SEQUENCE STRATIGRAPHY OF THE MIDDLE DEVONIAN AT THE BORDER OF THE MICHIGAN BASIN: CORRELATIONS WITH NEW YORK AND IMPLICATIONS FOR SEA-LEVEL CHANGE AND PALEOGEOGRAPHY

[1]Alexander J. Bartholomew, [1]Carlton E. Brett, [1]Michael DeSantis, [2]Gordon C. Baird, and [3]Cameron Tsujita
[1]*Rm. 500 Geology/Physics Bldg., Geology Dept., University of Cincinnati, Cincinnati, OH 45221-0013*
[2]*Geology Dept., SUNY Fredonia, Fredonia, NY*
[3]*Department of Earth Sciences, The University of Western Ontario, London, Ontario, Canada, N6A 5B7*

ABSTRACT: Middle Devonian (latest Eifelian-early Givetian) sediments of southwestern Ontario and northern Ohio, deposited in the Chatham Sag and on the eastern and western flanks of the Findlay Arch (EFA and WFA) in the Appalachian and Michigan basins, respectively, show similar patterns of 3rd and 4th order depositional sequence architecture; portions of these sediments can be correlated into the Oatka Creek, Skaneateles, Ludlowville and Moscow formations of New York based on sequence stratigraphic patterns within a framework of conodont/goniatite evidence. In Ontario and WFA Ohio, a package of thin coral-rich limestones situated near the base of the *hemiansatus* conodont Zone has been interpreted as deposits of an initial transgression (TST) of a 3rd-order depositional sequence, equivalent to the Stafford/Mottville members of the Skaneateles Fm. in New York. Where present, this coral-bearing limestone is everywhere overlain by an HST succession of gray to black mudrocks (Levanna Shale [NY], Arkona Shale [Ont.], Plum Brook Shale [EFA], Silica Shale [WFA]). Moreover, the Arkona, Plum Brook and Silica shale are sub-divisible into three small-scale (4th-order) argillaceous limestone-to-shale cycles that appear to correlate with the Delphi Station, Pompey and Butternut members of the Skaneateles Fm. in central New York. In all areas an uppermost, dark, leiorhynchid brachiopod-rich shale is sharply and unconformably overlain by a second coral-rich limestone (Centerfield member [NY], Hungry Hollow member [Ont.], lower Prout Limestone [EFA], lower Ten Mile Creek Formation [WFA]) representing the TST of the next 3rd-order sequence. The overlying HST succession and component 4th-order sub-sequences of the Ludlowville Formation in N.Y. are identified in the Widder Formation in Ontario. The upper Prout and Ten Mile Creek formations in Ohio represent the highly condensed HST of the Ludlowville Fm. A newly recognized stratal package of sediments in the subsurface of Ontario near Sarnia, identified as overlying the equivalents of the uppermost exposed beds in the Ipperwash area, is herein tentatively correlated with the Moscow Formation of New York representing deposits of the highest third-order sequence of New York. These high-resolution correlations in two basins suggest allocyclic control on deposition in both the Appalachian and Michigan basins during the Middle Devonian.

INTRODUCTION

During the past three decades sequence stratigraphy has developed as a tool for understanding the depositional dynamics of sedimentary successions. Important aspects of depositional systems that can be revealed within this framework include the origin of sedimentary cycles, the significance of sedimentation patterns in time and space, and the interpretation of local tectonics and paleogeography.

The Middle Devonian of the Appalachian Basin has long been studied from the perspective of detailed key-bed stratigraphy, an approach that can be likened to allostratigraphy in basic principle (Hall 1843; Grabau 1899; Cooper 1930, 1933). The Hamilton Group formations, as defined by Cooper (1933), are not, strictly speaking, lithostratigraphic units, but are thick packages of strata bracketed by thin, widespread and faunally distinct marker beds of bioclastic carbonates and calcareous siltstones/sandstones. These calcareous marker-beds are seen to overstep erosion surfaces interpretable as sequence boundaries (Brett and Baird 1985, 1986). Formations of the Hamilton Group, as traditionally defined, are temporally equivalent to third-order depositional sequences, as defined in the framework of sequence stratigraphers (Vail et al. 1977, 1991; Emery and Myers 1996; Coe 2003; Cateneaunu 2002). More detailed studies (Baird 1979; Brett and Baird 1994, 1996) have revealed smaller scale depositional cycles within these formation-scale stratigraphic intervals. Following the scheme of Vail et al. (1991), these smaller cycles might be termed fourth order sequences, each representing a time interval of approximately 100 to 500 kyr.

Constituent formations of the Middle Devonian Hamilton Group from adjacent areas in Ontario and Ohio provide a very interesting test case. These rocks have also been well studied and roughly correlated with units of the type Hamilton Group succession of the Appalachian Basin (Stauffer 1909; 1915; Stumm 1942; Mitchell 1967; Wright and Wright 1961, 1963; Kesling and Chilman 1975; Uyeno et al.1982, Tsujita et al. 2001), but they have not previously been examined critically from the standpoint of sequence stratigraphy. Nor have previous workers established the degree to which boundaries of various recognized units in Ohio and Ontario mesh with those of the Hamilton Group in New York. This area also records the interesting transition from a siliciclastic dominated foreland basin fill to a carbonate-dominated cratonic succession, providing further challenges for detailed correlation. Questions that can be investigated in these areas include: How widely can these two scales of depositional sequences be traced within and outside of the foreland basin? Do the sequences reflect primarily local tectonic effects or more widespread allocyclic processes? To what extent are the sequences modified by local tectonic processes? How geographically widespread are the faunal zones and epiboles that have, thus far, only been studied in the Appalachian Basin?

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Our current studies of the Hamilton-equivalent strata in Ohio and southwestern Ontario have been aimed at testing these issues to ascertain whether the sequences previously identified in the foreland basin can be extended into the craton or even into an intracratonic basin, the Michigan Basin. Previous attempts to correlate these regions based strictly upon gamma-ray profiles or biostratigraphic criteria have led to ambiguous and sometimes conflicting results (see Rickard 1984; Sparling 1985). It is clear that the correlations between these regions must be based on the consilience of varied lines of evidence, integrating aspects of lithostratigraphy, biostratigraphy, event stratigraphy, and cyclostratigraphy.

Our primary strategy in the present research was first to align units in various regions as closely as possible on the basis of biostratigraphy and physical tracing. The constraints are relatively broad and biostratigraphic control is lacking in portions of the section but sufficient data exist to build a basic framework. Working within the constraints of this framework, we have systematically examined strata in two separate outcrop areas in Ohio, in one outcrop area in southwestern Ontario, and in representative drill cores from intervening localities, to delineate and correlate sequences within the Hamilton Group succession. As sequence boundaries and maximum flooding surfaces are fundamental to the definition of sequences, much effort was focused on recognizing such surfaces consistently. We then compared internal details of the larger sequences to determine the number and pattern of smaller scale sequences. Pattern matching beyond this involved identification of epiboles and outages of key faunal elements and a search for widespread event horizons to provide better stratigraphic linkage between the Appalachian and Michigan basins.

GENERAL BACKGROUND

Geologic Setting

The study region, formerly part of the eastern Laurentian paleocontinent, includes the northwestern margin of the Appalachian foreland basin and the northeastern rim of the Michigan intracratonic basin. During the late Eifelian to middle Givetian eastern Laurentia lay south of the equator with the northern Michigan Basin positioned at about 25° S latitude and the northern Appalachian Basin about 30-35°S (Witzke and Heckel 1988; Scotese 1990; Fig. 1). Newly uplifting sediment source areas were created during the second tectophase of the Acadian Orogeny, reflecting oblique collision of the Avalonian terrane with eastern Laurentia (Ettensohn 1987; 1998). Lithospheric flexure associated with Acadian tectonic loading also produced a retroarc foreland basin in eastern Laurentia that extended from Alabama into Maritime Canada. At various times a complementary forebulge formed the western rim of this basin and the foredeep-forebulge couplet may have migrated cratonward through the course of Acadian

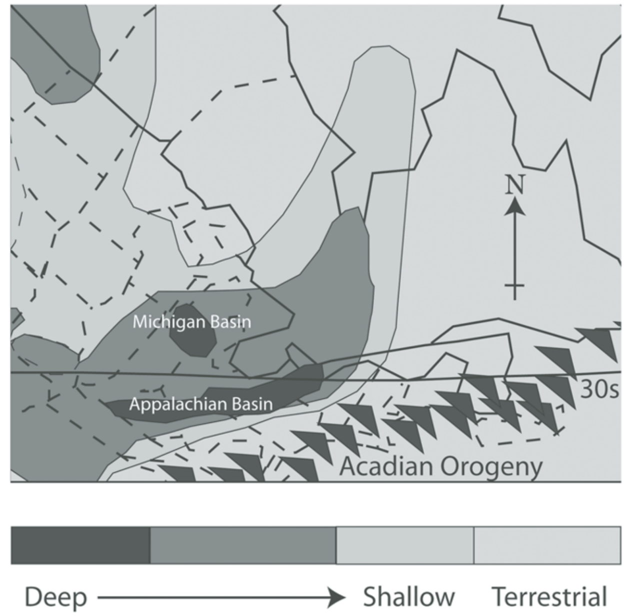

Figure 1. Paleogeographic map of eastern North America showing the location of the equator during the Middle Devonian as well as the orientation of the Avalon Terrane that was at that time colliding with the southeastern craton of Laurentia.

tectonism (Ettensohn 1987; 1998). However, details of this paleogeography and process remain incompletely understood; improved definition of this forebulge and its dynamics are a secondary objective of our studies.

At present, the strata of the Appalachian foreland basin are largely separated from those of the Michigan intracratonic basin by a basement arch system, of which the northeastern segment in Ontario is called the Algonquin Arch and the southwestern segment is called the Findlay Arch (Fig. 2). Due to erosion of post-Silurian strata over the crest of the Findlay Arch, Hamilton Group strata in Ohio occur in two principal outcrop regions - the east Findlay Arch region (EFA), near Sandusky, and the west Findlay Arch region (WFA), west of Toledo. Hamilton Group outcrops in southwestern Ontario, are restricted to the Chatham Sag, a small saddle located between the Algonquin and Findlay segments of the basement arch system. The Chatham Sag outcrop area includes well-known exposures in the vicinities of Arkona, Thedford and Ipperwash, that are considered in this report. The Findlay-Algonquin Arch and Chatham Sag may have existed intermittently during parts of the Paleozoic Era (Fig. 2). However, it should not be assumed that a major arch existed in this position during deposition of the Middle Devonian sediments considered herein. In fact, we will argue that there was no such barrier between the two basins, at least in the position of the modern Findlay Arch during deposition of most of the Hamilton-Traverse Group strata. However, a precursor arch may have developed to the southeast of the present Findlay-Algonquin axis during middle to late Givetian time.

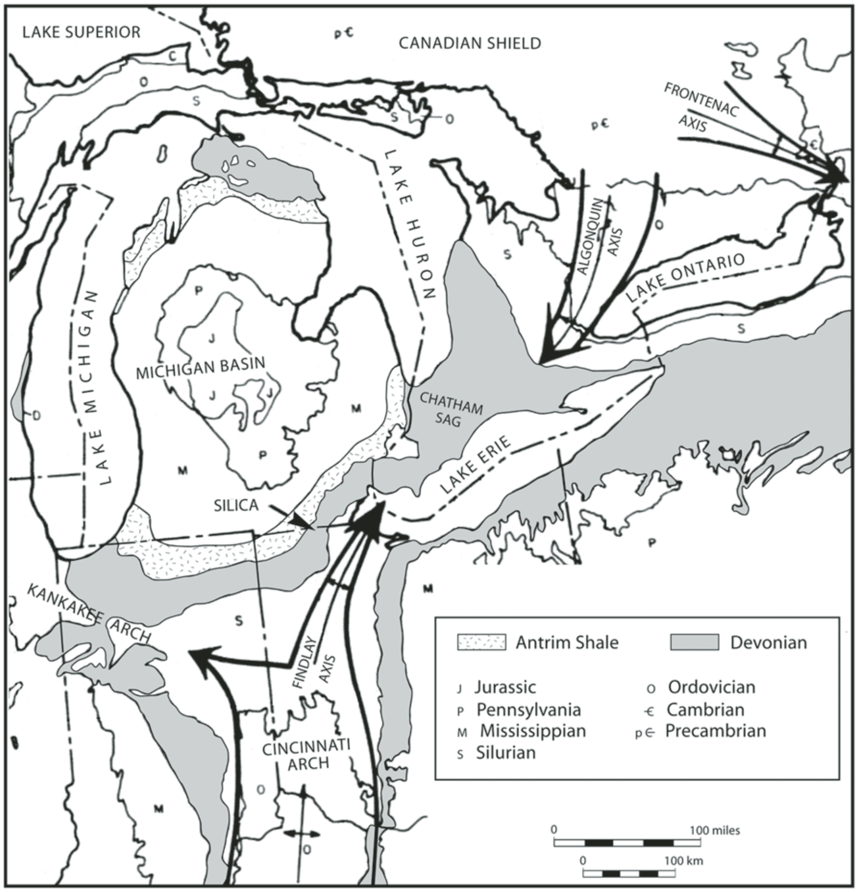

Figure 2. Map showing the outcrop pattern of Devonian rocks in the western Appalachian and Michigan basins.

An episode of renewed far-field tectonics and partitioning of the foreland basin with development of minor swells and basins took place before and during deposition of the Tully Formation carbonates in the middle-late Givetian (*ansatus* to *semialternans* zones; Heckel 1973; Baird and Brett 2003). It was perhaps at this time that arching southeast of the Findlay Arch (northeastern Ohio and southern Niagara peninsular Ontario) occurred, leading to condensation and erosional removal of higher Hamilton strata, and foreshadowing the third and largest tectophase of the Acadian Orogeny (Ettensohn 1985, 1987, 1998; Baird and Brett 2003).

Siliciclastic sediments began filling the under-filled foreland during late Eifelian time with the accumulation of black, laminated Marcellus facies in eastern New York. This early basin fill is a classic example of a clastic wedge, tapering westward from nearly 600 m (~1900'+) near the Catskill escarpment in eastern New York to approximately 6 m (19-20') in western New York. Depocenters of fine-grained siliciclastics shifted gradually westward with marine muds reaching the Michigan Basin areas by earliest Givetian time (Bell Shale). By the early to mid Givetian time, proximal portions of the foreland basin experienced overfilling with non-marine redbeds appearing in eastern New York approximately during the *hemiansatus* conodont zone time. While redbeds were being deposited in the proximal foreland, siliciclastic marine sediments were being deposited in more distal regions and while progradation of coarse clastics was limited to east central New York, large volumes of fine-grained siliciclastics were transported seaward ultimately to comprise the upper Skaneateles to lower Ludlowville formations in western New York, the Arkona Shale in Ontario, and the Plum Brook and Silica shales of Ohio.

Late in the deposition of the Hamilton Group, non-calcareous mudstones and siltstones were replaced by thin limestones and calcareous mudstones in western New York, and further west in Ontario, by argillaceous limestones and thin shales, indicating a reduction in siliciclastic sediment supply. A further extension of this trend is seen in the rather clean micrites of the overlying Tully Limestone (Johnson and Friedman 1969; Heckel 1973; Baird and Brett 2003).

Units Examined

Exposed units examined in western and central New York include the Oatka Creek, Skaneateles, Ludlowville, Moscow, and Tully formations (Fig. 3). In Ontario, exposed units examined include the upper Arkona Shale, "Hungry Hollow", Widder, and Ipperwash formations.

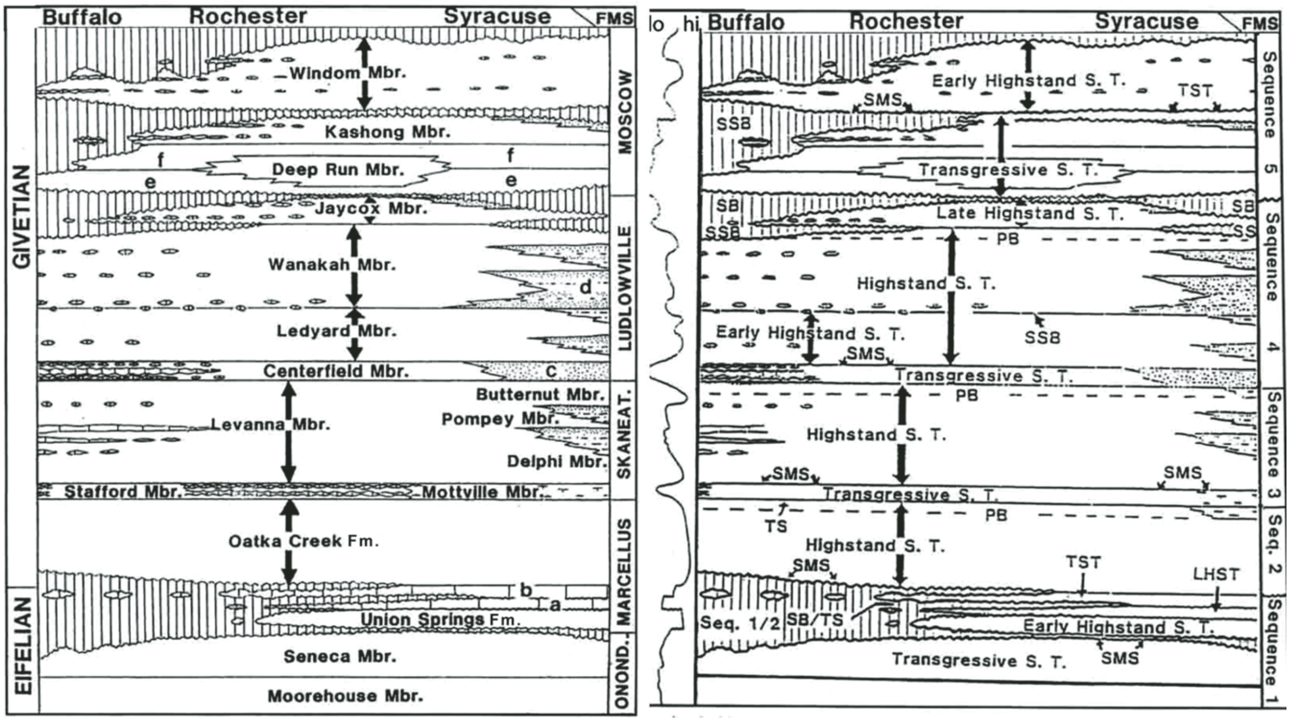

Figure 3. Diagram showing the exposure of Hamilton units across western and central New York State (left) and the sequence stratigraphic interpretation of the units (right). Between the two diagrams is an interpreted sea level curve for the Appalachian Basin during the deposition of the Hamilton Group.

