SILURIAN SEQUENCE STRATIGRAPHY, EVENTS, AND PALEOENVIRONMENTS ALONG THE CRATONIC MARGIN OF THE APPALACHIAN FORELAND

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INTRODUCTION

Silurian rocks of the Appalachian Basin and the North American mid-continent platform provide an excellent suite of strata for application of sequence, and event stratigraphic approaches. The strata are well exposed and display marked vertical changes in facies, commonly associated with distinctive condensed beds and/or discontinuities. The Niagara Escarpment in western New York and the Niagara Peninsula of Ontario represents a key reference area for the North American Silurian System. Indeed, the term "Niagaran," which has been variably applied to the middle or lower and middle portions of the Silurian, is still commonly used in North America. These rocks have been well documented by many researchers, beginning in the mid 1800s (Hall, 1852; Grabau, 1901; Foerste, 1906, 1935;Williams, 1919; Gillette, 1947; Bolton, 1957; Zenger, 1965, 1971; Sanford, 1969; Martini, 1971; Rickard, 1975; Duke, 1987; Duke and Brusse, 1987; Duke and Fawsett, 1987; Brett, 1983 a, b, 1985; Brett et al., 1990, 1995, 1998; Goodman and Brett, 1994; LoDuca and Brett, 1994).

Previous reports on the Silurian in the Niagara region have focused on identification of depositional sequences and depositional/faunal events. A theme of this guide is the documentation and interpretation of Silurian facies, events, and sequences along the northwestern rim of the Appalachian Basin. As such, the discussion is not restricted to the sequences and facies of western New York. A remaining research agenda is to trace these sequences into other regions, especially the mid-continent. Ongoing research along the Cincinnati Arch, in Ohio, Indiana, and Kentucky has revealed striking similarities of sequences and events among these seemingly disparate areas, some 500 to 700 km southwest of the main Niagara Escarpment (Fig. 1). In this paper we review and update information on depositional sequences and events in western New York and Ontario and then discuss their lateral relationships with those of the Cincinnati Arch. A companion field guide will highlight the Silurian strata of the Cincinnati Arch region.

The large-scale ("third order") sequences described herein are sharply bounded stratal packages, ranging from less than a meter (where partially truncated or condensed) to about 50 m in thickness. In each case, the sharp basal contacts, when traced in an upramp direction, change from facies dislocations (abrupt shallow over deeper facies change) to erosional surfaces that demonstrably truncate underlying strata. Most sequences recognized herein, display a generally deepening-shallowing
pattern.

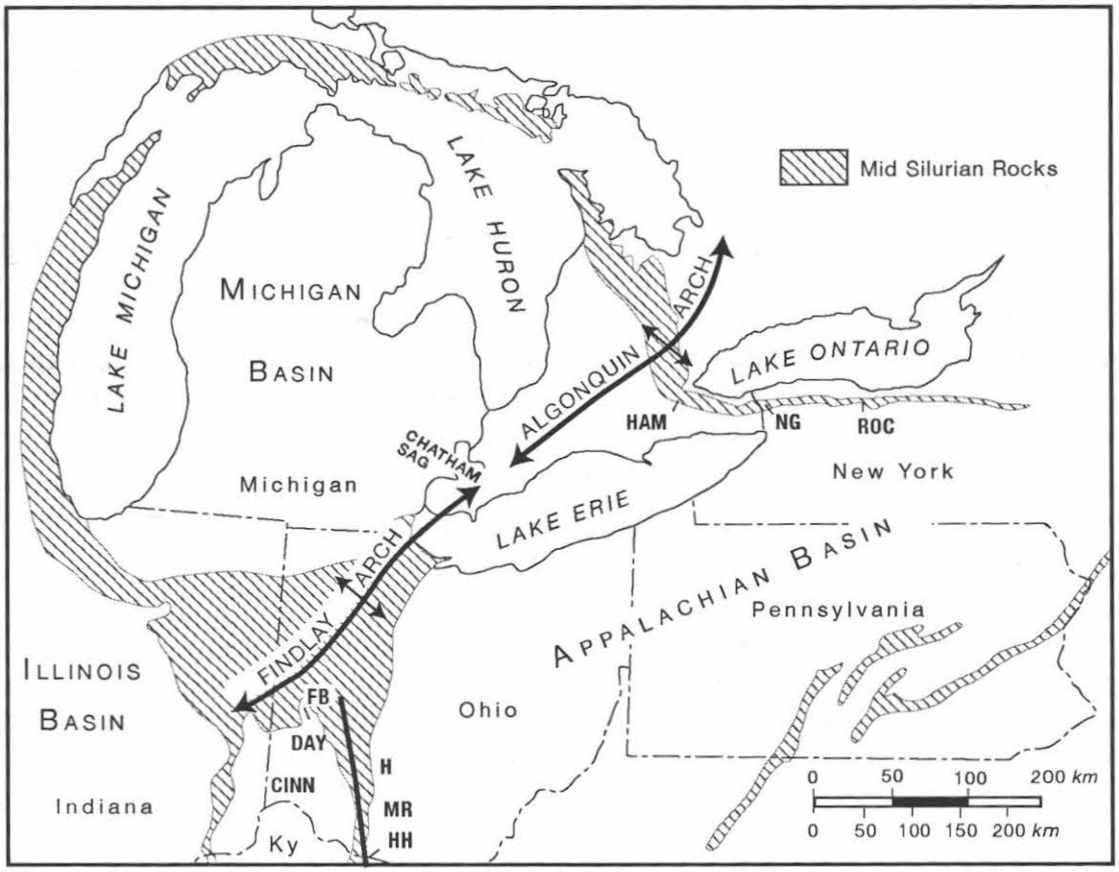


Figure 1. Geographic setting of Silurian in eastern North America. A) Map showing geomorphic features of eastern North America and outcrop belt of the Silurian; abbreviations: DAY: Dayton, Ohio; CINN: Cincinnati, Ohio; FB: FairbornQuarry near Dayton, Ohio; HAM: Hamilton, ONT; H: roadcut on Rte. 62 at Hillsboro, Ohio; HH: Cut on AA Highway at Herron Hill, Kentucky; MR: cut on US Rte. 32 at Measley Ridge, near Peebles, Ohio; NG: Niagara Gorge, NY, ONT; ROCH: Rochester, NY. Base map modified from Telford (1978).

However, in detail, the larger-scale sequences are composites, divisible into smaller, fourth-order sequences.

With its renewed emphasis on through-going discontinuities and condensed beds, the sequence stratigraphic approach, has encouraged a broader, more regional view of stratigraphy, and an attempt to understand the genetic significance of particular beds and surfaces. To some degree it vindicates the earlier "layer cake stratigraphy" approach. Sequence stratigraphy, originally developed from remote seismic studies of passive margin sediment wedges (Vail et al., 1977, 1991; Wilgus et al., 1988; Coe, 2003; Catuneanu, 2002), is now being applied at the outcrop scale to diverse depositional settings such as the Taconic foreland basin (Brett et al., 1990 a, b; Witzke et al., 1996; Brett et al., 1998; Brett and Ray, 2006). Many distinct horizons in the local stratigraphic record are interpretable as sequence boundaries, drowning surfaces, and forced regression surfaces. Moreover, a number of phenomena, which occur non-randomly in the geologic record, from phosphatic nodule horizons to reefs, fit in predictable ways into depositional sequences.

A second theme of this article is the recognition of widespread events, such as storm deposits, (tempestites), rapidly buried fossil horizons (obrution deposits), and even seismically deformed beds (seismites). The Silurian Period has typically been considered a tectonically quiescent time; however, growing evidence from eastern North America suggests the Silurian was more dynamic then previously considered. For example, sedimentology and stratigraphic mapping of Silurian deformed beds in eastern North America demonstrate that these event beds are extremely widespread and that their component sediment layers were not deformed during initial deposition, but slightly later, during shallow burial, likely the result of shaking induced by large-scale earthquakes (McLaughlin and Brett, 2006). The distribution of deformed beds, together with increased subsidence, clastic influx, and K-bentonite horizons, provides a meter of intensity and timing of pulses of Silurian orogenesis. A variety of such catastrophic events is recorded in the Silurian rocks of the Niagara region and will be examined on this trip.

REGIONAL GEOLOGICAL SETTING

Silurian strata of the Niagara Peninsula-western New York and Cincinnati Arch were deposited along the carbonate (cratonic) margin of the Taconic and Salinic foreland basins (Figs. 1, 2). Early Silurian Strata of the Niagara Peninsula were deposited in generally shallow, subtropical epeiric seas, situated 25-30° south of the paleoequator (Witzke, 1990; Fig. 1B). The axis of the Cincinnati Arch occupied a similar latitude and was oriented roughly parallel to the equator, resulting in broad, strike-parallel facies belts.

Siliciclastic sediments were derived from eastern and, possibly, northeastern (present-day orientations) source terrains that were uplifted during the Late Ordovician to medial Silurian orogenies. In addition to the major Ordovician Blountian and Taconian (Vermontian) tectophases, Ettensohn and Brett (2002) identified a third, Early Silurian (Median) tectophase of the Taconic Orogeny.

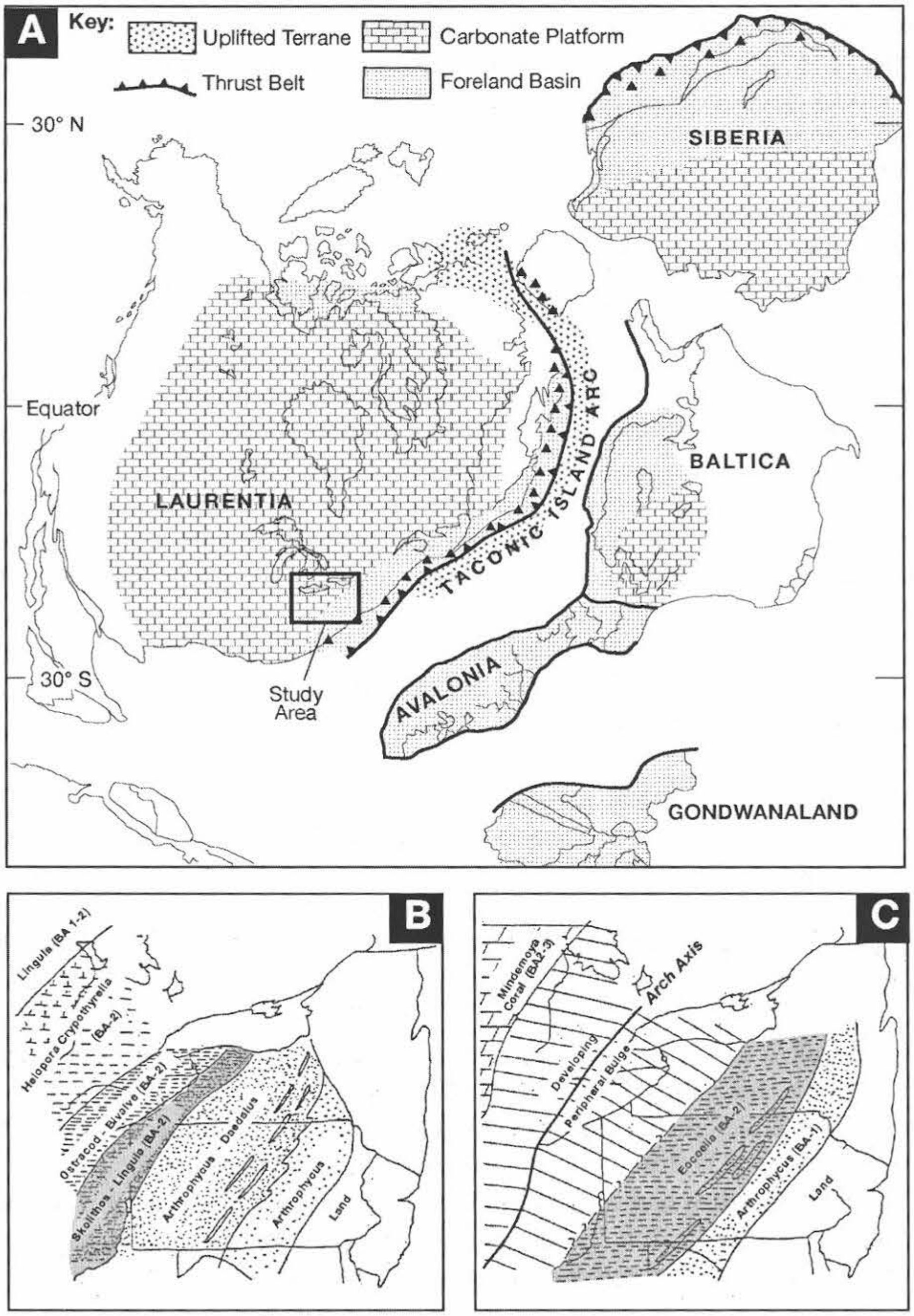


Figure 2. Paleogeography for Early Silurian. A) Reconstruction of Laurentia (ancestral North America) and adjacent paleocontinents during Early Silurian time. Note position of study area, shown with box and of the Taconic Arch and peripheral foreland basin. Modified from Scotese (1990). B,C) Paleogeographic reconstructions of New York and adjacent areas for two different times within the Early Silurian. B) Rhudannian; highstand of Sequence I. Medina Group; Castanea Member of Tuscarora Formation in Pennsylvania; note position of basin center in southern Ontario. C) Mid Telychian; highstand of sequence III; Sauquoit Shale-Otsquago red sandstone in central New York; upper Rose Hill Shale in Pennsylvania; lower Crab Orchard Shale in Ohio-Kentucky. Note development of regional uplift (forebulge) along the Algonquin Arch.

This phase of uplift produced a new episode of molasse deposition: the Tuscarora-Medina clastic wedge, centered in the southern and central Appalachians. This tectonism increased the gradients of source streams, producing an influx of coarse, quartz rich gravels and sands perhaps from reworking of vein quartz and older sandstones in the rejuvenated Taconic orogen. Renewed uplift of tectonic terranes may have occurred during the medial- and Late Silurian in the Salinic Disturbance (see Ettensohn and Brett, 1998). These tectophases produced an initial pulse of quartz sands, upper Shawangunk-Keefer-Herkimer conglomerates and sandstones in the proximal foreland basin, followed by a major influx of primarily fine-grained siliciclastics of the Vernon-Bloomsburg "delta", predominantly red molasse.

During the Early Silurian, Medina Group siliciclastics accumulated in non-marine to shallow marine environments in western New York and marine shales extended with little or no break into the region of the Michigan Basin and northeastern Ohio (Fig. 2B). However, by medial Silurian time (middle Llandovery), a narrow carbonate platform appears to have existed in the area around Hamilton, Ontario northwest into the Bruce Peninsula and extending southwest into central and southern Ohio and Kentucky (Algonquin-Findlay Arch; Fig. 2C). This platform was a region of shallow, epeiric seas, with lesser siliciclastic input than the foreland basin to the east punctuated by relatively thin packages of skeletal sand and chemical sediments. This arch formed a partial to nearly complete barrier between the Appalachian and Michigan Basins during the late Llandovery and Wenlock time (Fig. 2C).

The arch was probably emergent at times during the late Llandovery and mid Wenlock when relative base level drops produced major unconformities within the mixed carbonate-siliciclastic succession. During late Wenlock to Ludlow time, however, the Algonquin Arch, appears to have subsided such that the area between Hamilton, Ontario and the northern Bruce Peninsula was the locus of deeper water environments than areas to the southeast or northwest. During this time reefy carbonates were widespread in the Appalachian Basin.

