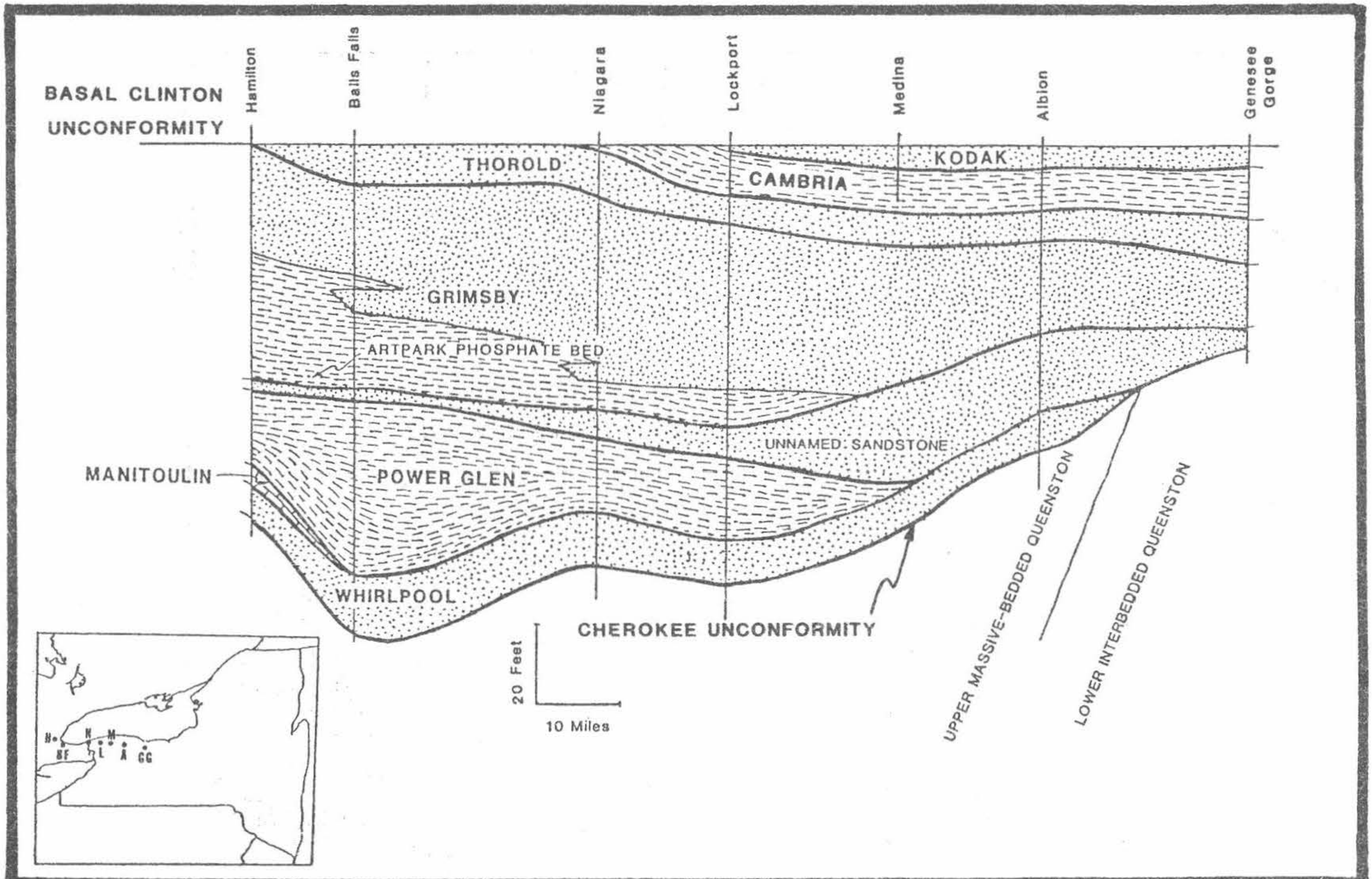


Figure 6. Regional cross-section of Medina Group (Sequence I) in western New York and southern Ontario. Note regional, eastward truncation of Ordovician units by basal Cherokee unconformity. Also note eastward pinching of lower Medina units (Whirlpool, Power Glen Formation) and somewhat complementary westward overstep of upper Medina units under regionally angular sequence I-II boundary unconformity.

In the central Appalachians the Cherokee Unconformity may not coincide precisely with the Ordovician-Silurian boundary. In New York State, the Cherokee Unconformity is a sharp surface under which occurs progressive eastward bevelling of Upper and Middle Ordovician strata (Queenston Shale downward to Frankfort or Schenectady Formation) and above which lie various Lower Silurian units.

The Cherokee Unconformity is nearly planar in New York and Ontario sections; i.e., a Type 2 unconformity (Van Wagoner et al, 1988). The unconformity surface may have been generated by the combined effects of a glacioeustatic regression and uplift along the tectonically active, southeastern basin margin. The Cherokee Unconformity has long been related to a major Late Ordovician sea-level lowstand caused by glaciation in North Africa (Dennsion and Head, 1975; Johnson, 1988). However, the geometry and magnitude the unconformity is not readily explained by sea-level change alone (Middleton et al., 1987). The angularity of the unconformity (Figs. 4-5) suggests that there must have been some tectonic rejuvenation of the Taconic Front in southeastern Pennsylvania late in the Ordovician or early in the Silurian as suggested by Quinlan and Beaumont (1984) and Tankard (1986).

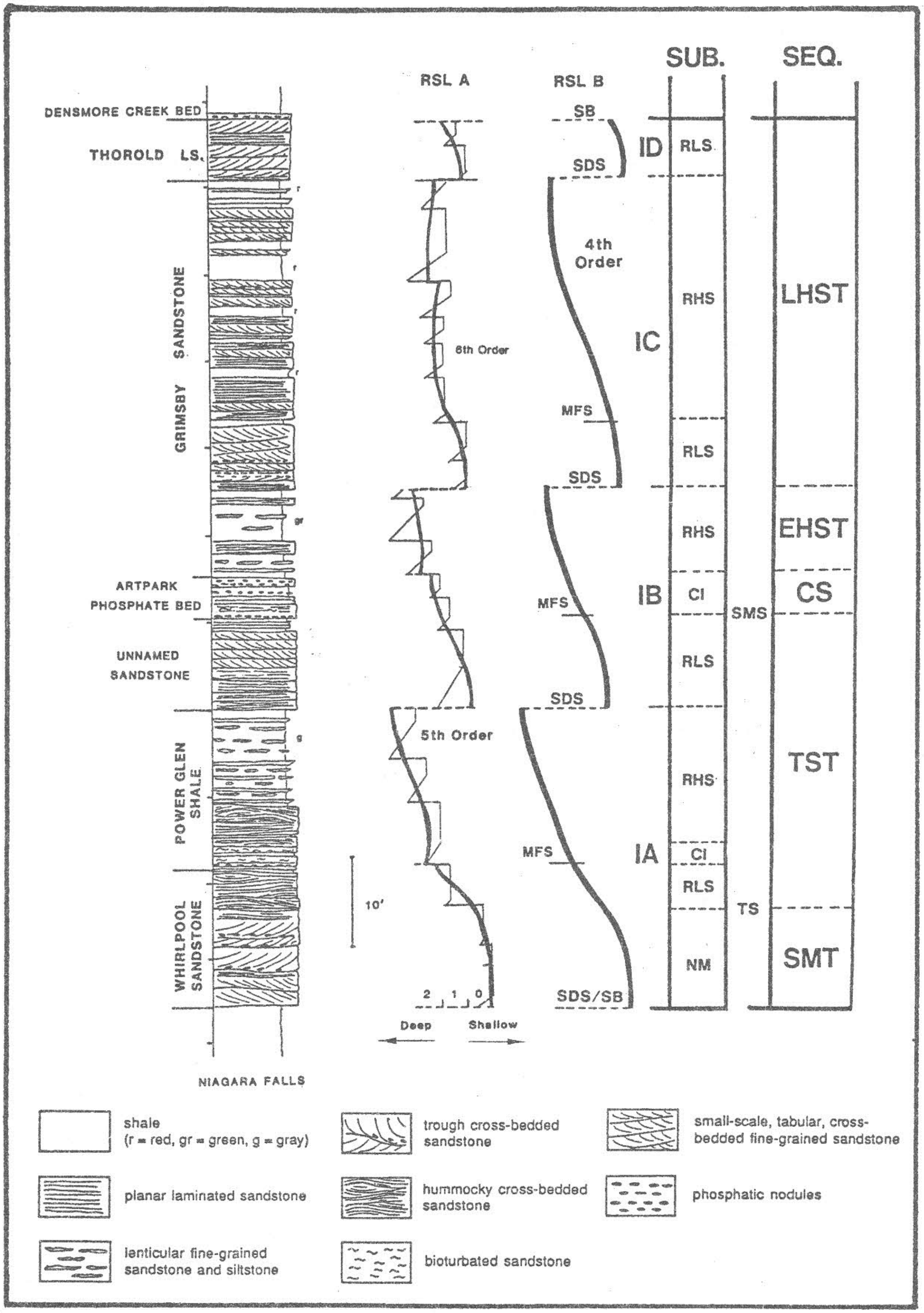
In western New York and the Niagara Peninsula of Ontario, the basal beds of Sequence I comprise the Whirlpool Sandstone, a relatively thin (5-8 meter) but widespread quartz arenite unit (Figs. 6, 7). Recent study of the Whirlpool by Middleton et al. (1987) demonstrates that the formation is subdivisible into two members; a lower unit of medium-grained, large-scale trough cross-bedded, white, quartzose sandstone which rests sharply on the underlying Late Ordovician Queenston red mudstones, and an upper lenticular bedded, fine-grained, white quartzose sandstone with green shale interbeds. Absence of marine indicators (fossil spores, but no acritarchs, A.J. Boucot, pers. comm., 1989) and consistent northwestward orientation of cross-beds led Middleton et al. (1987), to postulate a braided fluvial depositional setting for the lower member. This unit is inferred to represent a lowstand deposit (technically this is a "shelf margin systems tract" in the terminology of type 2 sequences; see Van Wagoner et al., 1988; but that term is entirely inappropriate here), that accumulated in a gently northeastward sloping braid plain prior to the major Early Silurian (Rhuddanian or early Aeronian (A-3 to B?) rise of sea-level (Johnson, 1988).

The upper 1-2 meters of the Whirlpool Sandstone display numerous indicators of deposition in shallow marine influenced environments. In some instances, green shale partings within trough cross-bedded sandstones near the top of the lower Whirlpool division contain Silurian marine acritarchs (M. Miller, unpubl. data) as well as reworked Ordovician palynomorphs. These occurrences suggest backfilling of relict tidal (?) channels during the initial sea-level rise. Macrofossils, including corals, lingulid brachiopods and echinoderms, and trace fossils have been noted in the upper Whirlpool beds of southwestern Ontario, In addition, the presence of hummocky cross-stratification (HCS) indicates deposition in shallow, storm-influenced shelf settings.

In eastern sections, the Whirlpool is separated from the heterolithic dark gray shale and tempestitic sandstone succession of the overlying lower Power Glen Formation, by a cryptic discontinuity (Figs. 7, 8). The discontinuity becomes more recognizable in a basinward (westward) direction. In the Niagara Peninsula the subtle discontinuity, marked by a thin (30 cm) calcareous, phosphatic, fossiliferous (crinoids, asteroids, brachiopods, bryozoans) sandstone, occurs at or near the top of the Whirlpool Formation. This bed appears to grade westward into the glauconitic top of the Manitoulin Dolomite, an argillaceous to arenaceous, fossiliferous carbonate with interbedded shales and hummocky cross-bedded siltstone/fine-grained sandstones. The Manitoulin contains a relatively diverse body and trace fossil assemblage, recording fully marine conditions. We interpret the Manitoulin and its correlative eastward condensed phosphatic beds as a signature of a relatively abrupt sea-level rise; the sea-level rise resulted in a brief period of siliciclastic sediment starvation during which the phosphatic pebble bed was generated on a marine-flooding surface (Fig. 7).

Figure 7. Lithostratigraphy, inferred relative sea level curve, and sequence terminology for the Medina Group (Sequence I) at Niagara Gorge, Lewiston, New York. RSL-A = relative sea level curve for higher lower order cycles; 6th order = small scale, shallowing upward cycles, thin line; 5th order, larger scale, subsymmetrical to upward deepening cycles of member scale; scale calibrated on fossil benthic assemblages. 0 = non-marine; 1 = benthic assemblage-1, lingulid and trace fossil community; 2 = benthic assemblage-2; fully marine shallow shelf fauna. RSL-B = relative sea level curve for large scale fourth order cycles, generally asymmetrical upward deepening cycles of subgroup scale.

Bars on right side of figure indicate subdivisions of subsequences (SS; left bar) and for systems tracts the sequence as a whole (SEQ; right bar). Abbreviations for subsequences: NM = non-marine lowstand deposit; RLS = relative lowstand (shallow marine deposit); RHS = relative highstand; MFS = marine flooding surface; SDS = sealevel drop surface; CI = condensed interval. For sequences SMT = shelf margin systems tract (lowstand deposit); TST = transgressive systems tract; MFS = marine flooding surface; CS = condensed section; EHS = early highstand; LHS = late highstand; SB = sequence boundary; TS = transgressive surface.



DENSMORE CREEK BED
THOROLD LS.
GRIMSBY SANDSTONE
ARTPARK PHOSPHATE BED
UNNAMED SANDSTONE
POWER GLEN SHALE
WHIRLPOOL SANDSTONE
NIAGARA FALLS
10'
RSL A
6th Order
5th Order
2 1 0
Deep
Shallow
RSL B
SB
SDS
4th Order
MFS
SDS
MFS
SDS
MFS
SDS/SB
SUB.
ID
IC
IB
IA
RLS
RHS
RLS
RHS
CI
RLS
RHS
CI
RLS
NM
SMS
TS
SEQ.
LHST
EHST
CS
TST
SMT
shale (r = red, gr = green, g = gray)
trough cross-bedded sandstone
small-scale, tabular, cross-bedded fine-grained sandstone
planar laminated sandstone
hummocky cross-bedded sandstone
phosphatic nodules
lenticular fine-grained sandstone and siltstone
bioturbated sandstone

The overlying beds (basal Power Glen dark shales, in New York and lower Cabot Head Shale in Ontario) reflect a time of maximum marine flooding and may represent the base of a highstand systems tract. The Power Glen contains offshore dysaerobic to aerobic marine muds with scarce to diverse faunas, and in the eastern, more proximal facies, thin siltstones, gutter casts and other indicators of storm deposition (Duke and Fawcett, 1987, in press; Duke et al., 1987).

The Power Glen-Lower Cabot Head succession is composed of at least two upward-coarsening, shale-sandstone cycles (parasequences). The top of the upper cycle is abruptly overlain by a prominent 2-3 m thick quartzose sandstone in western New York (= Devils Hole sandstone of Duke et al., in prep.). Locally, the upper portion of this sandstone is calcareous (dolomitic) and contains abundant phosphatized fossils (bryozoans, gastropods) and pebbles. At some localities, this bed is hematitic. This horizon, the Artpark Phosphate Bed, appears to represent a major marine flooding surface (Figs. 6-8). Although the basal 1-2 m of the Grimsby are green, marine shales resembling the Cabot Head, Grimsby beds are mainly maroon shales, and red, pink and white mottled sandstones. Duke and Brusse (1987) have recognized at least five to six parasequence-scale (1-3 m) upward coarsening cycles within the Grimsby succession of western New York. More complete successions from the base upward, consist of thin, fossil rich (typically lingulid and rhynchonellid brachiopods, bivalves and bryozoans) sometimes phosphatic beds, overlain by a succession of maroon shales with thin to medium bedded sandstones with hummocky cross stratification (HCS), and capped by almalgamated storm sandstones. In some parasequences the top beds are heavily bioturbated (*Arthrophycus*, *Daedalus*). At some localities, local channels filled with red sandstone may cut out upper parts of parasequences.

The Grimsby sequence is an overall shallowing succession considered to represent progradation of shallow, marine-tidal flat sands over marine muds (Martini, 1971; Duke and Fawcett, 1987). The shell rich phosphatic lags record minor marine flooding surfaces bounding parasequences. The shallowing trend of the Grimsby Formation culminates in a maximally regressive, laterally extensive sheet sandstone, the Thorold Formation. Thorold facies range from proximal, red, moderately to heavily bioturbated, tidal channel sandstones to fully subtidal interbedded white sandstones exhibiting ball and pillow structures and thin green silty shales.