C.Z.	Western Ontario	Northwest Ohio	Northeast Ohio	New York	Sequence Strat.	
ansatus	Sarnia (new)			Windom	HST	V
	Up. Ipperwash	Tenmile Creek	Prout	Portland Point	TST	
rhenanus/varcus	Petrolia			Wanakah	LHST	IV
	Low. Ipperwash					
	Widder			Ledyard	EHST	
timorensis	Hungry Hollow	Tenmile Creek	Prout	Centerfield	TST	
	H.H. under-bed	Silica	Plum Brook	Butternut	LHST	III
	Arkona			Pompey	EHST	
hemiansatus				Delphi Station	EHST	
ens.	Mottville/Stafford	Blue Limestone	Delaware	Mottville/Stafford	TST	
	Bell	Bell		Cardiff/Chittenango	HST	II
kockelianus	Halihan Hill	Halihan Hill		Halihan Hill	TST	
	Berne			Berne	HST	
	Dundee	Dundee		Cherry Valley	TST	
aust.				Union Springs	HST	I
cost.			Columbus	Seneca	TST	

Figure 4. Time-rock chart showing correlation of units across the study area with vertical lines representing unconformities. Conodont zones are listed on the left-hand side of the diagram.

Units examined in the subsurface of Ontario include the Bell Shale, Rockport Quarry, Arkona Shale, “Hungry Hollow”, Widder, Ipperwash, “Petrolia” formations, along with a new, unnamed unit herein termed the Sarnia Formation (Fig. 4). In EFA Ohio areas, exposed units examined include the Delaware, “lower Olentangy”, Plum Brook, and Prout formations. In WFA Ohio areas, exposed units examined include the Dundee, Silica, and Ten Mile Creek formations. All units were also examined in the subsurface.

Biostratigraphy

The biostratigraphic framework for this study is largely provided by conodonts. The uppermost Eifelian and lower Givetian is divided into six zones: *ensensis*, *hemiansatus*, *timorensis*, *ansatus*, *rhenanus/varcus and semialternans*

(Becker 2005). The boundaries of these zones have been recognized in certain Hamilton units in New York and the Midwest (Fig. 5). Unfortunately, many Hamilton Group units do not yield diagnostic conodonts. However, representatives of other faunal groups have proven useful for purposes of correlation. Of obvious importance are goniatites, primarily species of *Tornoceras*, which have long been recognized as reliable index fossils (House 1981). However, certain brachiopods, bivalves, gastropods, and even crinoids also have some utility in defining particular Hamilton Group intervals in the Appalachian Basin and marginal areas. Details of biostratigraphy are discussed in a separate paper (Bartholomew et al., in review).

SEQUENCE STRATIGRAPHY

The latest Eifelian and Givetian time interval under consideration in this study (*ensensis* to *ansatus* conodont zones) has been subdivided into a series of depositional sequences that have been traced widely within the northern Appalachian Basin (Brett and Baird 1996). To date, these sequences have not been traced beyond the boundaries of this basin. Accordingly, an important objective of this study is to investigate whether these sequences can be recognized in areas marginal to the Appalachian Basin, and in particular, the Michigan Basin. In the following sections we first review general concepts of sequence stratigraphy, as applied to the Appalachian foreland and review key features that permit recognition of important stratigraphic surfaces and systems tracts.

Stage	Conodont zones	Goniatite faunas	Unit
Givetian	*semialternans*	*P. amplexum*	up. Tully
	ansatus		mid. Tully
			low. Tully
		T. uniangulare	Windom
			Portland Pt.
			Jaycox
	rhenanus/ varcus	*M. n. sp./S. unilobatus*	Wanakah
		T. amuletum/T. u. aldenense	Ledyard
	timorensis		Centerfield
			Butternut
		T. arkonense	Pompey
	hemiansatus		Delphi Stat.
			Stafford
		Parodiceras/ T. mesopleuron	Chittenango/ Cardiff
?	?	?	
Eifelian	*ensensis*		Berne
	kockelianus	*A. vanuxemi*	Cherry Valley
		C. plebeifome	Hurley
	australis		Bakoven

Figure 5. Chart showing the current biostratigraphic zonation of conodonts and goniatites for eastern North America. Generic abbreviations are as follows: C. = Cabrieroceras, A. = Agoniatites, T. = Tornoceras, M. = Maenioceras, P. = Pharciceras, S. = Sellagoniatites. Units listed are those of New York State. Adapted from Kirchgasser (2000), and Becker (2005); goniatite zones from House (1978).

General Patterns of Sequence Stratigraphy

Each 3rd-order sequence begins with a basal transgressive limestone bed or beds, with a sharp, erosive base marking the combined sequence boundary and transgressive surface (ET surface; Fig. 3). The upper surface, commonly a hardground or a phosphate coated contact, is sharp, and represents the period of most rapid sea level rise (maximum starvation surface). From this surface a back-stepping pattern is often observed in the overlying stratal package, beginning with upward gradation into the siliciclastic-dominated portion of the transgressive systems tract, and ending with a sediment-starved omission surface recording the period of maximum flooding (maximum flooding surface; Fig. 3).

The highstand systems tract, represents a period of relative sea level still-stand to initial sea level fall. Comprising the lowermost part of this succession, and recording the deepest water conditions, are dark gray to black shales which contain a dysoxic fauna. The basal deep-water shales grade upward into coarser grained strata, recording the seaward progradation of siliciclastics into the basin during initial sea level fall; later highstand conditions are marked by dominance of fauna tolerant of high sediment influx.

The regressive or falling stage systems tract begins with a distinct shell bed showing a rapid shift to relatively shallower conditions and representing the period of most rapid sea level fall (forced regression surface or precursor bed; Fig. 3). The upper portions of the regressive systems tract, comprising bioturbated silts and fine sands, record the shallowest water conditions recorded within a sequence.

Third-Order Sequence Stratigraphy

Attempts to bridge the stratigraphic units of the Hamilton Group in the Appalachian Basin with those of bordering areas have been made in the past, but most have been strictly based on biostratigraphic evidence or have depended on gamma-ray logs (Cooper et al. 1942; Rickard 1984; Sparling 1985). This study synthesizes multiple criteria, including sequence stratigraphic evidence, to achieve the most accurate correlations possible. Sequence stratigraphic data allow for high resolution correlations, in some cases to bed level, across wide areas. Correlations at this scale provide a highly-detailed framework in which to test various sedimentologic and faunal hypotheses.

Sequence-by-sequence data, at the 3rd-order (formational) scale, are herein presented for all areas beginning with the well-defined New York sequences and extending westward into Ontario and Ohio. Evidence linking smaller scale 4th-order sub-sequences is presented within the discussion of each 3rd-order sequence. Up to five 3rd-order depositional sequences can be identified in the Hamilton Group in Ontario and correlated into the formations of New York. These sequences are best developed in the subsurface of southwestern Ontario in the Sarnia area; to the east of this area, the uppermost two sequences are truncated by an unconformity.

At least four 3rd-order depositional sequences are identifiable in EFA/WFA Ohio, the lower two are developed in the Delaware and Dundee formations, and the third, best developed in the Plum Brook-"lower" Olentangy formations (EFA) and Silica Formation (WFA). Portions of one to two sequences may be recorded in the highly-condensed Prout (EFA) and coeval Ten Mile Creek (WFA) formations. This paper deals only with the upper four sequences of the Hamilton Group, in ascending order: the Oatka Creek, Skaneateles, Ludlowville, and Moscow sequences. Particularly significant to this study are the details of the minor sequences (subsequences) of the Skaneateles and Ludlowville formations; these will be discussed in the following sections.

Sequence II: Oatka Creek Sequence

The lowest 3rd-order sequence considered here is represented in New York by the Oatka Creek Formation (Ver Straeten 1994). The Oatka Creek sequence in New York begins with a widespread TST unit, the Hurley/Cherry Valley members. The overlying HST can be split into three 4th-order sub-sequence represented by the Berne, Chittenango, and Cardiff members. In Ontario, the Oatka Creek sequence is exposed in the central part of the Niagara Peninsula and is present in the subsurface farther to the west near the Arkona/Thedford region. In Ohio the Oatka Creek sequence is represented by portions of the Delaware Formation (EFA) and the uppermost beds of the Dundee Formation (WFA), the entire sequence dramatically thinning to the west. Exact identification of the sub-sequences within this sequence is complicated (Fig. 6).

TST.-- The Oatka Creek Formation begins with the Hurley/Cherry Valley members, which together represent the 3rd-order TST of this sequence. The Hurley/Cherry Valley consists of dark, micritic limestone containing mainly a fauna of small brachiopods, corals, cephalopods and dacryoconarids; analogous to the "cephalopodenkalk" of the German nomenclature. The distinctly erosive base of the Hurley member represents the sequence boundary of the Oatka Creek Sequence. The top of the Hurley member is usually in erosional contact with the base of the overlying Cherry Valley member; in westernmost New York the Cherry Valley member rests directly on top of the Onondaga Formation, the underlying Hurley member and Union Springs Formation having been removed by erosion (Ver Straeten et al. 1994). The upper contact of the Cherry Valley member is marked by a widely-traceable "bone bed" that contains placoderm and acanthodian material along with abundant phosphatized crinoid ossicles. This distinctive contact, which records a period of sediment starvation, represents the maximum flooding surface of the Oatka Creek Sequence. Truncated cephalopods in its upper surface manifest the effects of submarine corrosion that accompanied rapid sea level rise (Ver Straeten et al. 1994).

The Hurley/Cherry Valley interval contains the youngest assemblages of the rather short-lived Stony Hollow Fauna in Appalachian Basin (DeSantis and Brett, in review; DeSantis et al. 2004). Restricted to the upper part of the *kockelianus* conodont zone (Klapper 1981), the Cherry Valley member is perhaps most famous for its cephalopod fauna, composed of large agoniatitid goniatites and orthoconic nautiloids. Together with other distinctive elements of the Stony Hollow Fauna, these cephalopods have been used for correlation of this unit across wide areas in the past (Cooper et al. 1942).

In Ontario, the basal TST of the Oatka Creek Sequence (Hurley/Cherry Valley Member) is recorded the upper portions of exposed Delaware Formation (with reported *Agoniatites vanuxemi*, Best 1953) in the central part of Niagara Peninsula. Equivalent strata, recognized in drill cores from the western Niagara Peninsula, are thin limestones that contain distinctive elements of the Stony Hollow Fauna (e.g., *Emanuella*). Although the whole of the lower Hamilton Group in Ontario is condensed in comparison with the New York succession, it is still possible to recognize, at least in western Ontario, that the base of the Cherry Valley Member is erosive; this is indicated by a reworked pyritic fossil lag that overlies the mudstones of the lower Union Springs Formation. The maximum flooding surface that defines the top of the sequence is marked by a pyrite-encrusted upper surface.

Identification of the basal TST of the Oatka Creek sequence in Ohio is still under investigation. The Delaware Limestone of the EFA region and the Dundee Limestone of the WFA region both contain elements of the Stony Hollow Fauna, indicating their approximate equivalence with at least the Union Springs sequence, but exact identification of the Hurley/Cherry Valley member equivalents has not yet been determined. DeSantis and Brett (in review) interpret the 1-2m limestone beds ("*Hadrophyllum*" beds of previous workers) near the top of the middle portion of the Delaware Limestone as being equivalent to the Hurley/Cherry Valley

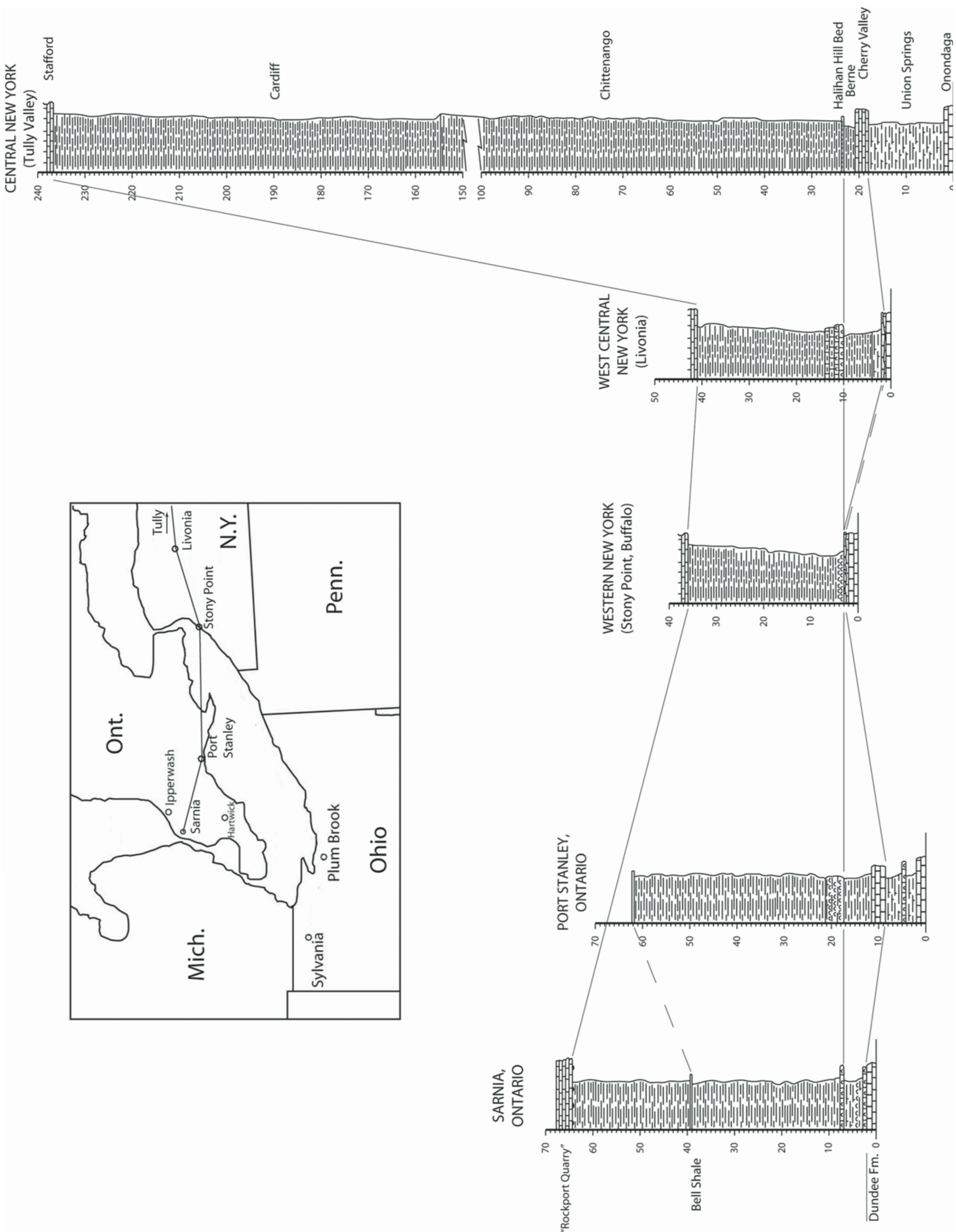

Figure 6. Cross-section displaying the change in thickness of the different units of the upper Union Springs and Oatka Creek formations across western New York State into southwestern Ontario through the sub-surface.

members, though they also contain a diverse fauna with closer affinities to the overlying Hamilton Fauna than the underlying Stony Hollow Fauna.

HST.--The HST of the Oatka Creek 3rd-order sequence is split into three 4th-order sub-sequences including the Berne, Chittenango, and Cardiff members (Fig. 7). The HST of the Oatka Creek sequence begins with the Berne Member, which consists of dark-gray silty-shale and contains a fauna composed primarily of styliolinids, chonetid and spiriferid brachiopods, bivalves, and small rugose corals (Ver Straeten 1994). The Berne Member is thickest in eastern New York State, thinning dramatically to the west. In the subsurface of Ontario, near Sarnia, the Berne Member is represented by about 1.25m dark-gray shale unit overlying the Cherry Valley-equivalent strata described above. The Berne Member has yet to be identified in either EFA or WFA Ohio.

Overlying the Berne Member is the TST of the next 4th-order sub-sequence, represented by the Halihan Hill Bed (Ver Straeten 1994). The Halihan Hill Bed is an important unit as it marks the initial influx of the diverse Hamilton Fauna in the Appalachian Basin. The Halihan Hill Bed consists of ~50cm of fossiliferous calcareous mudstone, rich in rugose and tabulate corals, including *Stereolasma*, *Heliophyllum*, *Heterophrentis*, *Cystiphylloides* and *Favosites*, as well as brachiopods including *Meristella*, *Mediospirifer*, *Pseudoatrypa*, *Elita*, *Athyris*, *Nucleospira*, and *Fimbrispirifer* (Lane 1955).

This bed is also present in the subsurface of Ontario, again marked by a distinct fauna compared with the beds below. In a core from near Sarnia, Ontario, it is represented by a ~15cm shell-rich interval overlying dark-gray mudstones, containing elements of the Stony Hollow Fauna. This Halihan Hill Bed equivalent interval carries a fauna composed of *Heliophyllum*, *Meristella*, *Protoleptostrophia*, *Pseudoatrypa*, *Ambocoelia*, *Longispina*, a few bryozoans, some crinoid ossicles and various other brachiopods including strophomenids, spiriferids, and chonetids.