As a broad generalization, Silurian strata in the northern Appalachian basin display a trend from a) siliciclastic dominated units in the Early Silurian (Alexandrian or early Llandovery) Medina Group, to b) mixed siliciclastics and carbonates in the medial Silurian (lower Niagaran, upper Llandovery-Wenlock) Clinton Group, c) dolomitic carbonates in the Lockport Group (upper Niagaran; Wenlock-Ludlow), and d) mudrocks, dolostones and evaporites in the Upper Silurian (Cayugan, upper Ludlow-Pridoli) Salina-Bertie Groups (Fig. 3). These patterns reflect the two major tectonic pulses: late Taconic Media tectophase in earliest Silurian and the medial Silurian Salinic Orogeny; these times were dominated by prograding clastic wedges and westward migration of the foreland basin depocenter (Fig. 3; see also Fig. 15; Goodman and Brett, 1994; Ettensohn and Brett, 1998). Intervening times of quiescence were marked by predominant carbonate deposition and eastward backstepping of the basin depocenters (Ettensohn and Brett, 1998).

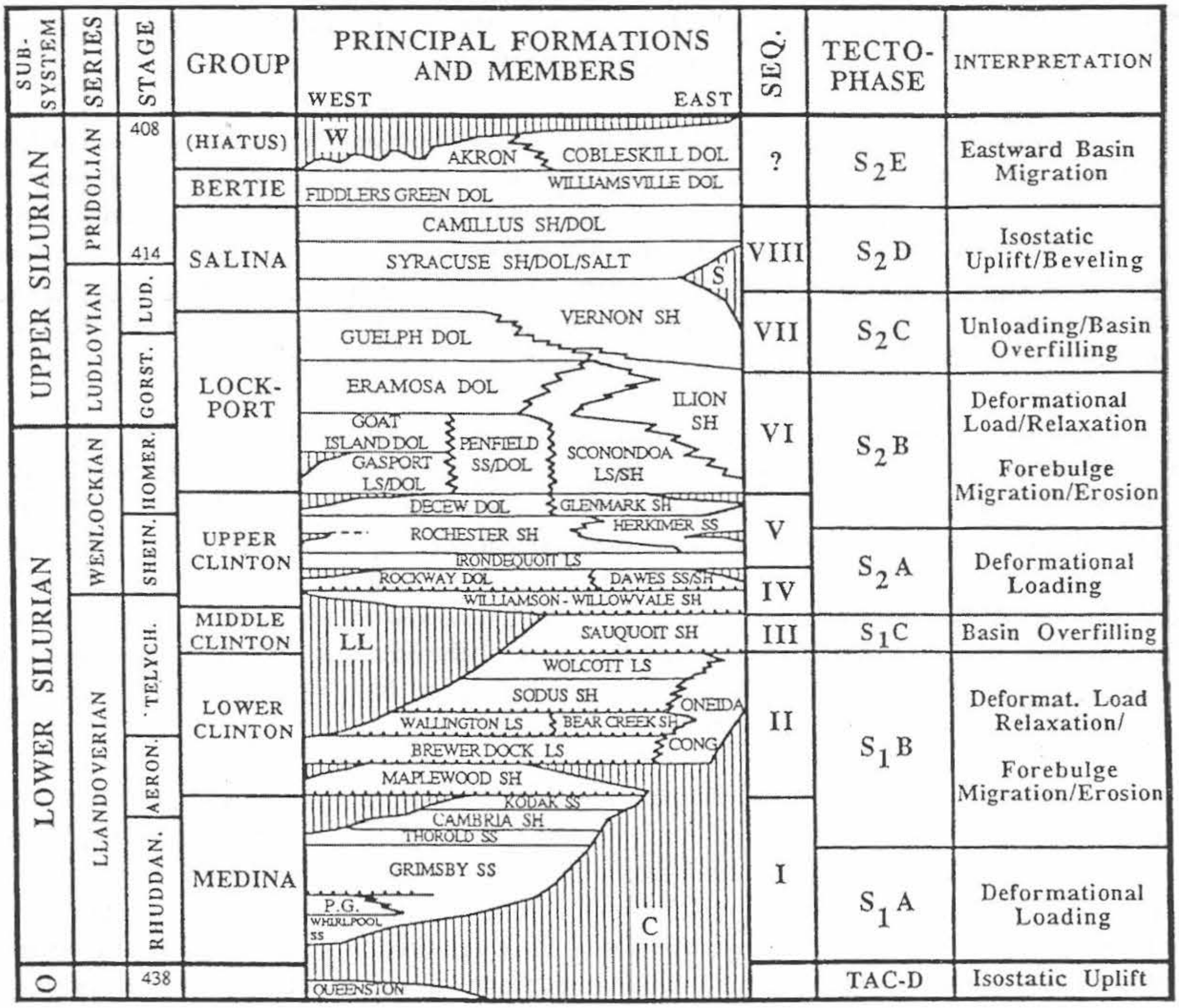


Figure 3. Generalized chronostratigraphic chart for the Silurian System along the east-west outcropbelt from Niagara County to Utica, New York; middle column shows subdivision of stratigraphy into depositional sequences(I-VIII) each marked by a basal sequence bounding unconformity; right two columns show inferred tectophases of latest Taconic (S1) and Salinic (S2) orogenies. Dots indicate phosphatic/ironstone rich condensed beds. Major unconformities marked by letters: C: Cherokee; LL: Late Llandovery; S: Salinic; W: Wallbridge.

SEQUENCE STRATIGRAPHY AND LATERAL CHANGES OF SILURIAN SEQUENCES IN SOUTHERN ONTARIO-WESTERN NEW YORK, COMPARSIONS TO OHIO AND KENTUCKY

The Silurian strata of western New York and the adjacent Niagara Peninsula of Ontario have been broadly subdivided into groups that correspond in part to large-scale (third order of sequence stratigraphers, see Van Wagoner et al., 1988; Vail et al. 1991; Catuneanu, 2002) depositional sequences (Figs. 3, 4); the Clinton Group, however, is divisible into at least three sequences, which correspond roughly to Gillette's (1947) "lower", "middle", and "upper" Clinton divisions. The larger sequences are also divisible into smaller (fourth-order) sequence-like units; we have termed "subsequences" (see Brett et al., 1990, 1995, 1998).

Silurian sequences are bounded by unconformities, three of which, the I-II, II-IV, and V-VI boundaries, are regionally angular (Figs. 3, 4). The magnitude of these three unconformities (i.e., extent of beveling on the erosion surface) increases westward along the Niagara Escarpment. These surfaces appear to have been accentuated by uplift along the "Algonquin Arch", probably an intermittently active forebulge (Figs. 3, 8). The I-II and II-IV boundaries are merged west of St. Catharines, Ontario, forming a compound unconformity (Figs. 3, 4). A very similar pattern is seen to the southwest along the flank of the Findlay Arch near Dayton, Ohio, where unconformities at the top of the Brassfield Formation (base of Plum Creek Shale and below the Dayton Dolostone merge westward (see Fig. 9).

Conversely, the basal sequence I unconformity (Cherokee unconformity and base of Silurian system) decreases westward (Fig. 4). In east central New York State the entire Queenston Formation is truncated and in places basal Silurian sandstones rest unconformably on Maysvillian or Edenian shales of the Frankfort or Schenectady formations with the magnitude of unconformity increasing progressively eastward. This regionally angular, eastward-opening unconformity apparently represents late Taconic or perhaps isostatic uplift of proximal flysch-to-molasse successions (Goodman and Brett, 1995; Ettensohn and Brett, 2002).

Varying east to west facies changes within each of the sequences along the Niagara Escarpment reflect differential subsidence and elevation of the Algonquin-Findley Arch and adjoining basins, as noted in the following sections. In each, the stratal unit name is followed by series/stage assignment based on biostratigraphy (see Brett et al. 1990, 1998, for details).

Sequence I: Medina Group, Lower Llandovery (Rhuddanian)

The stratigraphically lowest Silurian interval (S-I) is the predominantly siliciclastic Medina Group (Cataract Group of some Canadian authors). In west central New York the Medina Group contains, in ascending order: the Whirlpool Sandstone (2.5-4.5 m)

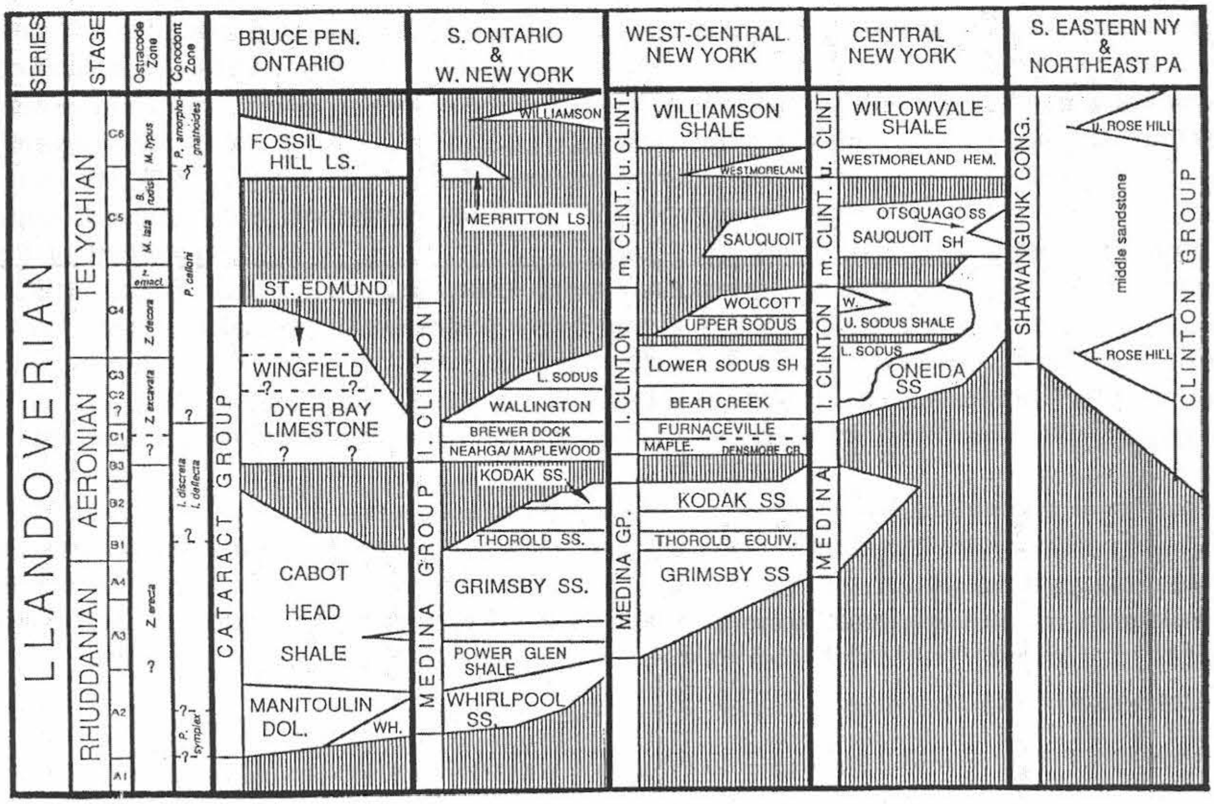


Figure 4. Correlation chart Lower Silurian (Llandovery) stratigraphic units in Ontario and New York State; columns arranged approximately west- to-east. Abbreviations: BC: Bear Creek Shale; Dol: Dolostone; Sh: Shale; SS: Sandstone; WH: Whirlpool Sandstone; WO: Wolcott Limestone.

whitish gray, trough cross bedded quartz arenite, Power Glen Shale (10-15 m) dark gray shale with thin sandstones and dolomitic limestones, Devils Hole Sandstone (2-3 m) whitish gray, phosphatic quartz arenite, Grimsby Formation, (12-15 m) maroon to green shale and reddish and white mottled sandstone, Thorold Sandstone (2-3 m) reddish to whitish gray, bioturbated quartz arenite with greenish gray sandy, bioturbated mudstones, Cambria Shale (0-3 m maroon shales and muddy sandstones, and Kodak Sandstone (0-3 m) whitish gray sandstones and greenish to maroon shales (Figs. 4, 5). The Medina represents a large scale depositional sequence with lowstand (non-marine) to transgressive (foreshore to shoreface) Whirlpool Sandstone (Middleton et al., 1991), overlain by maximally highstand Power Glen Shale (offshore marine muds), and later highstand (progradational shoreface and tidal flat) Devils Hole through Kodak strata. However, the interval is also divisible into smaller (4th order) subsequences at the bases of the Whirlpool, Devils Hole, Thorold, and Kodak transgressive quartz arenites (Figs. 4, 5).

The Medina Group exhibits relatively constant thickness along the Niagara Escarpment, but all of its component units show westward changes in facies corresponding to increasingly open, fully marine conditions (Figs. 4, 5). Thus, the lower, fluviatile (braided stream) Whirlpool Sandstone (Middleton et al. 1991) apparently pinches out (or changes facies to marine) to the north of Georgetown, Ontario (Rutka et al., 1991). The upper Whirlpool thickens and displays evidence of shoreface to shallow, sandy shelf deposition near Hamilton, and may be replaced laterally by the Manitoulin Formation open shelf carbonates (Fig. 5). Dark gray, sandy, sparsely fossiliferous Power Glen Shale in the Niagara region, grades westward near Hamilton into greenish gray shales with abundant bryzoan-rich carbonates, indicating open marine conditions. The Grimsby interval changes northwestward from red sandy mudstones and tidally influenced sandstones with a lingulid (BA-1) biofacies at Niagara Gorge (Martini, 1973; Duke and Fawsett, 1987) to red and green mudstone with only thin sandstones and hematitic bryzoan-rich limestones (BA-2-3) in the upper Cabot Head Formation (Duke and Brusse, 1987). Conversely, the Grimsby interval shows a return to marginal marine or non-marine red beds northward along the Bruce Peninsula (Fig. 2B). Thus, the Hamilton area was close to the deepest part of the foreland basin during Medina deposition (Fig. 2B; Ettensohn and Brett, 1998).

Westward erosion of the upper Medina Group below Sequence II beveled an upper fourth order cycle (Cambria-Kodak) between Rochester and Lockport, New York and culminated with removal of the Thorold Sandstone near Hamilton (Fig. 5). This pattern suggests an inversion of topography, with minor broad uplift on the Algonquin Arch region following Medina deposition.

The Medina is traceable in the subsurface of western New York, northwestern Pennsylvania and Ohio where its units are relatively well known as a result of oil and gas exploration. As a result the continuity of sandstone tongues, notably the Whirlpool, Devils Hole, and Thorold is demonstrable. As in Ontario he Power Glen and Grimsby appear to pass southwestward into a greenish gray to dusky reddish, shale-dominated succession of the Cabot Head Formation.