The upper part (supra-Thorold) of the Medina Group is a slightly more marine influenced, 2-3 m thick red and green shale with abundant leperditian ostracodes; we refer to this shale, informally as the Cambria Member for the exposure along Lockport Junction Road on the eastern townline of Cambria, New York (STOP 2A; Fig. 8). The shale is capped by a second, widespread, heavily bioturbated quartzose sandstone, the Kodak Formation. The distal (westward) end of this sequence is truncated by the upper bounding

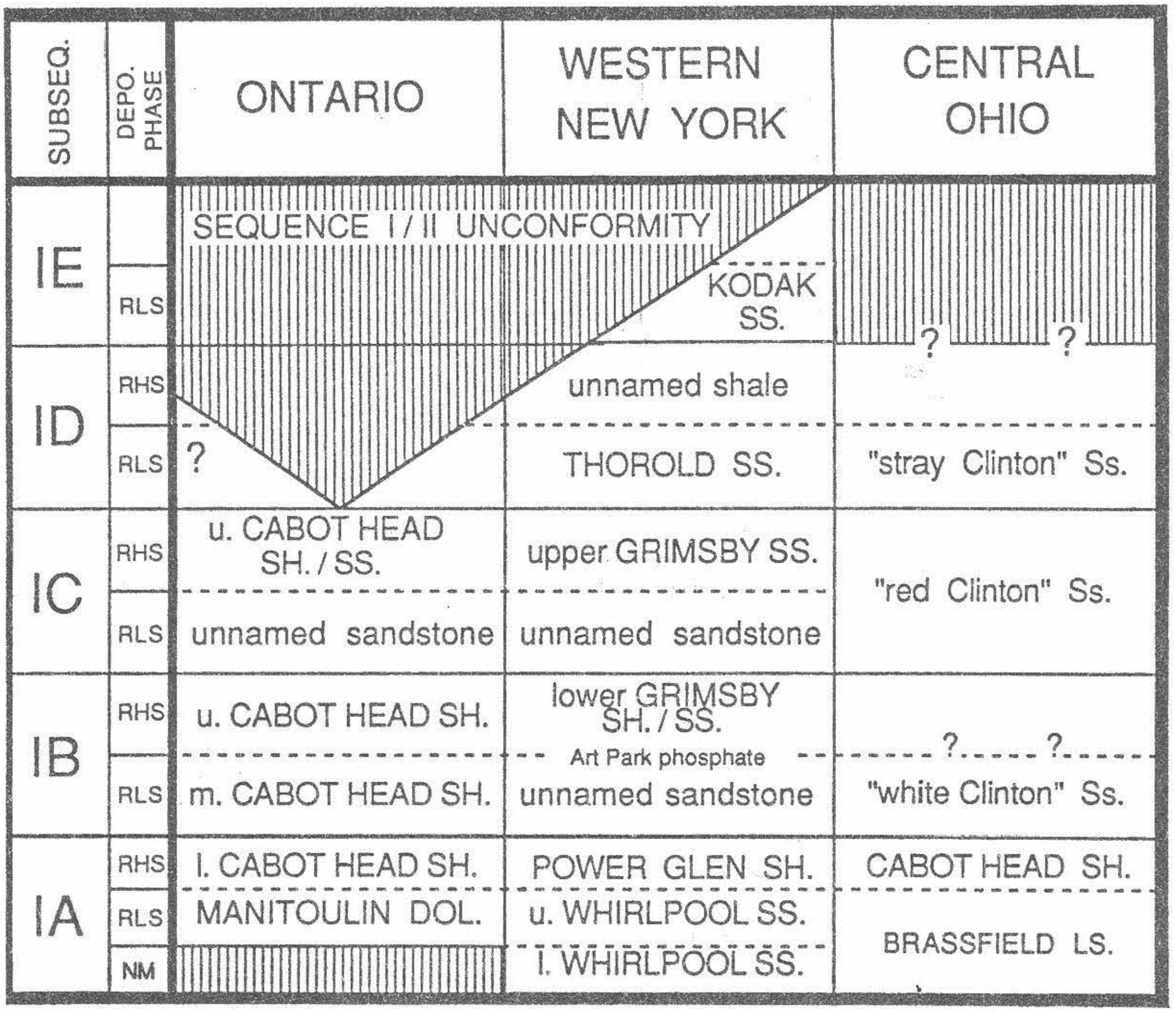


Figure 8. Summary chart of subsequence interpretation of the Medina Group (sequence I) in Ontario, western New York and Ohio. Units IA-IE are considered to represent subsequences. Subsequence terminology, as in Figure 4. Vertical scale does not represent thickness but estimated temporal duration of units.

unconformity of Sequence I. However, the proximal facies are preserved in the Rochester, New York area, and record the easternmost incursion of marginal marine faunas in the Medina Group.

Sequence II: Lower Clinton Group

Although the Clinton Group has long been accepted as a useful stratigraphic subdivision of the medial Silurian in eastern North America, it is now evident that this unit is actually an amalgam of parts of four distinct sequences. Thus, we informally divide the Clinton into lower, middle, and upper Clinton units, approximately following the usage of Gillette (1947).

As defined herein, the lower Clinton constitutes a genetic, unconformity-bound sequence of strata ranging from the Maplewood-Neahga Shale (or equivalent Furnaceville Hematite) to the top of the Wolcott Limestone in the western and central New York sections (Fig. 4).

Sequence II is bounded at its base by a nearly planar (type 2), unconformity that is a very low angle regional truncation surface. Successively lower beds of the Medina Group are beveled in a westward direction, starting at least in the Rochester area, as described in the previous section. As such, this unconformity has the opposite sense of truncation from the major Cherokee Unconformity. Because only a few meters of Medina Group shales and sandstones are removed at this surface, the temporal magnitude of the sequence II bounding unconformity is thought to be relatively slight, no more than one or two ostracode zones. Nonetheless, this surface is considered to be significant in that it truncates strata and separates distinct, genetically related packages, the Lower Clinton above and the Medina below. In the Ontario and western New York sections, the upper boundary of sequence II is a more prominent truncation surface underlying the Llandoverian C-6 Williamson-Willowvale shales and their correlatives (see below).

The basal boundary of sequence II is clearly demarcated by a thin (1-10 cm) but regionally extensive phosphate pebble horizon designated the Densmore Creek Phosphate Bed (Brett et al., in prep.) for good exposures on Densmore Creek, near Rochester. The bed can be traced from Wayne County, New York, west to near St. Catharines, Ontario. Phosphatic steinkerns, including those of gastropods and brachiopods (Eocoelia, Hyattidina, and Leptaena), indicate a shallow marine, but sediment starved setting. Locally, this unit contains Trypanites bored clasts up to 10 cm across, of phosphatic, fossiliferous pelletal packstone and grainstone.

In Niagara County, the Densmore Creek Phosphate Bed forms the base of the Maplewood - Neahga Shale. The Neahga Shale, a 0.5 to 4 m dark gray, fissile shale, crops out from near St. Catharines, Ontario to Lockport, New York. The Neahga thins to near pinch out along a narrow NE-SW belt in Niagara County (Fig.

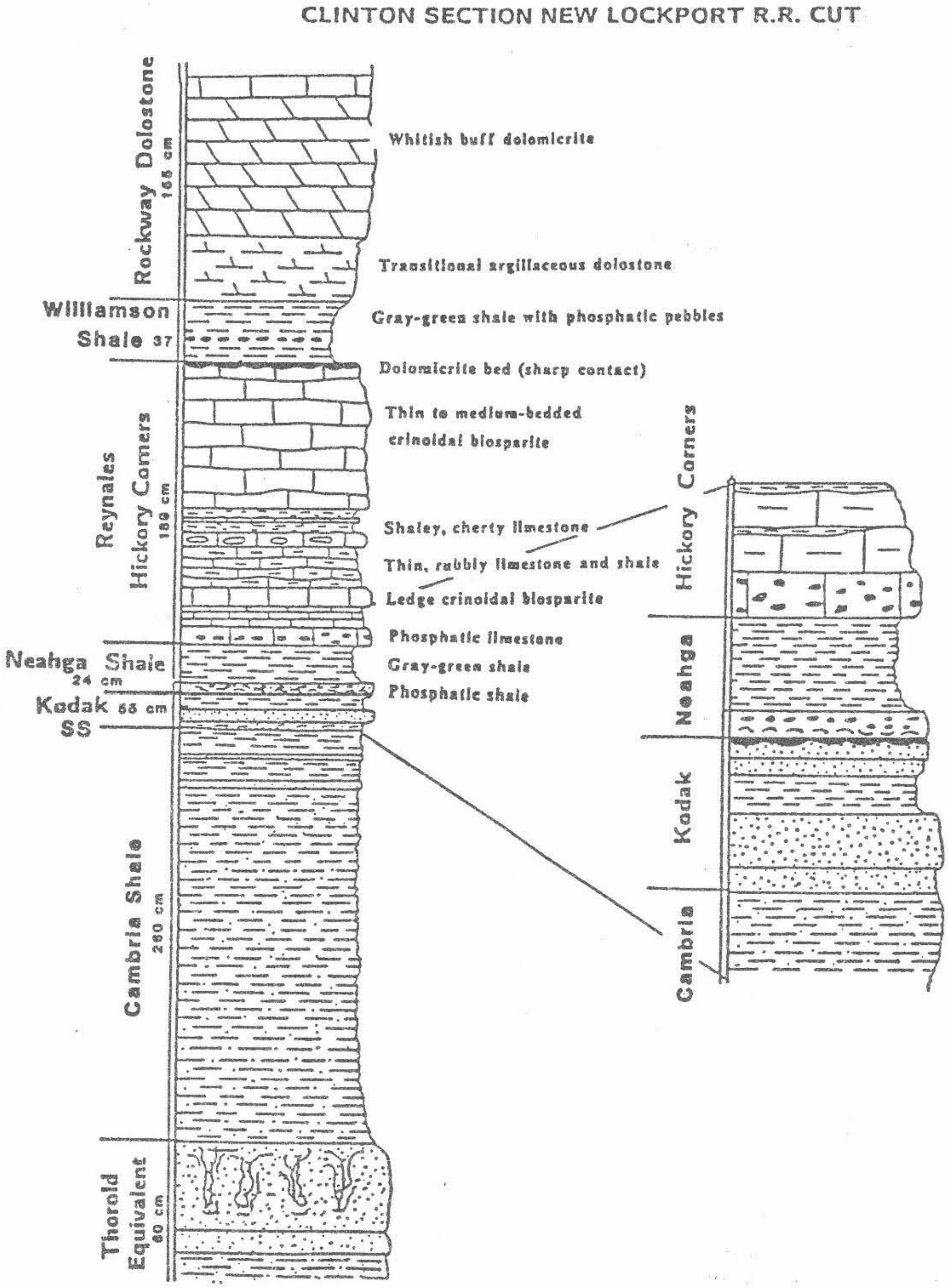


Figure 9. Stratigraphic section for uppermost Medina, lower Clinton, and base of upper Clinton.

10). Eastward of this region (approximately at Lockport, New York in the outcrop belt), the slightly lighter colored but equivalent beds are referred to as the Maplewood Shale. The Maplewood ranges up to 6 m in thickness near Rochester, but pinches out within 8 km in eastern Monroe county. This pinch-out, which trends approximately northeast to southwest, can be traced in the subsurface at least to Chatauqua County (Van Tyne, 1966). The Densmore Creek bed and a minor phosphatic limestone bed (Budd Road Bed, Brett et al., in prep.) above the top of the Maplewood merge as the Maplewood pinches out (Fig. 10). At this point, the composite phosphate bed becomes thicker (up to 30 cm), hematitic, and is referred to as the Furnaceville Iron Ore, a unit that contains multigenerational phosphatic conglomerates (LoDuca, 1988; LoDuca and Brett, 1990). Further east the Furnaceville merges into a thin quartz pebble conglomerate, the Oneida Formation.

The Densmore Creek Bed and the correlative Furnaceville Hematite are considered to represent sediment starved conditions associated with the initial transgression that initiates sequence II. The presence of an Eocoelia biofacies both within the shale and in the phosphate-hematite beds suggests a shallow subtidal (BA-2) setting.

Internally, sequence II is subdivided into two major (5 to 20m) sharply based stratal packages comprising shale to carbonate successions that appear to constitute upward-deepening fourth order cycles or subsequences, the Neahga (Maplewood Shale) to Reynales Limestone, and the Sodus Shale to Wolcott Limestone (Fig. 9). These stratal packages, in turn, are subdivisible into thin (1 to 6 m) but internally complex and condensed members that may be approximately analogous to fifth order cycles (Busch and Rollins, 1984); they also display deepening upward trends. These are, in ascending order: 1) the Maplewood/Neahga; 2) the Brewer Dock Member of the Reynales Formation, including the Seneca Park Hematite (Fig. 10); 3) the Wallington Member of the Reynales Formation(these three together forming the first fourth order cycle); 4) the Lower Sodus Shale; 5) the Upper Sodus Shale; 6) the Wolcott Limestone (together forming the second fourth order cycle). The base of each of these units is sharp, and, in some instances, demarcated by a very thin, phosphatic sandy horizon that appears to record an interval of sediment bypass and starvation associated with the onset of renewed transgression (LoDuca, 1988; LoDuca and Brett, 1990).

Only portions of the lower two formations (5th order cycles; parts of the 4th order subsequence III) are present in Niagara County, due to erosion at the top of sequence II (Figs. 9, 10). The basal unit, the Neahga Shale, consists of 0.5-2.0 m of dark gray, fissile shale dominated and contains a sparse Eocoelia biofacies. The Densmore Creek bed at the base of the Neahga shale also marks the transgressive surface of the Sequence II, as a whole.

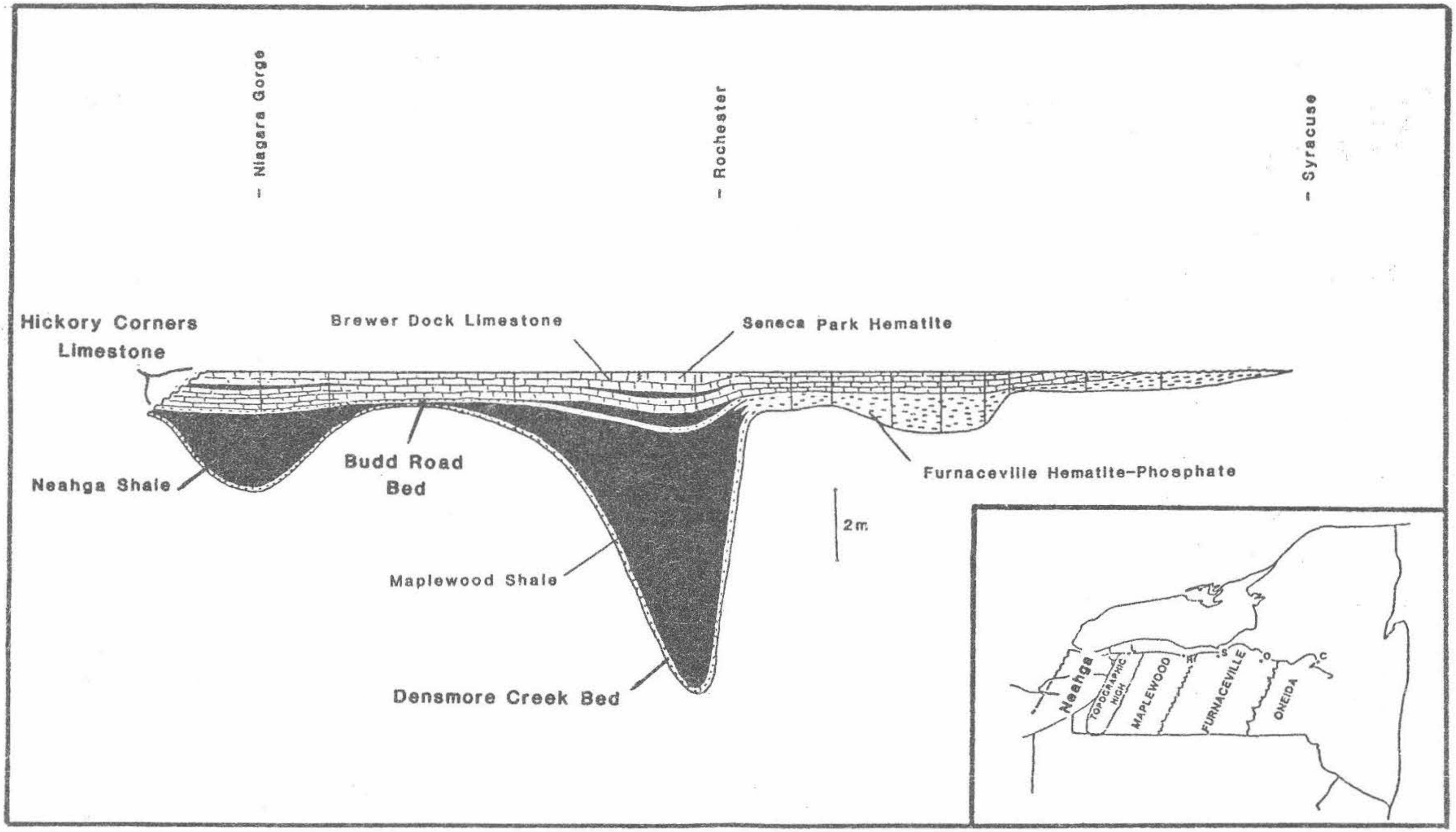


Figure 10. Regional east-west cross section of the basal units of Sequence II (lower Clinton Group) between Syracuse, New York and St. Catharines, Ontario. Note presence of two minor depocenters (for the Neahga and Maplewood shales, respectively) separated by a minor arch region; also note eastward passage of shales into highly condensed hematite and phosphate-bearing conglomerate (Furnaceville). Small inset map shows approximate orientation of extreme condensation and/or pinchout areas. West of Niagara County, the Neahga Shale is truncated by the major (sequence bounding) late Llandoverian unconformity.

The next 5th order cycle, as noted above, is demarcated at its base by a another thin phosphate pebble horizon designated the Budd Road Bed (Brett et al., in prep.). Overlying this bed are thin interbedded silty carbonates (greenish gray shale) of the Brewer Dock Member of the Reynales Formation. This cycle is capped by a thin (< 1m) crinoid/bryozoan rich, cross bedded unit which is locally hematitic (Fig. 10). A discontinuity may separate this cycle from the next based on conodont biostratigraphy (Kleffner, pers. comm., 1989), but does not appear to be substantiated by other zonations.

The third 5th order cycle, corresponding to the Wallington Limestone Member, begins abruptly with thin (< 0.5 m) green Eocoelia-bearing shales and passes upward into heterolithic argillaceous silty carbonates and shales. In western New York, the Wallington-equivalent beds are mainly crinoidal packstones and grainstones. In the Niagara region the Brewer Dock and truncated lower Wallington equivalents are difficult to distinguish and have, together, been termed the Hickory Corners Member (Kilgour, 1963). However, there still appears to be some justification for recognizing the two members.

It should be noted that, in most cases, only the eastern more proximal facies of lower Clinton sequence cycles are preserved. The western presumably deeper water facies have been removed in the New York - Ontario outcrop belt due to the major Late Llandoverian erosion surface that forms an upper boundary to sequence II. Sequence II is completely absent in the outcrop belt between Grimsby, Ontario and Owen Sound, (Fig. 11) Ontario where Sequence IV carbonates (Merriton - Fossil Hill) immediatly overlie the Medina Group (see below).

Sequence III: Middle Clinton Group

Sequence III is composed of the Sauquoit - Otsquago Formations in Central New York State, a 40 m-thick succession of greenish gray shales, with thin sandstone and conglomerate layers, which outcrops sporadically from near Cayuga to Madison County. No strata belonging to this sequence occur in western New York or Ontario.