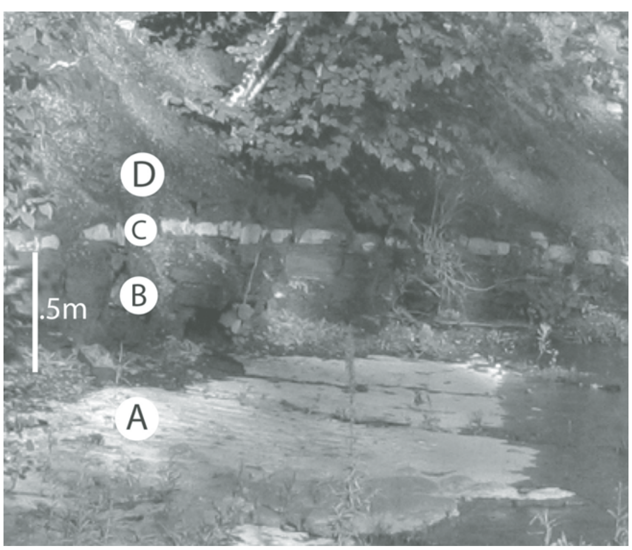

Figure 7. Succession at the base of the Oatka Creek Formation in New York along West Limestone Creek just south of Syracuse. A- Cherry Valley Limestone; B- East Berne Member; C- Halihan Hill Bed, ~15cm thick; D- base of overlying Chittenango Member.

In EFA Ohio, the identification of the Halihan Hill Bed interval is still under investigation. A possible candidate for this interval is the upper fossil-rich bed immediately above a *Hadrophyllum*-rich bed in the Delaware Limestone that contains an abundance of Hamilton Fauna taxa, including *Rhipidomella*. More evidence, specifically conodont data, is needed here to confirm this hypothesis. In WFA Ohio this unit has been removed by erosion beneath the overlying Skaneateles sequence boundary (Silica Formation).

The Halihan Hill Bed marks the base of the Chittenango Member of the Oatka Creek Formation in New York State. The bulk of the Chittenango Member consists of dark-gray shales with a rather depauperate fauna dominated by small, thin-shelled brachiopods and infaunal bivalves that suggest dysoxic conditions. Overlying the Chittenango Member are the Solsville and Pecksport/Cardiff members. The Solsville Member consists of relatively fossiliferous gray shales and siltstones with more compact shell beds near the top thought to represent the FST of the underlying 4th-order subsequence and the TST of the overlying 4th-order sub-sequence. The Cardiff Member consists of medium- to dark-gray shales, again with a rather depauperate (dysoxic) fauna much like that of the underlying Chittenango Member. The top of the Pecksport/Cardiff Member has a greater concentration of fossils, including auloporid corals and the button-shaped rugose coral *Microcyclus*, and is lighter gray in color indicating a relative shallowing of sea-level and a more oxygenated sea bottom. The thick, lower portion of the Pecksport/Cardiff is interpreted as the HST of the upper 4th-order sub-sequence of the Oatka Creek sequence and the thinner, upper portion of the member is considered to be the FST of this 4th-order sub-sequence. The Solsville Member grades laterally westward into one or more unnamed, thin brachiopod and auloporid-rich shell beds within the Cardiff Member in the eastern Finger Lakes Region.

Strata representing the upper portions of the Oatka Creek sequence can be found in the subsurface of Ontario and are represented by the Bell Shale of Uyeno et al. (1982). The Bell Shale of Ontario consists of up to ~18m of bluish light-gray to black mudstone with a few shell-rich beds; the contained fauna is rather depauperate overall and dominated by chonetid brachiopods with a few thin shell-rich beds interspersed throughout the unit.

The lower 10m of the Bell Shale begins with a few shell-rich beds grading out of the Halihan Hill Bed interval. Upward through this lower interval, the mudstone darkens slightly in color and faunal elements, such as *Eumetabolotoechia* and small chonetid brachiopods, become more sparse and scattered. This interval is thought to represent the bulk of the Chittenango Member of New York, here identified as the HST of the second 4th-order sub-sequence of the Oatka Creek sequence. At about 10m above the base of the Bell is a rather shell rich interval about 15cm thick with an abundance of crinoid ossicles, pterioid bivalves, and small chonetid and ambocoeliid brachiopods. This interval represents the Solsville Member of New York and fills the position of the TST of the overlying 4th-order sub-sequence. The upper ~8m of the Bell Shale is lighter-gray in color than the lower part and has a greater concentration of thin shell beds. The upper ~1.2m of the Bell Shale, composed of calcareous gray-shale with abundant shelly material, represents the Cardiff Member of New York and the HST of the upper 4th-order sub-sequence of the Oatka Creek sequence in Ontario.

In EFA Ohio, the upper part of the Oatka Creek sequence is tentatively identified as the upper portion of the Delaware Limestone, an interval consisting of rather barren dolostone with sparse, scattered shells of chonetid brachiopods, *Mediospirifer,* and crinoid ossicles. In WFA Ohio, the Oatka Creek sequence has been eroded beneath the disconformity at the base of the overlying Skaneateles sequence (Silica Formation).

Sequence III: Skaneateles Sequence

The second 3rd-order sequence to be considered is represented by the Skaneateles Formation of New York State (Vanuxem 1842). The Skaneateles sequence begins with 0.5 to 10 m of limestones and calcareous silty mudstones that comprise the Mottville/Stafford members (Fig. 8) and represent a TST. In western New York, this interval is overlain by 40-80 m of dark gray and black shales of the Levanna Member that constitute a third order highstand-regressive succession (Fig. 8).

The Skaneateles sequence is the best developed of the Givetian sequences across the Appalachian Basin and into the Michigan Basin, being recognized across northern Ohio, where it is represented by the Plum Brook Formation (EFA) and the Silica Formation (WFA). In Ontario, the Skaneateles sequence is represented by the Arkona Formation. Depositional patterns of both 3rd-order sequences and 4th-order subsequences are recognized here for the first time.

TST; sub-sequence IIIA.-- The Mottville and Stafford members are found at the base of the Skaneateles sequence in New York State. The Mottville and Stafford members occupy the position of the 3rd-order TST of the Skaneateles sequence. The Mottville and the Stafford members are laterally equivalent lithofacies and the two names are herein retained. The Stafford Member is up to ~2.5m thick in western New York State where it consists of a series of interbedded, condensed, skeletal limestones and argillaceous limestones (Fig. 9); this unit thickens eastward into the Mottville Member. In central New York, the Mottville Member consists of two coral-rich silty limestone beds each about 30 to 50cm thick, separated by an intervening silty-mudstone package that thickens eastward and containing and abundance of the brachiopod *Tropidoleptus carinatus* (Fig. 9A). The upper Mottville limestone grades upward into dark shales containing a dysoxic fauna; in central New York these shales form the base of a 7-10 m coarsening upward cycle, the informal Cole Hill submember (Grasso 1986). The upper Cole Hill succession consists of *Zoophycos*-churned siltstones that bear abundant bivalves.

The Mottville Member marks the first appearance of the conodont *Icriodus latericrescens latericrescens* and is identified by Klapper (1981) as being near the base of the *hemiansatus* conodont zone. The sharp base of the Mottville and Stafford members represents the 3rd-order sequence boundary of the Skaneateles Sequence. Although not notably erosional in most offshore sections of western and west-central New York, the basal limestone is locally sharply set off from the underlying Cardiff Shale in central and east-central New York.

In Ontario, strata equivalent to the Mottville Member have been identified only in the subsurface where they have been termed "Rockport Quarry Formation" (Uyeno et al. 1982; Fig. 10). This unit is composed of gray to brown, fine-grained limestones and interbedded shales up to six meters thick (probably coeval with the more proximal facies of the Rockport Quarry Formation in Michigan, Ehlers and Kesling 1970). The strata of this interval in Ontario have been found to more closely resemble the Mottville Member of the Skaneateles Formation in central New York State both lithologically and faunally than they do the probably coeval Rockport Quarry Formation of Michigan. The "Rockport Quarry" interval of Ontario is herein defined as consisting of four subunits: a) a lower crinoidal grainstone about 0.7 meters in thickness containing solitary rugose corals; b) a middle shale-rich interval up to 8 meters thick, containing the brachiopod *Tropidoleptus*; c) an upper crinoid grainstone about 0.5 meters thick containing rugose corals; and d) an upper dark gray mudstone up to 7-10m thick with scattered fossils up to a locally developed concretionary limestone bed. This pattern very closely resembles that of the Mottville Member in central New York State with the upper shale equivalent to the Cole Hill submember. It does not as closely resemble the lithology of the true Rockport Quarry Limestone in the Michigan Basin. Therefore, we suggest that the term "Mottville Member" be applied to the interval presently identified as "Rockport Quarry" in the Ontario subsurface, and be given member-scale status as the basal unit of the Arkona Formation. The "Rockport Quarry" interval and underlying upper Bell Shale of the Ontario subsurface have also been dated on the basis of

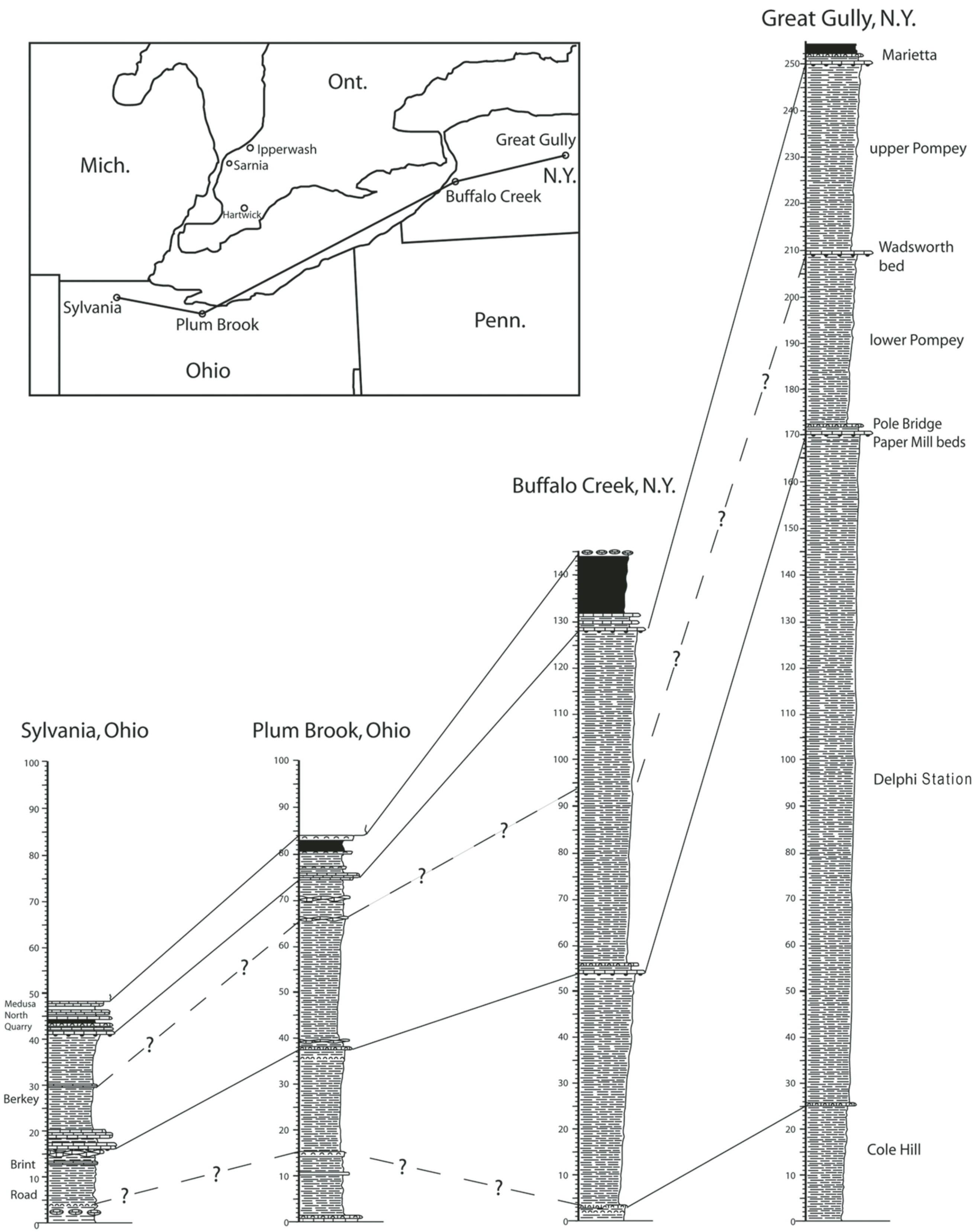

Figure 8. Cross-section showing the thinning of member scale units of the Skaneateles Formation across New York State and across northern Ohio in the Plum Brook and Silica shales. Scale in feet.

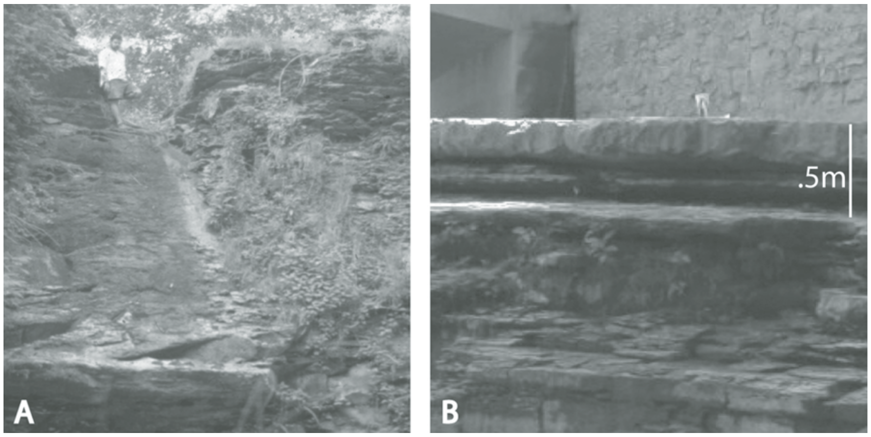

Figure 9. Basal limestone unit (3rd-order TST) of the Skaneateles Formation in New York. A- Mottville Member in Rattlesnake Gulf, N.Y., note person for scale; B- Stafford Limestone in Oakta Creek, LeRoy, N.Y., upper limestone bed is ~30cm thick.

conodonts as near the base of the *hemiansatus* conodont zone (Uyeno pers. comm. as reported in Sparling 1988).

The identification of the basal TST of the Skaneateles sequence in the EFA region of Ohio has been a major focus of this study. This portion of the Skaneateles sequence has gone undetected in cores and is exposed only at one locality near Sandusky, Ohio, in the Parkertown Quarry. Conkin (1984) described the section at the Parkertown Quarry in detail, noting that the upper ~3.25m of the section consists of grainstones and more argillaceous limestones. The lower-most portion of this interval is about 1.75m thick containing the distinctive brachiopods *Tropidoleptus carinatus*, *Orthospirifer* cf. *euryteines*, and *Devonochonetes* cf. *D. coronatus* with a "hardground" on the upper surface. Above this is a more argillaceous interval with *Zoophycos* bioturbation, abundant small chonetids and *Mucrospirifer*, capped by a more resistant bed containing cystiphyllid corals. Conkin identified the portion of the section above the "hardground" as the lower-most part of the Silica Formation. The brachiopod fauna reported by Conkin from this section is very much like that reported from other exposures of the basal TST of the Skaneateles sequence in WFA Ohio ("Blue Beds" of the Silica Formation) and southeastern Indiana (Swanville Member of the North Vernon Formation).

Sparling (1995), also examined the section at the top of the Parkertown Quarry, where he described ~1.2 m of interbedded limestone and shale as belonging to the Plum Brook Shale. Sparling's section consisted of a 26cm-thick, arenaceous limestone bed overlain by ~35cm of gray shale. Above this is ~35cm of interbedded limestone and shale overlain by a 20cm limestone at the top of the exposure. The lowest bed yielded a conodont assemblage indicative of the lowermost Givetian *hemiansatus* conodont zone. It is important to note that most of the conodont elements from this bed were described as being "silt-encrusted" indicating that they are perhaps reworked to some extent indicating erosion/condensation below this interval. The sequence identified by Sparling as belonging to the Plum Brook Shale is roughly equivalent to the upper portion of Conkin's section, beginning at the "hardground". The sequence identified by Conkin and Conkin (1984) and Sparling (1995) at the Parkertown Quarry is herein placed at the base of the Plum Brook Shale as the "Parkertown Member" of the Plum Brook Formation and recognized as representing the third-order TST portion of the Skaneateles sequence in the EFA Ohio region.

The basal TST of the Skaneateles sequence is positively identified in the WFA region of Ohio as the basal beds of the Silica Shale (Fig. 11, 10), corresponding to the "Blue Beds" of older terminology (units 1 through 6 of Stewart 1927). The "Blue Beds" consist of ~2.65m of interbedded grainstone, packstone, and argillaceous limestone containing numerous rugose corals and large brachiopods. The lower portion of the "Blue Beds" (units 1 through 3) overlies a cryptic disconformity (representing the basal Skaneateles sequence boundary) on top of the Dundee Formation and consists of fossiliferous, crinoidal grainstone containing an abundance of *Devonochonetes coronatus*, *Tropidoleptus carinatus*, *Hexagonaria*, and *Heliophyllum*. Overlying the lower "Blue Beds" is an unfossiliferous, discontinuous calcareous shale unit up to 15cm thick (bed 4). Overlying the discontinuous shale unit is a package of fossilierous packstone (units 5 & 6) that contain an abundance of the brachiopod "*Spirifer*" *euryteines*. The conodont *Icriodus latericrescens latericrescens* has also been identified in the lower beds of the Silica Formation (Klapper and Ziegler 1967), again indicating placement near the base of the *hemiansatus* conodont Zone and corroborating correlation with the basal Skaneateles Formation. The remainder of the Mottville-equivalent strata is encompassed in Silica units 7-8, a calcareous shale interval thought to be equivalent to the Cole Hill submember.