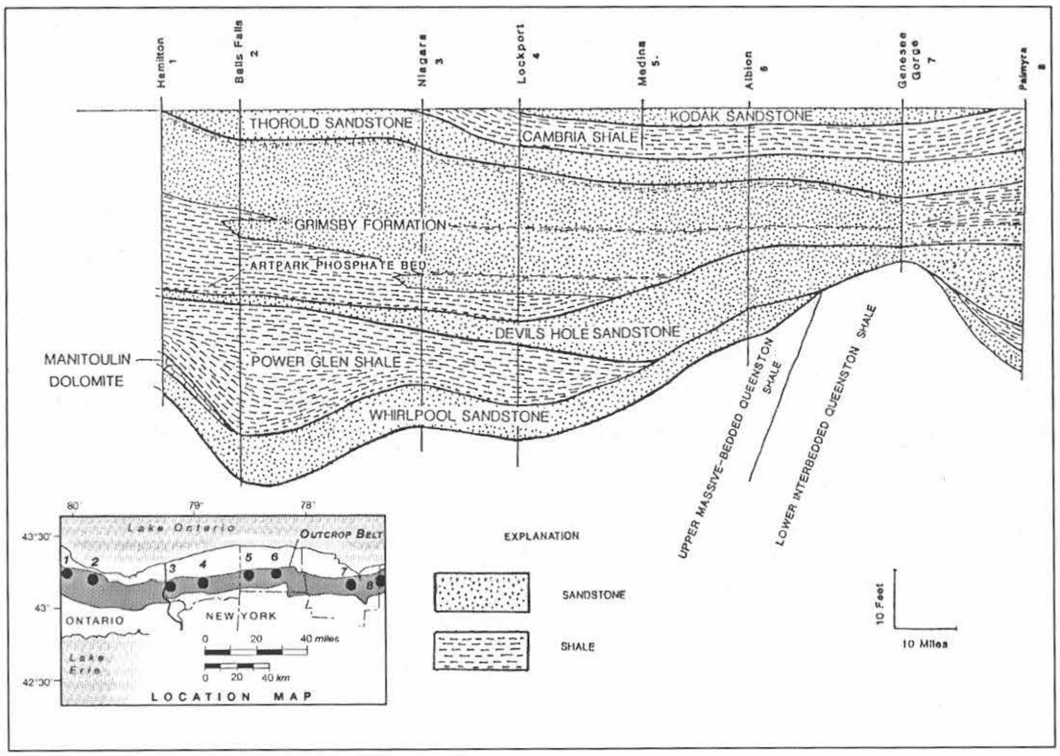


Figure 5. Regional cross section of Medina Group (Sequence 1) in western New York and southern Ontario.

In the outcrop area of southwestern Ohio the Medina interval is represented by the dolomitic carbonate-shale succession of the Brassfield Formation. This interval is divisible into informal members. A basal silty-sandy dolostone of the Belfast Member (0.5 to 2 m thick) may represent the same first 4th order sequence as the Whirlpool Formation of the western New York. A basal bioturbated, glauconitic sandy dolostone bed rests sharply on greenish to reddish silty mudstones of the Preachersville Member, Drakes Formation, representing distal marine facies of the Queenston formation. Hence, this contact represents the major Cherokee unconformity. In terms of the overall Medina sequence, this unit represents lowstand to early transgressive conditions. An overlying massive cherty unit carries much the same benthic fauna as the Manitoulin Dolostone in Ontario and probably represents the TST of the second major 4th order sequence. A higher shaly zone with localized bioherms in central Ohio may occupy the position of the Cabot Head Shale of Ontario. As noted above, there appears to be an association of biohermal development and transgression as the mounds protrude upward from an interval of skeletal grainstone and are surrounded by fine grained argillaceous carbonate and shale. As with the upper Cabot Head this mud is reddish suggests correlation with the lower Grimsby Formation. If so, the persistence of red coloration even into the carbonate dominated facies of central Ohio raises the intriguing issue of the significance of this coloration. Color in this case crosscuts facies as it definitely does in the Grimsby to Cabot Head transition in Ontario. Does the red Grimsby-upper Cabot Head reflect a distinctive weathering regime that produced large volumes of oxidized iron which were distributed over paraliac to offshore marine environments?

Clinton Group, Middle Llandovery (Aeronian) to Middle Wenlock

The Clinton Group consists of mixed carbonates and shales, representing offshore storm-influenced shelf environments, and was informally subdivided into lower, middle, and upper Clinton by Gillette (1947). This convention is adopted herein because two of the three divisions correspond to depositional sequences (Figs. 3, 4).

Sequence II: Lower Clinton Group, Middle Llandovery (Aeronian)

The lower Clinton (Sequence II) is very incomplete in western New York, consisting only of the Neahga Shale (0-2 m of greenish gray shale marked at the base by a phosphates dolostone) and Reynales Limestone (0-3 m of calcisiltite, nodular packstone and bryzoan-brachiopod-echinoderm grainstone, and minor shale) (Figs. 4, 6). To the northwest, in the Bruce Peninsula, up to 20 m of possibly correlative strata, the, Wingfield, St. Edmund formations, and lower Fossil Hill sharply overlie the Cabot Head Shale (Stott and Von Bitter, 1999; Fig. 4).
So little remains of Sequence II in the Niagara Peninsula that it is difficult to determine facies trends. However, facies changes in the Neahga and Reynales formations in western New York suggest westward deepening patterns (LoDuca and Brett, 1994).

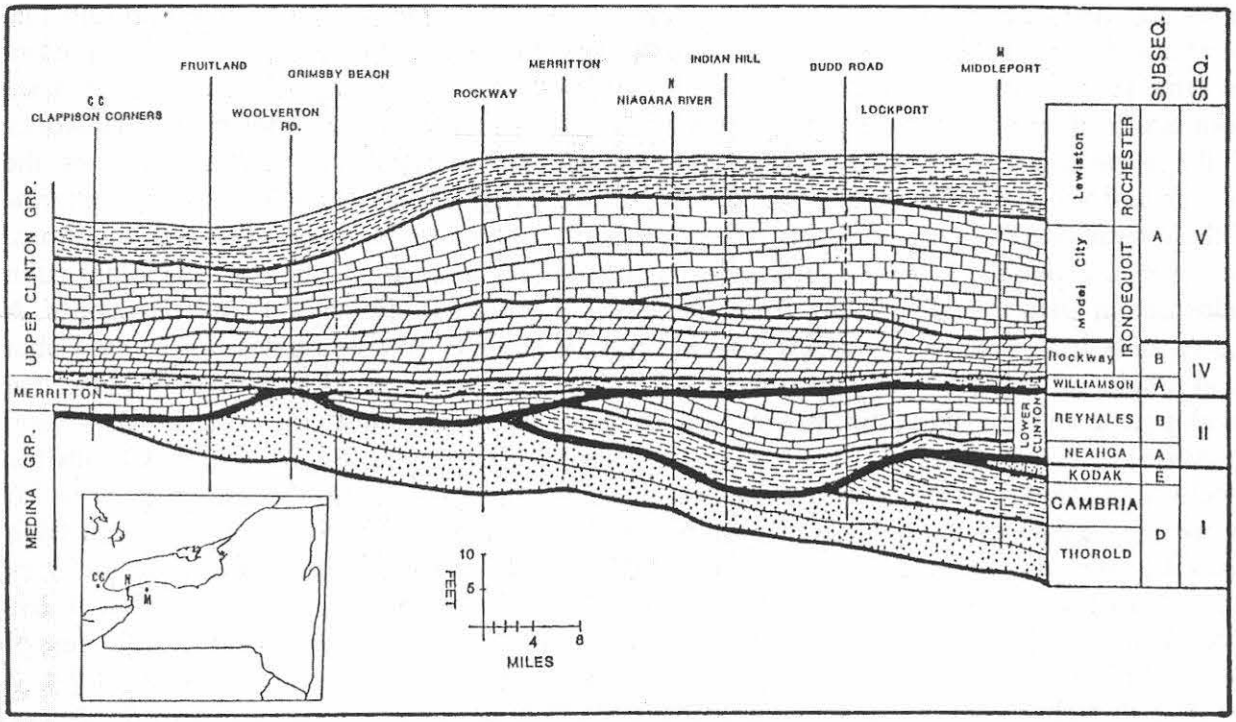


Figure 6. Regional cross section of upper Medina (Sequence I), lower Clinton (Sequence II), and upper Clinton (Sequences IV and lower part of V) through western New York and Ontario (see locations on inset map). Modified from Kilgour (1963). Strong vertical exaggeration to highlight sequence truncations.

In south central Ohio and into northern Kentucky, the position and approximate biostratigraphic equivalent of the Neahga Shale is occupied by the Plum Creek Shale (Figs. 7-10). This thin (0.5 to 2 m) package of greenish gray shale and thin limestones is locally highly fossiliferous with a fauna of tabulate corals, small solitary rugosans and atrypid brachiopods. The Plum Creek appears to be a more distal, offshore facies of the Neahga. A widespread oolitic/skeletal hematite bed (Rose Run ironstone of Foerste, 1906) marks the base of the Plum Creek may correlate with the Densmore Creek phosphate of the New York succession (Figs. 7, 10).

The Plum Creek is overlain, in turn by fossiliferous and locally hematitic limestone of the Oldham Formation, which is a correlative of the Reynales. In turn, the Oldham is overlain by up to 4 m of greenish gray slightly fossiliferous shale, the Lulbegrud Shale, which may be co-extensive with the Lower Sodus Shale of west central New York (Figs. 7-10).

Middle Clinton Unconformity: Upper Llandovery (Telychian)

Middle Clinton Group strata (Sequence III) are absent in the Niagara region, as in southern Ohio, and a major regionally angular unconformity separates the lower Clinton Reynales Formation from the overlying Sequence IV (Figs. 8, 10). A major change in depositional topography of the Appalachian foreland occurred during the mid Llandovery; throughout west-central New York State and Ontario the middle Clinton Group is missing and an erosion surface beneath late Llandovery (Telychian) strata truncates lower Clinton units in a westward direction along the outcrop belt (Lin and Brett 1988; Ettensohn and Brett, 1998; Fig. 2C, 8). This substantial

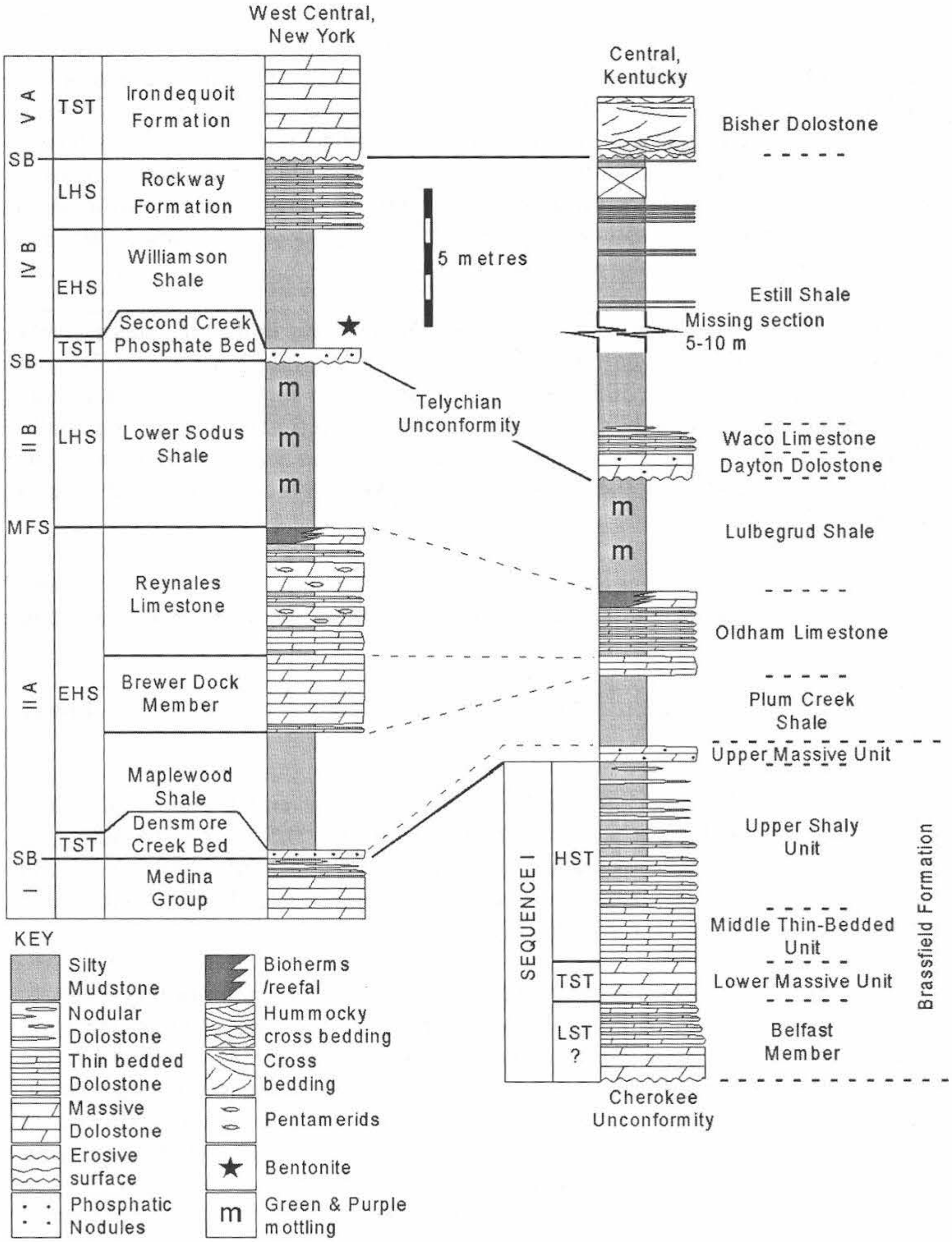


Figure 7. Comparison of Llandovery lithostratigraphic succession in west central New York (vicinity of Rochester, New York) and north-central Kentucky. Sequence stratigraphic abbreviations: EHS: early highstand systems tract; LHS: late highstand (or falling stage) systems tract ; SB: sequence boundary; TST: transgressive systems tract.

regionally angular unconformity suggests another period of broad regional uplift centered on the Algonquin Arch (Fig. 8). Stott and Von Bitter (1999) documented a complex pattern of local uplift/erosion and minor basins in the area of the southern Georgian Bay during this interval, suggesting reactivation of basement fault blocks in response to lithospheric flexure. Development of the unconformity also coincides with a shift in basin axis migration from eastward (Medina-middle Clinton) to westward (upper Clinton); it may signal renewed tectonic activity in the eastern hinterland (Ettensohn and Brett, 1998).

As in western New York, the Lulbegrud, Oldham and Plum Creek units are, successively truncated to the northwest onto the Findlay Arch in west-central Ohio, by an upper Telychian erosion surface (Horvath, 1964; Lukasik, 1987; Fig. 9). This truncation surface can be traced into central and southern Kentucky (McLaughlin, unpublished data) and reflects the same regionally angular unconformity as noted in western New York and Ontario. It indicates contemporaneous uplift along at least a 700 km trend along the Algonquin Arch. We suggest that this trend reflects activation of a forebulge.

It is still not entirely clear whether this feature formed in response to deformational load relaxation as interpreted in Figure 3,or actually reflects the initiation of a new tectophase associated with the Salinic Orogeny.

Sequence IV: Upper Middle Clinton Group, Upper Llandovery (Telychian)-Lower Wenlock

In western Ontario Sequence IV comprises the Merritton Dolostone and its apparent lateral equivalent, the upper Fossil Hill Formation in the Bruce Peninsula (0.5 to 5 m of dolomitic limestone with many corals and pentamerid brachiopods; Stott and Von Bitter, 1999), a very thin tongue of Williamson Shale (0-20 cm), and the Rockway Dolostone-Lions Head Member (3-4 m) of the upper Clinton Group (Figs. 3, 6;see also Fig. 22).