Sequence IV: Basal Upper Clinton Group

The fourth major unconformity-bounded stratal package constitutes the upper portion of the Clinton Group as presently defined. In the axial portions of the Appalachian Basin, Sequence IV is a heterolithic, siliciclastic-dominated succession comprising the Williamson-Willowvale and Dawes-upper Rose Hill Formations (Figs. 4, 5, 11). This sequence contains the deepest water deposits in the Silurian succession of the Appalachian Basin. In the vicinity of the Algonquin-Cincinnati Arch, Sequence IV is dominantly dolomitic carbonates.

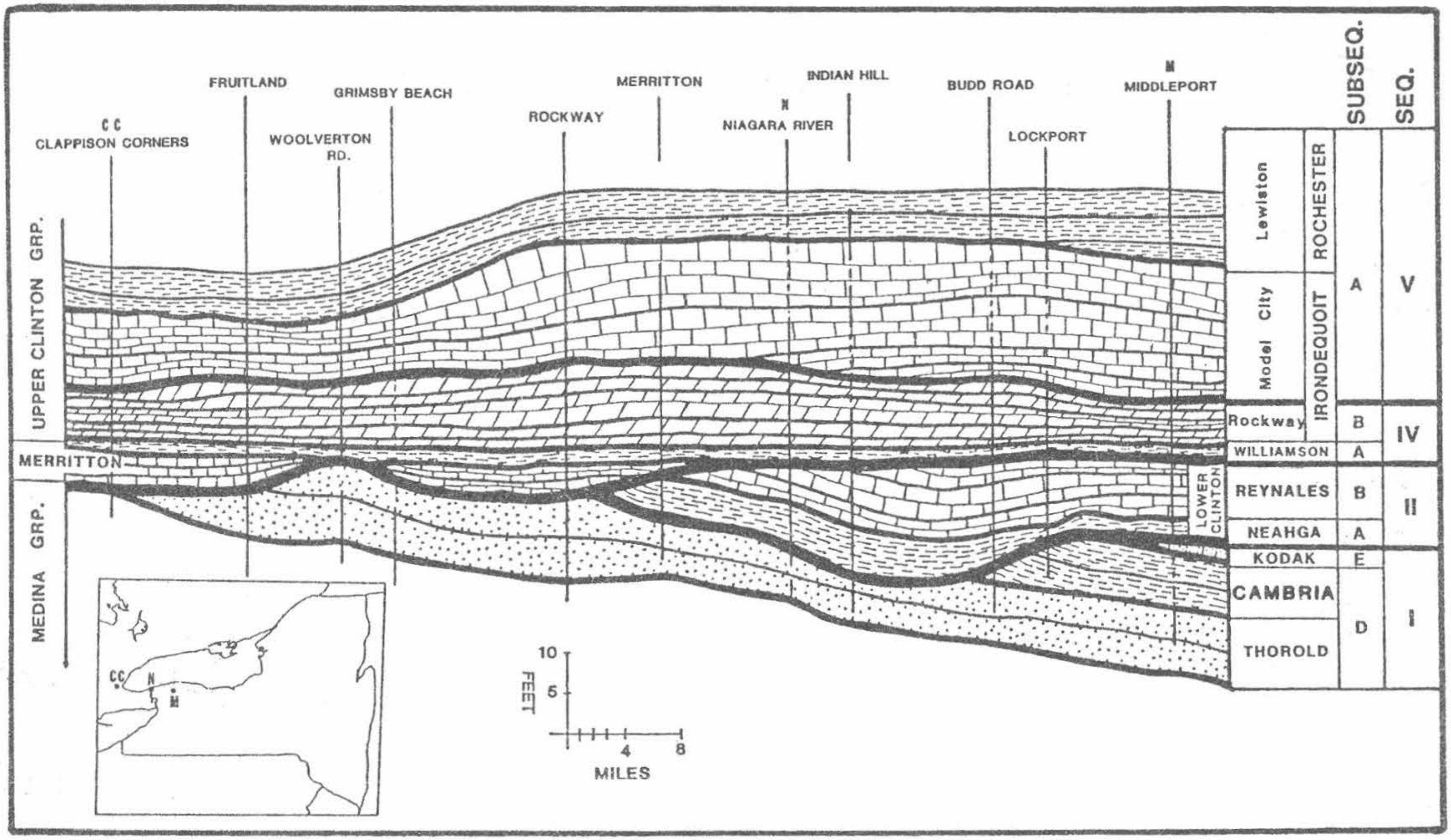


Figure 11. Regional cross section of upper Medina (sequence I), lower Clinton (sequence II) and upper Clinton (sequences IV and V) through western New York and Ontario outcrops (see inset map). Note convergence of two basal sequence boundaries (basal II and basal sequence IV unconformities) near the town of Merritton due to overstep of sequence II, and the insertion of a new unit (Merritton Limestone) apparently in the position of the Williamson Shale between the Niagara River and the Merritton outcrops. Also note beveling of upper Medina (sequence I) units beneath basal Clinton (sequence II) erosion surface east of Rockway and by combined sequence II - IV (and possibly III) erosion surfaces to the west. Modified from Kilgour (1963).

Sequence IV overlies the regionally angular, type 2 unconformity that truncates nearly the entirety of Sequences II and III between Syracuse, N.Y. and St. Catharines, Ontario. Details of this regional angular unconformity are described by Lin and Brett (1988). Subcropping units include (from east to west) the Sauquoit, Wolcott Furnace, Wolcott, Upper Sodus (Wayne County), Lower Sodus (near Rochester, N.Y.), Wallington, Brewer Dock (Niagara Gorge) and finally, the Neahga Shale (near St. Catharines, Ontario). The strike of the regional angular unconformity is approximately N30E (Fig. 12).

Between Grimsby and Owen Sound, Ontario, Sequence II is missing entirely. In this area, Sequence IV carbonates (Merritton-Fossil Hill) immediately overlie the Medina Group. In essence, the bounding unconformities of Sequence II, III and IV merge into a single unconformity atop the upper surface of the Thorold Sandstone and, north of Hamilton, Ontario, on the upper Cabot Head Formation (Grimsby equivalent) (Sequence I).

In the Bruce Penninsula, north of Owen Sound, Ontario, the two unconformities again splay apart as a wedge of Sequence II (Dyer Bay-Wingfield-St. Edmund Formations) strata is interposed. Hence, a southward or southeastward beveling of Sequence II units is evident in the Bruce Penninsula, approaching the Algonquin Arch. This is the crude "mirror image" counterpart of the north to northwest truncation surface observed at the Sequence II-IV boundary unconformity in western New York and Ontario. Hence, the geometry of the unconformity delineates the position of the Algonquin Arch which separated the subsiding Michigan and Appalachian basin.

In the New York outcrop belt, westward from the type Clinton, New York area, a 1-10 cm bed rich in phosphatic and quartz pebbles and limestone clasts, named the Second Creek Phosphate Bed (Lin and Brett, 1988) overlies the unconformity. This bed yields conodonts indicative of the <u>amorphognathoides</u> Zone and is traceable for some 240 km from near Syracuse at least to Niagara Gorge. In west-central New York this bed forms the base of the black to green Williamson Shale. About 10 km west of Niagara Gorge, the Second Creek bed overlies a distinct unit that appears immediately above the bounding unconformity. This unit is a thin (50 cm), glauconite-rich, dolomitic limestone termed the Merritton Limestone (Kilgour, 1963; Fig. 13). Although this bed has yielded few diagnostic fossils, the brachiopod <u>Pentameroides</u>, rare conodonts and <u>Palaeocyclus</u> corals suggest a late Llandovery C-5 to C-6 age (Kilgour, 1963; Berry and Boncot, 1970; M. Kleffner, pers. comm., 1990). The Merritton, (commonly, but erroneously, termed "Reynales Limestone" in Ontario) passes laterally into somewhat thicker Fossil Hill carbonates near Orangeville, Ontario. The Fossil Hill Dolostone of definite C-6 age, overlies the major unconformity that truncates the St. Edmund-Wingfield-Dyer Bay succession (probable Sequence II) on the Bruce Penninsula. A lithologically similar, also glauconite-rich limestone, the Dayton Limestone, overlies the unconformity in south-central Ohio.

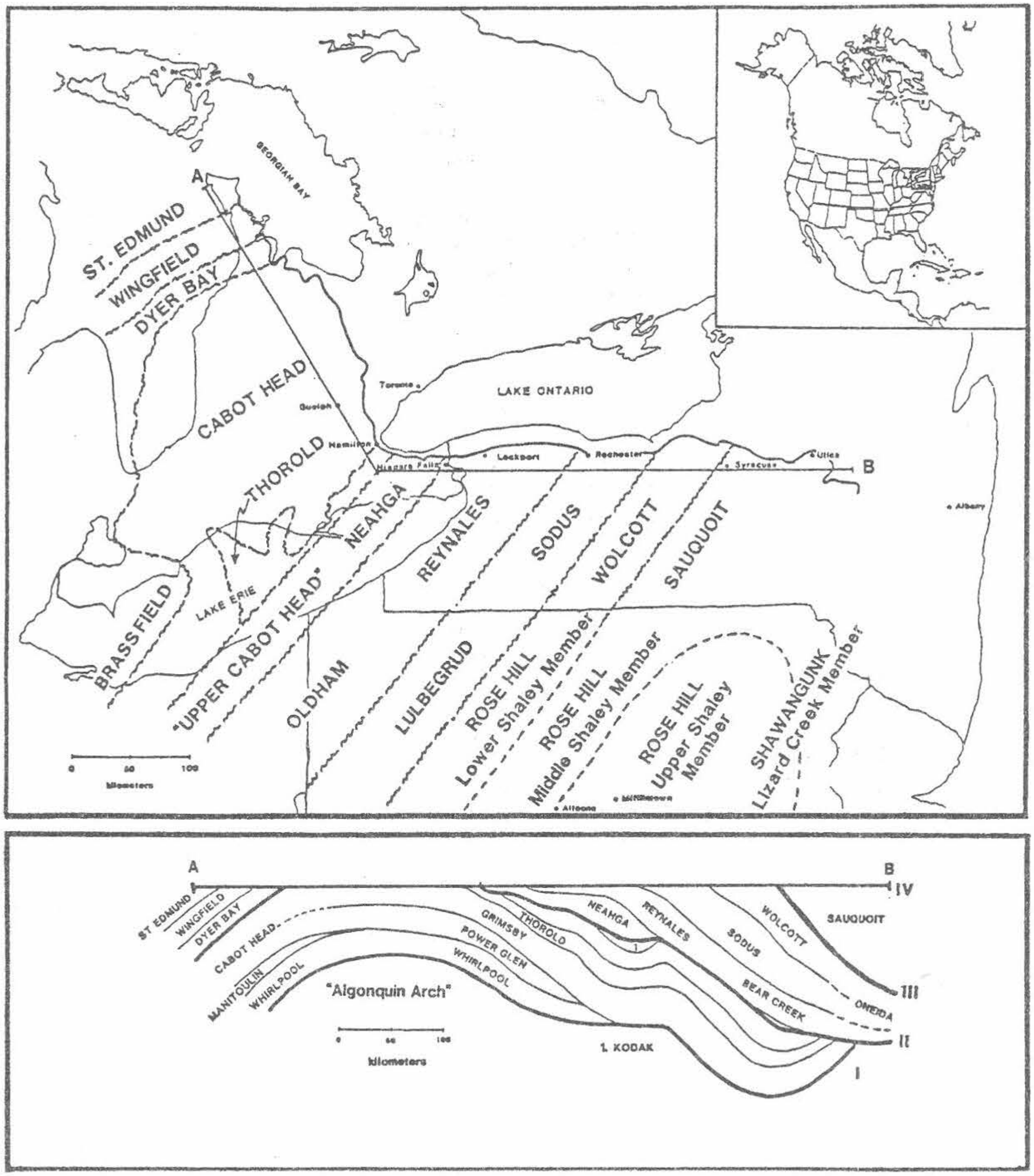


Figure 12. A) Subcrop map of beveled strata beneath Late Llandoverian (C6), Sequence IV unconformity. Line A-B shows location of cross sections shown in Fig. 12B. Subsurface data for Ontario from Winder and Sanford (1973); for New York and Ohio trends determined from data of Van Tyne (1966).

B) Schematic cross-sections along line A-B, indicated on map above. Note position of sequence I, II, and III basal bounding unconformities (labeled I, II, III): the II basal boundary displays beveling of underlying upper Medina units (Kodak, Thorold). Both sequence II and III boundaries are cross cut by the sequence IV basal erosion surface, shown as the horizontal upper line in cross section. Note regionally angular truncation surfaces on either side of region of maximum truncation - labeled "Algonquin Arch". Relative thicknesses of units on cross section are only approximate.

Where it is most typically developed in western New York and Ontario, the Sequence IV unconformity is the nearly planar but sharp contact between the Rockway Dolostone and the upper (Model City) Members of the Irondequoit Formation.

Overall, Sequence IV constitutes a large-scale (third order) symmetrical shallowing-deepening cycle. However, detailed investigation reveals that Sequence IV contains two very widespread (basin-wide) cycles (subsequences or 4th order cycles). The boundaries of these cycles correspond approximately to traditional formation and member contacts.

The first major cycle in sequence IV comprises the Williamson and eastern equivalent Willowvale shales; as noted above, this package commenses with the basal lag, condensed beds (Second Creek - Westmoreland) and passes upward into dark gray to black or greenish gray shale (Lin and Brett, 1988; Eckert and Brett, 1989). The entire Williamson-Willowvale interval remains rather uniformly thin over most of New York State but it pinches to a feather edge of green shale in Niagara County and adjacent Ontario. These muds accumulated during an early highstand when sea-level was near its highest point for the Silurian Appalachian Basin.

The overlying second subsequence is represented by the lower Irondequoit Formation (Rockway Member). The base of the Rockway is also marked by a widespread quartz granule-phosphate pebble bearing dolomitic wackestone, the Salmon Creek Bed (Lin and Brett, 1988) that appears to correlate westward with a diffuse zone of phosphatic nodules in the basal Rockway Dolostone of Ontario. This coarse-grained, condensed bed is, in many ways, analogous to the Second Creek horizon at the base of the Williamson Shale. In Ontario and western New York, the lower Rockway, is buff argillaceous dolostone with thin green shale; it contains abundant specimens of the large brachiopod Costistricklandia gaspensis and it thus belongs of an offshore (benthic assemblage 4) biofacies.

Sequence V: Upper Clinton Group

Sequence V comprises the bulk of the upper Clinton Group in the Niagara region (upper Irondequoit, Rochester Shale, DeCew Dolostone). This package is bounded at the base by the sharp lower contact of the upper Irondequoit Limestone (Model City Member). Although relatively little erosion occurred at this surface, the contact is sharp and displays an abrupt change from the relatively deep water shales and dolostones to crinoidal grainstone or sandstones. Furthermore, this is the local signature of a widespread low stand in sea level. Hence, we designate this surface as a sequence boundary.

The upper Clinton subsequences have recurrence intervals on the order of 1.0 m.y. and display a variety of internal motifs. There are three subsequences: 1) upper Irondequoit to Lewiston Mb.

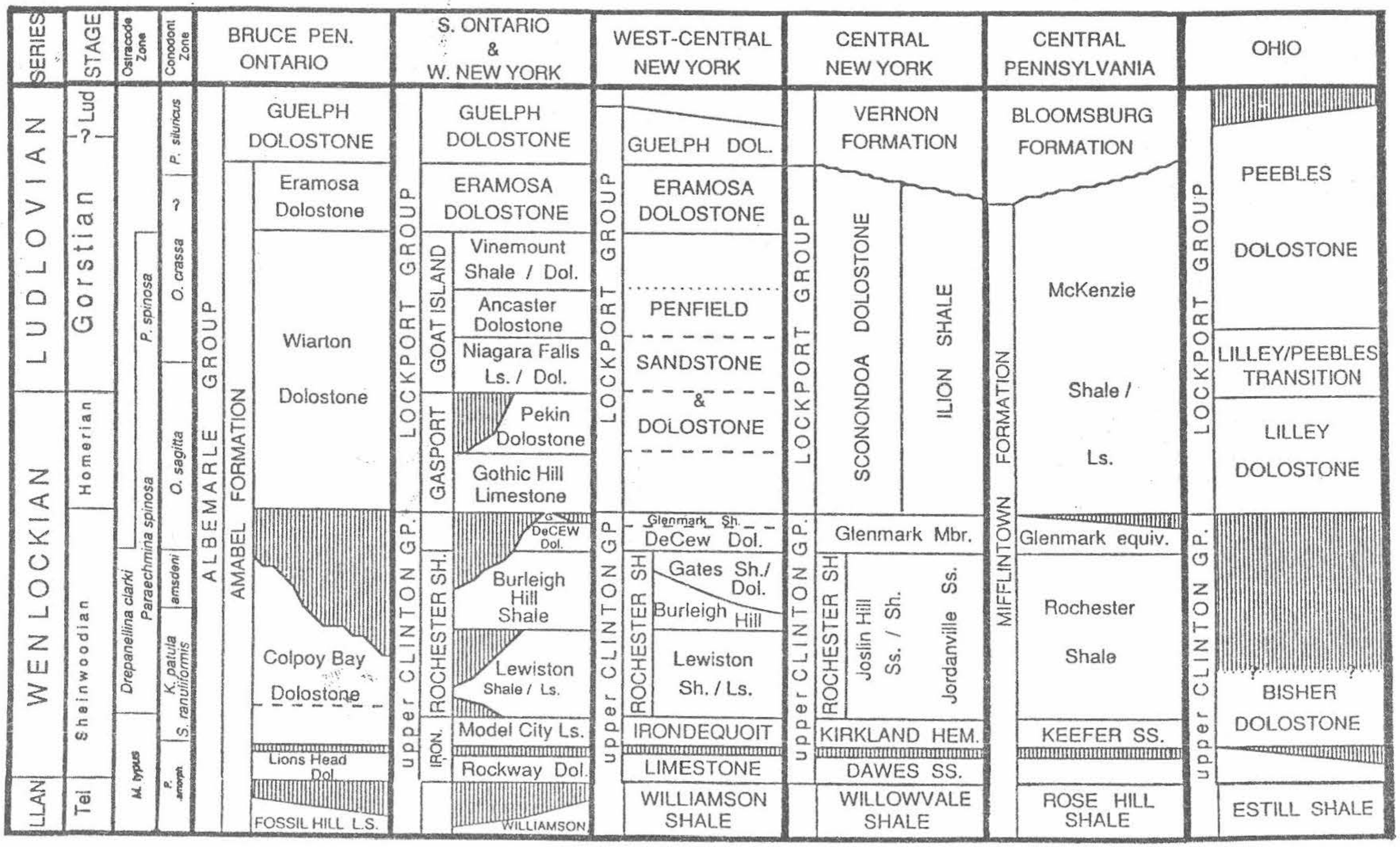


Figure 13. Chronostratigraphic correlation chart for units within the upper Clinton (sequences IV, V) and Lockport (sequences VI) groups, in Ontario, New York, Pennsylvania and Ohio. Formation names are listed in upper case, members in lower case.