HST.--In central New York State, the HST of the Skaneateles

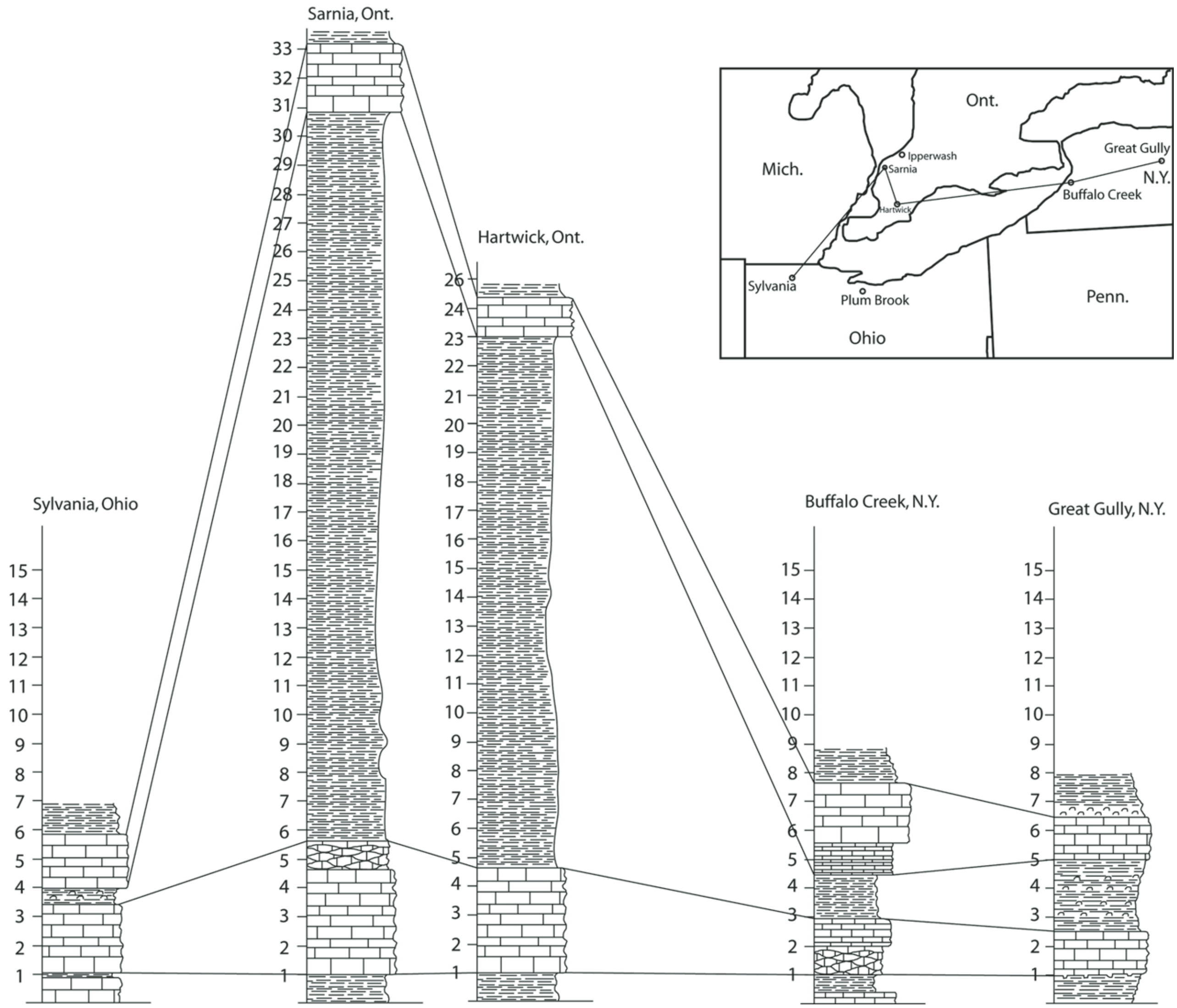

Figure 10. Cross-section showing the change in thickness of different beds of the 3rd-order TST of the Skaneateles Sequence in New York, Ontario, and Ohio. Scale in feet.

sequence contains four 4th-order sub-sequences represented by the Delphi Station, Pompey, and Butternut members and portions of each 4th-order sub-sequence are identifiable in all areas. Each of these, as presently defined, commences with thin (0.5 to 5 m) fossiliferous, calcareous siltstones, concretionary limestones or biostromes, which are overlain by a thicker (5-30 m), coarsening upward shale to siltstone succession. The thin basal concretionary carbonates of each cycle have been recently traced into the Levanna Shale of western New York (Baird et al. 1999, 2000).

HST: Subsequence IIIB; Delphi Station, lower Arkona Shale, lower Plum Brook Shale, Silica Shale units 7-13.-- The Delphi Station Member is the lowest of the 4th-order sub-sequences within the Skaneateles HST (Fig. 8) and begins with a thin, silty, auloporid-rich bed containing rare small rugose corals, brachiopods, and mollusks representing the TST of this sub-sequence. This unnamed, shell-rich bed lies at the top of the Cole Hill sub-member of the Mottville Member in central New York State. Above this horizon the Delphi Station Member in central New York State consists of ~15m to 50m of shale that coarsens upward to a calcareous silty-sandstone near its top.

In southwestern Ontario the strata representing the Delphi Station sub-sequence compose the middle portions of the Arkona Formation and are known largely from the subsurface (Fig. 12). In a core from Sarnia, the Delphi Station sub-sequence is represented by ~10.5m of barren dark-gray mudstone with a few pyritic burrows scattered throughout. The base of the Delphi Station sub-sequence is marked by a shell-rich zone a few centimeters thick with the brachiopod *Mucrospirifer* and various bryozoans.

In EFA Ohio, the Delphi Station sub-sequence is currently identifiable with certainty only in the subsurface from cores

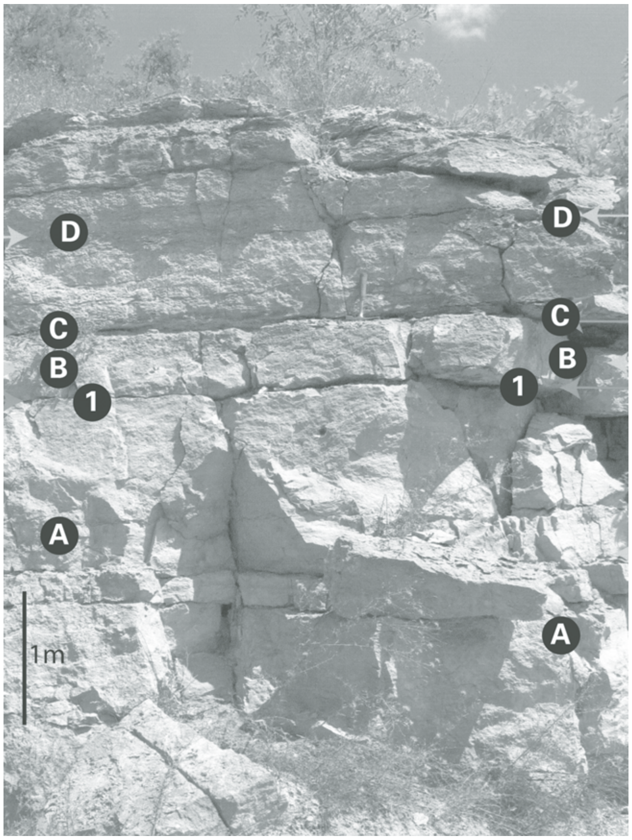

Figure 11. Upper portion of the Dundee Limestone and the lower portion of the overlying Silica Shale at the Medusa North Quarry near Sylvania, Ohio. "A" marks the top-most bed of the Dundee Limestone; "1" marks the contact between the Dundee and Silica; "B" marks the lowest bed (bed 1) of the Silica Shale; "C" marks the thin shale bed; "D" marks the upper "Blue Beds" of the Silica Shale. Note hammer for scale at "C".

near the type section where it is represented by the basal portion of the Plum Brook Formation. Strata representing the Delphi Station sub-sequence consist of ~7m of fine-grained, dark-gray mudstone with a few thin shell beds that coarsen upward into more calcareous mudstone, with a greater concentration of shell material near the top of the sequence (Fig. 8).

In WFA Ohio, the strata representing the Delphi Station sub-sequence are identified as units 7 through 13 of the Silica Formation (Figs. 8, 13). This interval includes beds containing the bulk of the renowned well-preserved fauna of the Silica Formation. These strata are composed of ~5m of interbedded shell-rich limestone and blue-gray shale that have a greater concentration of shell beds in the upper portion of the unit. The base of this unit contains several shell-rich beds (unit 7) interpreted as the TST of this sub-sequence, the equivalent of the unnamed auloporid rich beds in Ontario and the shell bed above the Cole Hill cycle in New York

HST: Sub-sequence IIIC. Pompey Member, upper Arkona Shale, upper Plum Brook Shale, Silica Shale units 14-18.-- The next 4th-order sub-sequence of the Skaneateles sequence is represented in New York State by the Pompey Member. The Pompey Member consists of sparsely-fossiliferous dark- to medium-gray shale with scattered shells of mainly chonetid brachiopods throughout and displays an overall westward thickening pattern across the state. The Pompey Member coarsens upward into arenaceous mudstones and silty-sandstones near the top. The base of the Pompey Member is marked by two distinct limestone beds that are traceable over much of New York State, the Paper Mill and Pole Bridge beds, interpreted to represent the TST of this sub-sequence. The Paper Mill Bed is a prominent ~0.7m-thick limestone bed that caps several waterfalls across New York (Figs. 8, 13). The fauna of the Paper Mill Bed is rather sparse in western New York, including auloporid corals, small bivalves and mollusks. Eastward, in central New York, the Paper Mill Bed contains a more diverse fauna of brachiopods such as *Pseudoatrypa, Rhipidomella,* and *Devonochonetes coronatus,* as well as small rugose corals. Overlying the Paper Mill Bed is about 1.5m of shale capped by the Pole Bridge Bed. The Pole Bridge Bed consists of two ~20cm-thick shell-rich limestones with abundant specimens of the brachiopod *Ambocoelia*, as well as the rugose coral *Stereolasma* and the trilobite *Phacops*. Together, the Paper Mill and Pole Bridge beds, along with the intervening shaly interval, display a back-stepping pattern consistent with their interpretation as a TST (Fig. 10). The upper Pole Bridge Bed is overlain by dark gray, platy shales with abundant tasmanitids. A third condensed molluscan and ambocoeliid-rich shell hash bed, termed the Wadsworth bed (Baird et al. 2000) occurs about 6.5 m (20') above the Pole Bridge bed in western New York. It is unclear whether the Wadsworth bed is traceable eastward, into the Pompey succession. Thus, at present, the Wadsworth horizon is treated as a bed within the Pompey Member. However, Baird et al. (2000) suggested that this bed overlies a major submarine erosion surface that truncates underlying shales and perhaps the Pole Bridge and Papermill beds westward. If so, the Wadsworth bed may reflect an additional major (4th order) cycle in the Skaneateles Formation; it is significant that this bed also appears to be present in Ontario (see below). The higher shales of the Pompey Member comprise 10 to 25 m of sparsely fossilferous dark gray shale, characterized by chonetid and ambocoeliid brachiopods and small bivalves; a concretionary interval high in the Pompey in central New York yields a distinct pyritized fauna of small cephalopods, including *Tornoceras (T.) arkonense* and *Bactrites arkonense*.

The Pompey sub-sequence is identifiable in Ontario as the upper portion of the Arkona Formation, which is exposed along the banks of the Ausable River at Arkona. Possibly equivalent to the lower part of this subsequence is a small exposure at "Lot 8," located at a meander cutoff of the

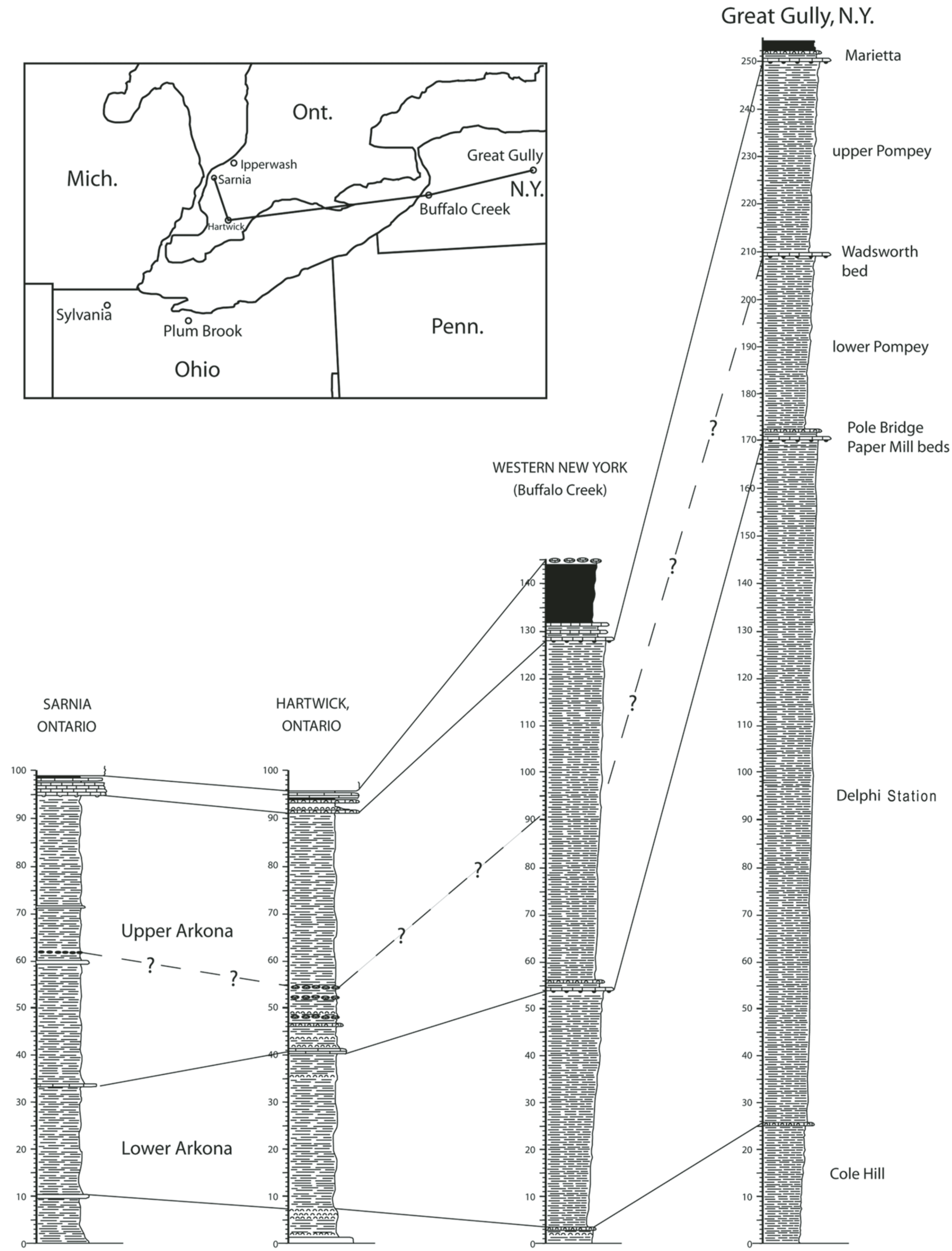

Figure 12. Cross-section showing the thinning of member scale units Skaneateles Formation across New York and the Arkona Shale across southwestern Ontario. Scale in feet.

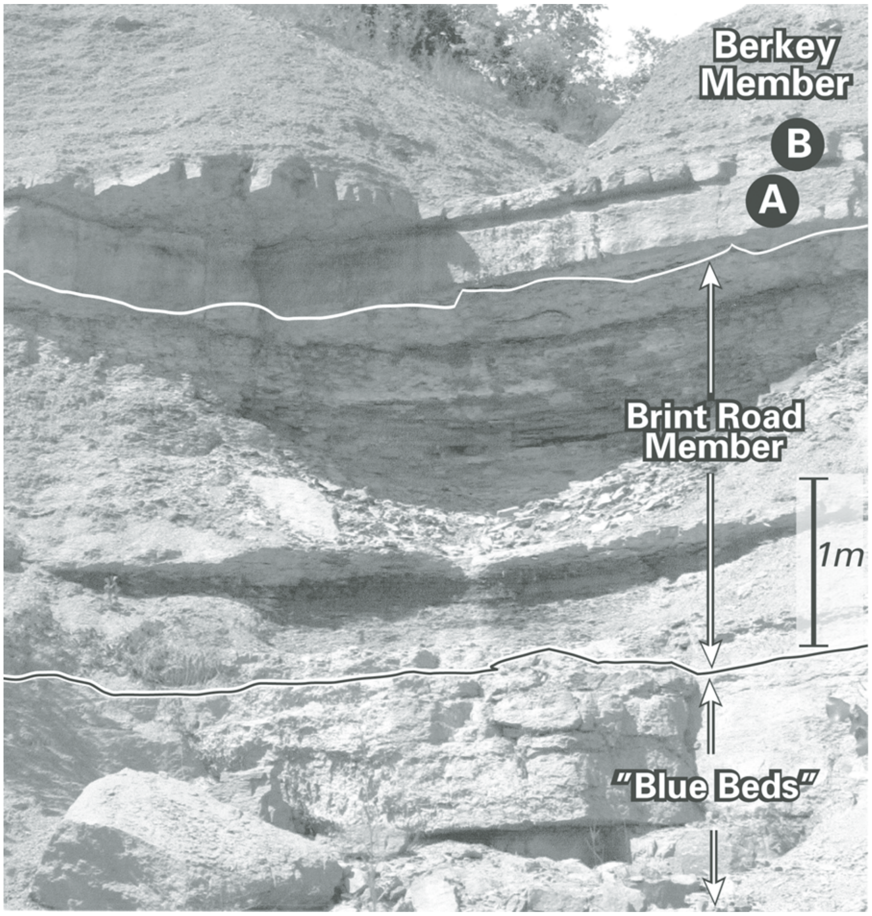

Figure 13. Lower-middle portion of the Silica Formation at the Medusa North Quarry near Sylvania, Ohio. Displayed are the upper portion of the "Blue Beds", the Brint Road Member, and the lower portion of the Berkey Member. Note the tripartite division of the lowermost Berkey Member with a basal grainstone ("A") displaying burrow-prods extending down into the upper-most shale bed of the Brint Road Member, overlying thin shale, and upper thin (~15cm) grainstone ("B"). An auloporid coral biostrome can be observed to encrust the above upper surface of "B" in the northern wall of the quarry.