The thin, condensed Merritton Dolostone overlies the major mid Clinton unconformity (Figs. 6, 9); it is unknown in western New York State, although it is roughly equivalent in age (mid Telychian) to the Westmoreland Hematite of central New York (Fig. 8). In general, the Merritton displays a slight westward shallowing trend from glauconite-rich wackestones at St. Catharines to pentamerid- and coral-rich packstone (upper Fossil Hill Formation) northwest of Hamilton. A similar, though very gradual, westward facies change is seen in the overlying Rockway Dolostone, which becomes increasingly carbonate-rich from west central New York to southern Ontario. Biofacies change from *Clorinda*-dominated (BA-5) to *Costistricklandia*-dominated associations (BA-4) also suggest gradual westward shallowing. Locally, in Ontario a feather edge of the dark gray Williamson Shale, as demonstrated by acritarch assemblages (M. Miller, personal comm., 1986) intervenes between the Merritton and Rockway Formations. The Williamson and laterally equivalent Willowvale Formations thicken eastward to a maximum of over 30 m in central New York.

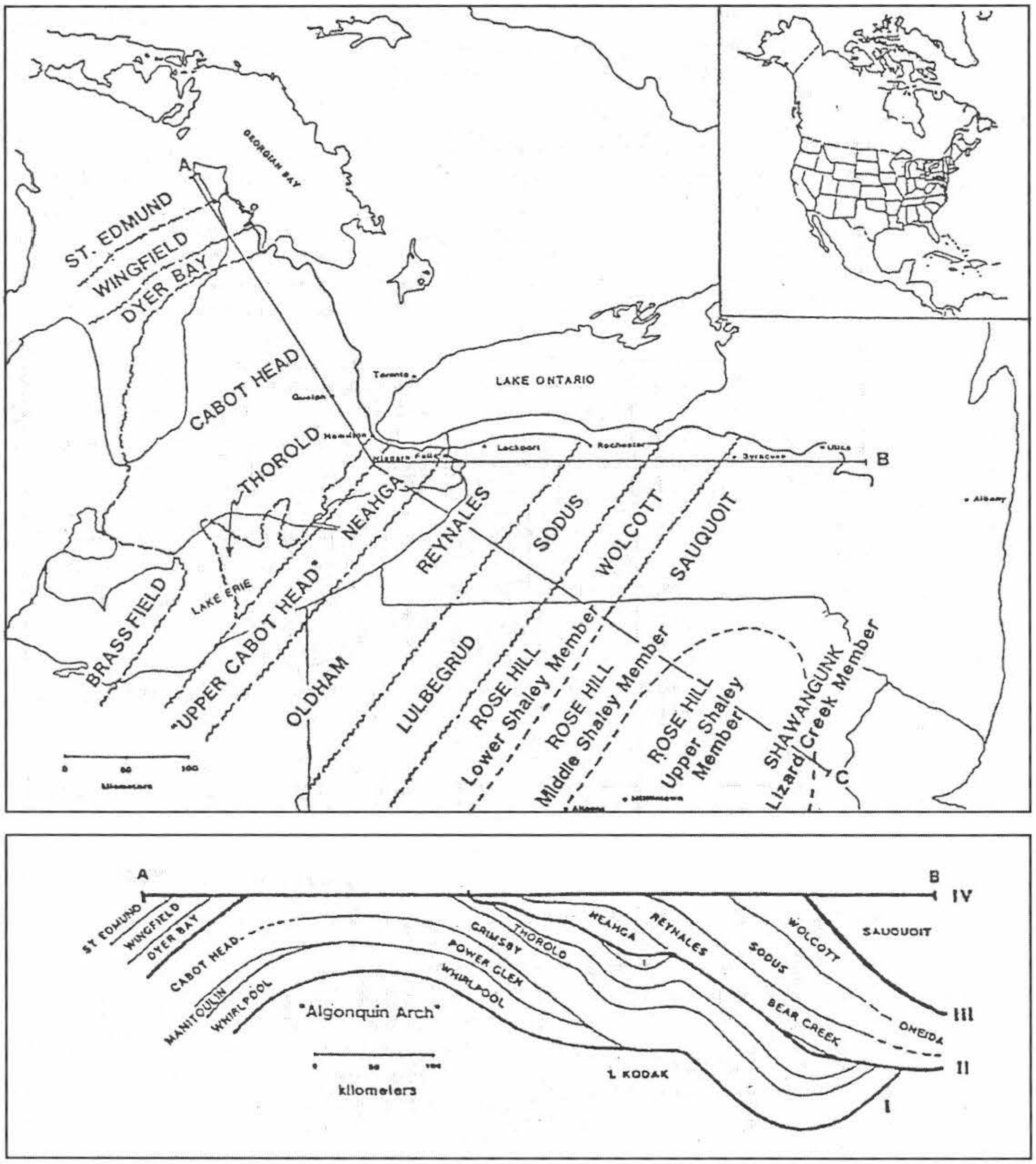


Figure 8. A) Subcrop map of strata beneath late Llandovery (S-IV) unconformity; inset shows general location. B) Hypothetical, vertically exaggerated cross section along line A-A' showing truncation of units along crest of Algonquin Arch and the reappearance of equivalent strata to the northwest.

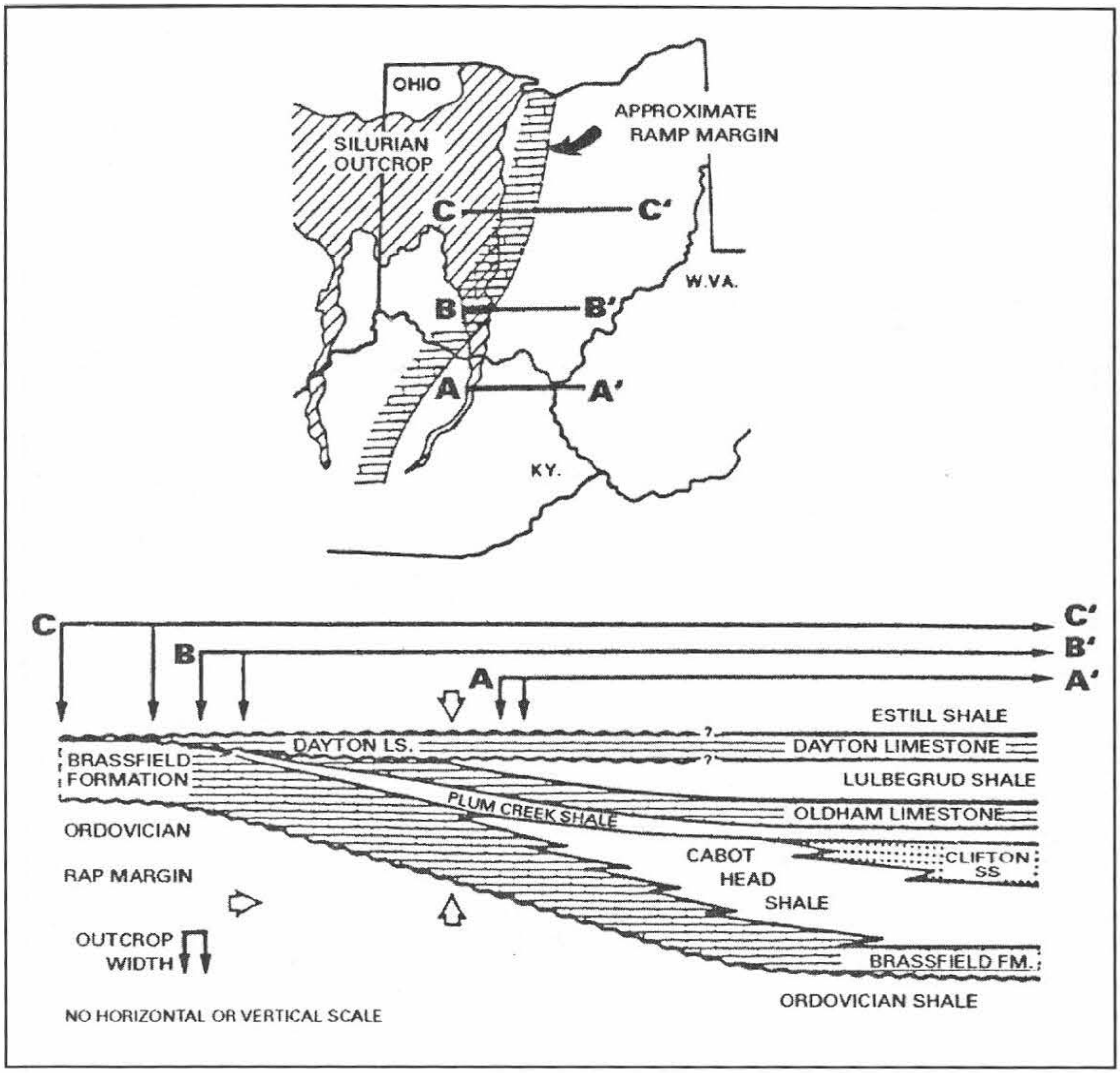


Figure 9. Regional cross sections of Silurian strata through south-central Ohio and northern Kentucky. Note the regional truncation of units along a proto-Findlay Arch (northwest or left side of cross section) below a major unconformity beneath the Dayton Limestone. Adapted from Lukasik (1988).

In southern Ohio a unit lithologically similar to the Merritton, termed Dayton Limestone also overlaps the regionally angular medial Silurian unconformity (Lukasik, 1988; Fig. 9).The Dayton consists of pale gray, glauconitic and heavily burrow-mottled limestone/dolostone. It passes upward into gray green Estill Shale up to 60 m thick, which is correlated with the Williamson-Willowvale interval on the basis of *amorphognathoides* Zone conodonts, as well as graptolites. The upper contact of the Estill is sharp at the base of the Bisher Formation, interpreted as a forced regression surface. The lower 1.0 to 2.0 m of the is composed of nearly barren dolomitic calcarenites to calcisiltites in 5 to 10 cm amalgamated and semi-tabular beds (silty carbonate facies of Bowman, 1956), greatly resembling the age-equivalent Rockway Dolostone of New York.

Sequence V: Upper Clinton Group, Lower to Middle Wenlock (Sheinwoodian)

The Irondequoit Limestone (crinoidal grainstone; 3-5 m), Rochester Shale (gray, calcareous mudstone with interbedded calcisiltites and bryzoan-brachiopod-pelmatozoan packstone storm beds; 0.5-20 m), and DeCew Dolostone (argillaceous laminated and typically heavily deformed dolostone; 3-4 m) together, form another genetically related sequence (Sequence V) in the upper Clinton Group (Figs. 3, 10, 11). The lateral equivalents of these units in the Bruce Peninsula are assigned to the Amabel Formation of the Albemarle Group (Fig. 8; Bolton, 1957; Armstrong and Goodman, 1990).

The basal Irondequoit Disconformity (Sequence IV-V boundary) is nearly planar with little evidence for regional truncation (Figs. 10, 11). However, this contact becomes increasingly sharp westward from Rochester, New York (probable basin center) and the basal Irondequoit contains clasts of the underlying Rockway dolostones. The Irondequoit, changes from thin bedded skeletal wackestones and packstone in the basin center to massive, amalgamated grainstone to the northwest. The unit represents open shelf to crinoids shoal (BA-3) environments. The upper contact of the Irondequoit is an abrupt, but conformable flooding surface. Locally, in Niagara County, small thrombolitic-bryzoan bioherms occur at the Irondequoit-Rochester transition zone; the mounding apparently associated with rapid deepening (Sarle, 1901; Cuffey and Hewitt, 1989).

In southern Ohio the interval corresponding to the Irondequoit Formation is represented by a unit of the Bisher Dolostone, informally designated "*Cryptothyrella*" beds, consists of 0.5 to 1 m of medium, thick and massive bedded fossiliferous dolostone. It tends to weather buff to pale orange in color and is rather porous owing to the weathering of crinoidal ossicles and other fossil debris. Internally, beds may display slightly irregular, darkly stained surfaces, apparently hardgrounds, especially near the top. The topmost 20-50 cm ledge is typically most heavily fossiliferous and comprised mainly of crinoidal pack- to grainstone. The sharp basal contact of this unit is interpreted as the sequence boundary of Sequence V.

Near Dayton, Ohio the Bisher is referred to as the "Laurel Dolostone". This is apparently based on erroneous correlations with sections in southeastern Indiana (Kovach, 1974). Detailed measurements indicate instead that this unit is correlative with the middle Osgood Limestone of Foerste (1897), whereas the true Laurel of Indiana correlates with a thicker succession of crinoidal dolostones identified as Euphemia-Springfield in Green County, Ohio.

The basal Bisher has been sampled and identified as belonging to the *K. ranuliformis* Zone; underlying upper Estill Shale has been identified as upper *P. amorphognathoides* zone (Kleffner, 1989. 1990; pers. comm. 2000); as such, the interval appears to be time correlative with the Irondequoit Limestone in New York and Ontario, and with the Keefer Sandstone of the central Appalachians (Figs. 10, 12). All of these units also share a similar two-fold subdivision with middle shaly intervals, and an abundance of the brachiopod *Whitfieldella*. All are interpreted as parts of the transgressive systems tract of Sequence V.

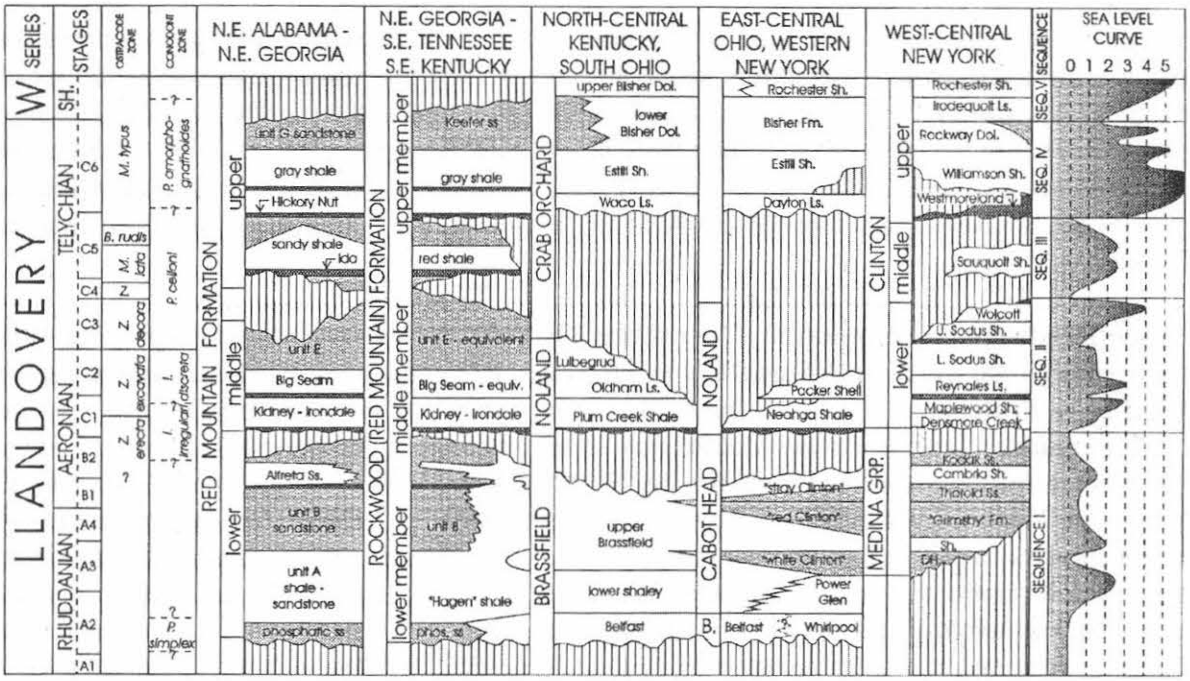


Figure 10. Correlation of Lower Silurian sequences in eastern USA; note particularly the comparisons of Kentucky, Ohio, and New York State. Curve on right side of diagram shows relative sea level curve for central New York State calibrated to benthic assemblages (BA-: shoreline, BA-2 above wave base; BA-3: average storm wave base; BA-4 deep storm wavebase; see Brett et al. (1993) for discussion of depths of these assemblages. Adapted from Brett et al. (1998).