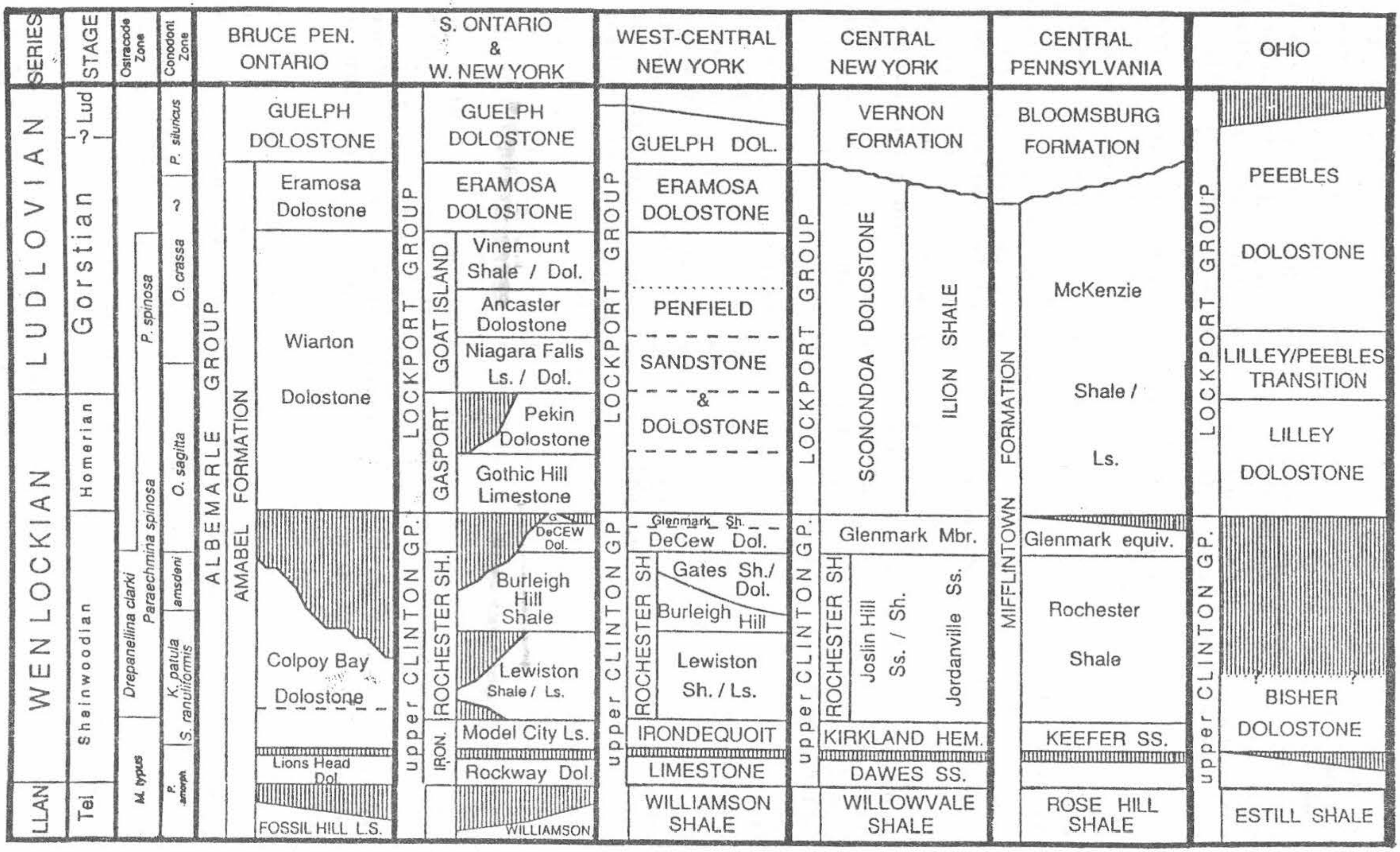


Figure 13. Chronostratigraphic correlation chart for units within the upper Clinton (sequences IV, V) and Lockport (sequences VI) groups, in Ontario, New York, Pennsylvania and Ohio. Formation names are listed in upper case, members in lower case.

of Rochester Shale; 2) upper Rochester Shale; 3) DeCew Dolostone - Glenmark Shale. In western New York and Ontario, each subsequence commenses rather abruptly with thin bryozoan and crinoid-rich pack and grainstones or calcisiltites that sharply overlie discontinuities on underlying mudstones. The crinoidal carbonates then pass upward into thin bedded to nodular wacke- and packstone carbonates and calcareous dark gray shales or mudstones (Fig. 15).

The upper Irondequoit displays facies that are everywhere shallower than those of the underlying Rockway beds and appears to mark a fairly major, albeit short-lived, sea-level lowstand of early Wenlockian age. The contact with the Rockway is sharp and is overlain by coarse crinoidal pack- to grainstone facies. Rip-up clasts, derived from the underlying fine-grained Rockway carbonates, are present locally within the basal 10-20 cm in western New York and Ontario. This bed is overlain by medium-bedded to massive, rarely cross-laminated crinoidal pack and grainstones. Near the basin center, at Rochester, New York, these beds grade upward into shaley brachiopod packstones and grainstones near the top of the Irondequoit which locally display small micritic bryozoan-algal bioherms. These structures, many of which are based on the top of a single coarse crinoidal grainstone horizon, may extend all the way through the upper Irondequoit and a short distance into the Rochester Shale. In Niagara County exposures, the entire Irondequoit is an amalgamated grainstone; this lower set of bioherms is absent, but comparable bioherms occur at or near the top of the Irondequoit in its transition to the Rochester Shale (Fig. 15). Evidently, upward growth of bioherms occurred in response to minor deepening events, a pattern also manifested in the higher Lockport section (= keep up carbonate pattern of Sarg, 1988; see below).

To the east, in the type Clinton area of New York, a similarly abrupt surface separates coarse grainstones of the Kirkland Hematite from the underlying hummocky cross-stratified calcareous sandstones of the Dawes Formation. Similarly, medium to coarse, hematitic, crinoidal, quartz arenites of the upper Keefer rest sharply on sandy shales of the Dawes equivalent (lower Keefer - upper Rose Hill) in Pennsylvania (Fig. 14). Hence, an episode of submarine non-deposition and minor erosion occurs circumbasinally in early Wenlockian time.

Crinoidal gravels and sands accumulated in shallow agitated skeletal shoals on the northwest rim of the basin, while clean quartz sands, possibly as a series of offshore sand ridges, accumulated on the southeastern margin. We suspect that these cannibalized shoreface sands were reworked during the early phases of sea level rise and the sharp surface beneath them may record a ravinement that modified a pre-existing surface of non-deposition and erosion.

In central New York State, the upward change from Irondequoit to Rochester Shale is gradational, but marked by a transitional, condensed, greenish, silty interval less than 1 m

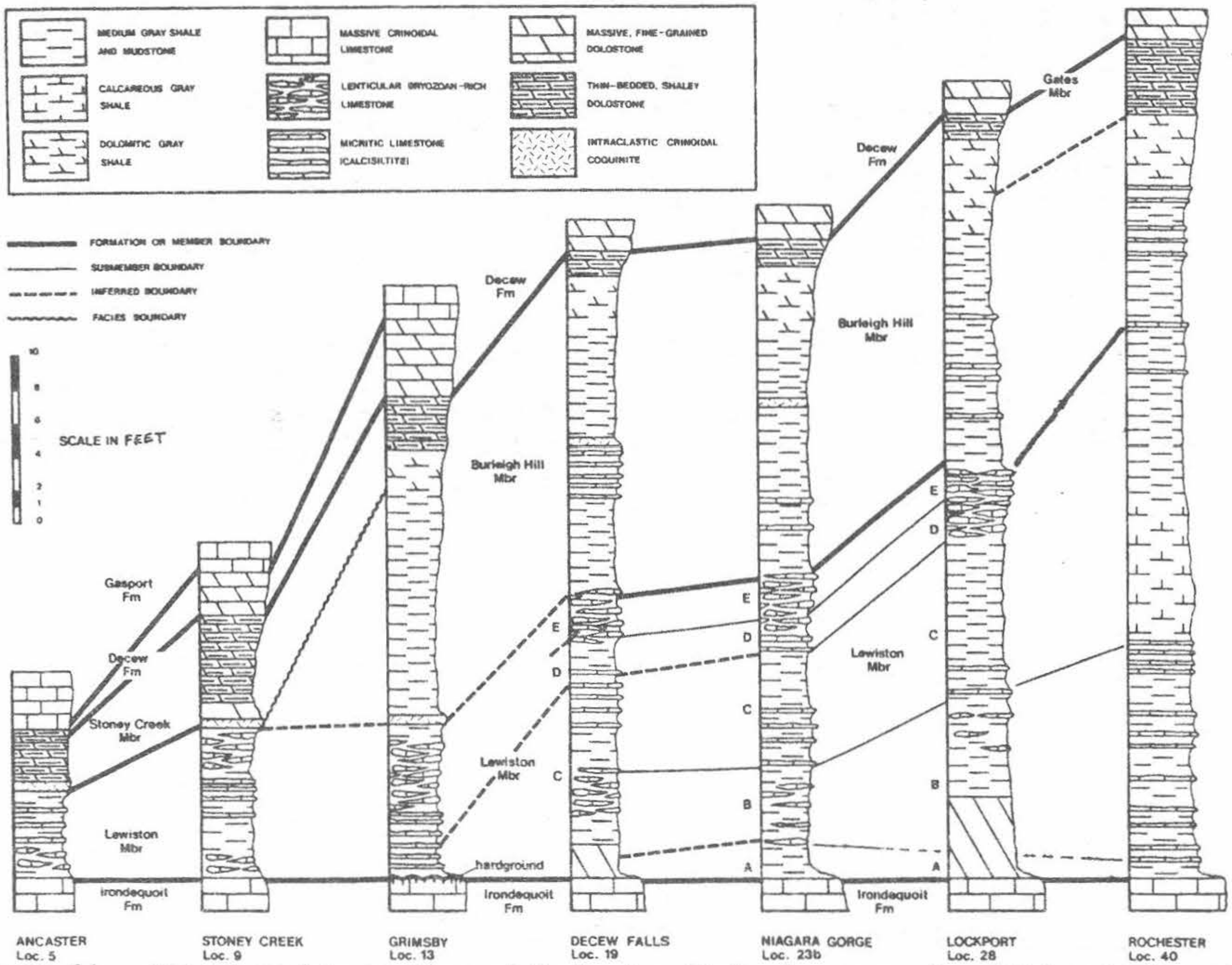


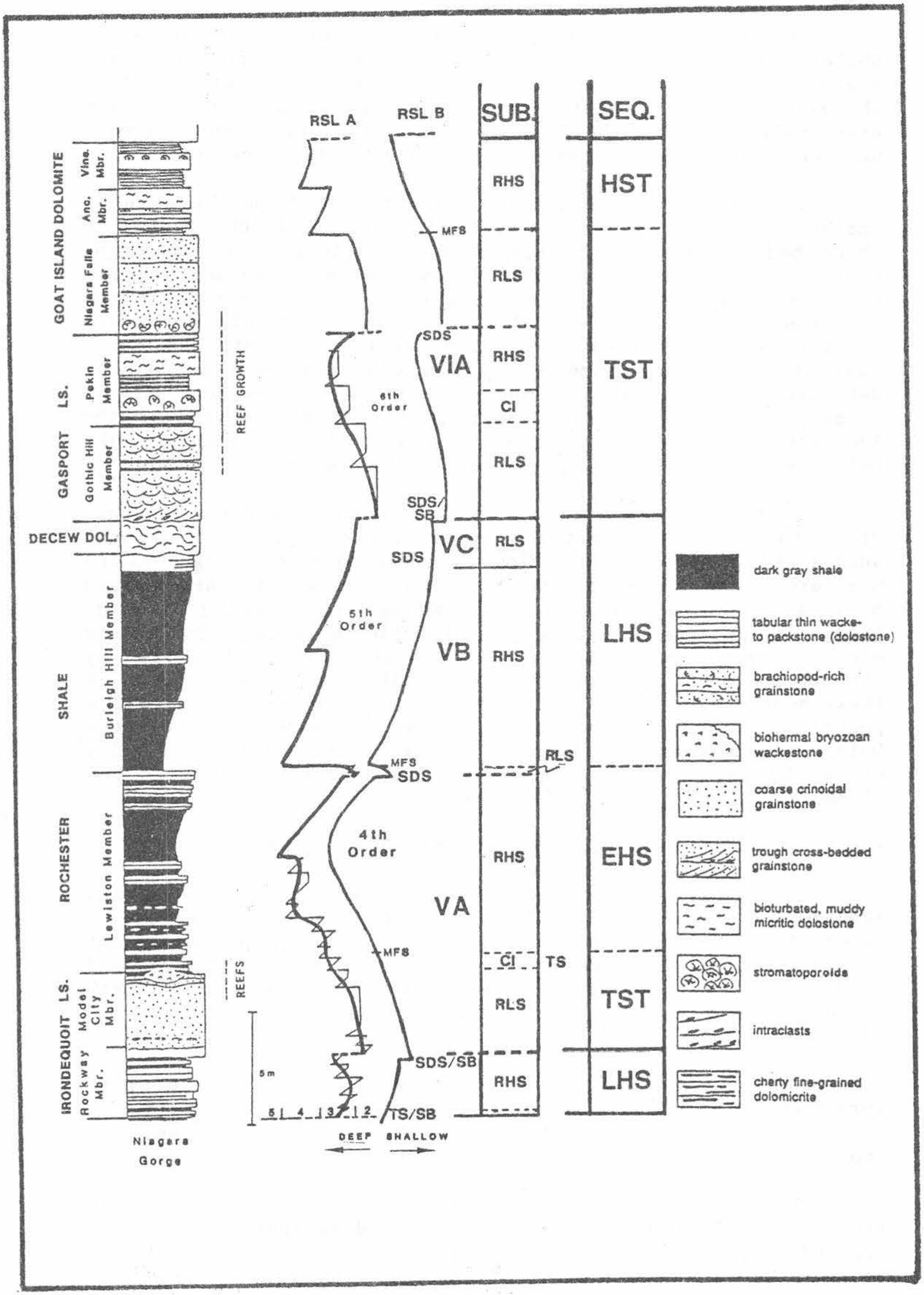
Figure 14. Stratigraphic section of Rochester Shale for seven localities in Ontario and western New York. Locations of numbered sections are shown in Figure 1. See Brett (1983) for descriptions of numbered localities.

thick. Bioherms from the Irondequoit commonly extend upward into this bed. Westward into Ontario, the top surface of the Irondequoit becomes a sharp and locally phosphate-impregnated hardground beneath the Rochester Shale. We infer that this sharp change upward to deeper water mudstones - siltstones of the Rochester Formation and the associated evidence for non-deposition and/or condensation records a marine flooding surface and probably also surface of maximum starvation.

Internally, the Rochester Shale is divisible into at least three cycles--corresponding to lower and upper submembers of the Lewiston Member and upper Burleigh Hill- Gates Members (Figs. 14, 15). The Lewiston Member displays two subsymmetrical cycles of upward decrease and increase in frequency of tempestites and in faunal diversity within the Lewiston Member; the central interval of nearly barren dark gray shale (Lewiston C) was inferred by Brett (1983) to represent deepest water conditions. The bundle of calcarenite beds at the top of the Lewiston Member (=E submember) represents a shallowing event. The sharply overlying Burleigh Hill -Gates Member records an abrupt return to dark mudstones comparable to Lewiston C and thus implies a second deepening event (Fig. 15).

The medial Rochester (Lewiston E) carbonates can be traced in the subsurface into eastern Ohio and western Pennsylvania. They occur, but are rather obscure, in the central Pennsylvania fold belt. In east central New York State, the top Lewiston carbonates appear to correlate with a westward extending tongue of coarse Herkimer Sandstone. Locally, this tongue displays a coarse phosphatic or hematitic lag on its upper surface. The sharpness of its basal contact with the lower Rochester in proximal sections and the hematitic character suggest that the Lewiston E marks the boundary of the upper Rochester subsequence.

Figure 15. Lithostratigraphy, inferred relative sea level, and sequence stratigraphic interpretation for upper Clinton and basal Lockport Groups (sequences IV, V, and basal VI) at Niagara River Gorge near Lewiston, New York. Note bases of three sequences labeled IV, V and VI, respectively; also note two zones of reef growth corresponding to early highstand (condensed) phases. Relative sea level curve calibrated to litho- and biofacies, as follows: 1 = pelmatozoan grainstone (inner BA-3); 3 = fossiliferous pack- and wackestone and calcareous (dolomitic) mudstone with diverse corals, bryozoans, pelmatozoans and brachiopods (outer BA-3 and BA-4); 4 = calcareous to dolomitic mudstone with diverse brachiopod (<u>Striispirifer</u> or <u>Costistricklandia</u>), bryozoan, pelmatozoan, and trilobite fauna (BA-4); 5 = nearly barren, dark mudstone or shale with low diversity brachiopod, trilobite or graptolite fauna (BA-5). For abbreviations, see Figure 7.