Ausable River, approximately 5.5 km north-northeast of Arkona. Here, a < 0.5m interval of dark-gray mudstones with thin pavements of *Mucrospirifer* and *Arcuaminites*, is overlain by ~5m of medium-gray mudstones with scattered *Arcuaminites*. This succession may be equivalent to the Paper Mill/or Pole Bridge beds at the base of the Pompey, as suggested by subsurface correlation.

The next highest exposure of the Pompey sub-sequence is along the banks of the Ausable River just downstream from the mouth of Rock Glen (Fig. 14A). Exposed here are the "Black Beds" of previous workers (Stauffer 1915), which includes two shell-rich, dark-colored packages of calcareous silt containing auloporid corals, chonetids, and *Tentaculites*, each about 15-20cm thick. The "Black Beds" are interpreted to represent lateral equivalents the Wadsworth Bed of the New York sequence and may represent a smaller-scale (fifth-order) TST of this sub-sequence in Ontario, displaying a pattern of two shell-rich beds separated by a thin shale demonstrating a back-stepping pattern.

Directly overlying the upper siltstone unit is a distinctive, 2-5 cm thick, black-colored, phosphatized shell hash bed chiefly composed of *Mucrospirifer* debris. Many of the contained shell fragments are very well-rounded, indicating long-term abrasion, and probably repeated episodes of reworking with minimal sediment input. Highly abraded and bored shells of *Spinocyrtia*, and fragmented placoderm remains are also abundant in this bed. The low rates of sedimentation implied for this bed, together with its high phosphate content, and its position above the small-scale TST suggest that it represents a maximum flooding surface. Though this package represents a minor sea level rise, the lateral equivalent in New York can be traced widely (Fig. 8) and overlies a distinct unconformity that removes the upper portion of the underlying Delphi Station Member across the western portions of the state.

The "Black Beds" package is overlain by ~9 meters of moderately to poorly fossiliferous, blue-gray shale. This interval accounts for the bulk of the exposed Arkona Formation and are also identifiable in the subsurface of

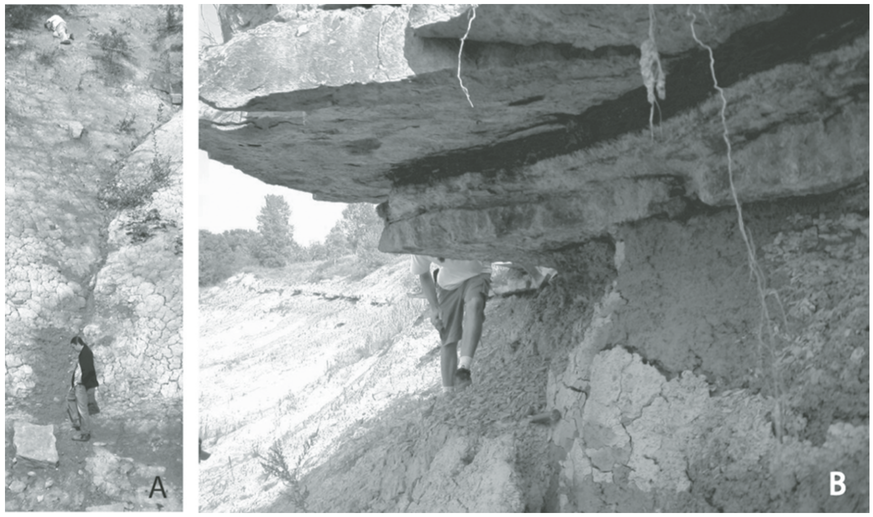

Figure 14. Upper portion of the Arkona Shale in southwestern Ontario. "A" shows the lowest exposed portion of the Arkona Shale along the Ausable River at Rock Glen Conservation Area. "B" shows the uppermost portion of the Arkona Shale exposed in the clay pits at Thedford displaying the upper limestone beds and overlying thin black shale containing an abundance of leiorhynchid brachiopods. The limestone overlying the black shale is the basal portion of the Hungry Hollow Formaiton.

Ontario. The lowest ~3m of this interval contain a few thin stringers and lenticular beds of concentrated shell material, dominated by remains of *Tentaculites*, the brachiopods *Mucrospirifer* and *Arcuaminetes*, and an assortment of pelmatozoans. The remainder of the interval is poorly fossiliferous, chiefly yielding scattered pyrite steinkerns of diminutive bivalves and cephalopods (*T.(T.) arkonense* and *B. arkonense*; Fig. 15).

In EFA Ohio, the Pompey sub-sequence accounts for the bulk of the thickness of the Plum Brook Formation, although it is very poorly exposed in the type area (Fig. 8). Possibly coeval mudstone exposures are present near Delaware, Ohio, where the sub-sequence has been identified as the "Lower Olentangy Shale". The Pompey sub-sequence occupies the major portion of the Plum Brook Formation and consists of ~16 m of dark-gray mudstone with scattered pyrite burrows and a few small shells, some of which are pyritized, including *B. arkonense*. The "Lower Olentangy Shale" is up to ~4m thick and is composed of light- to dark-gray mudstones with scattered pyritized burrows and shells, including *T.(T.) arkonense* and *B. arkonense*. The "Lower

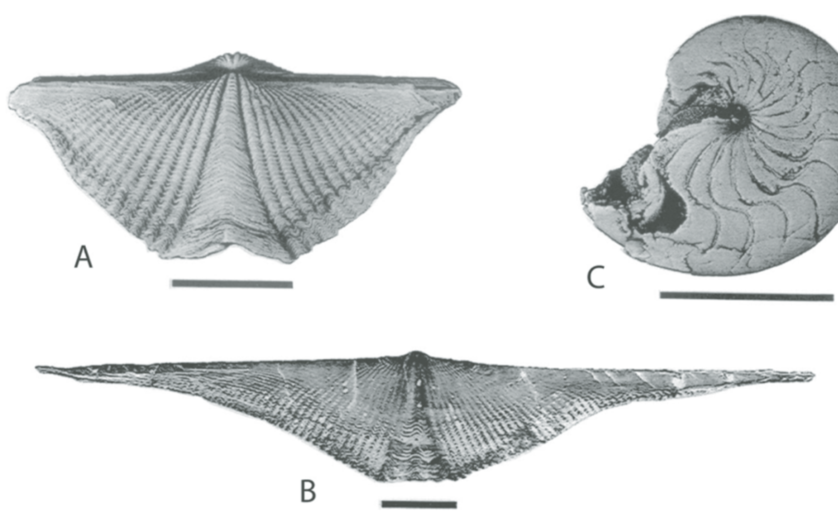

Figure 15. Figure showing fossils from the Arkona and Widder formations of southwestern Ontario. A- "Mucrospirifer" thedfordensis from the "Rock Glen" member of the Widder Formation; B- Mucrospirifer arkonensis from the Arkona Shale; C- Tornoceras (T.) akonense from the Arkona Shale. T.(T.) arkonense is also found in the Plum Brook, "lower Olentangy", and Silica shales of Ohio, and the Pompey Member of the Skaneateles Formation of New York. Black scale bar is 1cm in all pictures.

Olentangy Shale" rests on a discontinuity surface at the top of the Delaware Limestone and the underlying units of the Skaneateles sequence have yet to be positively identified here' they are most likely missing due to erosion. It is in turn, overlain by a major unconformity (Taghanic Unconformity) and succeeding strata of the "upper Olentangy Shale" of late Frasnian age (Fuentes, Over, and Brett 2001).

The Pompey sub-sequence is identified in WFA Ohio as containing beds 14-18 of the Silica Formation. Units 14-17 consist of two thin limestone bands and an intervening shale bed, the lower bed shows a marked discontinuity at its base with exichnial burrows projecting down ~3cm into the underlying shale (Fig. 14). This disconformity is clearly erosional as it locally truncates underlying unit 13 in the Sylvania area; it is herein interpreted as the sub-sequence boundary. Above this basal limestone is ~30cm of blue-gray shale (unit 15) above followed by a double bed (units 16-17) limestone somewhat shalier than the basal bed, rich in the brachiopod *Ambocoelia* (Fig. 13). The upper surface of this limestone is encrusted with auloporid corals, a biostrome of which extends up to ~5m into the overlying shales. These beds collectively are thought to represents the lateral equivalent of the Paper Mill and Pole Bridge TST package and they display the distinctive back-stepping pattern of these units. Overlying these limestones is the thickest siliciclastic unit of the Silica Formation. This unit (18) includes 6.5m of medium-gray very sparsely fossiliferous shale, with the only fossils consisting of auloporid corals and small, thin-shelled brachiopods (Figs. 15b, 10).

HST: Sub-sequence III D. Butternut Member; uppermost Arkona Shale, upper Plum Brook Shale, Silica Shale units 19-22.-- The uppermost 4th-order sub-sequence of the Skaneateles sequence is represented in New York State by the Butternut Member (Figs. 7, 15b). This unit represents the deepest-water conditions recorded in the Skaneateles sequence, being represented in New York by 3-40m of dark-gray to black shale, often containing few if any body fossils, with a fauna consisting primarily of leiorhynchid brachiopods and cephalopods. The Butternut Member begins with a package of shell-rich limestones, informally termed the Marrietta submember (Baird et al. 2000). These beds contain a moderately diverse fauna, including the brachiopods *Arcuaminetes*, *Ambocoelia*, *Mucrospirifer*, *Athyris* and *Rhipidomella*, as well as auloporid and rare rugose corals. These beds are interpreted as the TST of the Butternut sub-sequence. The Butternut Member thins markedly westward from 80m near Cazenovia to only ~3m in Seneca County (Baird et al. 1999). Its thickness in Erie County, New York is not precisely known due to poor exposures in that area.

The Butternut sub-sequence is represented in Ontario by a very thin, condensed package of limestone and shale previously assigned to the lowermost beds of the Hungry Hollow Formation (Fig. 12, 14B; sensu Mitchell 1967). These beds had originally been placed at the top of the "Arkona Formation" (Cooper and Warthin 1942) and this definition is revived due to consistency of stratal and faunal patterns, and is also in accordance with Uyeno et al. (1982). The basal bed of the upper Arkona interval, herein termed the Tile Yard Bed for exposures in the old tile yard of the Parkhill Brick Company at Thedford, Ontario, is a 5-10cm-thick limestone bed that sharply overlies the dark gray mudstones of the Pompey subsequence. As described by Landing and Brett (1987), the base of the Tile Yard bed (then considered lowermost Hungry Hollow) bears very large *Cruziana* and *Rusophycus* burrows (similar to those at the bases of units 14 and 19 of the Silica Formation) that reach up to 10 cm in width and preserve fine scratch marks on their walls. The preservation of scratch marks in these hypichial burrows indicates that the burrows must have been excavated in a mud firmground that, in turn, could have only existed after the seafloor had been stripped of several meters of soft, uncompacted mud. Thus, the sharp basal contact of the Butternut subsequence, as preserved in southwestern Ontario, necessarily records a significant discontinuity (Fig. 16) and represents the 4th-order sequence boundary of the Butternut subsequence.

Supporting the interpretation that significant erosion took place at the beginning of the Butternut cycle, the lower part of the Tile Yard bed (<5 cm thick) is a lag deposit of fish remains and pebbles of reworked limestone (Fig. 14B). Components of the lag are severely abraded and bored, indicating prolonged exposure on the seafloor, and therefore very low rates of sedimentation. The upper part of the Tile Yard bed (styliolinid wackestone to packstone), marks renewed sedimentation under dysoxic conditions. The Tile Yard bed, taken as a whole, is interpreted to represent the TST of the Butternut sub-sequence in Ontario and deemed equivalent to the Marietta Beds of New York.

Directly overlying the Tile Yard bed are a few centimeters of gray, calcareous mudstone containing *Eumetabolotoechia*, *Mucrospirifer*, and *Arcuaminites* that, in turn, grade upward into a thin (~10 cm) unit of weakly calcareous, laminated black shale with profuse *Eumetabolotoechia*. Thus, the upper part of this interval records a continued, but relatively small, influx of muds with a concomitant decrease in carbonate deposition, and is interpreted here as the HST of the Butternut subsequence; that this shaly unit is exceptionally thin fits well with the pattern of westward thinning displayed by the Butternut Member (Fig. 12).

The Butternut sub-sequence is identified in EFA Ohio as embracing the moderately well-exposed upper beds of the Plum Brook Formation (Figs. 8). In the Plum Brook Formation, the lower part of subsequence consists of a series of micritic limestones, about 30cm thick, with interbeds of thin shell-rich limestone and barren dark-gray shale. The shell-rich limestones contain taxa in common with the

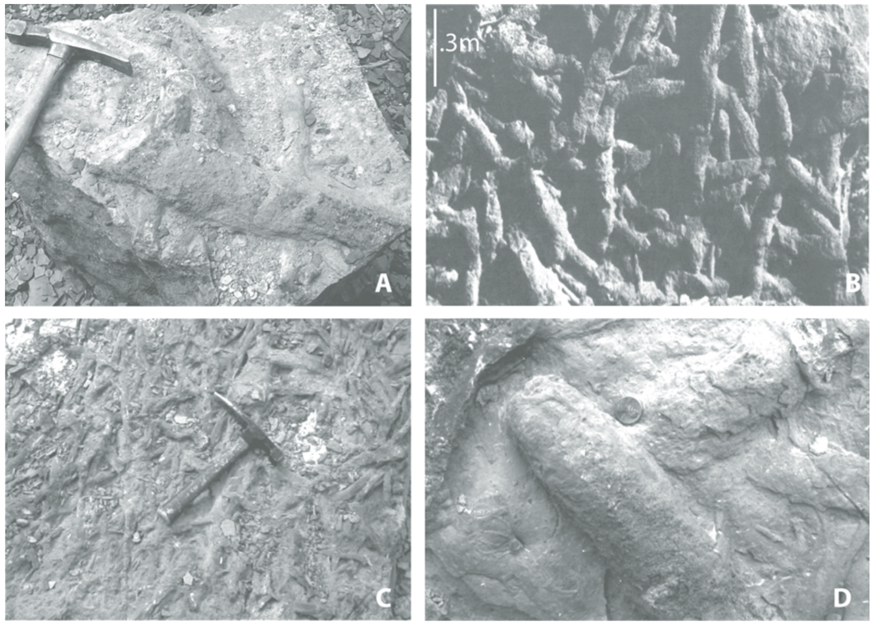

Figure 16. Examples of exichnial burrow-prods from various units across the study area. A- base of Tichenor Member of the Moscow Formation at Highland-on-the-Lake, New York; B- base of the Berkey Member of the Silica Shale at Silvania, Ohio (prods are ~5cm across); C- base of "Tile Yard member" of the Arkona Formation of Thedford, Ontario; D- base of the Ipperwash Member of the "Sarnia Formation" of Thedford, Ontario.

Marietta interval of New York and are correlated with these beds as the TST of this sub-sequence in EFA Ohio. The upper shaly beds contain an abundance of the brachiopod *Eumetabolotoechia kellogi*, much like the Butternut Member shales in New York and Ontario. This portion of the Skaneateles sequence is missing from the Delaware, Ohio area where erosion under the Taghanic Unconformity has removed all units down to the Pompey sub-sequence represented by the "Lower Olentangy Shale".

In WFA Ohio the Butternut sub-sequence is represented by beds 19-29 of the Silica Formation (Fig. 17). The Butternut sub-sequence here is ~2.25m thick and consists of interbedded shell-rich limestones and dark gray shales. This portion of the formation begins with another package of shell-rich limestones correlated with the Marietta interval of New York, again with burrow-prods at the base indicating a discontinuity beneath the basal TST of the sub-sequence (Figs. 8, 16). This unit appears to be nearly identical to the Tile Yard bed at Arkona, Ontario. The upper beds are shalier, contain an abundance of the brachiopod *Eumetabolotoechia kellogi* in some beds, and are correlated with the overlying Butternut Member shales of New York and the upper portion of the Plum Brook Formation of EFA Ohio. This unit is herein removed from the upper portion of the Berkey Member of Mitchell (1967) and defined as the Medusa North Member, named for excellent exposures in the old Medusa North Quarry at Silica.