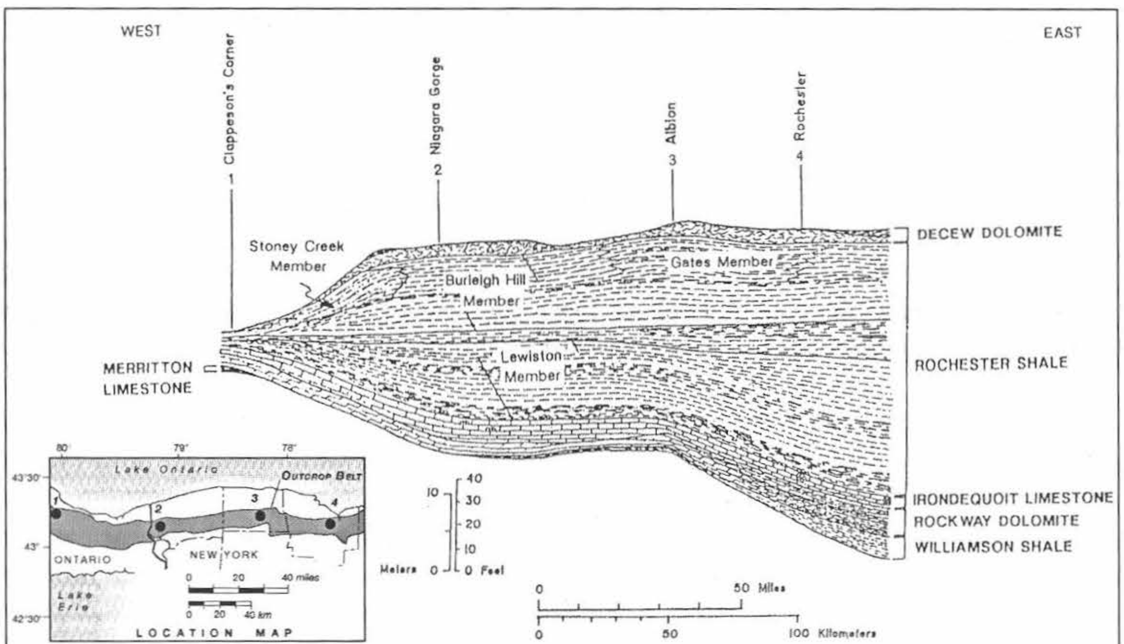


Figure 11. Regional stratigraphic cross section of Sequence V (upper Clinton Group) between Clappison Corners, Ontario and Rochester, New York. Datum is contact of Lewiston and Burleigh Hill Members of the Rochester Shale. From Brett et al. (1995).

To the west, in southeastern Indiana, the "*Cryptothyrella* bed" is represented by a 1 to 2 m thick compact dolomitic crinoidal pack to grainstone, generally mapped as the middle member of the Osgood Formation (*sensu* Foerste, 1897). It shows a sharp but cryptic basal contact. Its upper surface is also a sharp contact with the upper Osgood (=Massie) Shale. Locally, as at Napolean, Indiana, small fistuliporoid bioherms very comparable to those of the upper Irondequoit in western New York protrude upward from this flooding surface into the overlying upper Osgood Shale. This situation is precisely analogous to the small bioherms of the upper Irondequoit and underscores the lateral persistence of mounding events associated with this transgression (Fig. 11).

The Rochester Shale of western New York is divided into two members (Brett, 1982,1983a, b; Fig. 11). The lower-Lewiston Member- is highly fossiliferous along most of the Niagara Escarpment, with over 200 species of bryozoans, brachiopods, mollusks, crinoids, blastozoans, trilobites, and graptolites; bryzoan-brachiopod rich limestone beds occur near its base and top. This facies represents deeper, storm-influenced shelf environments (BA 3-4). However, to the south of the main outcrop, as in southern Niagara Gorge, the Lewiston becomes dark gray shale with sparse brachiopod-trilobite (BA-4 to 5) assemblages, indicating a southward dipping ramp (Brett, 1982, 1983 a, b). The upper Rochester shows two distinct facies: the Burleigh Hill Member-dark gray, sparsely fossiliferous shale-east of Grimsby, and the Stony Creek Member - banded dolomitic mudstone and argillaceous dolostone-to the west (Fig. 11; Brett, 1983). The Rochester Shale becomes increasingly carbonate-rich and thins dramatically to a feather edge from Niagara to Hamilton (Fig. 11). Thinning represents both condensation and erosion below the bases of the Stony Creek Member, and overlying DeCew and Gasport formations. Rochester-equivalent strata may reappear to the northwest in the lower Amabel Dolostone of the Bruce Peninsula (Bolton, 1957). Together, these observations indicate that during the late Llandovery to late Wenlock interval, the topographic center of the foreland basin lay to the southeast and that Hamilton was situated close to the crest of the Algonquin Arch (Fig. 11).

The Rochester Shale-equivalent interval in the Cincinnati Arch outcrop belt is best developed near Hillsboro, Ohio, where it has previously been identified simply as the dolomitic shale facies of the Bisher Formation (Bowman, 1956; Fig. 10). In this vicinity the interval is nearly 3 m thick and comprised primarily of medium dark gray, dolomitic shale with minor fossiliferous, dolomitic packstones in the lower half meter. These beds yield varied brachiopods, especially *Atrypa*, *Coolinia*, and small *Whitfieldella*, as well as ramose and fenestrate bryozoans, the trilobites *Dalmanites* and *Trimerus*, and pelmatozoan ossicles. The upper portion of this unit is dominantly barren dolomitic shale and thin laminated calcisiltites.

A similar, but slightly thinner (190-200 cm) dark gray shale occurs in the corresponding position in the Dayton area where it has been termed the Massie Shale (Foerste, 1935; Fig. 9). Again, the lower half-meter contains scattered fossils and shows a relatively abrupt contact with overlying barren dark gray shale.

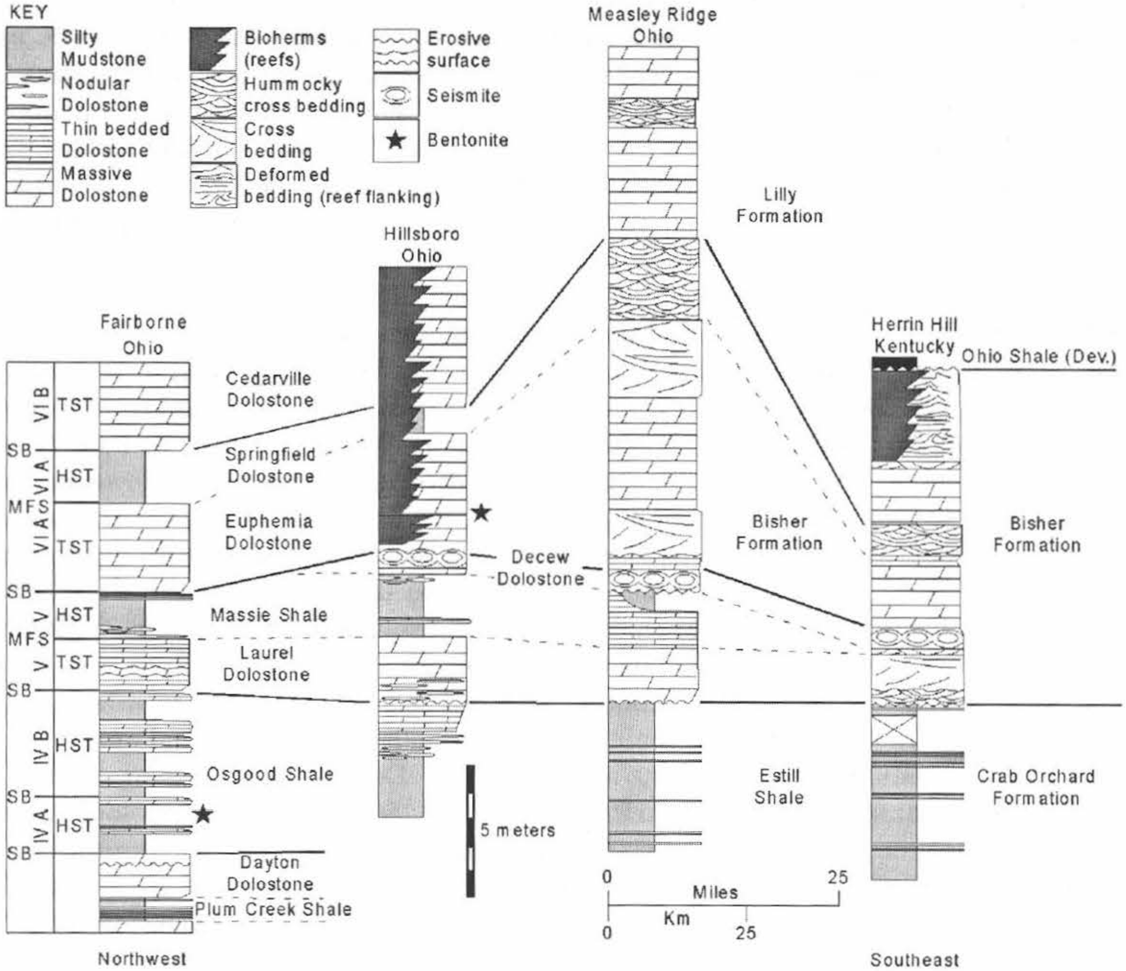


Figure 12. Correlated stratigraphic columns along NW to SE cross section from Fairborn, SE of Dayton, Ohio to Herron Hill, Lewis County, Kentucky. Note comparison to western New York-Ontario terminology. Sequence stratigraphic abbreviations as in figure 7.

To the southeast of Hillsboro, Ohio the interval becomes substantially thinner and more dolomitic but retains its general fine-grained aspect. A crinoidal packstone, about 50 cm above the base of this interval may represent the *Cryptothyrella* bed. The upper two thirds of the unit consists of thin-bedded, argillaceous dolostone and thin dark gray shales. This interval is evidently truncated at the top along a wavy contact with the overlying tan weathering hummocky laminated dolostones .

Correlation suggests that the dolomitic shale facies of the lower Bisher Formation is laterally equivalent to the Massie Shale. The Massie, in the Hillsboro to Dayton area closely resembles the Rochester Shale of the northern Appalachian Basin in both lithology and stratigraphic position. Moreover, near Dayton it has yielded a few fossils that elsewhere are found only in the Rochester. Nine of the 54 species found in the Massie have only otherwise been reported from the Rochester Shale (Busch, 1939). From these observations and the general conodont biostratigraphy we conclude that the Massie Shale is probably coeval with and coextensive with Rochester Shale. Indeed, the division of the Massie into a lower fossiliferous unit and upper barren dolomitic shale is consistent with division of the Rochester into lower fossiliferous Lewiston Member and upper sparsely fossiliferous Burleigh Hill Member (Brett et al., 1995; Figs. 10, 14). Finally, by outcrop to outcrop tracing, the Massie appears to correlate with the upper shale member of the Osgood Formation in Indiana. This interval has yielded a diverse fauna of brachiopods, bryozoans, and pelmatozoans that is very similar to that of the Rochester Shale in New York and Ontario (see Frest et al, 1999, p. 729, for a detailed faunal list).

All evidence indicates that the Massie Shale represents a deepening during early middle Wenlock time (Fig. 14). As such it is interpreted as the highstand systems tract of Sequence V. This same deepening, represented by the Rochester Shale, is also associated with a widespread interval of mud to sand deposition in the Appalachian foreland and may record a tectonic pulse in the Salinic Orogeny (Ettensohn and Brett, 1998). However, a similar interval of relatively deep-water mud deposition also occurs at least in Avalonia (e.g. the early mid Wenlock Coalbrookdale Formation in Britain, suggesting at least some eustatic influence (Brett et al 1990, 1998).

The DeCew comprises hummocky laminated, dolomitic calcisiltite, probably derived from storm-winnowing of carbonate shoal areas north of the present outcrop limit. A zone of extreme soft sediment deformation in the DeCew has been traced laterally along the Niagara Escarpment from east of Rochester, New York, westward to Hamilton, Ontario (Fig. 11) and into southwestern Ohio. The DeCew deformed zone represents a widespread seismite associated with a severe seismic shock and consequent slumping on the south-dipping ramp.

The middle of the Bisher Formation in southwestern Ohio, is a buff weathering planar to hummocky bedded silty dolostone ranging in thickness from 0 to 3 m. It is well developed in Adams and Highland county (Figs. 12, 14). This unit locally displays convoluted bedded, including overturned isoclinally folded laminated and intraclastic beds at several exposures in Adams County (Kallio, 1976). Thin lenses of similarly deformed fine-grained dolostone have also been recognized within the middle of the Bisher Formation at Herron Hill, Kentucky. This middle Bisher is stratigraphically equivalent to a thin bedded interval at the base of the Euphemia Dolostone in the Dayton area, originally described by Foerste (1917).

Both the lower and upper contacts of middle unit in the Bisher are sharp and probably disconformable. Locally, this dolostone exhibits an undulatory lower contact with as much as 20 cm of relief and truncates underlying shaly beds. The upper contact with crinoidal dolostones is planar.

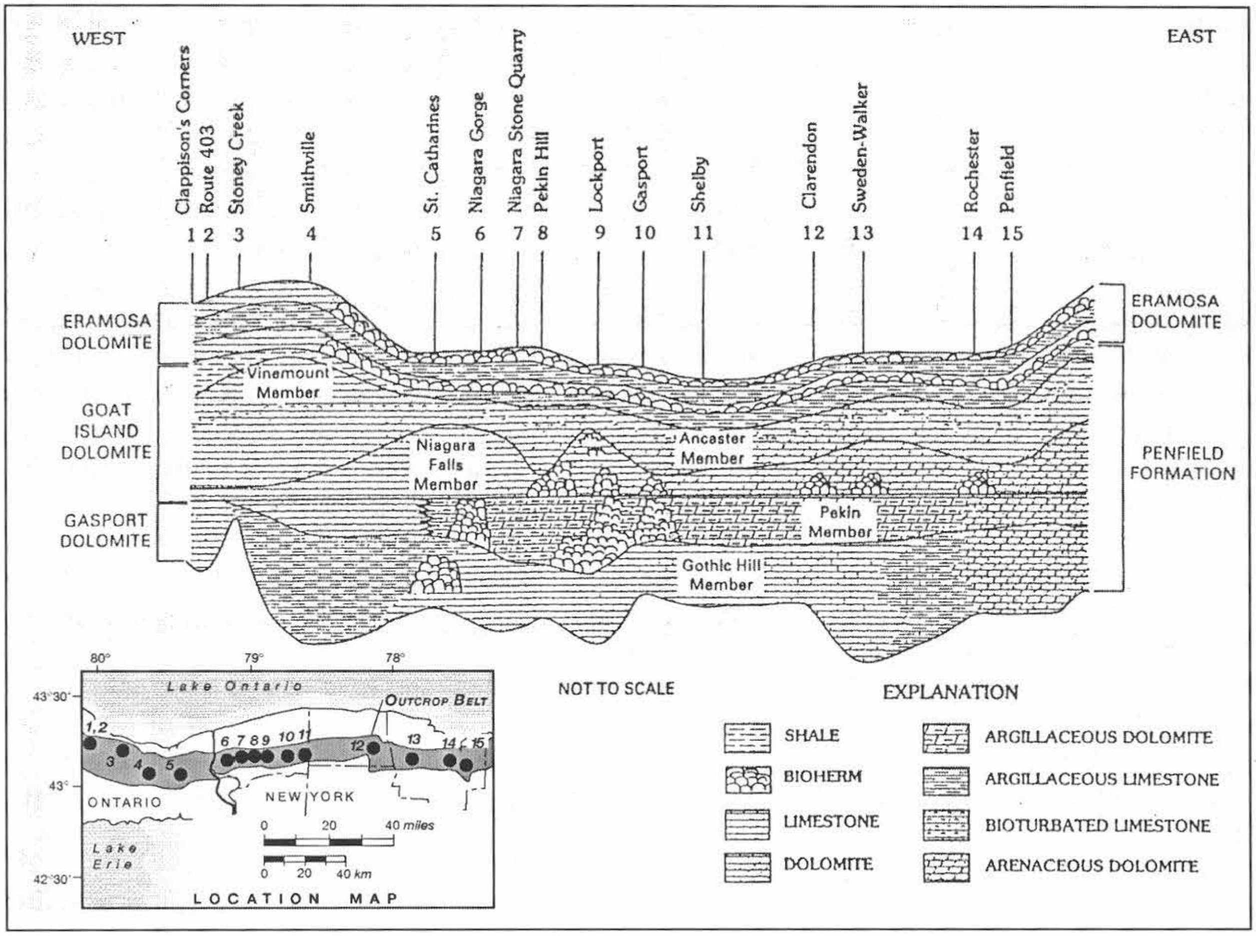


Figure 13. Regional stratigraphic cross section of Sequence VI, lower Lockport Group, between Clappison Corners, Ontario and Rochester, New York. Datum is contact of Gasport and Goat Island formations. From Brett et al. (1995).