RSL A
RSL B
SUB.
SEQ.
GOAT ISLAND DOLOMITE
Vine. Mbr.
Anc. Mbr.
Niagara Falls Member
GASPORT LS.
Pekin Member
Gothic Hill Member
DECEW DOL.
SHALE
Burleigh Hill Member
ROCHESTER
Lewiston Member
IRONDEQUOIT LS.
Model City Mbr.
Rockway Mbr.
Niagara Gorge
REEF GROWTH
REEFS
5m
5 4 3 2
DEEP
SHALLOW
MFS
SDS
VIA
6th Order
SDS/SB
VC
5th Order
VB
MFS
SDS
4th Order
VA
MFS
SDS/SB
TS/SB
RHS
RLS
RHS
CI
RLS
RLS
RHS
RLS
RHS
CI
TS
RLS
RHS
HST
TST
LHS
EHS
TST
LHS
dark gray shale
tabular thin wacke- to packstone (dolostone)
brachiopod-rich grainstone
biohermal bryozoan wackestone
coarse crinoidal grainstone
trough cross-bedded grainstone
bioturbated, muddy micritic dolostone
stromatoporoids
intraclasts
cherty fine-grained dolomicrite

The overlying Burleigh Hill-Gates Member of the Rochester Shale displays an upward increase in tempestite frequency and coarse detrital carbonate (calcisiltite) indicative of a shallowing or progradational trend. The DeCew sharply and erosionally overlies the Rochester Shale in shallow shelf areas, but approaches relative conformity toward the basin center.

The DeCew Dolostone, which appears to form the base of another deepening upward cycle, is a 2 to 3 m thick, medium to thick bedded dolomititic pelsparite and calcisiltite containing beds of intraformational (storm rip-up) conglomerates and abundant hummocky cross-stratification. Its most notable feature is the occurrence of strong internal deformation, particularly in the lower beds. Overturned isoclinal folds (enterolithic structure) suggest submarine slumping. This distinctive 1-2m bed of deformation is traceable at least 150 km in the New York-Ontario outcrop belt and a similar calcisiltite bed at the top of the Rochester Shale in Pennsylvania displays similar deformation. The DeCew is tentatively interpreted as a seismite horizon.

In west-central New York the DeCew dolostone forms the base of a distinct 2 - 10 m-thick succession of uppermost Clinton shales and argillaceous brachiopod-rich carbonates, designated the Glenmark Member by Brett (1983b). This interval is characterized by a distinctive brachiopod assemblage (Howellella sp., H. bicostata, Nucleospira pisiformis, Whitfieldella marylandica) and minor thrombolitic horizons. Westward the unit is truncated by the sub-Lockport unconformity. A possible erosional remnant of these beds occurs at St. Catharines, Ontario where a local 2-3 m pod of shale and argillaceous limestone occurs between the DeCew Dolostone and overlying Lockport. The occurrence of Howellella cf. H. bicostata with corals suggests a correlation with the Glenmark Shales of central New York.

Sequence VI: Lockport Group-Vernon Shale

The sixth Silurian depositional sequence is an upward shallowing carbonate dominated succession, represented by heterolithic McKenzie Shales and limestone facies in the central Appalachians and the Lockport Dolostones in New York, Ontario and Ohio. The upper portion of the sequence comprises Bloomsburg-Vernon red and green siliciclastic mudstones (see Figs., 4, 16, 17).

Sequence VI spans the upper Wenlockian to Ludlovian interval. The exact position of the series boundary is the subject of ongoing study by LoDuca and Brett (in press); it apparently occurs low in the Lockport Group.

The lower boundary of sequence VI is demarcated by an erosion surface separating the Clinton and Lockport Groups, and located below the base of the Gasport Limestone in western New York. This flat, to gently undulatory, unconformity truncates part or all of the Glenmark, DeCew and Rochester Formations of the underlying Clinton Group (Sequence V). A correlative, but cryptic, discontinuity probably occurs within the Amabel Formation north of Hamilton, Ontario.

The top of Sequence VI is tentatively placed at a major truncation surface above the Vernon Shale in eastern New York State. This angular unconformity bevels Vernon-Ilion Shales (Lockport equivalent) and eventually all of Sequences V, IV and III in eastern New York. This is believed to represent an episode of uplift and erosion along the eastern basin margin associated with the Salinic Disturbance, as discussed under Geologic Setting.

The basal sequence VI erosion surface is overlain by a conglomeratic layer containing carbonate and mudstone clasts, frequently darkened by phosphatic or glauconitic impregnation, eroded from underlying beds (Fig. 16). These clasts occur at the base of thick-bedded to massive crinoidal grainstone belonging to the Gothic Hill Member of the Gasport Formation. The latter displays prominent trough and bidirectional cross-bedding indicating deposition on a tidally influenced shallow shelf. The unit locally varies in thickness form over 8m (25') to near zero within distances of 2-5 km and may have accumulated in a series of crinoidal ridges with intervening swales of minimal deposition. Near Rochester, New York, this unit is replaced by cross stratified, crinoid-bearing quartz arenites (Penfield dolomitic sandstone). Small tabulate coral-stromatoporoid bioherms occur within the carbonate grainstones in Niagara County. The lower Gasport grainstones grade upward into dark argillaceous dolostones (Pekin Member) with a sparse fauna. Locally bioherms up to 5 m high extend upward from the top of the grainstones into this upper argillaceous member. Hence, again, a deepening event is associated with upward growth of bioherms.

A second unit of pack- and grainstone, with a small stromatoporoid tabulate coral bioherm unit, occurs above the Gasport in the basal Niagara Falls Member of the Goat Island Formation. Again, there is a sharp contact on underlying Pekinargillaceous beds. The grainstones, like those of the Gothic Hill Member, are highly variable in thickness and pass upward into dark gray, cherty thin-bedded to argillaceous dolostones (Ancaster-Vinemount Members). At least two comparable grainstone-packstone based fining upward cycles occur in the succeeding Eramosa Formation. They have not yet been studied in detail.

The overlying Guelph displays cycles that include stromatolitic beds alternating with flaggy micritic beds. Together, these cycles define an upward shallowing sequence in the Lockport, although the component 4th order cycles are typically upward deepening. Each 4th order cycle appears to be marked at its base by a marine flooding surface. As in Clinton cycles, shallowing portions of cycles are poorly represented and are reflected primarily in minor hiatus surfaces below coarse, transgressive grainstone-packstone shoal deposits. Internally, the formation scale deepening upward cycles are composed of minor PAC-scale cycles that show the classic shallowing upward motifs.

The upper Lockport grades upward into a thick (30 to 100 m) package of greenish gray to black shale, dolostone and red mudstone, the Vernon-Bloomsburg Formation. This package represents a major progradational wedge of marginal marine to non-marine muds.

SUMMARY and CONCLUSIONS

Recent study of outcrop and drill core sections in the Niagara Frontier region indicates that the classic Niagaran Series, ranging in age from Early Llandoverian to Late Ludlovian, is divisible into at least five major unconformity bounded sequences, designated sequences I, II, IV, V and VI (see Fig. 4). The sequences recognized herein are comparable in duration to those recognized by seismic stratigraphers in various portions of the Mesozoic and Cenozoic column. Each of the Silurian sequences is bounded at its base by a major erosional unconformity; two of these unconformities appear to be regionally angular surfaces which bevel strata of underlying sequences. Sequence III, the Middle Clinton Group of the type-Clinton area in central New York State, is completely missing due to erosional unconformities in western New York. The most pronounced of these major erosional surfaces is the basal Cherokee Unconformity which also coincides with a megasequence boundary of the Tutelo Holostome recognized by Dennison and Head (1975; see Dennison, 1989). The surface bevels older Upper Ordovician siliciclastic rocks of the Queenston clastic wedge in an eastwardly direction. The other sequence boundaries are less pronounced, but have been recognized at least as local unconformities by some workers. These are, in ascending order: the basal Clinton unconformity marked by the Densmore Creek Phosphate Bed; the upper Clinton angular unconformity marked by the Second Creek phosphate bed; the sub-Irondequoit unconformity marked by a zone of hardground and intraformational

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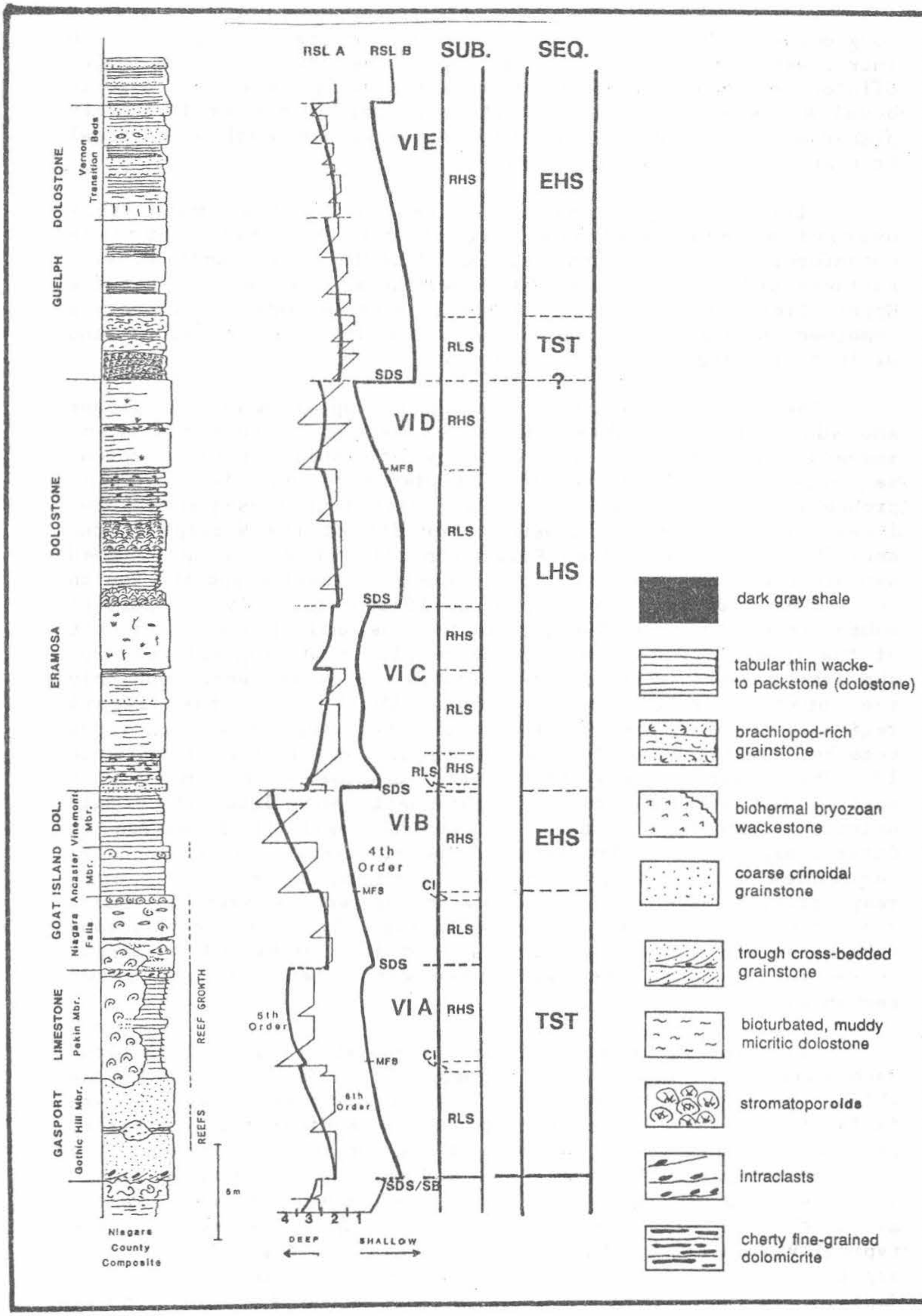
Figure 16. Lithostratigraphy, inferred relative sea level, and sequence stratigraphic interpretation of Lockport Group (sequence VI), Niagara County, New York. Note intervals of upward reef (bioherm) growth corresponding to early highstand (condensed section) phases. Calibration of relative sea level curves based on litho- and biofacies, as follows: 2 = crinoidal grainstone with abundant stromatoporoids and tabulate corals (inner BA-3 to BA-2); 3 = argillaceous, reefy dolostones with diverse small rugose corals, tabulates, bryozoans and brachiopods (outer BA-3 to BA-4); 4 = dolomitic shales with scattered small rugose corals, brachiopods, including astrypids, rhynchonellids, and Leptaena, and trilobites (inner BA-4). For explanation of abbrieviations, see Figure 7.


RSL A
RSL B
SUB.
SEQ.
GUELPH DOLOSTONE
Vernon Transition Beds
ERAMOSA DOLOSTONE
GOAT ISLAND DOL.
Vinemont Mbr.
Ancaster Mbr.
Niagara Falls
GASPORT LIMESTONE
Pekin Mbr.
Gothic Hill Mbr.
REEF GROWTH
REEFS
5m
Niagara County Composite
VI E
VI D
VI C
VI B
VI A
4th Order
5th Order
6th Order
SDS
MFS
CI
SDS/SB
RHS
RLS
EHS
TST
?
LHS
4 3 2 1
DEEP
SHALLOW
dark gray shale
tabular thin wacke- to packstone (dolostone)
brachiopod-rich grainstone
biohermal bryozoan wackestone
coarse crinoidal grainstone
trough cross-bedded grainstone
bioturbated, muddy micritic dolostone
stromatoporoids
intraclasts
cherty fine-grained dolomicrite

conglomerate; the basal Lockport unconformity marked, again, by an intraclastic conglomerate. Of these, the lower Clinton, upper Clinton and basal Lockport are demonstrably regional, angular bevel surfaces. The sub-Irondequoit disconformity is nearly planar and shows only minor evidence for erosion without regional truncation of underlying strata.

Distinctive phosphatic, intraclastic beds immediately overlying unconformities (except for the basal Cherokee unconformity) mark both sequence bounding (lowstand) erosion surfaces and marine transgressive surfaces. In the case of the Upper Clinton unconformity, the basal sequence boundary reflects a combined lowstand erosion surface, initial transgression, and maximum flooding/ sediment starvation.

The Silurian sequences correspond approximately to groups and subgroups and subsequences correspond to formations and members. Systems tracts are variably developed within different sequences recognized herein. The Medina Group, for example, probably is subdividisible into at least four subsequences, the lowest corresponding to lowstand deposits of the Whirlpool, the second to the Power Glen Formation, the third to an unnamed sandstone and the overlying lower Grimsby Formation and the fourth to the Thorold Sandstone. Sequence II contains only one partial subsequence in Niagara County, due to erosional truncation of most of the Lower Clinton Group; Sequence III is missing entirely for the same reason. Sequence IV contains two subsequences but only the upper one is of any substantial thickness in the Niagara region. The Williamson Shale and the overlying Rockway Dolostone together constitute early and late highstand portions of sequence IV. The transgressive systems tracts of sequence IV is missing in most of the area, although the phosphatic and glauconitic, thin dolomitic limestone referred to as the Merritton Formation in Ontario may be a thin transgressive basal interval of sequence IV. Sequences V and VI (uppermost Clinton, Lockport Groups, respectively) have well developed transgressive systems tracts consisting of crinoidal grainstone facies. Overlying argillaceous carbonates and shales record early and late highstands. Hence, three subsequences are recognized within each of these two sequences.

Silurian subsequences display a consistent internal pattern. Each subsequence begins with a sharp to slightly erosional base which typically juxtaposes shallow water, coarse-grained winnowed facies (quartz arenites in the case of the Medina Group; crinoidal pack- and grainstones in the case of the uppermost Clinton and the Lockport Groups) onto deeper water mudstones. In sequences II and IV, these basal shallow water facies are absent. In subsequences, as in the larger sequences, the lower coarse-grained beds are typically abruptly set off from an upper finer grained, typically argillaceous portion, herein referred to as a relative highstand deposit, by a surface of sediment starvation (marine flooding surface) which is often marked by minor amounts of phosphate,

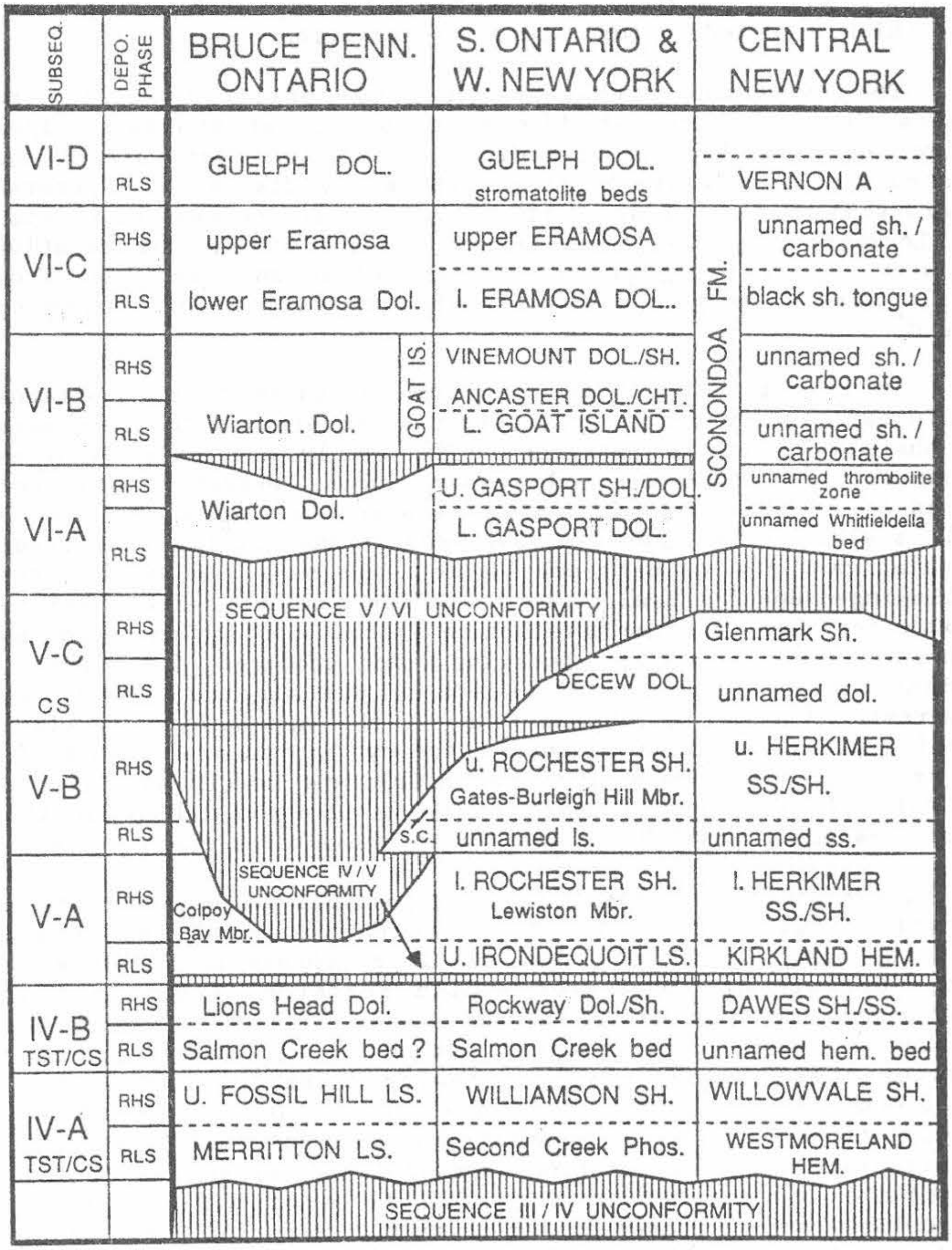


Figure 17. A) Summary chart showing subsequence division of correlative upper Clinton and Lockport Groups (sequence IV and V) in the Bruce Peninsula, southern Ontario to western New York, and central New York. Note major sequence boundaries. Abbreviations as in Figure 4. Units not scaled to thickness, but estimated relative time. In subsequence VB, SC = Stoney Creek (upper) Member of the Rochester Shale.

glauconite or hematite. Within each sequence, as a whole, one of the marine flooding surfaces of a smaller scale subsequence also corresponds to the surfaces of maximum starvation or downlap surface. These sharp internal surfaces within the subsequences are the result of maximally increased rates of relative sea level rise which produced maximal sediment starvation.