FSST: Subsequence IIIE Chenango- "Lower Centerfield" Submember; uppermost Plum Brook Shale; Silica Shale units 25-19.-- A thin, but distinctive shell hash bed, the Peppermill Gulf bed, was used to define the base of the Chenango submember, a 10-15 m thick, coarsening upward package of silty shale and siltstones in central New York State (Gray 1991). The Chenango is laterally equivalent to a thin (1.4 to 5m), shallowing-upward succession of dark shales, highly fossiliferous, gray, calcareous mudstones and thin skeletal limestones, including coral biostromes, previously assigned to the lower part of the Centerfield Member of the Ludlowville Formation (Fig. 18A). However, these beds and the Chenango underlie the sharp basal contact of the main Centerfield limestones and laterally equivalent Stone Mill Limestone, interpreted as a sequence boundary. Thus, in sequence stratigraphic terms, the "lower Centerfield" and equivalent Chenango submembers belong with the Skaneateles sequence and are interpreted as recording a forced regression, echoing the earlier view of Smith (1935). The sharp basal contact of the Peppermill Gulf bed is both a minor (4^{th} order) sequence boundary and a forced regression surface; the condensed shell bed itself has been termed a "precursor" bed (Brett 1995; Brett and Baird 1996), as it shows evidence of abrupt shallowing with respect to underlying black shales; it lies at the base of an abrupt shallowing upward succession interpreted as the falling stage systems tract of the third order Skaneateles sequence. Faunal changes in western New York suggest shallowing by tens of meters, recorded in a very thin succession (Figs. 18A). The coarsening upward Chenango Siltstone is interpreted as a rapid progradation of coarse siliciclastics triggered by decreased accommodation space during forced regression.

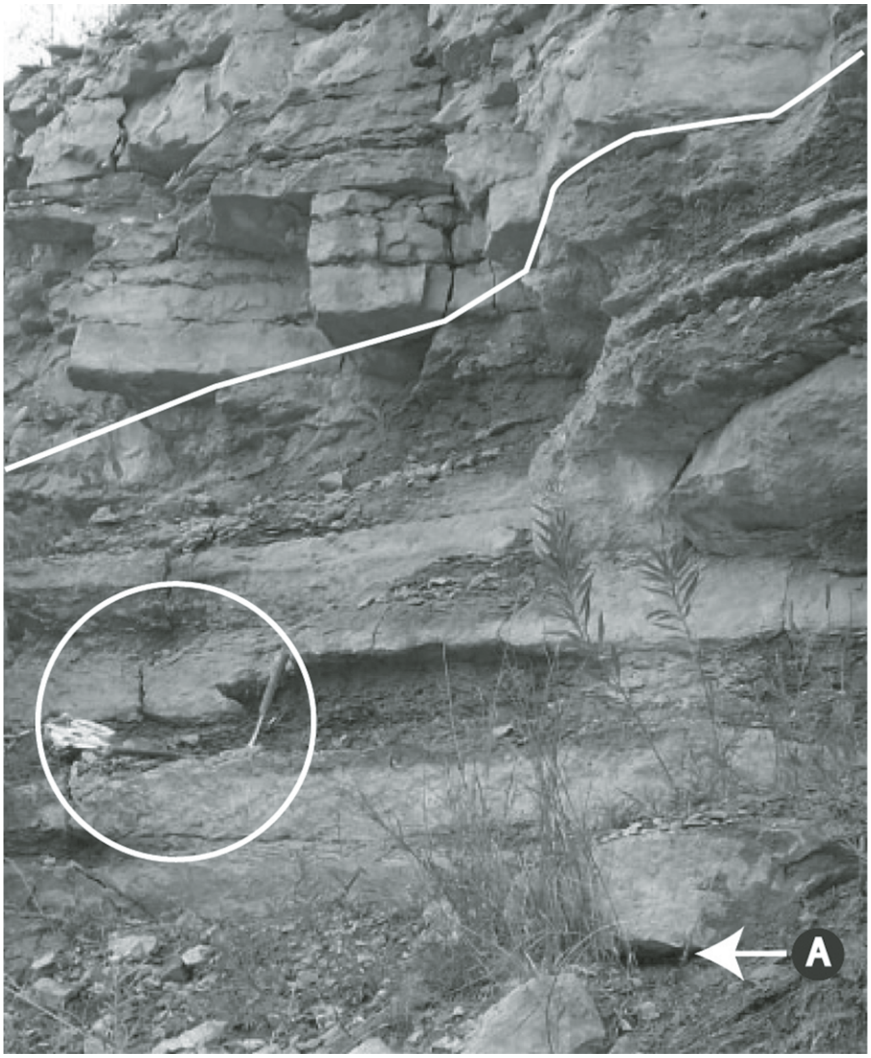

Figure 17. Upper-most portion of the Silica Shale at the Medusa North Quarry near Sylvania, Ohio. Beds above the thick shale (unit 18) and below the Ten Mile Creek Dolomite are herein removed from the upper portion of the Berkey Member and named the "Medusa North Member" of the Silica Shale. This unit begins with a grainstone unit ("A") marked by burrow-prods that extend down from the base of the bed into the uppermost shale of the Berkey Member. The hammer and tape lie on a bed with abundant leiorhynchid brachiopods. The line marks the upper boundary of the Silica Shale with the overlying Ten Mile Creek Dolomite.

This final shallowing sequence is absent in Ontario where the basal bounding erosion surface of the Ludlowville Sequence has apparently removed these transitional beds, juxtaposing shallow water, coral-bearing limestones directly on a remnant of black shales equivalent to the Butternut Member.

However, in EFA Ohio a fossil rich bed near the top of the Plum Brook Shale appears to represent the Peppermill Gulf bed. It lies slightly below the sharp basal erosion surface of the Prout Limestone (Fig. 8). Also, in WFA Ohio the Peppermill Gulf bed may be represented in a fossiliferous argillaceous limestone, bed 25, which rests sharply upon dark Eumetabolotoechia-rich shales. Again, the upper part of the transition is removed by erosion beneath the Ten Mile Creek Dolostone (Fig. 8).

Sequence IV. Ludlowvville Formation

The Ludlowville Formation represents the next higher 3rd-order depositional sequence. Like the Skaneateles, the Ludlowville has a thin, persistent carbonate-rich interval (Centerfield Member) at its base; this basal unit represents the 3rd-order TST of the sequence and can be considered analogous to the Mottville Member (Fig. 4). The shaly portion of the Ludlowville Formation overlying the Centerfield Member in central New York represents the 3rd-order HST of this sequence and can be subdivided into a series of six 4th-order sub-sequences in the Ledyard-Otisco (lower and upper submembers), Wanakah-Ivy Point (lower and upper submembers), Spafford, and Jaycox members. As with the Skaneateles subsequences these are represented in central and eastern New York State by thin, shell- and

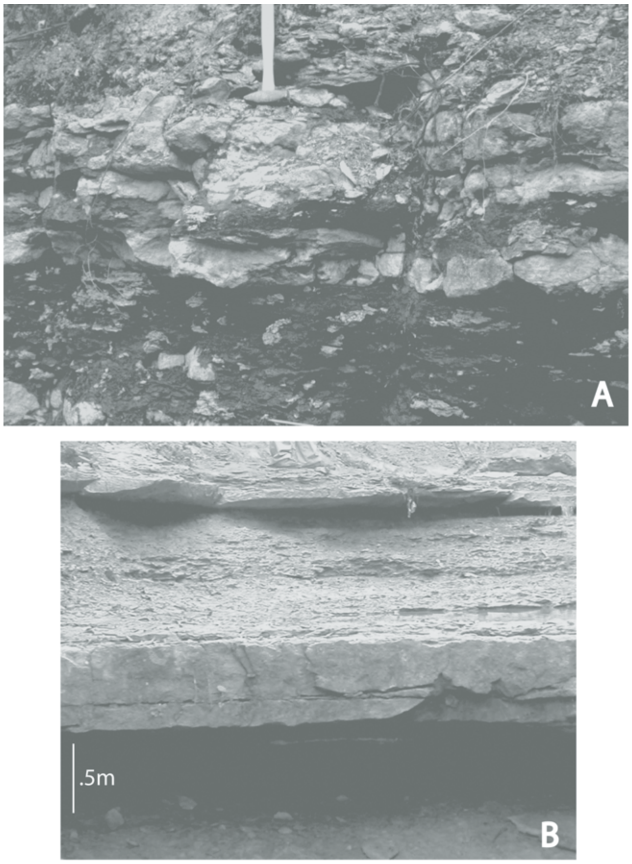

Figure 18. Pictures showing the basal limestone units (3rd-order TST's) of the Ludlowville and Widder Formations. A- Centerfield Limestone Member at Browns Creek, York, N.Y.; B- Hungry Hollow member at Rock Glen, Ontario.

coral-rich intervals that are abruptly overlain by shales which, in turn, coarsen-upward to siltstones and sandstones. The thin, transgressive, shell rich beds and concretionary carbonates are traceable into western New York where they separate intervals of dark to medium gray shales and mudstones.

In Ontario, deposits of the Ludlowville 3rd-order sequence are represented in the Widder Formation. As defined by Stauffer (1915), the Widder Formation embraced all strata between the base of the Hungry Hollow limestone and the base of the Ipperwash limestone. Based on stratal and faunal continuity within the succession, the upper boundary of this unit is herein redefined to lie at the base of the former "upper Ipperwash". Thus, the Petrolia and lower and middle Ipperwash of previous workers are here included in the Widder Formation (Fig. 19). The Ludlowville sequence is poorly recorded in Ohio, although the basal TST, correlative with Centerfield Limestone is still recognizable in the Prout and Ten Mile Creek dolostones. Highstand portions of this sequence are so condensed and altered by dolomitization that individual components are difficult to recognize.

TST: Subsequence IVA: Centerfield-Hungry Hollow members; lower Prout; lower Ten Mile Creek formations.-- The Centerfield Limestone, *sensu stricto* is a thin (0.5 to 5m) but exceptionally fossiliferous, pack to grainstone; an eastward extension of this bed is the Stone Mill Limestone a coral-bearing crinoidal grainstone that rests sharply on the Chenango Siltstone. The basal contact of the main Centerfield limestone with underlying transitional facies (presently assigned to "lower Centerfield") is sharp, and locally slightly erosional in western New York and represents a combined sequence boundary and transgressive surface (ET surface; Fig. 18A). This limestone passes upward into an interval of calcareous mudstones and thin limestones replete with rugose and tabulate corals in western New York. The top of the Centerfield Member has been drawn at a thin, shelly, phosphatic pebble layer, the Moonshine Falls Bed, interpretable as a maximum flooding surface. This bed is abruptly overlain by dark to medium gray mudstone of the lower Ledyard Member; eastward, the Ledyard passes into silty shales and siltstones of the lower Otisco Member, represented by a basal coarsening-upward cycle, and capped by a rugose coral biostrome (Staghorn bed).

The Hungry Hollow Limestone of southwestern Ontario is herein given member-scale status at the base of the Widder Formation in accord with Stauffer's (1915) original definition. This unit, initially miscorrelated with the Tichenor Member of New York by Grabau (1899), was identified by Cooper and Warthin (1942) as being equivalent to the Centerfield Member on the basis of macrofauna; this is corroborated by conodont studies, which place both units in the *timorensis* Zone (Klapper 1971, 1981; Landing and Brett 1987; but see Sparling 1999 for a dissenting opinion).

As with the Centerfield, the Hungry Hollow is composed of two divisions: a lower crinoidal grainstone bed containing worn shell material and corals, and an upper, more argillaceous pack- to wackstone division abounding in rugose and tabulate corals known traditionally as the "coral zone." The coral zone appears to correlate with upper Centerfield coral biostrome in western New York (Fig. 18B; Donato 2002). A thin, pyrite-encrusted, phosphatic bed at the top of the "coral zone" appears to be a local correlative of the Moonshine Falls phosphate bed. In accordance with stratal pattern as defined in the Hamilton Group of New York State, the Hungry Hollow forms the major, 3rd-order, transgressive limestone at the base of the formation.

Correlation of the Centerfield Member (s.s.) with the basal two units of the Prout Limestone of EFA Ohio seems nearly certain, not only because of biostratigraphic evidence provided by conodonts, but because of the very high degree of macrofaunal similarity, including such distinctive faunal elements as *Fimbrispirifer venustus* and *Callipleura nobilis*, which are nearly restricted to the Centerfield (Stumm 1942). The basal coral-rich grainstone of the Prout probably links

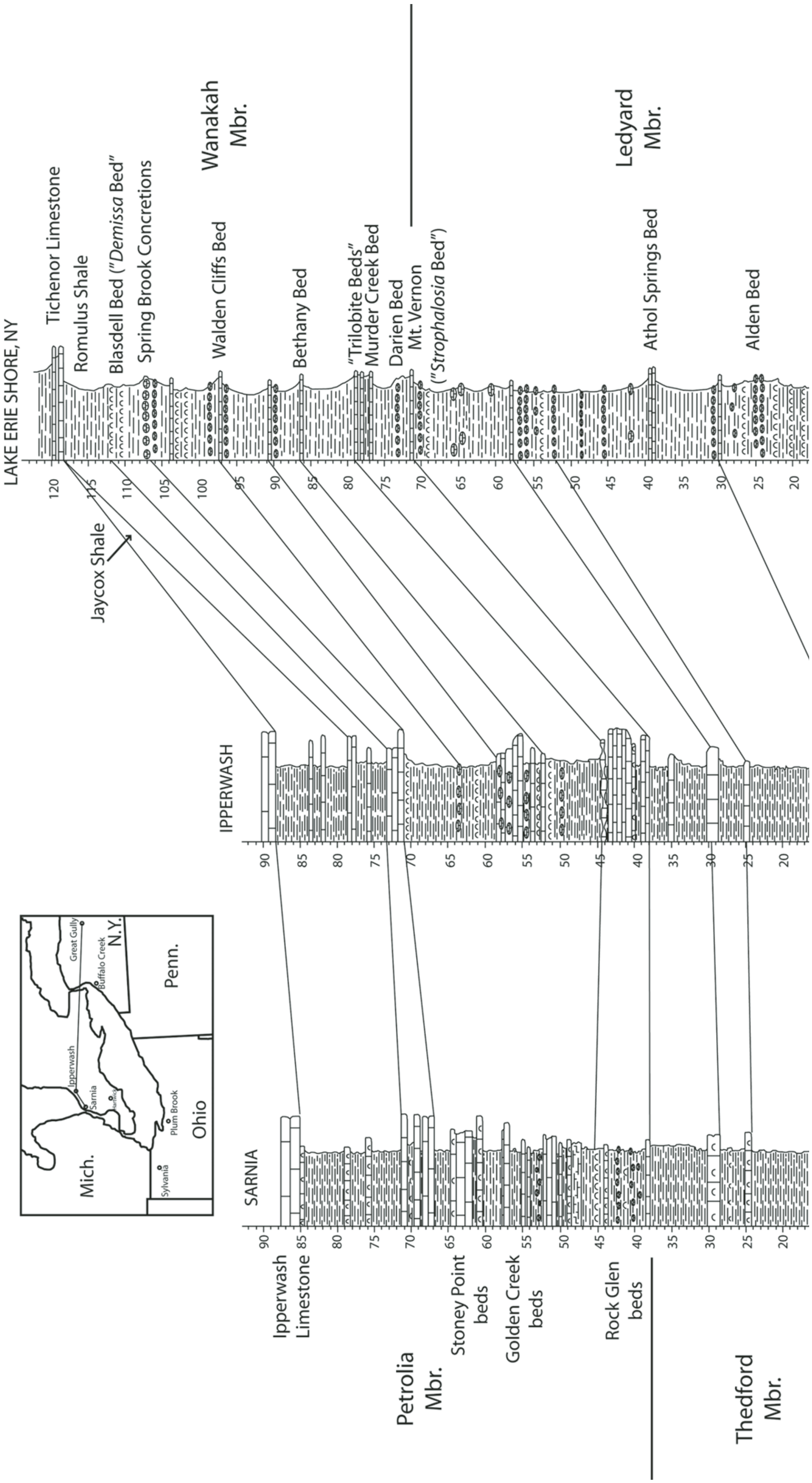

Figure 19. Cross-section showing change in thickness of units of the Ludlowville and Widder formations across New York and Ontario.

with the main Cenerfield Limestone, its sharp basal surface representing the Ludlowville sequence boundary. The shaly, coral-rich, succession that overlies this unit probably represents the upper Centerfield and upper Hungry Hollow biostromes.

In WFA Ohio the basal units of the Ten Mile Creek Dolostone also show a very high degree of similarity with the lower Prout, Hungry Hollow and Centerfield. Again a sharply erosive base of the lowest Ten Mile Creek forms the Ludlowville sequence boundary. Dolomitization has obscured details of most of the higher beds of the Ten Mile Creek. However, a less dolomitized area of this succession, formerly exposed at the Seaway Quarry south of Sylvania, has been noted to include an upper shaly coral biostrome with unique blastoids and the trilobite *Basidechenella rowi* that are typical of the upper Hungry Hollow Member (A. Fabian, personal communication 2004).

HST Subsequences IVB, C; Ledyard –Otisco Shale; lower Widder Formation.-- The Centerfield Member of New York is sharply overlain by 20 to 30 m of dark gray to black Ledyard Shale in western New York and its eastern lateral equivalent the, Otisco Shale in central N.Y.; this interval represents the 3rd-order HST of the Ludlowville sequence. The gray, fossiliferous Otisco Shale exhibits two slightly coarsening upward cycles. Each of these is based at a coral biostrome (Staghorn and Joshua submembers, Smith 1935), which sharply overlie erosional lag deposits rich in phosphatic pebbles, that, in turn, overly siltstones of the lower cycle (Fig. 19). The coral beds and associated phosphatic beds are interpreted as minor transgressive systems tracts.