The contorted fine-grained dolostones of the Bisher very closely resemble an interval of convolute bedded dolostone in the DeCew Formation in New York State and southern Ontario (Figs. 12, 14). This dolostone occupies an analogous and probably coeval position between the Rochester Shale and crinoidal dolostone of the overlying Gasport Formation. Consequently, we correlate unit with the DeCew Formation. The latter is considered to represent a falling stage systems tract of Sequence V. It shows a conformable to slightly erosional, channeled base and is locally truncated by the overlying sequence bounding unconformity at the base of the Lockport Group (Sequence VI).

Sequence VIA: Lower Lockport Group, Gasport Formation; middle Wenlock

The lower part of the Lockport Group (Sequence VI) comprises crinoidal pack- and grainstones, bioherms, and dolomitic wackestones near the base of the sequence (Gasport Formation), and vuggy grainstones, argillaceous, cherty wackestone and minor shales (Goat Island Formation). A clear-cut sequence boundary exists at the erosive base of the Gasport Formation (Figs. 3, 13). Tabulate-stromatoporoid bioherms typically extend upward from lower crinoidal grainstones into the argillaceous Pekin Member; this indicates that the upward growth of these reefs may have been stimulated by rising sea-level (Crowley, 1973; Brett, 1985; Brett et al., 1990). However, cap beds of fragmentary stromatoporoids suggest that the bioherms were extinguished and truncated by sea-level drop (Crowley, 1973)

Westward thinning, coarsening, and loss of argillaceous, biohermal facies in the Gasport Dolostone also suggests shallowing in that unit toward the Algonquin Arch (Fig. 13). The merging of Gasport and Irondequoit grainstones and associated total truncation of the Rochester Shale-near Hamilton also appears to mark a relative topographic high.

North of Hamilton, Ontario, where the Rochester Shale is absent, the grainstones of the Irondequoit and Gasport merge at a cryptic unconformity. In this area the succession of dolostones, including the equivalents Rockway (locally termed Lions Head Member), Irondequoit, Gasport and Goat Island are combined into the larger unit termed Amabel Formation (Armstrong and Goodman, 1990; Fig. 13). This interval presumably contains two important sequence boundaries (Sequence IV-V and V-VI). However, these key surfaces have been obscured by extensive secondary dolomitization.

The Amabel, especially the Wiarton Member, equivalent to Gasport and Goat Island formations along the northeast side of the Michigan Basin (Sanford 1969), is flat-lying and composed of locally porous, dolomitized bioclastic grainstone. Bioclasts are mostly crinoid pluricolumnals (segments up to 1 cm in width and 10 cm in length), with rhynchonellid brachiopods and stick-like bryozoans becoming the most common elements of a more diverse biota that characterizes the upper few meters. The unit ranges from less than 10 m to nearly 30 m in thickness over an along-strike distance of some 30 km (Hewitt, 1971); this is thought to reflect a primary mounded topography of the megashoal complex (Pratt and Miall, 1993). The Amabel changes in character northward, and it is lithologically more heterogeneous on the Bruce Peninsula (Bolton, 1957). These coarse crinoidal grainstones thin and grade laterally westward and southward, in the seaward direction, to thin- and wavy-bedded, argillaceous, locally cherty, dolomitized lime mudstone and wackestone and subordinate grainstone of the Lockport Group; landward equivalents have been removed by erosion, but were probably thin-bedded, argillaceous dolostones of peritidal aspect.

Throughout southern Ohio, the fine grained dolostones of Unit D of the Bisher Formation are abruptly overlain by a massive interval of cross bedded, sandy textured crinoidal dolostone. In the northwest, at Yellow Springs and Dayton, this 3-6 m interval has been identified as Euphemia Dolostone (Figs. 12, 14). It contains a distinctive interval rich in pentamerid and *Whitfieldella* brachiopods near the base. This same basic stratigraphy,

including the lower brachiopod shell beds, persists at least to Hillsboro, Ohio where the interval is simply referred to as upper Bisher Dolostone. Farther south, near Peebles, Ohio the equivalent interval thickens substantially to over 10 m and consists mainly of trough and tabular (including herringbone) cross-bedded sandy dolostone or dolomitic sandstone with thin intervals rich in crinoidal grainstone. A similar but thinner lithological unit is present at Herron Hill, Kentucky. The correlation of this interval into Indiana is somewhat uncertain, but we suggest, based on stratigraphic position that it is represented in the lower crinoidal dolostones of the Laurel Formation.

The upper Bisher resembles the Gothic Hill Member of the Gasport Formation in Ontario and western New York (Brett et al., 1995) and is probably coeval with that unit (Fig. 14). The sharp base of this unit is interpreted as the Sequence V-VI boundary, corresponding to the sharp, erosive base of the Lockport Group (base of Gothic Hill Member) in New York and Ontario (Fig. 14). Consequently, this interval is interpreted as the LST and TST of fourth order sequence VIA. Substantial lateral variations in thickness are typical of the Gothic Hill Member in western New York and Ontario as seems to be evident in the corresponding interval in southern Ohio-Kentucky. The interval may have developed as a series of sand-pelmatozoan megashoals during regional transgression (see Pratt and Miall, 1993).

A smectitic clay seam, identifiable as a K-bentonite (W. Huff, pers. comm. 1999), occurs about 1.5 m above the base of this unit a Hillsboro and a similar thin seam has been found in a small outcrop along the AA Highway near Vanceburg, Kentucky. Reconnaissance study of the Gasport Formation near Lockport, New York has also resulted in discovery of a clay bed, possibly also a K-bentonite in the Gothic Hill Member. Although these are preliminary observations, this horizon may provide a useful datum for time correlation. Its occurrence seems to corroborate sequence stratigraphic inferences.

At Hillsboro, Ohio a large (>100 m across and up to 10 m thick) mound of massive dolomicrite extends upward from within (Fig. 12). Bedding of the succession beneath this mass has been deformed into a local syncline apparently due to differential compaction beneath the mound. Although this mass was previously attributed to contorted bedding from collapse, close observation revealed the presence of encrusting bryozoans, pelmatozoan holdfasts, and tabulate corals. The mass is interpreted as a bioherm or mud mound. Along its flanks it interfingers with beds of coarse pack- and grainstone composed of large crinoid pluricolumnals. These beds show hints of graded bedding (fining upward) and they are interpreted as flank debris beds. The bioherm appears to be slightly inflected (notched) at the level of a prominent shale bed that overlies the crinoidal dolostone unit (see below). It is not clear whether the bioherm extends upward into overlying massive dolostones, or whether these beds merely drape the mound because this contact is poorly exposed near the top of the exposure.
The Hillsboro bioherm occupies a stratigraphic position that is consistent with the Gasport reef zone of western New York-southern Ontario (Crowley, 1973) and the "Lockport reef zone" in the McKenzie of Pennsylvania and West Virginia (Smosna and Patchen, 1978). Evidently, bioherms developed very widely in this interval (i.e. at the Gothic Hill-Pekin member boundary in terms of New York stratigraphy; Fig. 13). In a sequence context, these bioherms seem to have grown upward on a substrate of stabilized echinoderm sand/gravel associated with a condensed interval and maximum flooding zone during middle Wenlock time.

The massive, cross bedded crinoidal dolostones of the Bisher (or Lilly) are everywhere overlain by thin bedded, argillaceous, planar to hummocky cross laminated dolostones and shales. Near Fairborn and Yellow Springs, Ohio this interval of thinly and regularly bedded fine grained dolostones/dolomitic shales is referred to as the Springfield Dolostone (Fig.14). At the Hillsboro roadcut this zone is particularly shaly, with up to 40 cm of greenish gray dolomitic shale near the previously discussed bioherm. As noted this shale appears to interfinger with the bioherm. Near Peebles the upper is recorded as a 4-6 m finer grained hummocky laminated dolostone above the massive unit.

Overall, the thin bedded, argillaceous dolostone of the Springfield-upper Bisher closely resembles that of the Pekin Member in New York and its relationship to the bioherm at Hillsboro is similar to that seen in the Gasport bioherm zone of New York. This interval, like the coeval Pekin Member shows a vague shallowing upward trend and is interpreted as the HST of fourth order subsequence VIA.

Sequence VIB. Goat Island Formation

A second fourth order sequence boundary at the sharp, erosive base of the Goat Island Formation. Locally, as at the Rte. 427 roadcut at Pekin, New York, there is substantial erosional relief at this sequence boundary and mounds of biohermal stromatoporoid-rich dolomicrite appear to infill this erosional topography. In the Goat Island Formation, massive crinoidal grainstone shoal facies (BA-2-3) characteristic of the Niagara Gorge are replaced westward by thin-bedded, cherty wackestone (Ancaster Member; BA-3-4), which thicken to a maximum in the Hamilton area before passing laterally again into massive dolostones (Fig. 13). This westward deepening trend is also evident in the Vinemount Member, which is a slightly cherty dolowackestone to the east but is represented by dark, dolomitic shales near Hamilton, Ontario. These shales only persist northwest to near Dundas where they are replaced or pinched out against upper Amabel dolostones (Fig. 13).

The picture is not entirely straightforward, as small areas of shaly and/or cherty dolostone also occur locally in the Goat Island position in Niagara County, New York. This pattern suggests that minor fault block-controlled basins may have formed during Goat Island deposition. (Sanford et al., 1985) This irregular topography may have been associated with an abrupt westward migration of the main basin center to the Vinemount-Hamilton region (Fig. 13).

In southwestern Ohio the lower Goat Island interval appears to be represented by massive, vuggy, crinoidal dolostone (originally pack- or grainstone) identified near Yellow Springs and Dayton, as the Cedarville Dolostone and to the southeast as the Lilly Formation. This interval closely resembles the lower massive Niagara Falls Member, of the Goat Island Formation in western New York-Ontario with which it is tentatively correlated (Figs. 9-13). Both units have been dated as belonging to the *O. sagitta rhenana* Zone (Kleffner, 1990; pers. comm. 2000). This unit is interpreted as a LST and TST; its sharp, undulatory basal contact is the subsequence S-VIB boundary. Farther southeast, near Vanceburg, a small roadcut on the AA Highway, an interval of bioturbated stromatoporoid-rich dolostone sharply overlies shaly dolostones. This interval shows no trace of mounding but instead carries abundant coenostea of stromatoporoids and favositid and cladoporid corals in a bioturbated dolomitic calcisiltite (Mason et al. 1992). Upper portions of the outcrop show abundant cream colored chert nodules. This outcrop most closely resembles Ancaster facies of the lower Goat Island Formation in New York and Ontario. Stromatoporoid-coral biostromes and local mud mounds (e.g. the Pekin "Bioherm" see Brett et al., 1994) are typical of the Niagara Falls Member immediately overlying the Pekin shaly dolostone, whereas light chert nodules locally characterize the middle Ancaster Member (see Brett et al., 1995, for discussion). Together, this evidence suggests correlation with the lower Goat Island Formation and, as with that succession, the Lilly Formation is interpreted as the combined LST-TST of fourth order subsequence S-VIB (Figs. 12, 14).

Throughout south-central Ohio a 0 to 3 meter thick interval of medium gray shale and argillaceous dolostone abruptly overlies massive crinoidal dolostone of the Lilly. Several small (< 1 m high) bioherms protrude above this surface and very minor mounds with small stromatoporoids occur in association with a middle dolomitic band that splits the shale-rich beds into upper and lower portions. This contact is interpretable as a major flooding surface; it seems to correlate with the base of the Vinemount Member- a succession of shales and thin bedded argillaceous dolostones, particularly well developed near Hamilton, Ontario (see Brett et al., 1995, for formal definition). Again, the positioning of the biohermal beds is consistent with the model discussed above. Mounding is correlated with deepening and perhaps cleaning of the sea water at a maximum starvation surface. The post-Lilly shale beds and probably coeval Vinemount beds of the Goat Island Formation represent the HST of subsequence VIB.

Sequence VII: Upper Lockport-Vernon Formation, upper Wenlock to Ludlow (Ludfordian)

Biostromal to flaggy argillaceous, dolostones (Eramosa) and massive, buff, biostromal to biohermal dolostone (Guelph Formation) form the upper part of the Lockport (or Albemarle) Group (Fig. 3). The Eramosa, interpreted by Armstrong and Johnson (1990) as an inter-reefal, dysoxic environment (BA-2-3), has recently yielded assemblages of soft-bodied fossils, including algae, and unusual arthropods (Waddington and Rudkin, 1992; LoDuca, 1995, 1996; Tetreault, 1995, 1996). A disconformity at the base of the Eramosa Formation in New York is now interpreted as the boundary of a sequence (VII) not previously recognized by Brett et al. (1990). Still further westward migration of the basin axis (and final subsidence of the "Algonquin Arch") appears to have occurred during deposition of the Eramosa and Guelph Formations, in which deepest facies (BA-3) occur northwest of Hamilton, Ontario, while biostromal to stromatolitic facies (BA-2) occur in the Niagara region (Brett et al., 1995).

In southern Ohio the post-Lilly shale zone is abruptly overlain by massive vuggy, stromatoporoid, coral, and brachiopod-bearing Peebles Dolostone. This contact is thought to correlate with the sharp (sequence bounding) basal contact of the Eramosa Dolostone in Ontario and New York (Sequence VII). However, the details of this transition are presently under study and are beyond the scope of this paper.

In drill cores the Guelph can be seen to pass gradationally upward through series of interbedded shaly dolostones and dolomitic shales of the Vernon Formation (upper Ludlow; Salina Group). The Vernon Formation represents a tongue of siliciclastic sediments from the Bloomsburg-Vernon clastic wedge that was shed from tectonic regions (Salinic Orogeny) in the mid-Atlantic region. In central New York, the Vernon consists mainly of red mudstones, but in western New York and Ontario the unit consists of over 60 m of greenish gray shales and buff dolostone with interbedded anhydrite.