The overlying highstand deposits consist typically of shales, hummocky cross-bedded siltstones, sandstones, and/or carbonates. In the case of Medina cycles, the upper part of the subsequence or relative highstand phase may display a general upward shallowing or progradational trend. In the case of Clinton and Lockport sequences, the upward pattern within the relative highstand of the subsequences is less clear and may range from nearly static to even slightly retrogradational or deepening upward.

It is, of course, one thing to recognize cyclic patterns within sedimentary rocks, and another to understand the processes responsible for these patterns. The widely traceable Silurian sequences, subsequences, and parasequences certainly were not formed by local basin subsidence, because the cycles, even at a small scale, can be traced across depositional strike from areas of relatively low to high subsidence. In order to explain the shallowing-deepening cycles, basin tectonic models would have to account for their extreme persistence in the Appalachian region as a whole. Hence, the minor buckling which produced, for example, condensation and erosion of beds near the Algonquin Arch or, conversely, thickening of sections in the Appalachian foreland itself are too localized to explain the cyclic patterns. In fact, any tectonic model would have to incorporate nearly synchronous downward flexure and in some cases, rapid up-buckling of the entire eastern edge of North America to account for these cycles.

Conversely, at present it is impossible to substantiate a eustatic origin for cycles. Also, mechanisms for small scale cyclicity based upon old global sea level change are obscure at best. Certain of the larger cyclic patterns, sequences and subsequences in particular, appear to be traceable beyond the Appalachian Basin. For example, Johnson et al. (1985) provided evidence that Llandoverian shallowing-deepening cycles that correspond to our sequences and subsequences could be traced very broadly, if not globally. Johnson et al. (1985) provide evidence for worldwide relative lowstands during Llandoverian A-1 to B-2, C-3 to C-4 time, and in late C-5 to earliest C-6 time. Particularly strong pulses of sea level rise occurred about in the Llandovery A-2 to A-3 and in the C-1 to 2, and C-6. All of these signatures can be found in the strata of the Niagara region.

Recent work suggests that relative lows and highs of sea level in the Wenlockian and Ludlovian interval may be equally widely correlative. Early Wenlockian lowstands, corresponding to the Irondequoit limestone, and two closely spaced lowstands in the latest Wenlockian corresponding to the Gasport and lower Goat

Island Formations appear to be correlative into the British Silurian section. There, the Buildwas Beds of the Welch borderland and the Much Wenlock limestone correspond to the late Wenlockian sea level drop intervals. The highstands corresponding to the Rochester Shale and the upper Goat Island formations respectively, occur in the British successions as the Coalbrookdale beds (Wenlock Shale of older literature) and the basal Ludlow Elton beds (see Siveter et al., 1990a,b). Late-early to middle Ludlovian sea level lowering corresponding to the Eramosa and Guelph interval in New York and Ontario may occur in high Ludlow section (Whitcliff and Leintwardian beds) in the type Ludlow section of the Welch borderland.

Further work is required to corroborate these correlations and extend them into other geographic areas. There is certainly a strong suggestion that the major sequence and subsequence of sea level highs and lows may be eustatically produced. Since these cycles represent from 1 to 3 million year sea level fluctuation patterns, it may not be entirely unreasonable to propose a plate tectonic explanation for them. On the other hand, the smaller scale megacyclothems, cyclothems, and PACs are not so readily explained by plate tectonic eustatic processes. Either relatively poorly understood glacioeustatic processes or possibly geoidal fluctuations might account for these small scale oscillations in relative sea level.

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ROAD LOG FOR SILURIAN SEQUENCES

Note: From Fredonia take I-90 (NY State Thruway to junction of I-290 (Youngman Highway). Take I-290 westbound (toward Niagara). Road log begins at junction of I-90 and I-290.

CUMULATIVE MILES	MILES FROM LAST POINT	ROUTE DESCRIPTION
0.0	0.0	Junction I-90 (North)/I-290 west; exit onto I-290 west.
0.4	0.4	Main Street Exits;
0.5	0.1	Note road cuts in cherty Onondaga Limestone (Middle Devonian). This is the old Vogelsanger Quarry.
1.4	0.9	Exit at Route 324/240.
3.0	1.6	Exits for Millersport Highway
3.8	0.8	Cuts on left at underpass are in Upper Silurian Camillus Shale (and gypsum).
3.9	0.1	Exit 4 for I-990 North; take exit to right onto I-990.
4.7	0.8	Exit 1 for SUNY Buffalo
5.7	1.0	Exit 2 for Sweet Home Road
6.5	0.8	Exit 3 for Audubon Parkway
8.0	1.5	Exit 4 for North French Road (end I-990).
8.2	0.2	Junction North French Road; turn left (west).
8.6	0.4	Junction NY Rt. 270; turn right (north).
11.0	2.4	Bridge over Tonawanda Creek, enter Niagara County.
12.8	1.8	Junction Bear Ridge Road, Town of Pendleton.
14.0	1.2	Junction Fiegel Road.

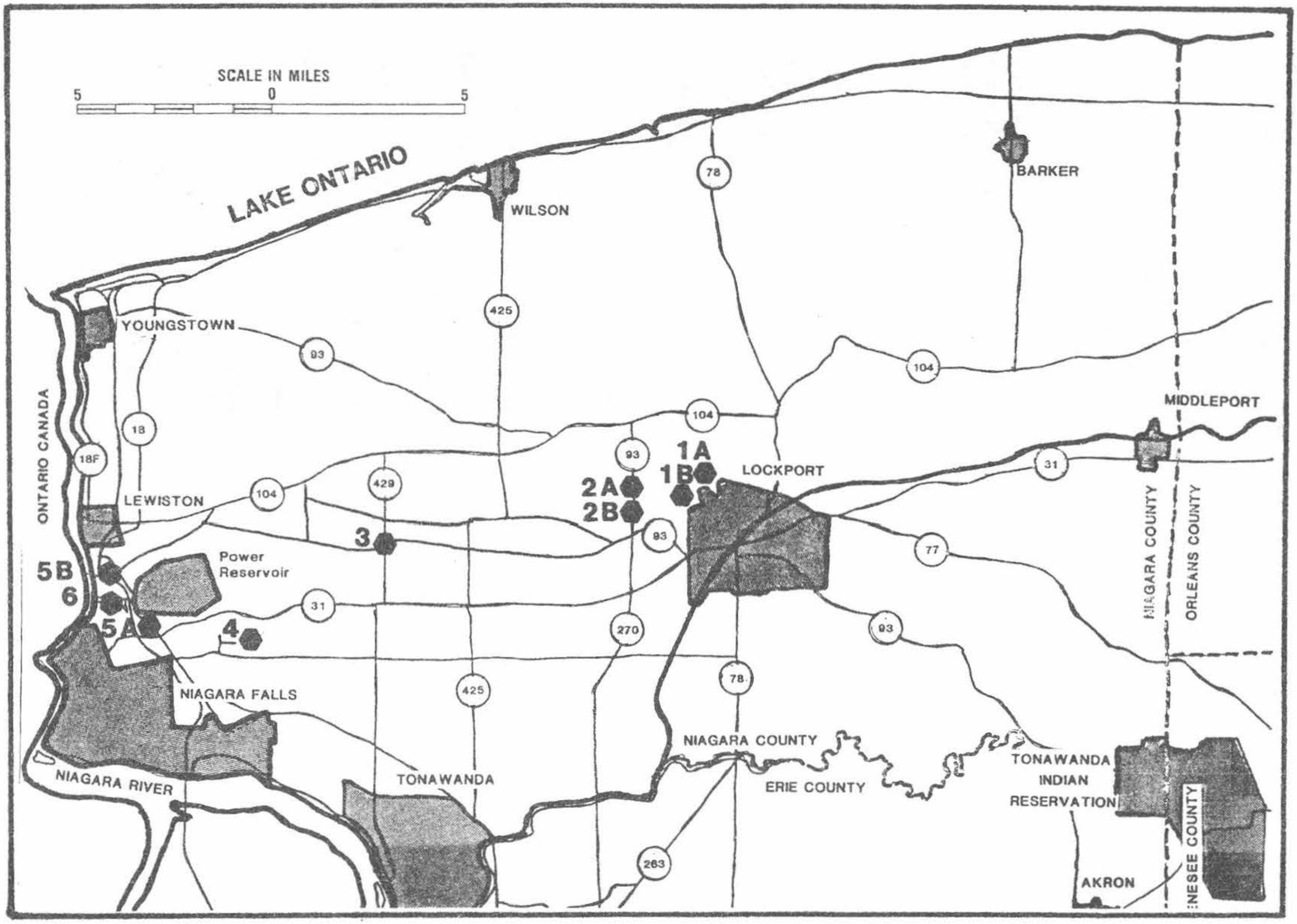

Figure 10. Map of Niagara County, New York showing location of field trip stops.

15.0	1.0	Junction Mapleton Road.
15.8	0.8	Junction Lockport Road; Route 270 becomes Lockport/Cambria Townline Road.
17.0	1.2	Junction Saunders Settlement Road (Route 31).
18.5	1.5	Junction Upper Mountain Road; Route 270 ends. Turn right (east) onto Upper Mountain Road (Route 93 east). Town of Lockport, NY.
19.0	0.5	Junction Gothic Hill Road (type section of lower Gasport Fm. grainstone is cut on this road). Turn right (north).
19.5	0.5	Junction Niagara street (lower Mountain Road). Turn right (east).
20.15	0.6	Junction Sunset Road.
20.4	0.25	Junction West Jackson Street; turn left (northeast).
21.2	0.8	Small cut in red Grimsby Sandstone.
21.5	0.3	Note sewage treatment plant on left.
21.7	0.2	Junction Plank Road; turn right and pull into parking area near base of railroad viaduct.

STOP 1: ROAD CUT ON W. JACKSON STREET BELOW SOMERSET RAILROAD VIADUCT (QUEENSTON SHALE - MEDINA GROUP).

This excellent and relatively new outcrop has been described previously in considerable detail (see Friedman, 1982; Duke et al., 1987). It provides an outstanding exposure of the basal Silurian Cherokee Unconformity and a good opportunity to study the lower units of the Medina Group as well as the uppermost beds of the Queenston Shale.

About 6 m (20') of upper red mudstones and siltstones of the Queenston Formation (Upper Ordovician, Ashgillian) are exposed at this locality. The Queenston has been interpreted as either very shallow marginal marine or non-marine red beds. The Cherokee unconformity in this area is the basal surface of Whirlpool Sandstone which is nearly planar. It is also a megasequence boundary separating the early or Creek phase of Sloss' Tippecanoe "megasequence" from the later Tutelo phase (see Dennison, 1989).

The Medina Group (Sequence I of the Silurian System), consists of an Early Silurian (early Llandovery, A1-B), siliciclastic wedge derived from tectonic source areas to the southeast (Figs. 1, 2). The lowest Silurian unit, white Whirlpool sandstone is about 3.5 m (11.5') thick at this location. Basal beds of the Whirlpool Sandstone are quartz arenites with northwest dipping cross strata which have been interpreted recently as non-marine, braided stream deposits (Middleton et al., 1987). Large-scale channel-like structures occur in, or at least at the top of, these sands. Shale drapes within such channels at Lockport have yielded marine acritarchs (M. Miller, unpublished data) indicating that the channels were backfilled by very shallow marine sands and minor muds during a rise of sea level. Hence the irregular channeled surface that separates lower Whirlpool braided fluvial facies from upper Whirlpool hummocky cross-stratified, sparsely fossiliferous beds is a transgressive surface. The Whirlpool Sandstone thus is interpreted to contain both a lowstand (or shelf margin) systems tract and a transgressive deposit. A thin bed containing phosphatic pebbles and fossil grains occurs the Whirlpool-Power Glen contact. This phosphatic pebble bed may mark a marine flooding surface, or surface of maximum starvation associated with relatively increased rates of sea level rise. This surface marks the change from shallow shelf sands of the upper Whirlpool into deeper shelf muds and storm sands of the Power Glen Formation, herein interpreted as relative highstand deposits (subsequence IA). The Power Glen exhibits two small-scale parasequences.

This outcrop is one of the easternmost exposures of the Power Glen Shale. At this locality the Power Glen Shale comprises of about 5 m (16') of greenish gray shale with thin tempestitic siltstone and sandstone beds. The basal meter-thick transitional zone consists of thin (2-10 cm) muddy sandstones with interbedded sandy shales. Sandstones in the Power Glen Shale feature small-scale hummocky lamination and gutter casts suggestive of shallow, storm influenced shelf deposition. Small burrows (<u>Planolites</u>) are common, but body fossils are rare.

Greenish to reddish sandy shales and reddish sandstones occur near the top of the Power Glen suggesting a minor upward shallowing trend. However, the top of the unit (as defined herein) is sharply demarcated at the base of a massive white to pink mottled sublitharenitic sandstone about 2.5 meters (7.7') thick. This unnamed unit corresponds with lenticular sandstone beds ("Devil's Hole Sandstone" of Duke et al., 1987) seen at Niagara Gorge (Stop 6). The basal and upper beds of the sandstone contain lingulid brachiopods and probable <u>Lingula</u> burrows.

The white sandstone appears to record a relative sea-level drop during which sands were distributed widely into the basin. The unit has some characteristics in common with the upper member of the Whirlpool Sandstone and, by analogy, is considered to be a relative lowstand to transgressive deposit.

The unnamed sandstone, in turn, is overlain by about 2.0 meters of brick red shales and interbedded sandstones assignable to the lower Grimsby Formation. These beds are ferruginous and exceedingly rich in fragments of lingulids with rare nautiloids and bryozoans. Thin spastolithic (oolitic) hematite stringers occur near the top of the unnamed sandstone and probably reflect reworking of sediments in shallow marine environments during an interval of sediment starvation. Hence, these shell-rich ferruginous sediments represent a condensed interval at the base of the Grimsby highstand deposits.

The reddish marine shales near the base of the Grimsby Formation pass upward into red and white-mottled sandstones and thin sandy shales. These beds are exposed high in the cut and are not readily accessible. This upper interval will be seen to better advantage at Niagara Gorge (Stops 4, 5, 6).

Return to vehicles and reverse direction turning left at West Jackson Street.

23.1	1.4	Junction Niagara Street If time permits, we may make an optional stop at the upper railroad cut. In such case we will <u>turn left</u> proceede for 0.5 miles up the Niagara Escarpment, and pull off into parking area just before Sommerset Railroad crossing. Then proceed on foot northeast along the railroad for about 0.4 mile to outcrops.

OPTIONAL STOP 1B: CUTS ALONG SOMERSET RAILROAD, NORTHEAST OF NIAGARA STREET CROSSING, LOCKPORT, NY (UPPER MEDINA AND CLINTON GROUPS)

Cut banks along both sides of the railroad track provide an excellent exposures of the upper beds of the Medina and Lower Clinton groups (Fig. 9). Lowest exposed units are reddish and white, mottled sandstones and sandy shales of the upper Grimsby Formation. A prominent 2.2 meter thick, pale pinkish sandstone unit (Thorold-equivalent), the overlying 3.0 meters (9') of red to greenish silty shale (Cambria Member), and about 0.5 m of pale greenish to white sandstone and sandy shale, referred to as the Kodak Formation, complete the Medina Group.

The Lower Clinton Group (Sequence II) rests unconformably on the Medina Group with the contact marked by a thin phosphatic, calcareous sandstone. Only 24 cm (17") of Neahga Shale (Fig. 9) overlie the unconformity, followed by 1.9 m of crinoidal grainstone belonging to the Hickory Corners Member of the Reynales Formation. These units and the underlying Medina strata are comparable to the section seen at Lockport Junction Road (Stop 2A), and are described in greater detail for that section.

The upper contact of the Reynales Limestone (upper sequence II boundary) is well exposed along the top of the cut on the southeast side of the railroad tracks. Here, the uppermost bed of Reynales crinoidal packstone crops out from beneath the soil cover. The surface is an irregularly sculpted and bored hardground with black phosphatic staining and what appear to be phosphatized stromatolites. This is a local manifestation of the major Upper Clinton unconformity.