The coeval Ledyard Shale in western New York (Fig. 20A) has not been formally subdivided, but McCollum (1991) recognized two informal submembers comprising two gray concretionary intervals separated by dark gray to black shale and styliolinid limestone (Fig. 19). Of particular interest is the Alden pyrite zone, a widespread pyritic nodule and fossil steinkern bed in the lower Ledyard that has yielded the distinctive goniatite *Tornoceras (T.)uniangulare*

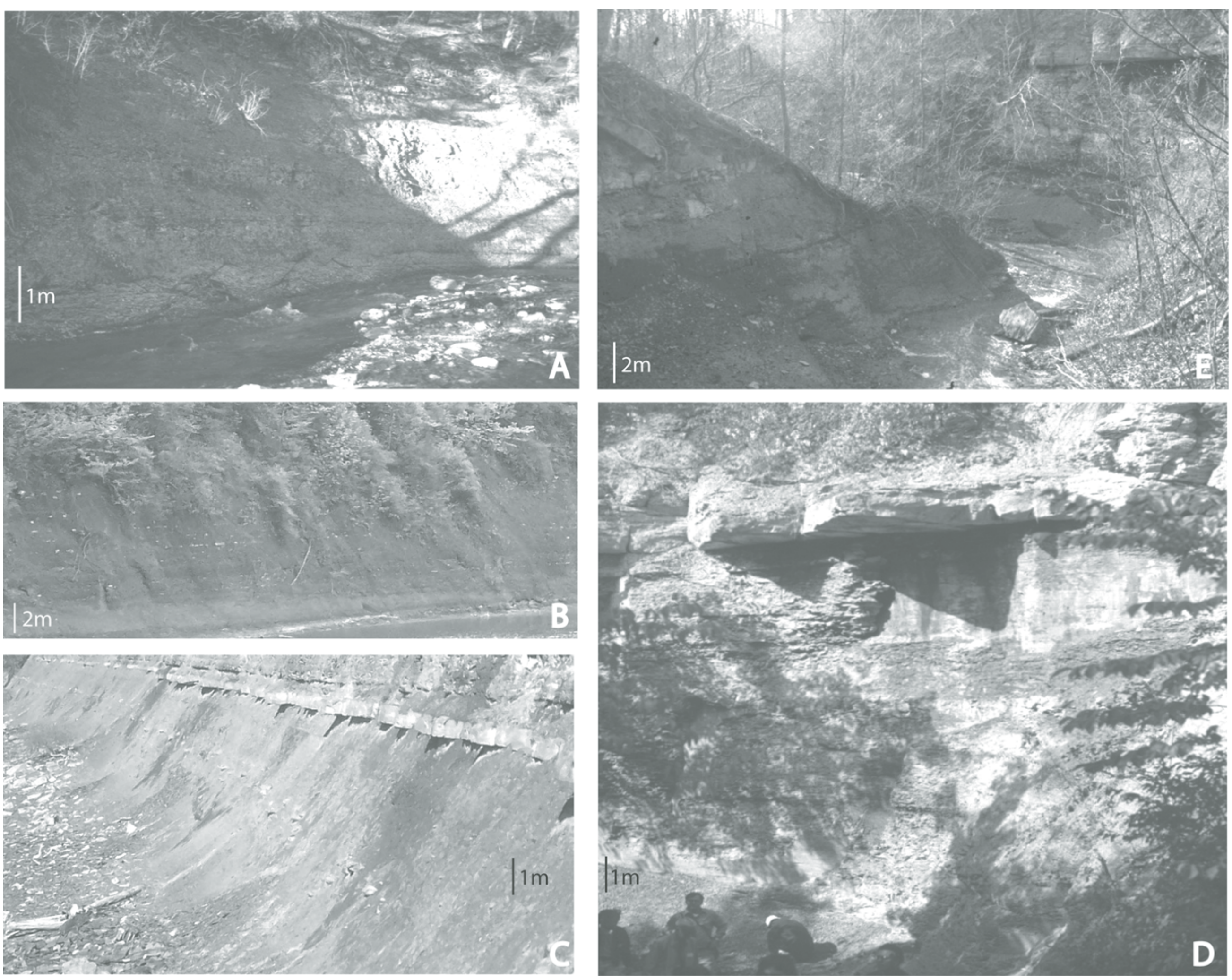

Figure 20. The main shale units of the Ludlowville Formation in New York State. A- Ledyard Shale; B/C- Wanakah Shale; D/E- Jaycox Shale.

widderi (House 1965). Rare spiriferid brachiopods have been collected in the lower shale below the Alden bed in western New York that resemble "*Mucrospirifer" thedfordensis*, a key taxon of the lower "Thedford member" of the Widder Formation in Ontario (Fig. 15) (G. Kloc, personal communication 2004).

The lower shale-rich portion of the Widder Formation represents the Ledyard-Otisco interval in southwestern Ontario (Fig. 19). This interval is well-exposed in tributaries of the Ausable River, including Rock Glen, Golden Creek, and the original railroad cut sections, all near Thedford, Ontario. It is herein referred to provisionally as the "Thedford member". This interval, corresponding to beds 1 through 14 of Wright and Wright (1961), is ~10 meters thick - approximately half the thickness of the Ledyard Member in western New York. The Thedford member consists of gray calcareous shale with leiorhynchid brachiopods, pyritized ammonoids, including *T. (T.) uniangulare widderi*, and an exceptional abundance of the brachiopods "*Mucrospirifer" thedfordensis, Arcuaminetes scitulus, Eumetabolotoechia* cf. *E. multicostum,*and the trilobite *Greenops* cf. *G. grabaui*. This morphotype of *Greenops* closely resembles those found in the Ledyard Shale of western New York. As with the Ledyard-Otisco shales, the Thedford member is characterized by two concretionary limestone beds separated by a pyritic shale interval. These two submembers may correspond to the two cycles of the Ledyard-Otisco interval (Fig. 19).

Equivalents of this succession are not securely recognized in the upper portions of the Prout or Ten Mile Creek formations in Ohio, although it is likely that shales and cherty micritic limestones in the lower Ten Mile Creek may be partial equivalents.

HST Subsequences III D, E, F: Wanakah Shale, lower-middle Widder Formation.-- Miller (1986, 1991) and Batt (1995) have made very high-resolution correlations of the Wanakah Member of western New York and recognized and correlated in detail at least four orders of cycles (Fig. 20B/C). The Wanakah Member cycles are marked at their bases by shell- and coral-rich beds. In central New York, these correspond to four (5 to 15 m scale) upward-coarsening cycles of the Ivy Point siltstone of which the lower and upper are by far the most prominent. The Ledyard-Otisco succession of New York is overlain sharply by a basal concretionary limestone to calcareous siltstone at the base of the Wanakah Member, the Mt. Vernon-Elmwood Point bed. This bed, typified by an epibole of the brachiopod *Truncalosia truncata* (Fig. 19), and formerly called the *"Strophalosia truncata"* bed by Grabau (1899), was used by Cooper (1933) to delimit the base of the Wanakah Shale in western New York. It is overlain by a distinct upward shallowing pattern which culminates in up to 10m of siltstone in the lower tongue of the Ivy Point Member in central New York. Dark, more sparsely fossiliferous shale of the middle Wanakah contains a second less well pronounced shallowing upward succession overlain by a shell rich interval. The major shell-rich beds (Mt. Vernon-Elmwood Point, Darien Center, Barnum, and Bloomer-Blasdell beds) each shows a back-stepping pattern. The middle and upper intervals of the Wanakah and Ivy Point are the finest grained and darkest shales, being represented by black *Eumetabolotoechia*-bearing shales in the central Finger Lakes trough.

The lower Wanakah (Darien Center submember Miller 1986, 1991) consists of highly fossiliferous shales and concretionary limestones, referred to as the "Pleurodictyum beds" by Grabau (1899) because of an abundance of this small tabulate coral. A coral biostrome, the Darien coral bed, overlies this interval and is inferred to represent the base of a transgressive succession. A backstepping pattern is apparent in the constituent argillaceous limestones, which are rich in small rugose corals and the trilobites *Phacops rana* and *Greenops grabaui* ("trilobite beds" of Grabau 1899; Murder Creek, Bidwell bed and Bethany bed of Kloc 1983; Miller 1991). These beds are overlain by dark shales that pass upward into a distinct concretionary unit (Walden Cliffs Bed), and in the east, into an upward coarsening succession (Barnum cycle). The middle part of the Wanakah Member contains a third and more prominent shallowing upward succession that corresponds to the upper tongue of Ivy Point siltstone.

Finally, the upper Wanakah, or Bloomer, submember commences with a pair of shell rich intervals, the lower and upper Blasdell beds (*Strophodonta demissa* and *Stictopora* beds of Grabau 1899) that pass upward into dark shale. In central New York the upper and lower Blasdell beds each overlie a minor coarsening upward shale-siltstone cycle. Overlying the upper Blasdell bed is the highest unit assigned to the Wanakah Shale that can be recognized throughout western New York. This unit, informally called the Romulus shale (Brett et al. 1986), consists of dark, sparsely fossiliferous shales, and is apparently truncated beneath another disconformity.

In southwestern Ontario, the detailed pattern of Wanakah-Ivy Point interval appears to match that of the upper part of the Widder Formation (Fig. 19; best discussed by Wright and Wright 1961), herein referred to as the Petrolia Member. As the unit is incompletely exposed in the type area, and is known primarily from drill cores, it has been rather ill-defined by previous authors. Stauffer (1915) used the term "Petrolia" to refer to shales and limestones below the "Ipperwash limestone". It is fairly clear that his concept of the Ipperwash included a chert-rich upper band, exposed at Silica Point near Ipperwash Beach. This is the "upper Ipperwash" of Wright and Wright (1963); we herein restrict the term Ipperwash to this upper bed and redefine Petrolia Member as the interval between bed 15 at the base of the informal Rock Glen submember and the base of the true Ipperwash. The Petrolia Member thus consists predominantly shales and argillaceous limestones (wackestones) with minor chert nodules, and includes beds of pack- to grainstone, formerly termed "lower Ipperwash"; see below). The Petrolia Member is subdivided into Rock Glen, Golden Creek, Stony Point, and upper submembers. Wright and Wright (1963) logged the Petrolia Member roughly in a series of poor exposures along Golden Creek near Thedford, Ontario and at the upper falls of an unnamed tributary of the Ausable River near Jura Line Road, a locality traditionally known as "Number Four Hill" (Wright and Wright 1961).

Above the "Thedford member" shales are a series of beds consisting of argillaceous limestones and fossil-rich shales. These beds were formally well exposed along railroad cuts near the village of Widder, where the original type locality of Stauffer (1915) was located; unfortunately these sections are now largely covered. This unit is well exposed in the falls at "Number Four Hill" and in the upper falls at the Rock Glen Conservation Area, for which this distinctive interval is informally named. Corresponding to beds 15 through 22 of Wright and Wright (1961), the Rock Glen submember is ~3.8 meters thick and consists of shell-rich, crinoidal packstone/grainstone beds (each approximately 15-50cm thick) that alternate with thinner beds of soft, gray, calcareous shales containing brachiopods and auloporid corals (Fig. 19). A thin, fossiliferous limestone with phosphatic pebbles, together with an overlying shale unit containing an *Aulocystis* biostrome within unit 14, are thought to correlate with the base of the Wanakah (Elmwood Point bed) succession. This interval, originally recognized by Wright and Wright (1961), was found to be traceable in the Ontario subsurface at least to Sarnia. Wright and Wright's units 15-16 appear to record an upward shallowing succession, corresponding to the lowest Wanakah Shale cycle. Unit 17 is a massive, fine-grained, limestone bed ~50 cm thick containing *Megastrophia concava*, *Strophodonta demissa*, and *Michelinoceras anax* (bed 17 of Wright and Wright 1961) that is tracable around much of the Thedford-Arkona area (Wright and Wright 1961; Fig. 19). We herein correlate this bed tentatively with the Darien coral bed of the lower Wanakah Member (see Miller 1986, 1991). The base of this bed is sharp and erosional into underlying shales and probably represents a sub-sequence boundary. The overlying beds 18 to 22 are an alternation of shales and thin argillaceous limestones that show a back-stepping pattern into unit 23, a thick, sparsely fossiliferous, calcareous shale at the base of the Petrolia Member (Fig. 19). This pattern of beds closely resembles the "Trilobite beds" of the lower middle Wanakah Member.

The middle Petrolia interval (above the shales of unit 23) is exposed in patches along Golden Creek, near Thedford, Ontario, where Wright and Wright (1961) logged it roughly. We examined this interval, which we refer to as the "Golden Creek submember" (of the Petrolia member), in drill cores from the Ipperwash and Sarnia areas. In both areas it is about 4 m thick and consists of sparsely fossiliferous shales and argillaceous, nodular and cherty limestones. A prominent middle limestone (crinoidal wackestone), overlying a cherty nodular interval, is identifiable throughout the area. We suggest correlation of the sparsely fossiliferous Golden Creek submember with the middle Wanakah interval and suspect that the marker limestone represents the weakly developed Barnum Creek bed of New York (Baird 1981). In any case, it is clear that the upper third of the Golden Creek interval shows an increasing abundance and diversity of fossils (e.g., brachiopods *Mucrospirifer*, *Pseudoatrypa*, *Strophodonta*, *Pholidostrophia*, and the bryozoan *Sulcoretepora*), suggesting a third shallowing upward cycle, presumably based at the crinoidal marker bed.

The middle Petrolia beds are exposed at Stony Point along the Lake Huron shore southeast of Ipperwash Provincial Park, where Stauffer (1915) identified them as part of the Ipperwash Limestone. These beds, the "lower Ipperwash" of Wright and Wright (1963), are herein referred to as the "Stony Point submember (of the Petrolia Member), as they are distinct from the typical Ipperwash Limestone exposed at Ipperwash Point (see below). At Stony Point about 1.5m of crinoidal, glauconitic limestones (wackestones and packstones) are exposed above soft bluish gray shale at the top of the Golden Creek submember. These beds carry an abundance of large brachiopods, especially the spiriferid *Spinocyrtia carinata*, an unusual morphotype of *Spinocyrtia* characterized by a smooth fold (without medial groove). This form very closely resembles *S. granulosa* (s.s.) as redefined by Wright and Wright (1963), a form of the genus restricted to the upper Wanakah Shale (Blasdell-Bloomer Creek beds) in western New York. The lowest 15-20 cm crinoidal pack- and grainstone (unit 1 of Wright and Wright 1963) at Stony Point contains an abundance of corroded fragments of *Spinocyrtia* and specimens of the crinoid grapnel *Ancyrocrinus bulbosus* (also abundant in the upper Wanakah Shale in New York), suggesting a reworked lag bed. The basal surface of this bed and of a second glauconitic grainstone bed rich in *Strophodonta* and *Megastrophia* (unit 5), about 40 cm higher at Stony Point, both show sharply incised *Cruziana*-type megaburrows, suggesting erosive discontinuity surfaces Both sharply based beds are identifiable in drill core from Sarnia, Ontario. We suggest that these represent two divisions of the Blasdell-Bloomer Creek beds; these are the "*Strophodonta demissa*" and "*Stictopora*" beds of the upper Wanakah Shale of western New York (Grabau 1899). The lower of these beds is notably erosive in central New York, where Baird (1981) documented truncation of beds and reworked concretions. The second condensed bed occurs about 0.5 to 1 m higher.

HST-FSST: Subsequences IIIF-G Spafford and Jaycox Members-upper Petrolia Shale.-- A relatively thin shale unit (0.5 to 3 m) including a basal shell-rich, calcareous siltstone or limestone, the Limerick Road bed, overlies the top of the Wanakah (Romulus) Shale throughout west central New York. This bed defines the base of a bluish gray shale- mudstone interval, typically 6 to 7m in thick central New York, the Spafford Shale Member. This member is typified by a rich brachiopod fauna including chonetids, *Mucrospirifer*, and *Spinocyrtia* cf. *S. ravenswoodensis* Ehlers and Wright (1955) (a form with a distinct groove in the fold). The Spafford thins in western New York as it is truncated by a higher disconformity at the base of the Jaycox Member.

The uppermost unit assigned to the Ludlowville Formation in western New York is highly fossiliferous, calcareous mudstone and limestone with abundant coral beds (Fig. 20D/E), termed the Jaycox Member by Baird (1979). The basal Hills Gulch bed, another shell-and coral-rich, calcareous siltstone, rests sharply on underlying shales with incised megaburrows on its base. The Hills Gulch bed is overlain by a series of traceable coral and shell rich beds that were mapped in detail by Mayer et al. (1994). The Jaycox coarsens and thickens eastward to about 15m before being largely truncated beneath the basal Moscow unconformity (Mayer et al. 1994). Only a thin (<1 m) siltstone, the Owasco Member, persists eastward; this interval apparently is a lateral equivalent of the Hills Gulch bed.

The uppermost unit of the Ludlowville sequence, in Ontario, herein referred to as the "upper Petrolia submember" (of Widder Formation), comprises about 2-3 m of soft, bluish gray shales and thin very fossiliferous limestones overlying the Stony Point beds up to the base of the Ipperwash Limestone (*sensu stricto* = "upper Ipperwash" as defined by Wright and Wright 1963). These beds are not well exposed anywhere in Ontario and can only be observed in the subsurface. A meter of dark shale immediately overlying the lower Ipperwash may be equivalents of the uppermost Wanakah and/or Spafford shale. A thin, persistent crinoidal limestone at the top of this interval may represent the Hills Gulch bed and the uppermost bluish gray shale and highly fossiliferous limestone may represent the Jaycox Member (Fig. 19). Blocks of this rock brought up by dredging for boat slips near Kettle Point yield a diverse fauna featuring typical upper Ludlowville brachiopods, especially "*Chonetes" vicinus*, *Mucrospirifer* sp., and a morphotype of *Spinocyrtia*, *S. ravenswoodensis*, with a deep furrow in the fold (Wright and Wright 1961) as is typical of members of this genus in the uppermost Ludlowville in New York. This evidence supports correlation of these beds with the Jaycox Shale.

The equivalents of the upper Lulowville members are thought to be represented by cherty dolowackestone and packstones in the middle to upper Ten Mile Creek Dolostone in Ohio. The nodular, cherty facies resemble somewhat those seen in the Petrolia Member in Ontario, but the details remain obscure.