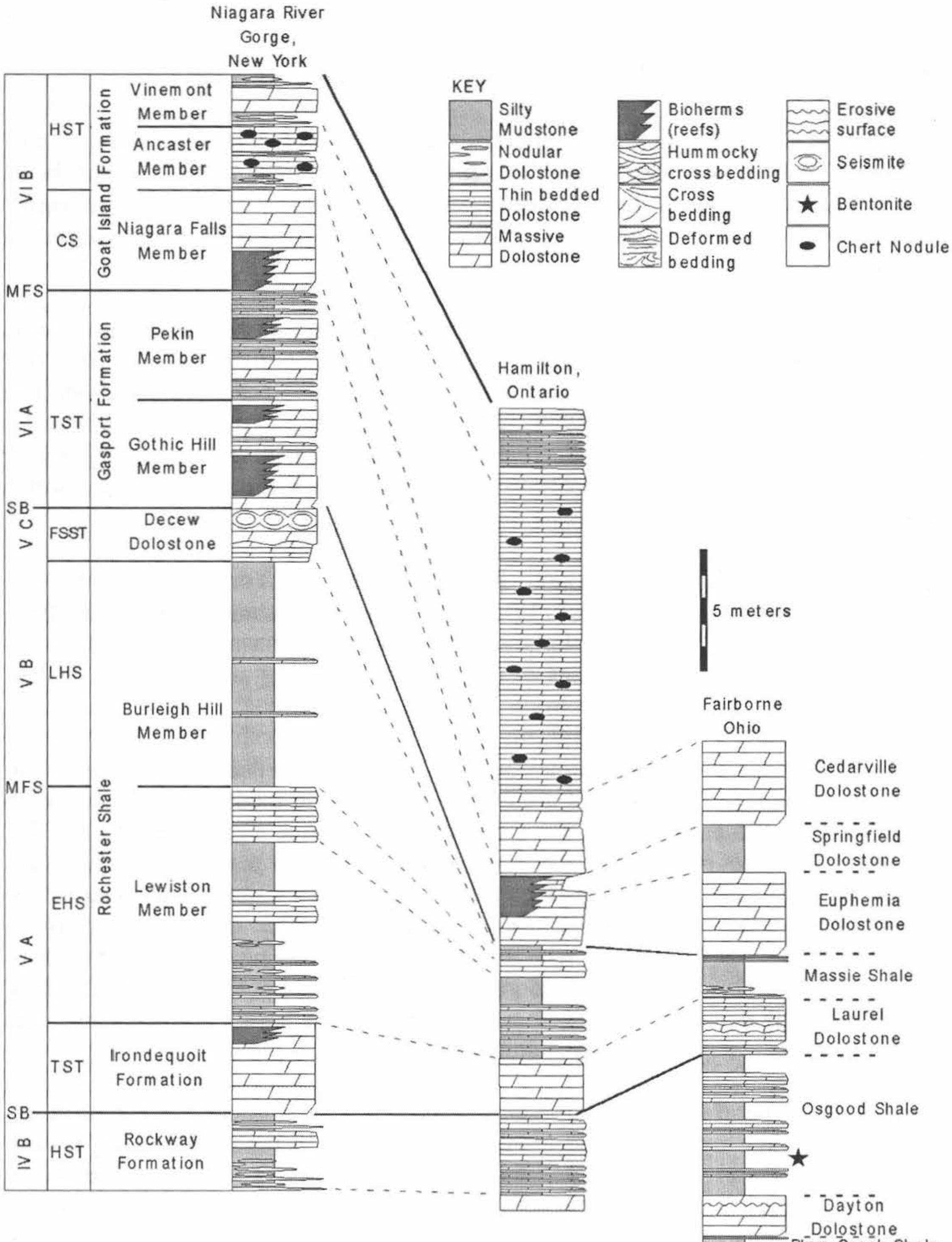


Figure 14. Correlation of late Llandovery to Wenlock stratigraphy of Niagara Gorge, New York and Dayton, Ohio, showing basic similarity of succession. Sequence stratigraphic abbreviations as in Figure 7.

Sequences VIII, IX: Upper Salina and Bertie Groups, Upper Ludlow-Pridoli

In southern Ontario the upper Salina Group comprises over 60 m of dolostones, shales, and evaporites but it is very poorly exposed. Detailed sequence stratigraphy has not been undertaken. Brett et al. (1990) noted that an erosion zone and regionally angular unconformity exist between the Vernon and overlying Syracuse Formation in central New York and suggested that a sequence boundary exists at this level within the Salina Group (Figs. 3, 15).

The Syracuse and Camillus formations, each about 30 m thick, comprise gray to green-maroon mudstones, buff dolostones and evaporites (Fig. 11). Key salt-gypsum horizons within the Syracuse have been traced in subsurface through Ontario from the Appalachian foreland into the Michigan Basin (Fig. 11; Rickard, 1969; 1975; Milne, 1992). These strata were evidently deposited under arid subtropical climates in interconnected but restricted basins. The widespread nature of the evaporite-dolostone-shale alternations indicates both that topography (e.g. on the Algonquin Arch) was subdued and that the cycles were due to eustatic-climatic effects.

The highest Silurian strata (middle-upper Pridoli) in the western New York-Ontario areas are presently assigned to the Bertie Group (Figs. 3, 15). They comprise a relatively thin (16-18 m) cyclic succession of distinctive, buff gray, slightly argillaceous dolostones ("waterlimes", so-named because of their geochemical properties of natural cement rocks) and dolomitic shales. The basal Oatka Formation is dominantly dolomitic shales and is gradational with the underlying Camillus Shale. The Fiddlers Green (5.5-8 m; 18-25') contains both massive brownish waterlimes and some thrombolitic dolomitic limestone that represents the deepest water facies of the Upper Silurian. Scajaquada Formation is a thin unit of dolomitic mudstone, apparently of sabkha origin, while the Williamsville carries a repeat of waterlime facies resembling the Fiddlers Green. Both units are noted for the occurrence of excellently preserved eurypterids, phyllocarids, and other fossils that are suspected to represent a brackish water estuarine biofacies that bordered hypersaline shallow seas. Finally, the Akron Dolostone (2.8 –2.5 m; 6-8') consists of massive burrow mottled, vuggy dolostone with molds of corals. This unit apparently records a return to somewhat more normal marine lagoonal environments. Locally, a higher (latest Silurian to earliest Devonian dolostone, the Clanbrassil Formation has been identified above the Akron; it records a return to "waterlime" deposition (Ciurca, 1990).

During deposition of the upper Salina and Bertie Groups there is a west to east displacement of depocenters (typically marked by thickest accumulations of halite in the Appalachian Basin) through central to east central New York State (Rickard, 1969). The Lower Devonian Helderberg Group was deposited in a basin the axis of which lay southeast of New York State, while western New York- Ontario were above sea level. The lateral consistency of upper Salina and Bertie Group units along the central New York-southern Ontario outcrop belt suggests also that the facies strike in this region is roughly east-west, parallel to the northern rim of the foreland basin.

Silurian-Devonian (Wallbridge) Unconformity

In western New York and southern Ontario Upper Silurian strata are unconformably overlain by upper Lower Devonian quartz arenites of the Oriskany Sandstone, and cherty, fossiliferous carbonates of the Bois Blanc and/or the Middle Devonian Onondaga Formation (Figs. 15). This second order "Wallbridge Unconformity" marks the boundary between the Tippecanoe and Kaskaskia supersequences (Sloss, 1963; Dennison and Head, 1975). It displays evidence of karst development, with irregular relief of up to 3 m. This unconformity apparently records a major late Early Devonian draw-down in sea-level which exposed older Silurian carbonates and evaporites to subaerial weathering and erosion. Sea-level rise in the late Early Devonian (late Pragian to Emsian) resulted in flooding of the irregular erosion surface. Kobluk et al. (1977) described rockground features of the *Trypanites* bored and glauconite-coated upper contact of the Silurian Akron Formation in southern Ontario (see Brett et al., 2000, for description of a similar surface in western New York). To the west, near Hagerstown, Ontario the basal fossiliferous quartz arenites of the Oriskany Formation (Pragian) rest unconformably on the Wallbridge Unconformity, but in the Ft. Erie-Port Colbourne area and in western New York the Oriskany has been removed by subsequent erosion and the basal Devonian unit is the Bois Blanc Limestone.

BASIN TECTONICS: MIGRATING DEPOCENTERS AND FOREBULGE

The ability to delineate and correlate thin sequence stratigraphic intervals also permits recognition of regional patterns that may be the result of minor tectonic adjustments and shifting depocenters within the Appalachian Foreland Basin (Goodman and Brett, 1994; Ettensohn and Brett, 1998). Within the Silurian as a whole, we recognize a large scale pattern of eastward-westward-eastward migration of the deepest water area and depocenter of the Appalachian Basin during the Early Silurian to Early Devonian time. This tectonically driven effect is superimposed on the more widespread (eustatically controlled) pattern of sea-level fluctuation manifest in the depositional sequences (Fig. 16).

In addition, minor abrupt facies changes within discontinuity-bound sequences, on the scale of a few kilometers, provide evidence for localized flexure of the crust, probably in the form of subsurface fault blocks, as described by Sanford et al. (1985). These local flexures may not be independent from the overall tectonic pattern but may record the local crustal response to migrating "waves" of compression due to episodes of tectonic loading and relaxation (Beaumont et al., 1988).

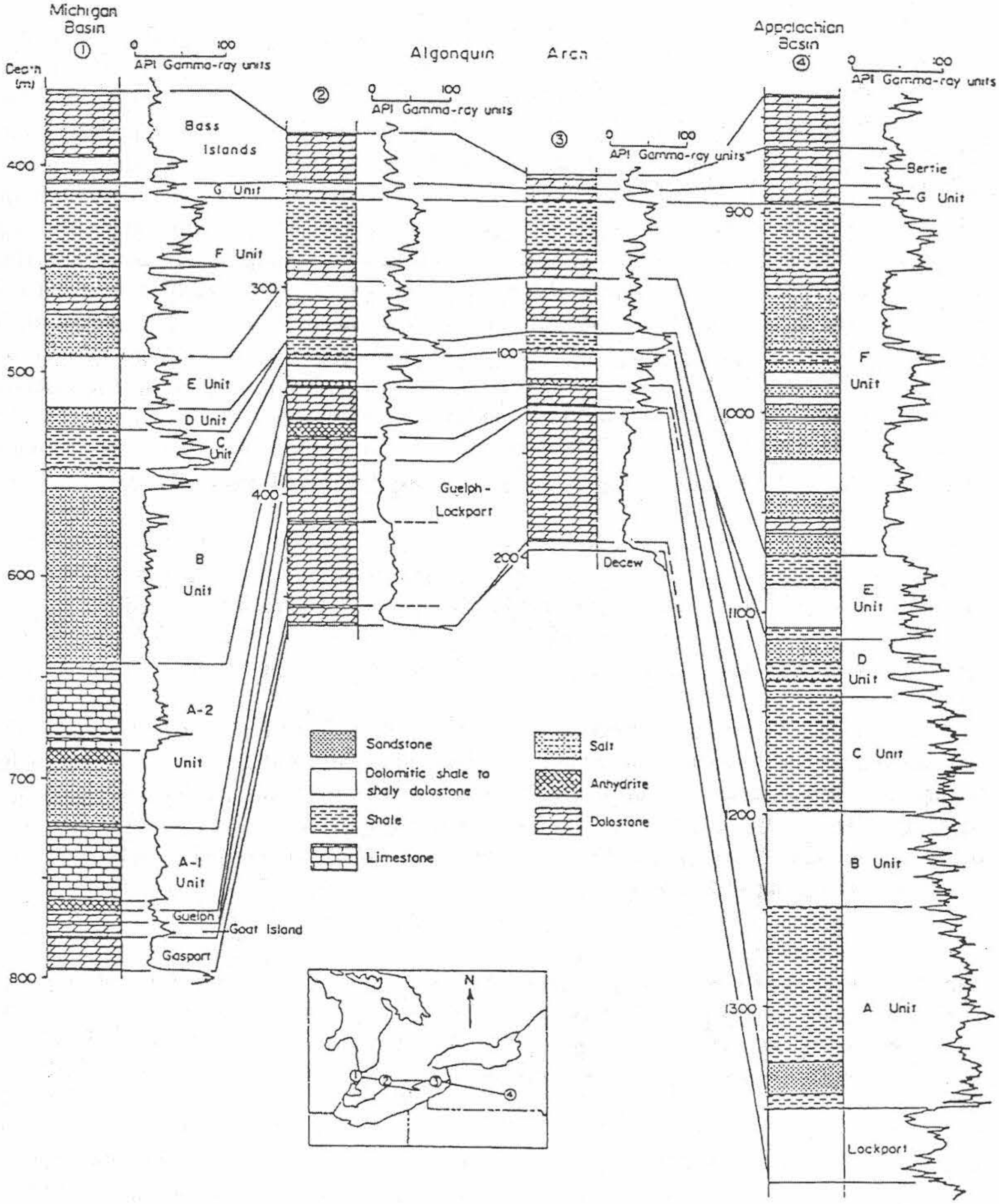


Figure 15. Correlated columns and gamma ray profiles of Upper Silurian Lockport, Salina, Bertie and Bass Islands groups in southern Ontario and south-central New York. Note persistence of salt marker units in the Salina Group and the irregular Wallbridge Unconformity beneath Devonian strata. From Thurston et al. (1992).

PALEOECOLOGY

Throughout the Early to mid Silurian marine waters in the foreland basin and mid-continent platform were of normal salinity and diverse invertebrate faunas formed a series of onshore-offshore biofacies gradients. These biofacies formed extensive belts parallel to paleoshoreline (Brett, 1999) that have been termed Benthic Assemblages (BAs; Fig. 2) by Boucot (1975). Benthic assemblages have been calibrated to absolute depths by Brett et al. (1993). Benthic Assemblage-1 (BA-1) is dominated by lingulid brachiopods, bivalves, gastropods, or, in carbonates, stromatolites/thrombolites and ostracodes deposited within just a few meters of sea level. BA-2 is dominated by low diversity brachiopod associations (especially *Eocoelia* in the Early Silurian; Fig. 3) and tabulate coral and stromatoporoid biostromes and bioherms deposited above fair-weather wave-base (<20 m). Tabulate-stromatoporoid patch reefs of BA-2 were particularly well developed during the Wenlock-early Ludlow of the Niagara region (Crowley, 1973; Armstrong and Johnson, 1990). BA-3 is characterized by diverse pelmatozoan associations and pentamerid brachiopods deposited near or just below fair-weather wave base (~20-30 m). BA-4 is typified by diverse assemblages of brachiopods, bryozoans, trilobites, mollusks, and pelmatozoan echinoderms deposited between fair-weather and storm wave-base (30-60 m). BA-5 is characterized by small brachiopods, a few bivalves, and, in some areas, graptolites deposited near storm wave-base (>60 m). These benthic assemblages have proven to be widely mappable and useful in determining the depths of the interior seas (Johnson, 1987; Brett, 1999). Events of storm-related deposition buried organisms rapidly on the sea floor leaving them largely intact, resulting in spectacular obrution deposits of crinoids, rhombiferan cystoids, asteroids, and trilobites, especially in the Cabot Head and Rochester shales (Brett and Eckert, 1982; Taylor and Brett, 1996).

During Late Silurian (Cayugan or Pridolian) epeiric seas in the Appalachian and Michigan basins became restricted by barriers of the Bloomsburg clastic wedge (to the south) and barrier reef complexes (around the Michigan Basin) and developed hypersaline conditions under which evaporites formed and few organisms, other than rare ostracodes, occupied open shelf environments. In estuarine areas, where fresh water streams mixed with the hypersaline environments, distinctive brackish water biofacies developed (Clarke and Ruedemann, 1912; Ciurca, 1990). These peritidal (BA-1 to 2) biofacies were dominated by eurypterids, and a few species of ostracodes, mollusks and algae. Only in the latest Silurian were normal marine salinities partially restored in the Appalachian Basin.