Southwest of the main railroad cut are small, partially overgrown exposures along the southeast side of the tracks. Here a thin remnant of the upper Clinton Group (sequence IV and parts of V) can be observed. In the ditch, southwest of the end of the main outcrop are exposed about 37 cm of dark gray shale rich in phosphatic nodules. The unit, which yielded an acritarch assemblage identical to that of the Williamson Shale of the Rochester area, lies between the top of Reynales unconformity and the basal phosphatic bed of the Rockway Dolostone. The pale buff-weathering Rockway Member (0.5 meters thick) and its contact with the overlying pinkish gray grainstones of the Irondequoit Formation are visible in the small outcrop.

Rochester Shale is poorly exposed in slumped banks between this outcrop and the Niagara Street crossing. Well-preserved bryozoans, brachiopods, and even cystoid calyces are occasionally found in patches of weathered shale along the southwest side of the tracks.

Return to vehicles and reverse directions, returning to the junction of Niagara Street and West Jackson Street.

23.1	0.4	Junction Niagara Street and West Jackson Street. Turn or continue west on Niagara Street.
23.5	0.4	Junction Sunset Road
23.9	0.6	Junction Gothic Hill Road

24.3	0.4	Junction Leete Road
24.5	0.2	Overpass over Lockport Junction Road (Route 93).
24.55	0.22	Access road to Route 470 on left; <u>turn left onto road</u>.
24.6	0.05	<u>Pull off</u> along berm on left side of road and park. Proceed on foot directly down embankment along Route 98 to road cut.

STOP 2A: LOCKPORT JUNCTION ROAD CUT (LOWER) (UPPER MEDINA AND LOWER CLINTON GROUPS)

This newly widened (1986) cut along Lockport Junction Road exposes a similar section to that seen along the the Somerset Railroad cut (optional stop 1B). However, this cut does not show the upper Clinton beds.

The lowest beds are exposed beneath and just north of the overpass of Lower Mountain Road over Route 93. The basal units seen here are red shales near the top of the Grimsby Formation. These shales are overlain by a 1.0 to 1.2 meter thick, blocky, pinkish gray sandstone that displays color mottling due to bioturbation. Swirly spreiten of the trace fossil <u>Daedalus</u> occur sporadically near the top of the sandstone ledge. Detailed regional correlation by Duke and Fawcett (1987) indicates that this unit is the equivalent of the Thorold Sandstone at the Niagara Gorge. The upper contact of the sandstone is marked by a thin red silty bed containing a "hash" of lingulid shell fragments.

The Thorold, in turn, is overlain by 1.7 to 1.8 m of dominantly red silty shale of the (Cambria Member) uppermost Medina Group. This shale bears distinctive fine, white mottling due to bioturbation. Although previously assigned to the Grimsby Formation, this is a distinctive, ostracode-bearing shaley unit that <u>overlies</u> the Thorold Sandstone and is traceable regionally at least as far east as the Rochester area. We informally identify this unit as the Cambria Shale Member of the Thorold Formation, using this section as the type locality.

The upper portion of the Cambria Member is pale purplish to greenish gray sandstone and sandy shale that was formerly termed Thorold Sandstone. In actuality, this is simply a leached sandy zone in the Cambria Shale. The Kodak Sandstone, observed at Stop 1B, and about 1 m of Cambria Shale, have been removed here at the sequence I/II unconformity. Sandstones contain small <u>Skolithos</u> burrows and intercalated green shale beds, especially the topmost layer, contain prolific leperditiid ostracodes. The greenish color extends down about 30 to 50 centimeters below the upper contact where sandstones are mottled pale purple and green. This discoloration is probably associated with the top unconformity and deposition of overlying reducing sediments (Duke et al., 1987).

Here, as at the Lockport railroad cut, the top of the Medina Sandstone is an erosion surface overlain by a thin (3 to 5 centimeter) dark gray, phosphatic sandy limestone (Densmore Creek Bed) with prolific Hyattadina brachiopod valves. A thin laminated siltstone rests on the bed at the contact with the greenish gray Neahga Shale, which at this locality is about 1.0 meter thick--substantially thicker than at Lockport (STOP 1B).

At the base of the Hickory Corners Limestone (Reynales) is a thin (3 to 5 centimeter) pyritic, sandy limestone packed with black phosphatic pebbles and shell fragments (Budd Road phosphatic Bed). It is overlain by about 40 centimeters of alternating greenish gray shales and thin limestones capped by a 60 centimeter thick ledge of nodular crinoidal pack- and wackestone at the top of the roadcut. These beds contain a prolific fauna including corals, brachiopods (Hyattidina, Dalejina, Platystrophia) and pentameric crinoid stems belonging to a newly described inadunate. The upper surface at this locality is a glacially striated pavement and the post-Reynales erosion surface cannot be observed.

Reboard vehicles and continue on exit lane.

24.7	0.1	Junction with Lockport Junction (Townline) Road (Route 93); turn right (south) and proceed up escarpment.
25.0	0.3	Pull into small parking area at gap in guard rail (for driveway) to left.

STOP 2B: LOCKPORT JUNCTION ROADCUT (UPPER) (UPPER ROCHESTER, DECEW, GASPORT FORMATIONS)

This large roadcut displays the upper part of the Rochester Formation (about 5 meters), DeCew Dolostone (2.5 meters), and Gasport Limestone (over 7 meters); it was described in detail as Stop 1 of Brett's (1982) NYSGA Guidebook article. However, since that time the exposure has been freshly blasted to widen Route 93.

A subsequence boundary occurs between the dolomitic calcisiltites and shales of the upper Rochester Shale and the overlying DeCew Dolostone. The latter is a buff-weathering, silty dolostone with thin layers of intraclasts and contorted bedding. The basal contact is sharp and locally channeled, but nearly conformable. The upper Rochester and DeCew are burrowed in some levels; body fossils are rare but this exposure has produced long columns of crinoids in the lower DeCew.

The sharp and undulatory upper contact of the DeCew Dolostone with the Gasport Formation forms the boundary between the Clinton and Lockport Groups, and is interpreted as a sequence bounding unconformity (between sequences V and VI). The surface represents an abrupt lowering of relative sea-level and beveling of older strata. The basal Gasport bed is a greenish gray brachiopod-rich, crinoidal grainstone conglomerate with dolostone clasts eroded from the DeCew. Missing at this contact is the newly recognized Glenmark Shale, a fossiliferous gray shale with litho- and biofacies resembling the Rochester Shale.

Only the lower (Gothic Hill) member of the Gasport is present here. At this locality and at cuts along adjacent Gothic Hill Road this unit is exceptionally thick (7-8 meters) and composed of well to poorly sorted pelmatozoan pack- and grainstones. This facies is interpreted as a high energy crinoidal bank. Brachiopods are common in an argillaceous, thin-bedded unit near the top of the unit. A small bioherm composed of algal and bryozoan boundstone (micrite) occurs within the Gothic Hill Member. The overlying units will be examined at the next stop.

Reboard vehicles and turning left out of the driveway, continuing south along Route 93.

25.3	0.2	Upper end of roadcut
25.5	0.3	Junction Upper Mountain Road (Rt. 270/93). Turn right (west).
26.2	0.7	Junction Thrall Road on right. Exposures of fossiliferous Rochester Shale along Thrall Road were described as Stop 2 in Brett (1982).
28.0	1.6	Junction Blackman Road.
28.9	0.9	Junction Cambria Road (North).
30.1	1.2	Junction Route 425 (South).
30.2	0.1	Junction Route 425 (North). Shawnee Road.
30.9	0.7	Junction Baer Road.

32.2	1.3	Pekin Village; fire department on left.
32.3	0.1	Junction Old Pekin Road (one way). Turn right and proceed down hill.
32.6	0.3	Park on shoulder before stop sign at junction with Route 429 and walk to outcrop along Route 429 turning left (up hill) at intersection.

STOP 3: PEKIN HILL (ROUTE 429) ROAD CUT AT UNDERPASS BENEATH UPPER MOUNTAIN ROAD. (GASPORT-GOAT ISLAND FORMATIONS).

This classic exposure, described in detail by Crowley and Poore (1974), displays biohermal structures characteristic of the lower Lockport Group. Although the exposure is becoming overgrown, it has been restudied recently as part of our stratigraphic revision.

The lowest stratum, barely visible in the northernmost end of the outcrop (east side of road) is a crinoidal grainstone which marks the top of the Gothic Hill Member (seen at the last stop). The crinoidal grainstone is overlain on the east side of the road cut by approximately 4 to 5 meters of thin-bedded, bioturbated argillaceous dolostone which Brett et al. (in prep) refer to as the Pekin Member of the Gasport Formation. A small bioherm, "rooted" in the underlying Gothic Hill Member, protrudes upward into the sparsely fosssiliferous Pekin Member on the west side of the road cut.

Of particular importance is the sharp upper contact of the Pekin Member with pink, fine-grained crinoidal and cladoporid coral-bearing dolomitic grainstones of the basal (Niagara Falls Member) of the Goat Island Formation on the east side of the road. This contact can be traced to near the concrete wall for the Upper Mountain Road overpass. Here, it is seen to drop in elevation, apparently defining a channel-like feature that underlies stromatoporoid-rich biohermal dolomicrites. The latter appear to laterally replace the pink grainstone facies of the Goat Island.

On the west side of the road, the main mass of the bioherm described by Crowley and Poore (1974) can be seen. It is evidently a continuation of the biohermal mass seen near the bridge footing on the east side. This bioherm appears to occur <u>above</u> the sharp and distinctly irregular contact of the Goat Island Formation. Again, this contact is channelized into the dark, argillaceous dolostones of the underlying Pekin Member. Hence the so-called "Gasport bioherm" at this locality appears to be a biohermal mass within the lower Goat Island Formation.

The bioherm consists of dolomicrite containing very abundant, large stromatoporoid heads, many of which are re-oriented or overturned and hence, are not preserved in situ. Near the center of the biohermal mass, the dolomicrite facies passes abruptly into pale pinkish gray fine-grained grainstone, closely resembling the non-biohermal basal Goat Island facies on the east side of the road. The pale gray "reefy" dolomicrite facies appears both north and south of the grainstone pocket which appears to have filled the center of the large channel-like feature cut into the top of the Pekin Member. Also note two or more sharply defined surfaces within the biohermal masses that may represent minor erosion surfaces. Overall, we interpret the bioherm here as a possible bank of algally (?) bound micrite and stromatoporoids (and a few tabulates) that lined a (storm surge?) channel cut into the muddy carbonates of the Pekin Member. The center of the channel was occupied by fine carbonate sand but was eventually "overrun" by the biohermal facies developing inward from the two channel margins. The channel itself was apparently oriented NW/SE, roughly perpendicular to regional facies strike. The erosion of the Pekin Member mudstones may have occurred during a relative sea-level lowstand that marks the boundary between Gasport and Goat Island depositional subsequences. (For a radically different interpretation of the stromatoporoid facies as a late successional stage of a Gasport bioherm, see Crowley, 1973, and Crowley and Poore, 1974).

The outcrop continues south of the Upper Mountain Road bridge. Here the upper portion of the stromatoporoid biohermal mass is abruptly overlain (contact now obscured) by thin-bedded, fine-grained, buff-weathering dolomicrite with bands of white chert nodules. We refer to this facies as the middle or Ancaster Member of the Goat Island Formation. Note a distinctive marker bed of silicified Whitfieldella brachiopods. The cherty facies records a general deepening trend in the upper Goat Island. It is somewhat comparable to the Pekin Member of the Gasport, but the latter is not cherty.

Return to vehicles and drive to intersection with Route 429. Turn left (south) at Route 429 (as you did on foot) and proceed up through the cut.

32.6	0.1	Upper end of road cut.
32.8	0.2	Junction Grove Street (access to Upper Mountain Road).
34.4	0.6	Junction Route 31 (Saunders Settlement Road). Turn right (west).

35.1	0.7	Junction Bridgeman Road.
36.2	1.1	Junction Chew Road.
36.9	0.7	Junction Walmore Road. Turn left (south).
37.5	0.6	Jog in Walmore Road.
38.5	1.0	Junction Lockport Road at 84 Lumber. Turn right (west).
39.0	0.5	Niagara Airforce Base on left.
39.6	0.6	Tuscarora Road (on right).
40.0	0.4	Road forks; proceed straight ahead on Lockport Road.
40.5	0.5	Railroad overpass.
40.7	0.2	Junction Miller Road. Turn right (north).
40.75	0.05	Junction Quarry Road. Turn right (east).
41.3	0.55	Office headquarters of Niagara Stone Quarry. Check in then proceed by vehicles into quarry.

STOP 4: NIAGARA STONE QUARRY (LOCKPORT GROUP)

This active quarry provides the most complete section of the Lockport Group in the Niagara region. Aspects of the jointing and hydrogeology of the Lockport at this locality are discussed in detail in the contribution by Tepper et al., this guidebook). We will briefly examine the overall stratigraphy focusing on the Goat Island Formation. The section extends from the top of the DeCew Dolostone and its unconformable contact with the overlying Lockport Group (sequence V/VI boundary) to beds near the base of the Guelph Formation at the quarry rim. The lower Gasport limestones appear to fall in the *sagitta* conodont zone making them late Wenlockian in age. Furthermore, recent graptolite discoveries indicate that the Wenlockian/Ludlovian boundary lies close to the Gasport/Goat Island contact (LoDuca and Brett, in press). Kleffner (1989) obtained *siluricus* zone conodonts from the upper Eramosa beds here.

The DeCew Dolostone is observable in the deepest part (lowest lift) of the quarry where it exhibits a contorted upper surface and internal hummocky cross-stratification. The sequence bounding unconformity between the DeCew and the Gasport Formation of the Lockport Group is marked by a thin, greenish (glauconitic) grainstone containing rip-up clasts of DeCew Dolostone up to 10 centimeters across. The lower or Gothic Hill Member of the Gasport is a massive, 5 meter thick interval of light pinkish gray, commonly orange weathering, crinoidal grainstone. The overlying Pekin Member is a 5 meter-thick interval of thin to medium-bedded, medium gray argillaceous dolostone. A bioherm extends up through the interval in the northwest corner of the deep pit.

The lower Goat Island (Niagara Falls Member) can be examined along the top of the ramp road leading to the lowest pit of the quarry, although the basal contact with the Pekin Member is obscure and inacessible. The upper 1.5 meters of the Niagara Falls Member is a distinctive interval (Niagara Falls C unit) consisting of very dark gray, vuggy dolostone with distinct, white weathering stromatoporoids and corals. These and immediately underlying beds reflect a relative sea-level lowstand corresponding to the biohermal bed of Pekin cut. Beds overlying the Niagara Falls Member are assigned presently to the Ancaster and Vinemount Members of the Goat Island Formation. Both of these units have their type sections near Hamilton, Ontario.

The middle Goat Island interval is well developed in the walls above the second lift. The platform below is bulldozed off on a surface within the Ancaster Member. Thin flaggy beds of pale buff-weathering, fine-grained dolostone in the lower half meter of contain the chert nodules that characterize the Ancaster Member in its type area. However, the overlying interval is medium to thick-bedded, buff colored, medium-grained and generally non-cherty dolostone. A distinctive layer of silicified and valves of <u>Whitfieldella</u> brachiopods occurs about 1.5 meters above the second lift. This layer may correlate with the <u>Whitfieldella</u> bed seen at the Pekin road cut (Stop 3).

Ancaster facies are interpreted to represent a similar offshore, low energy shelf environment. The abundance of chert in the Ancaster is unique among the Silurian units in the Niagara region; the cherts may reflect the availability of biogenic silica from the abundant sponges which occupied the seafloor at this time, although this is probably not a complete explanation.

The uppermost half meter of the Ancaster Member is marked by numerous vugs that appear to represent small corals and stromatoporoids. This bed is abruptly overlain by a layer of dark gray dolomitic shale that marks the base of a 3 m-thick bituminous argillaceous unit. Detailed outcrop and subsurface tracing of the unit indicates that it is coextensive with the Vinemount shale beds of the Hamilton, Ontario region. These argillaceous beds appear to grade laterally and vertically into Ancaster cherty dolostone beds and hence both are assigned member status in the Goat Island Formation. The Vinemount here comprises about 3 meters of dark gray, bituminous and argillaceous dolostone with some shale partings. Fossils are rare and poorly preserved, but include rhynchonellid and atrypid brachiopods, small rugose and favositid corals and the large nautiloid Dawsonoceras.

Together, the three members of the Goat Island Formation comprise an upward deepening (retrogradational) subsequence. It is marked at the base by an erosion surface between the Pekin Member of the Gasport Formation and the Niagara Falls Member of the Goat Island. The top of the Niagara Falls Member constitutes a marine flooding surface. Cherty beds of the basal Ancaster reflect relatively slow deposition during the early highstand.

The upper quarry walls above the Vinemount display the entirety of the Eramosa Formation (formerly called Oak Orchard Member; see Zenger, 1965). Recent work (Brett et al., in press) indicates that "Oak Orchard" is an invalid term since the highest unit is exposed on Oak Orchard Creek is equivalent to the Vinemount beds. Furthermore, tracing of key units into Ontario indicates their correlation with the Eramosa and lower Guelph Formations in the type areas of Canada.

A number of informal units are recognizable within the Eramosa and are visible in the wall. Lowest is a 1.8 meter thick, massive, biostromal bed containing white gypsum filled vugs. This is succeded by a rather nondescript, fine-grained facies 3.5 m which, in turn, is overlain by biostromal or thrombolitic dolomicrite. Notable are the two flaggy-weathering intervals at the top and base of this zone that may represent minor discontinutiies. Toward the top of the quarry are 6 m Eramosa Formation, containing large, lenticular stromatolitic bioherms observable in the south wall.

Overlying units, at or near, the quarry rim are about 1.5 to 2.0 m of biostromal brownish gray dolostones with very abundant Favosites corals some of which are infilled by purple fluorite. The topmost bed in parts of the quarry is a light gray-weathering, stromatolitic (LLH) dolostone which forms a regional marker.

The Eramosa interval appears to represent an upward shallowing succession (subsequence) reflecting late highstand conditions.

Reboard to vehicles and return to quarry entrance.

41.9	0.6 (approx.)	Miller Road. Turn left.
41.95	0.05	Junction Lockport Road. Turn right (west).