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Sequence V. Moscow Formation

The Moscow Formation of New York has been studied in detail (Cooper 1933; Baird 1979; Brett and Baird 1994). Again, the interval is based at a crinoidal grainstone and coral rich interval, the Tichenor Limestone, analogous to the Centerfield and Stafford-Mottville. The Tichenor is the lower unit of a complex of calcareous shale and limestones (Deep Run Shale; hard silty, calcareous mudstone), Menteth Limestone (silty bioturbated wackestone), and Kashong Shale (bluish gray shale rich in *Tropidoleptus*, with middle and top condensed shell beds); these limestones thin and become stacked into a 0.5 to 3m interval in both western and central New York. In central New York, they and the Tichenor Limestone are collectively termed Portland Point Member (Baird 1979). The upper Moscow comprises the widespread Windom Shale Member. Windom is divisible into two major shallowing (coarsening) upward cycles.

Strata lying above the redefined Widder Formation are herein placed within a newly recognized formation-scale unit apparently correlative with the Moscow Formation. This unit is best developed in the subsurface in the Sarnia, Ontario area. The lowest portion of this unit consists of the "upper Ipperwash bed" of previous workers (Cooper et al. 1942; Wright and Wright 1963), herein redefined as the Ipperwash Member (restricted), as this was the original unit identified at Ipperwash Point by Stauffer (1915). The Ipperwash Member is the only portion of the Moscow exposed in Ontario, being best developed along the shore of Lake Huron at Silica Point and also present in blocks dredged from boat slips along Lake Huron 4 miles to the south and at Smith's Falls on the Sydenham River, near Shetland. This unit, up to 1 m thick, consists of dark-gray limestone with whole and broken fossils, including the brachiopods "*Chonetes" vicinus*, *Spinocyrtia ravenswoodensis*, *Mucrospirifer*, *Tropidoleptus*, and *Protoleptostrophia*; sharply incised megaburrow-prods filled with pyritic skeletal debris occur at its base. The upper portion of this bed is *Zoophycos*-churned calcisiltite, with black to bluish-purple chert. We suggest that the sharp prodded basal surface of the Ipperwash Limestone represents the basal Moscow sequence boundary and that the overlying Ipperwash (s.s.) may represent a combination of Tichenor and Menteth members.

The Ipperwash appears to correlate with upper cherty coral beds to biohermal mounds at the top of the Prout Formation in the EFA Ohio, and possibly to upper coral beds in the Ten Mile Creek Dolostone of the WFA area.

HST Beds above Ipperwash.-- Beds above the Ipperwash Member in Ontario are only present in the subsurface in the area near Sarnia, Ontario, although samples of the Ipperwash-Kettle Point contact can be examined in dredged blocks at the boat slips near Kettle Point. In its type area, the Ipperwash Member is capped by a pyrite-coated discontinuity at the base of the Upper Devonian Kettle Point Formation that locally preserves a patchy, fine-grained, phosphatic lag; this surface is presumably the "conodont hash" cited by Winder (1968). However, in a core from the subsurface near Sarnia, about 6m of calcareous, fossiliferous, gray shales are observed to overlie the same chert bed at the top of the Ipperwash Member. At the top of this 6m unit is a pyritic discontinuity overlain by the Kettle Point Formation. This unit has heretofore gone unnoticed in the study of the Middle Devonian of Ontario and it helps to identify a top-down removal of units to the east by the overlying unconformity with the Upper Devonian Kettle Point Formation. At this time the fauna of the Sarnia Formation is poorly understood, but it does contain brachiopods indicative of a Middle Devonian age, such as *Rhipidomella penelope*. We tentatively correlate these beds with the upper Kashong Shale interval and possibly parts of the Windom Member.

SUMMARY

Within the Middle Devonian strataigraphic succession discussed above, each sequence and its component divisions (systems tracts) possess unique characteristics, which are persistent across the basin and onto the cratonic ramps adjacent to the Michigan Basin, transcending thickness and facies changes. Sequence boundaries (SB) are marked by abrupt facies offsets with fossil rich carbonates abruptly overlying shales, siltstones or shaly carbonates. Regionally, these contacts show evidence for truncation of underlying units. Sharp, erosive discontinuity surfaces are typically indicated by large hypichnial burrow-casts filled with shell hash that extend down from the base of overlying limestones into the underlying mudstones or shale. Sharpness of scratches and absence of deformation in the burrow walls indicate that burrows were cut down into stiff, over-compacted muds exposed by removal of up to several meters of overlying sediments.

The basal transgressive beds generally consist of well-sorted bioclastic pack- to grainstones to silty or sandy sediment. TST grainstones consist of reworked shell material with little or no argillaceous matrix. The fauna of this portion of each sequence consists of stenotopic taxa, including tabulate and rugose corals, large brachiopods, and crinoids. The basal limestone typically has a pyrite/phosphate encrusted upper surface indicating strong sediment starvation. We interpret this surface as representing the maximum rate of sea level rise. The upper portions of TSTs generally display a back-stepping pattern composed of interbedded limestones and shales with increasing amounts of argillaceous material upwards and are bounded at the top by another pyrite/phosphate pebble bed representing the maximum flooding surface.

The highstand systems tract in Hamilton sequences is generally characterized by a relatively thick package of shale, mudstone, or siltstone with a few, thin limestone beds. The fauna of the early portion of the highstand is typically rather depauperate not only in the diversity of taxa, but also in the abundance of the fauna throughout the systems tract. The lower portions of HSTs typically contain taxa interpreted to be indicative of dysoxic conditions (e.g., leiorhynchid brachiopods). The upper portion of the highstand represents shallower-water conditions and contains a slightly more diverse fauna that is typically well-preserved due to rapid burial. Although usually the thickest parts of sequences in proximal foreland basin areas due to high siliciclastic sediment influx, HSTs tend to be thin and may be highly condensed in more distal basin areas due to sediment starvation.

The falling stage systems tract (FSST; formerly termed "regressive systems tract"; Brett and Baird 1996; see Cateneanu 2002 for clarification of terminology) is typified by an abruptly shallowing-upward or progradational pattern. The base of the FSST in the Hamilton of the Appalachian Basin is locally marked by a condensed shell-rich bed representing the most rapid period of sea level drop ("precursor bed" of Brett 1995). Above the precursor bed sediments coarsen upward rapidly, changing from dark shales to gray mudstones and siltstones. In shallow shelf facies a slightly higher sharp contact occurs at the bases of coarse hummocky to swaly cross bedded siltstone and sandstone; this facies dislocation is interpreted as a regressive ravinement surface representing shoreface erosion during rapid sea level fall.

A key result of this study is the correlation of formations (third order sequences) and members to submembers (fourth order sequences) from New York State into Ontario and Ohio (Fig. 4). In Ontario a one-for-one match can be made between slightly redefined lithostratigraphic entities and the Hamilton formations of New York State (i.e. third order depositional sequences). The Bell Shale of the subsurface (locally termed Marcellus Shale in eastern drill cores) is redefined to include basal limestone beds previously included in the Dundee Formation. As such, the Bell Formation is equivalent to the Oatka Creek Formation (Marcellus subgroup) with basal Cherry Valley Limestone. The Arkona Formation is herein redefined to include basal limestone beds presently called the "Rockport Quarry" Limestone, as a member, and to include the uppermost black calcareous shales that were formerly considered lowermost Hungry Hollow Formation. With this slight modification, which brings Arkona Formation back to approximately the definition of Stauffer (1915), the Arkona Formation is considered to be the exact allostratigraphic equivalent of the Skaneateles Formation (Sequence III). The Rockport Quarry Limestone is equivalent, in both age and lithology, to the Mottville Member of New York State. This interval represents the third order TST. Overlying shales are sub-divisible based upon subtle shelly limestones into equivalents of the Delphi Station, Pompey (=main exposed

Arkona Shale) and Butternut (=thin limestone and dark leiorhynchid bearing shale unit at the top of the Arkona section.

The original definition of the Widder Formation is also restored to include the strata from the basal Hungry Hollow Member upward through the Petrolia Member (redefined and including beds formerly assigned to the lower Ipperwash and herein termed the Stony Point beds). In this redefinition the Widder is likewise considered as the precise sequence equivalent of the Ludlowville Formation in New York. The basal Hungry Hollow Member is considered equivalent to the Centerfield basal transgressive limestone and the Ledyard Member of the western New York succession is tentatively correlated to the lower shaly Widder (herein informally termed the Thedford member). The overlying Wanakah Member of New York State corresponds to the middle argillaceous limestones herein assigned to the Rock Glen, Golden Creek, and Stony Point submembers (or beds) of the Petrolia Member. Equivalents of upper Ludlowville strata (Spafford and Jaycox members) are tentatively recognized in the upper Petrolia Shale, but as yet this interval remains poorly known, as it is only observable in drill cores.

The Ipperwash Member is here redefined (again returning to the original definition of Stauffer, 1915, as comprising only the “upper Ipperwash”) beds exposed at Ipperwash Point. This 0.6 to 1 m silty limestone with a sharp erosive base and silty, chert-rich top is considered equivalent to the Tichenor and Menteth members of the basal Moscow Formation (also termed Portland Point interval when condensed as in this case, Baird 1979). With the discovery of still higher strata overlying the Ipperwash, we recognize the Moscow sequence for the first time in Ontario. Thus, all third order depositional sequences can be identified in southwestern Ontario (Fig. 4).

An abbreviated Oatka Creek, Skaneateles and a partial Ludlowville sequence can be recognized in Ohio. The Oatka Creek sequence may be represented by the uppermost portion of the Delaware Formation, although it is probable that most of the sequence was removed by erosion beneath the overlying Skaneateles sequence. The equivalents of the full Skaneateles–Arkona interval with all members (fourth-order cycles) can be identified in the higher Silica Formation, with the basal Mottville-Rockport Quarry transgressive carbonate unit represented by the coral rich limestones (“Blue Beds”) of the basal Silica Formation (units 1-7), the Delphi Station represented by units 9-13 (Brint Road member of Mitchell 1967), the Pompey by a bundle of basal limestones (units 14-17) and the main thick shale unit (18) of the Silica (Berkey Member of Mitchell 1967; Fig. 4). The Butternut Member (including basal Marietta limestones, informal), is recorded in units 19-22, and features a sharp-based limestone that is overlain by a black leiorhynchid-bearing shale unit; the same pattern is apparent in the topmost beds of the Arkona Shale. Finally, there is slightly more preservation of the transitional (“lower Centerfield”) regressive beds in units 24-29 of the Silica Shale. East of the Findlay arch the Oatka Creek sequence is probably represented by the upper portions of the Delaware Formation. The Pompey succession is recorded in the Plum Brook Shale with an even thicker, sparsely fossiliferous and pyritic shale equivalent to unit 18. This interval appears to constitute a majority of the lower Olentangy Shale in south central Ohio; the lower Olentangy, main Plum Brook, upper Arkona and Pompey Shales are all characterized by a zone of pyritized fossils, including the distinctive goniatite *Tornoceras (T.) arkonense* near the top.

Again, the topmost fossiliferous shale and limestone beds of the Plum Brook record the Butternut-to-basal Centerfield transition of the New York succession.

The Ludlowville sequence is recorded in the Prout and Ten Mile Creek formations of EFA and WFA, respectively. The lower portions of these intervals carry a distinctive brachiopod-coral fauna that links them with the Centerfield Limestone (s.s.) in New York. Details of the higher Ludlowville succession remain obscure due to variable condensation and dolomitization of the carbonates.

There is little record of the Moscow sequence in Ohio, although condensed lag beds near the top of the Prout Limestone may contain conodonts of the *ansatus* zone suggesting the presence of Moscow equivalent marine deposits in this area.

Discussion: Tectonic Implicatoins

Exposures of the Plum Brook-Prout succession of north central Ohio, in the Sandusky area are presently presently separated from the outcrop belt of the Silica Shale in western Ohio near Toledo by an area stripped of post-Silurian strata; this area corresponds to the axis of the Findlay Arch. Due to this separation of outcrop belts, the Plum Brook-Prout strata are typically considered to be a part of the Appalachian Basin Hamilton Group, whereas the Silica-Ten Mile Creek units are mapped as parts of the Traverse Group of the Michigan Basin. Conversely, the Arkona Shale appears to grade westward into Silica Shale, with concomitant thinning of shale intervals and increase of fossiliferous limestones to shales; the greater thickness of the Arkona Shale, relative to equivalent Silica Shale strata reflects sheltering of Middle Devonian units from erosion in the Chatham Sag. However, comparable stratigraphic patterns and facies and faunal similarities indicate that the Arkona, Plum Brook and Silica shales are all genetically related units with stratigraphic continuity throughout. In fact, the similarities of stratigraphic successions, continuity of units and similarity of faunal successions suggest that, at least during some of the interval considered, there was no disconnection between the southeastern Michigan

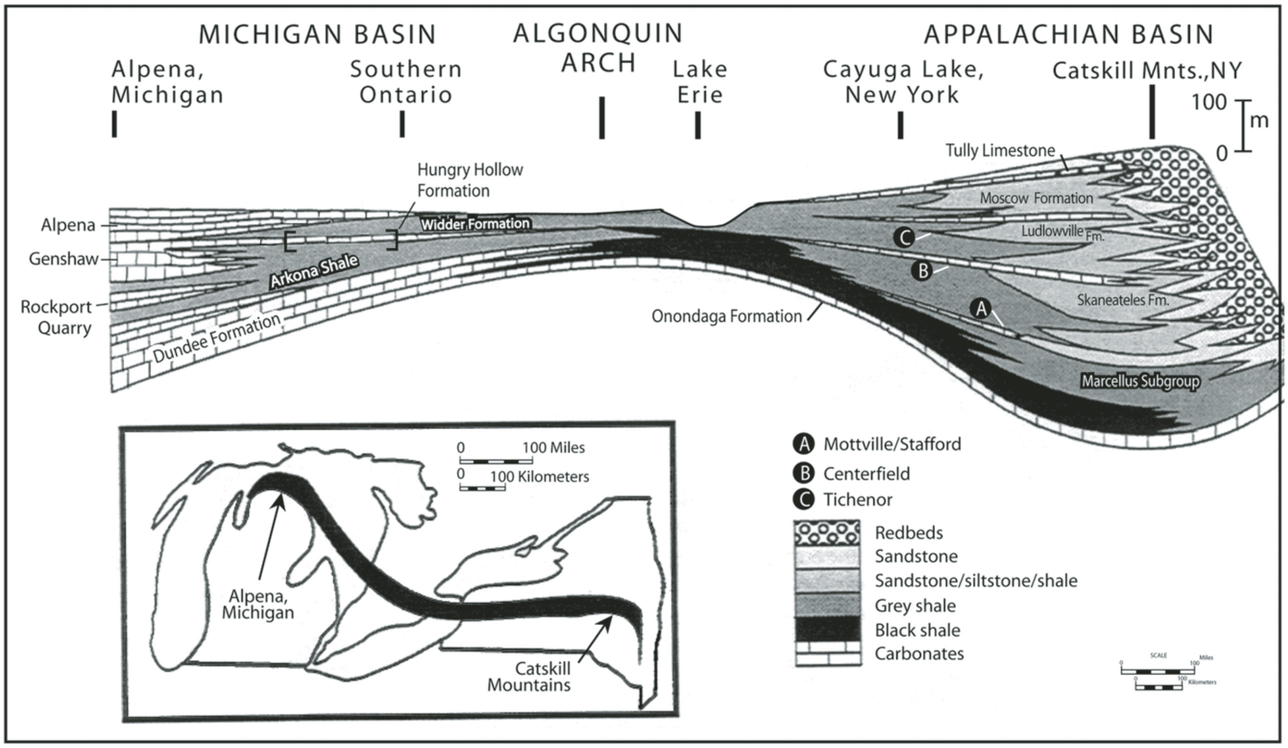

Figure 21. Cross-section showing the thinning of units across the Frontenac Arch through the Chatam Sag in southwestern Ontario. Units can be seen to thicken as they are traced into the more proximal portions of the Appalachian and Michigan basins. Modified after Tsujita et al. (2001).

Basin and the Appalachian Basin. Instead, a gradually westward shallowing ramp was responsible for the facies changes among the units. This westward shallowing, marked by further thinning of shales and increased ratio of fossiliferous limestone to shale, is seen in westernmost Ohio and Indiana.

On the other hand, it should be noted that further east of the Findlay Arch, from northeastern Ohio into Ontario, higher Hamilton Group strata have been regionally truncated by erosive beveling, such that the lowest Hamilton beds are unconformably overlain by Upper Devonian strata. Exactly when this presumed arching and erosion took place is unclear. Our results suggest that erosion of the region did not take place until late in the Givetian. However, the stratigraphic condensation seen in the Prout Limestone near Sandusky, relative to the thicker Ludlowville Formation to the east and Ten Mile Creek Formation to the west, suggests that uplift in northeastern Ohio may have already begun during the middle Givetian (*timorensis* to *ansatus* zones).

CONCLUSIONS

The results of this study are several. A detailed third and fourth order sequence stratigraphic subdivision has been established for the first time in Ontario and northern Ohio and detailed correlations have been established between this pattern of sequences and those of the Appalachian foreland basin. The implications of this correlation are manifold. They include: a) strong evidence for eustasy as a control on foreland basin-carbonate ramp stratigraphic successions; b) indication of a near balance of subsidence and deposition over much of the study area; and c) a high degree of connectivity between strata of the Appalachian Basin and cratonic successions bordering the Michigan Basin, suggesting that all three studied areas were not separated by any major barriers from the Appalachian Basin. The Findlay Arch, as such, was not in place at this time. However, the removal of much of the middle and upper Hamilton Group strata in northeastern Ohio and Ontario (Fig. 21) indicates that erosion may have occurred over the crest of an arch, possibly a forebulge, that was initiated to the east of this region.

Finally, the studies of these successions, provide a detailed sequence stratigraphic framework that will allow for more detailed bridging of Hamilton Group strata between the Appalachian and Michigan basins. In the next phase of the study we will attempt to extend this framework into the Traverse Group outcrop belt of the upper part of lower Peninsular Michigan. This will facilitate further comparisons of the geological and faunal dynamics recorded in the Middle Devonian of the Michigan Basin with those in the foreland.

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