42.15	1.1	Junction Military Road (Route 265). <u>Turn</u> <u>right</u> <u>(north)</u>.
43.75	0.8	Junction Route 31 (Saunders Settlement Road). Go straight.
44.65	0.9	Junction back access road (marked for <u>Deliveries</u>) for Robert Moses Power Plant. <u>Turn</u> <u>left</u> <u>(west)</u>.
44.60	0.15	Underpass beneath Route I-190. Outcrop of stromatolites (Stop 5).
45.0	0.2	Turn right into parking area near chain link fence overlooking Robert Moses forebay. Examine upper Lockport strata in forebay and proceed on foot to roadcut Stop 5A.

STOP 5A: ROBERT MOSES ACCESS ROAD AND FOREBAY (UPPER LOCKPORT GROUP)

Higher units of the Lockport Group are visible along the fore bay and access road to the Robert Moses Power Plant, just west of Military Road and 0.9 miles north of Route 31. Here we will briefly examine, from a distance, exposures in the forebay canal of the upper Eramosa (new usage in New York) and lower Guelph Formations. Note the large algal bioherms which characterize the uppermost units of the Eramosa Formation in Niagara County (seen at Stop 4). The highest units in the forebay canal are more or less tabular stromatolitic dolostone which are, at present, assigned to the basal beds of the Guelph Formation (Fig. 16). Exposures in the small road cut at the underpass of the access road beneath the lanes of I-190 contain exceptionally large stromatolites. These strata represent a very distinctive marker horizon in the basal Guelph beds in western New York. The stromatolite heads are approximately 2 meters across but superimposed on these are small digitate upward growths of stromatolitic boundstone. The stromatolitic horizon is thought to be traceable at least to Hamilton where it comprises the basal transition bed between the Eramosa and Guelph.

Reboard vehicles and return to Military Road.

45.3	0.3	Junction Military Road. <u>Turn</u> <u>left</u> <u>(north)</u>.

45.7	0.4 0.5	Pass by forebay area (on left) and Robert Moses Pump Generating Station (on right).
46.5	0.8	Junction Upper Mountain Road (right) and entrance road to Route I-190, Route 104, and Robert Moses Parkway (left). <u>Turn left onto entrance road</u>.
46.55	.05	Exit for Route I-190 north onto Lewiston-Queenston International Bridge.
46.75	0.2	Exit for Route I-190 south.
46.75	0.2	Exit for Route 104 east (north) to Lewiston.
47.10	0.15	Exit for Route 104 west (south) to Niagara Falls. <u>Bear right onto exit ramp</u>.
47.2	0.1	Merge onto Route 104.
47.4	0.2	Stop light at Irving Drive. Turn <u>left</u> (east).
47.45	0.05	Old Lewiston Road. <u>Turn right</u>. Park vehicles near small building on right. Proceed on foot through railroad underpass (under Route 104). At far end turn left, walk up slight embankment then down other side to exit lanes onto Robert Moses Parkway. Turn Turn left and walk across exit lane and carefully cross two lanes of Rober Moses Parkway. At 55 mph sign step step over guard rail and down a slope bearing right (north) to cliffs along Niagara Gorge. (Note: permission should be obtained from Niagara Parking Commission for access to this stop.)

STOP 5B: NORTH END, NIAGARA GORGE BETWEEN LEWISTON-QUEENSTON BRIDGE AND ROBERT MOSES POWER PLANT (CLINTON GROUP)

The Rochester Shale in this cliff exposure along the east face of Niagara Gorge was described in detail by Brett (1982). It provides an excellent section of the entire Clinton and lower Lockport units. It also provides excellent fossil collecting in the Rochester Shale.

Proceed down to a small ditch in the gorge nearly opposite the Irondequoit-Rochester contact in the main cliff exposure. At its base, this gully exposes orange-weathered Thorold Sandstone, overlain by a thin (about 0.5 m) maroon and pale green sandy shale situated beneath the Neahga Shale. This is the last vestige of the Cambria Shale. To the south and west it has been lost to pre-Neahga erosion. A thin, Hyattidina-bearing, calcareous sandstone (Densmore Creek Bed equivalent) occurs at the base of the Neahga Shale. The latter is about 2 meters thick, dark gray, fissile gray shale. The overlying Reynales Limestone with a thin basal phosphate bed (Budd Road Bed) is nearly identical to that seen at Lockport Junction Roadcut (Stop 2). Note thick, nodular, coral-bearing packstone at the top.

Exposures in the main wall of the gorge show the basal contact of the overlying Rockway Dolostone. A 10-15 cm phosphatic, black shale resting on the Reynales represents a thin tongue of the Williamson Shale. This contact is sharp and represents a major unconformity at which most of the lower and middle Clinton units have been beveled (compare STOP 1B).

The overlying Rockway Member (of the Irondequoit Formation, Kilgour, 1963) is a buff-weathering, argillaceous dolostone with thin shales. The Rockway shows prominent bands, ranging from a few centimeters to half meter thick, of argillaceous dolomite, which are interbedded with thin green shales. These two interbedded facies define a small scale cyclicity which can be traced on a regional basis. Rockway beds apparently record relatively sediment starved, off-shore marine lime and siliclastic muds. Extensive dolomitization has obscured the fossil content of this unit. However, large brachiopods (Costistricklandia) are locally abundant, particularly in the middle thick bedded unit of the Rockway. Dendroid graptolites, rare favositid corals and nautiloids fossils are occasionally found. On the basis of conodont biostratigraphy, the Rockway belongs to the upper part of the amorphognathoides zone (latest Llandovery to earliest Wenlock Series).

It should be noted that the rock, here termed Rockway Member of the Irondequoit Formation, whose type section is in Canada (15 Mile Creek at Rockway, Ontario), is commonly referred to as the upper beds of "Reynales" limestone by Canadian geologists. However, the Sequence IV boundary unconformity, cuts out the true Reynales Limestone just west of the Niagara Gorge. Hence, the true Reynales is absent in Canada, except along the Niagara River.

A sharp contact separates the Rockway from the overlying massive, crinoidal grainstones of the upper (Model City) member of the Irondequoit. Clasts of fine-grained dolostone derived from the underlying Rockway occur in the basal thin bed of the Model City.

The upper member of the Irondequoit Formation (Model City Member of Brett et al., in press), consists of massive, pinkish-gray, crinoidal limestone and dolostone which rests with the sharp and slightly disconformable surface on the upper shaley, beds of the Rockway Member (Subsequence IVB). In places a thin phosphate or pyrite crusted surface delimits the upper surface of this 6 inch band. This pyritic crust probably marks a hardground. The Model City member shows a minor trend of upward deepening toward the top and a conformable, although abrupt, contact with the overlying Rochester Shale. Faunal density is interpreted as representing a shallow, highly agitated (near wave base) crinoidal shoal environment; brachiopod assemblages suggest a benthic assemblage-(BA) 3 paleobathymetry. Conodonts indicate an earliest Wenlockian age.

The Model City in turn, is interpreted as a transgressive systems tract of subsequence VA (Fig. 15). Its sharp upper contact with the Rochester Shale, which is locally glauconitic, is considered to be a surface of maximum starvation (marine flooding surface). In the cliff opposite the small ditch (which exposes the Thorold-Reynales) a small micritic (algal?) bryozoan bioherms protrude from the top of the Model City into the overlying Rochester Shale.

The overlying Rochester Shale, which is about 18 m thick, is a gray calcareous to dolomitic mudstone with numerous thin carbonates representing shell-rich and carbonate-silt storm deposits (Fig. 15). It can be examined by walking south along the base of the cliff toward the Robert Moses Power Plant. Though the Rochester initially appears homogeneous, it shows a distinct internal cyclicity which is traceable very widely. Most notable is the medial band of bryozoan-rich carbonates that occurs about 9 m above the base of the Rochester Shale. The sharp top of this unit has been used to demarcate the boundary between the Lewiston and Burliegh Hill Members of the Rochester Shale (Brett, 1983).

The Lewiston Member itself displays an alternation of fossiliferous limestones and calcareous shale intervals with nearly barren shale. Bryozoan rich beds occur up to about 10 feet above the base (Lewiston B unit). This fossiliferous unit is followed by a barren shale zone containing only thin calcisiltites (Lewiston C). This barren unit, in turn, gives way upward to bryozoan rich mudstones and finally, bryozoan pack- and grainstones (Lewiston D and E; Fig. 14). These facies alternations are interpreted as defining small scale cycles (parasequences).

The overlying Lewiston E limestone appears to be a weak signature of a relative sea-level fall and subsequent transgression. In short, a relative sea level drop followed by a rather rapid sea level rise is envisioned for this portion of the section (Fig. 2). Although no erosion or even sharp surfaces are seen at the base of the Lewiston E bed at Niagara Gorge, as this bed is traced westward onto the Algonquin Arch, it shows an increased sharpness to its base and, eventually, an erosion surface beneath the Lewiston E truncates most of the beds of the lower Lewiston. The upper surface of the Lewiston is sharp and locally glauconitic, and shows an abrupt change to the barren dark gray Burleigh Hill shales. This contact, again, is interpreted as a surface of relative sediment starvation, or marine flooding surface, associated with increased rates of sea level rise.

The Burleigh Hill shales are largely barren of fossils and show relatively few interbeds, except in the upper third, where the unit becomes silty and contains some thin fossil stringers (Fig. 7). The member on the whole is considered to be an upward shallowing or regressive cycle (highstand deposit). As such, it can be interpreted as representing highstand conditions with minor progradation of carbonate silt toward the end of Rochester Shale deposition. The contact with the overlying DeCew Dolostone may locally appear sharp or gradational. A minor diastem is likely and subsequence boundary is placed at the bottom of the DeCew dolostone, but no major sequence bounding unconformity occurs at this surface.

The DeCew is an interesting 9 m thick, blocky dolostone which shows spectacular soft sediment deformation. The deformation may be interpreted as a response to single event, possibly a seismite associated with early pulses of tectonic activity during the onset of the Salinic Orogeny in eastern New York. Shaley beds of the DeCew are present locally along Niagara Gorge but have been removed in most areas seen on this trip.

The base of the Gasport crinoidal grainstone also seen at STOP 2B, is similar to the base of the Model City grainstone in that it contains rip-up clasts of dolomitic, argillaceous dolostone derived from the underlying, finer grained unit. To the west, this erosion surface removes the DeCew entirely in the vicinity of Hamilton, Ontario and further cuts out the upper beds of the Rochester Shale northwest of Hamilton.

The lower Gasport Gothic Hill Member shows spectacular small scale trough and planar cross stratification. Some of this bedding appears to be bipolar, possibly indicating the influence of tidal currents. Like the similar Irondequoit grainstones, the lower Gasport grainstone is interpreted as an amalgamated crinoidal shoal deposit consisting of multiply reworked pelmatozoan sand and gravel. No Pekin Member is present here. Instead, a 2 meter thick vuggy, stromatoporoid-bearing dolostone (basal Niagara Falls Member A) of the Goat Island Formation rests directly on the Gothic Hill (lower Gasport) grainstone. Overlying beds, largely inaccessible, consist of bluff dolostone and tan cherty dolostones (Ancaster Member).

Retrace route back to vehicles. Turn vehicles around, proceed to intersection of Old Lewiston Road and Irving Drive. Turn left.

47.5	0.5	Light at intersection of Route 104. Turn left (south).
47.85	0.35	Pass by forebay area at tops of conduits for water inflow to generator turbines.
48.2	0.35	Robert Moses Power Vista.
48.5	0.3	Junction Hyde Park Blvd. (Rt. 62) at entrance to Niagara University. Turn left off Route 104 on Rt. 62.
48.75	0.25	Entrance to south haul road access to Robert Moses Power Plant and fishermen's access to Niagara River. Turn right, cross RR track.
48.75	0.25	Parking area for fisherman on left. Pull in and park. We will proceed on foot down the south haul access road for about 0.3 miles to the fishing area near the bottom of the gorge. **Please note: access to this section must be obtained from the Power Authority; hard hats are required and collecting is not permitted.**

STOP 6: SOUTH HAUL ROAD TO ROBERT MOSES POWER PLANT

This outstanding outcrop, arguably the most complete Silurian section in New York State, provides an opportunity to summarize and review all of the points of the preceding trip.

The section begins with about 8 m of the upper Ordovician Queenston Shale. Its sharp contact with the overlying Whirlpool Sandstone is the Silurian sequence I boundary. The Whirlpool, here as at Lockport (Stop 1), is represented by channel facies which record a nonmarine to marine transition. Minor phosphatic material occurs at the upper contact (starvation surface, or marine flooding surface) with the Power Glen.

The Power Glen is both thicker (8 m) and shalier at this locality than the section seen at stop 1. It is entirely gray shale, lacking the upper reddish sandy zone seen at Lockport.

As at Lockport, the Power Glen is overlain by a 2 meter thick massive white quartzose sandstone (Devil's Hole Member of Duke et al., in press), the base of subsequence IB of the Medina Group. Overlying (lower Grimsby) shales here are green and fossiliferous, in contrast to the red, ferruginous, lingulid shales seen at Lockport. The locality represents a more offshore section.

At the north end of Niagara Gorge a distinct, meter-thick phosphatic sandy dolostone, the Artpark Phosphate Bed, occurs in this position. Here, only minor phosphatic sandstone overlies the "Devil's Hole" Sandstone. These beds and the ferruginous zone at Lockport constitute a condensed section associated with rapid sea-level rise.

The main body of the Grimsby Formation (about 15 m thick) is red shale with thin sandstones. Three or four small-scale shallowing upward shale to sandstone cycles have been recognized by Duke et al. (1987) in this interval. This section is one of the most shale-rich exposures of the Grimsby in Niagara County. Sections both north and south of this locality contain more channel sandstones.

The upper beds of the Medina Group comprise about 2 meters of white, crossbedded Thorold Sandstone. The Thorold has a sharp erosive base which marks the base of the next Medina subsequence. Overlying Cambria Shale, seen at stops 2 and 5, is completely missing here. The sandy phosphatic Densmore Creek Bed rests sharply on the Thorold, marking the sequence I/II boundary.

The Neahga Shale is poorly exposed but is about the same thickness as at stop 5 on the north side of the power plant. The two phosphatic beds of the basal Reynales Limestone and the nodular capping bed are nearly the same as in the other sections seen in Niagara County. A prominent black phosphatic staining occurs on the upper surface of the Reynales Limestone (see near one of the protective cages on the outcrop). This stained surface is the sequence II/IV contact.

The Rockway/Model City (sequence IV/V boundary) is also well displayed. No bioherms occur here at the upper contact of the Irondequoit Limestone with the Rochester Shale, but a 30 centimeter thick shell bed marks the condensed zone.

The lower Rochester Shale is partly obscured by a protective cage (toxic chemical seep?), but upper limestone beds of the Lewiston Member are well exposed. Overall the Lewiston Member is somewhat less fossiliferous and contains fewer limestone beds than at stop 5, just on the north side of the power plant. This loss of interbeds reflects the beginning of a major facies change into sparsely fossiliferous Rochester Shale southward along Niagara Gorge (see Brett, 1982).

The upper Rochester displays a sharp contact with the enterolithic DeCew Dolostone beds, herein interpreted as the basal unit of a partially eroded upper Clinton subsequence. The sequence V/VI boundary at the DeCew/Gasport contact is well exposed near the entrance to the "tunnel" beneath the Robert Moses Parkway at the top of the cut. Weathered surfaces of the Gothic Hill grainstones display probable bipolar cross-stratification. In contrast to the cut on the north side of the power plant (stop 5) some 2.5 meters of argillaceous upper Gasport (Pekin Member) strata are present here. These beds display a sharp undulatory contact with overlying vuggy dolostones of the Niagara Falls Member of the Goat Island Formation. The base of the Niagara Falls Member is a subsequence boundary which erosionally bevels the 2.5 meters of Pekin Member strata between the two sides of the power plant.

As a whole, the Gasport Formation comprises a complete subsequence. The basal crinoidal grainstones of the Gothic Hill Member represent transgressive systems tract deposits, the contact with the Pekin Member is a marine flooding surface and the Pekin muddy carbonates represent relative highstand deposits (Fig. 15). This subsequence is analogous to the Model City - lower Rochester Shale subsequence.

The dark, argillaceous dolostones of the upper Gasport Formation are sharply and erosionally overlain by basal medium-bedded dolostones of the Goat Island Formation (Fig. 16). This erosionl contact is the same one observed at Pekin Roadcut (Stop 3). These dolostones, in turn, are overlain by massive, dolomitic, crinoidal grainstones appear at the type section of the Goat Island Formation at the brink of Niagara Falls. The south haul road section is a reference section for the lower portion of Goat Island Formation (Zenger, 1965). The unit is crinoidal and contains scattered <u>Cladopora</u> corals and stromatoporoids. Upper beds of the Niagara Falls Member display abundant vugs which appear to be solution cavities in a stromatoporoid-rich zone. This layer is locally highly biostromal, as noted at Niagara Stone quarry (STOP 4).

The Ancaster Member is poorly developed compared to that seen at Niagara Stone quarry (STOP 4), thin (~2.5 m) and only sparingly cherty. However, in the cliffs immediately north of the Robert Moses Power Plant, this member is developed in its typical thick cherty phase. There appears to be a complimentary relationship, in terms of thickness, between the Niagara Falls Member and the overlying Ancaster Member; i.e. where the Niagara Falls Member is thick, the Ancaster is thin to nonexistent and vice versa. Argillaceous gray dolostones of the Vinemount Member form the uppermost unit on the access road.

The Goat Island Formation as a whole here appears to be a "twin cycle" to the Gasport. The lower or Niagara Falls grainstone member constitutes the transgressive portion; its sharp boundary with the overlying Ancaster Member is a surface of starvation, sometimes recorded in the relatively glauconitic cherty beds of the lower Ancaster (Fig. 16). Ancaster and Vinemount Members represent highstand deposits.

Reboard vehicles and retrace route to road.

49.25	0.25	Junction Hyde Park Blvd. Turn left (north).
45.5	0.25	Junction Route 104. Turn right (north).
50.5	1.0	Exit for Route I-190. South to Buffalo; turn right and proceed south on I-190 to the Thruway and return to Fredonia.

END FIELD TRIP