Silurian marine invertebrates and their biofacies exhibit long term concurrent evolutionary stability punctuated by abrupt intervals of extinction, immigration, evolution, and restructuring. Brett and Baird (1995) termed this pattern "coordinated stasis" and recognized distinctive stable faunas (or ecological evolutionary subunits) in the Silurian of the Appalachian Basin; these correspond very roughly to depositional sequences and were termed the: 1) Medina; 2) Lower Clinton; 3) Upper Clinton-Lockport; and 4) Salina faunas. The latest Silurian-Early Devonian E-E subunits are absent from the study area due to erosion at the Wallbridge Uncoformity.

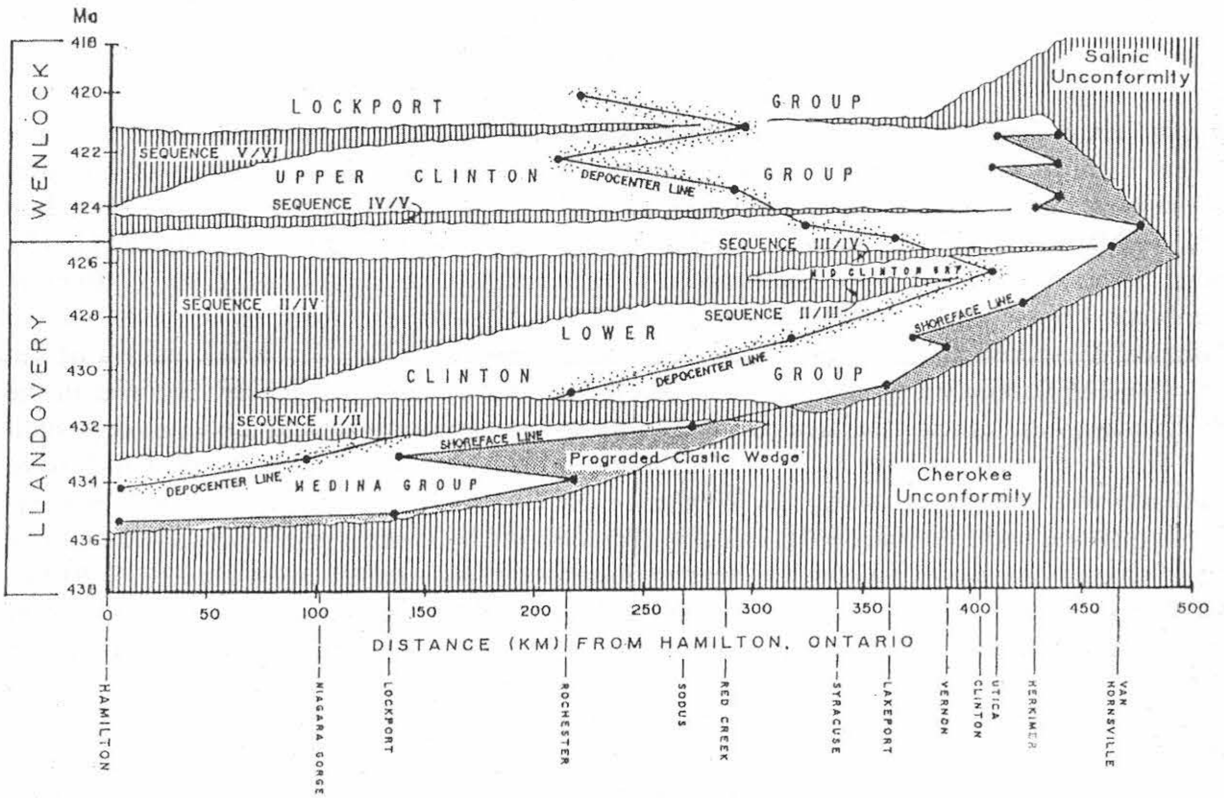


Figure 16. Migration of depocenter and shoreface facies during early to medial Silurian time relative to locations along the east-west outcrop belt (~470 km) from Hamilton, Ontario to Van Hornesville in central New York State. Note time-scale on vertical axis in millions of years. Vertical ruling indicates unconformity. From Goodman and Brett (1994).

EVENT STRATIGRAPHY

Two excellent examples of probable seismites occur in the Silurian of the Niagara area. The first consists of a ball and pillow horizon in the reddish sandstones of the upper Grimsby Formation (McLaughlin and Brett, 2006). The larger deformed masses, up to 2 m, across, show overturned folds and flame structures; The deformation is not observed everywhere but seems to be concentrated in areas of thicker sandstone beds that may represent shallow tidal channel fills (Duke and Brusse, 1987). Basal surfaces of the pillows display small-scale load casts, striations, deformed burrows and load crack casts indicating deformation of semi-plastic muds by loading. To date, this horizon has been traced from Niagara Gorge, near Lewiston, NY westward to Hamilton, Ontario.

The second example of a probable seismite horizon in the Niagara region is the well-known "enterolithic" interval in the DeCew Dolostone (Nairn, 1973; McLaughlin and Brett, 2006). The DeCew consists of buff weathering, medium dark gray, hummocky laminated dolostone (originally fine calcarenite or calcisiltite) with scattered layers of small (1-4 cm) intraclasts (Fig. 17). The lower 1 to 1.5 m of the DeCew displays extraordinary deformation that includes, ball and pillow style deformation and recumbent folds in the intraclasts beds. Overlying beds in the upper DeCew are unaffected. Preliminary study of orientations of deformed beds in the DeCew indicates that these folds do not show a consistent overturn direction (Fig. 18). This chaotic orientation suggests liquefaction and foundering, possibly accompanied by some very local submarine sliding. The bases of these beds show numerous invaginations, consistent with squeezing of liquefied sediments upward into the overlying beds. A very similar, but much less extensive, bed of deformed laminated, silty dolostone occurs in the upper Rochester Shale in the southern Niagara Gorge. The most impressive aspect of the DeCew deformed interval is its broad lateral extent. Deformation within this unit can be traced along nearly all Niagara Escarpment exposures from Penfield, east of Rochester, NY, to Hamilton, Ontario, where the DeCew has been erosionally truncated by erosion at the basal Lockport erosion surface (Sequence S-6 boundary). Similar deformation has been identified in a silty dolostone bed at the top of the Rochester Shale near Allenwood, Pennsylvania (Brett et al., 1990). Recently, a very similar zone of deformed dolostone has been identified in age-equivalent strata mapped as upper Bisher or lower Lilly formation in southern Ohio (Flanigan, 1986; Brett and Algeo, 2001). This bed also appears underlie the basal Lockport (Sequence VI) boundary at the base of the upper Bisher Formation in some outcrops. At Hillsboro, Ohio the deformed bed overlies a unit closely resembling, and probably equivalent to, the Rochester Shale (Brett and Ray, 2001, 2006). If the Pennsylvania and Ohio occurrences indeed correlate with the DeCew, this would indicate an enormous area of deformation of more than 200,000 km^2, making the DeCew one of the most widespread deformed zones yet reported. Deformed zones with similar areal distributions have been described from the Upper Ordovician of eastern North America (McLaughlin and Brett, 2004) and from the Triassic of Britain (Simms, 2003). Very large earthquakes (>7M) and bolide impacts are implicated as possibly triggering deformation (Simms, 2003).

At present there is no good indication of any one fault, which may have produced the seismic energy to cause the deformation of the DeCew sediments. However, the zone of deformation appears to lie adjacent to deep-seated basement faults, which bound the so-called Bass Island Structure in southwestern New York, northwestern Pennsylvania, and into eastern Ohio. Thrust induced loading of the cratonic margin likely resulted in reactivation of an entire network of basement faults well in to the cratonic interior, providing the triggering mechanisms to produce wide spread soft-sediment deformation.

The Silurian deformed beds display a range of sedimentary features that supply information about the environment and timing of deformation. Sedimentary structures demonstrate that these sediment layers were not deformed during initial deposition, but later, during shallow burial. In some instances there is evidence that these deformed beds were truncated while exposed at the seafloor indicating penecontemporaneous deformation. The deformed strata themselves are typically composed of thin shales, overlain by laminated silt- to fine sand-sized sediments (both carbonate and siliciclastic). The shales typically show little evidence of bioturbation; those burrows that are present are sharply defined indicating formation in firm muds. The overlying fine-grained carbonates/sands commonly contain hummocky to swaly cross bedding, suggesting lower shoreface deposition. These beds display sole marks (e.g., scratches, prods, and flutes) suggesting deposition on firm, over-compacted mud substrate that were stable, even during deposition of uneven sediment loads. The contacts between the mud and the overlying silt-sandstone are very sharp; an interface that is poised at instability given the thixotropic properties of the mud.

Observation of the deformation structures (e.g., ball-and-pillows, mudstone diapirs) suggests that mobilization of thixotropic mud caused deformation of the surrounding sediments during gel to sol transitions. In the gel state the muds were cohesive enough to record sole marks and to support the load of overlying silt or sand. However, during episodes of seismic shaking muds flowed upward as diapirs, evacuating from the lower part of a deforming interval (Fig. 17). Experimental data suggests that compact thixotropic muds will not deform unless triggered by a sudden shock, such as an earthquake wave (Brenchley and Newall, 1977). Detailed interpretation of similar occurrences in the Upper Ordovician of the Virginia-Kentucky region by Pope et al. (1997) and McLaughlin and Brett (2004) indicates that such widespread deformation over areas of a few tens of square kilometers would accompany large earthquakes with magnitudes in excess of 7 on the Richter scale. Pope et al. suggested that the ball and pillow horizons and related slumps might have been triggered by earthquakes in the Taconic Orogen or

movements of local basement faults. In any case, these dramatically deformed intervals provide excellent stratigraphic markers. They also indicate that the Appalachian foreland basin was not tectonically quiescent through the Silurian (see Ettensohn and Brett, 1998).

Lower Silurian deformed beds correspond in time with formation of shale basins and occurrence of minor K-bentonites. The timing and degree of tectonic loading of the Laurentian cratonic margin during the Silurian has been established by analyzing the distribution of dark shale basins (Goodman and Brett, 1994). The only deformed beds of the Llandovery (Grimsby and Thorold formations), for that matter since the Upper Ordovician early Maysvillian stage (~5 million years older), are coincident with these indicators of resumed tectonism. Similarly, Wenlock strata were deposited during the Salinic Orogeny (Ettensohn and Brett, 1998), a period noted for widespread formation of dark shale basins with different geometries than Taconic basins.

K-Bentonites

Altered volcanic ash beds provide some of the most valuable marker beds in the geologic record. In theory, these beds record single events of tephra deposition from explosive volcanic eruptions. Not only do they form excellent time lines but also many bentonites can be radiometrically dated. Few K-bentonites have been reported from the Silurian of the Niagara region. However, recently, thin clay layers that appear to be bentonites have been identified in the lower Lockport Group of western New York. These might correlate with probable K-bentonites that have been found in the medial Silurian on both eastern and western flanks of the Cincinnati Arch in Ohio, Kentucky, and Indiana (Brett and Algeo, 2001). Work on these beds is in very preliminary stages and will only be briefly discussed on this field trip.

Tempestites

Storms produce a distinctive suite of sedimentary deposits that range from coarse, amalgamated skeletal debris beds to small-scale hummocky laminated siltstones and sandstones, to distal mud layers. In some cases, particular conditions associated with a given storm bed may make it distinctive and usable for local or regional event correlation. Such applies to certain coarse skeletal debris layers, notably pavements or shingled shells of flattish to gently concavo-convex brachiopod shells and oriented them in edgewise clusters over a large area of seafloor; several

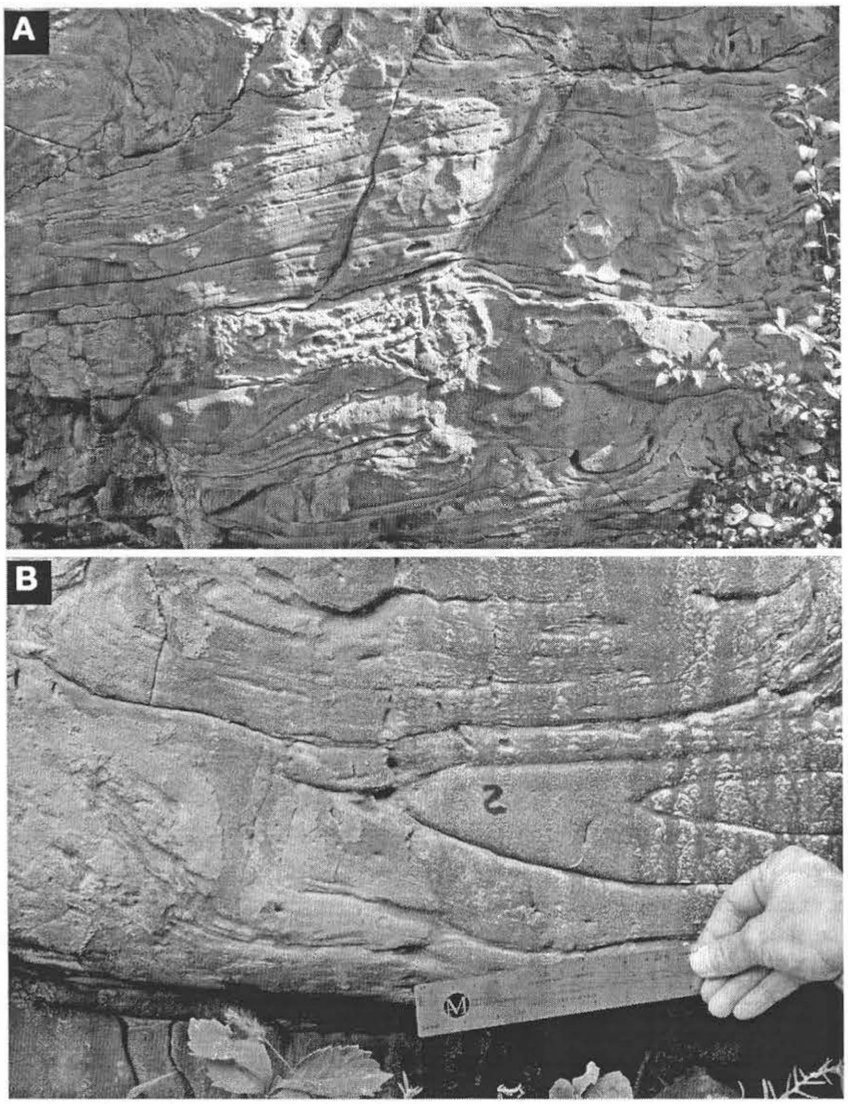
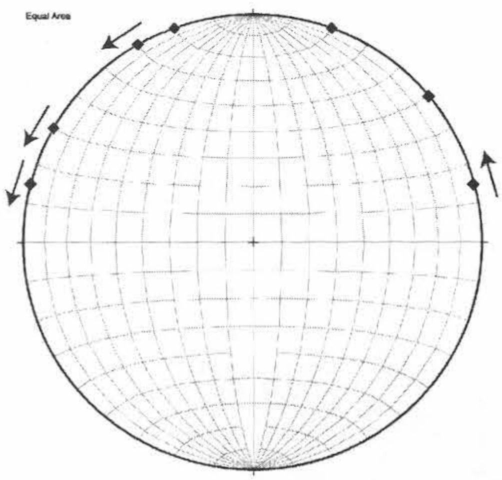
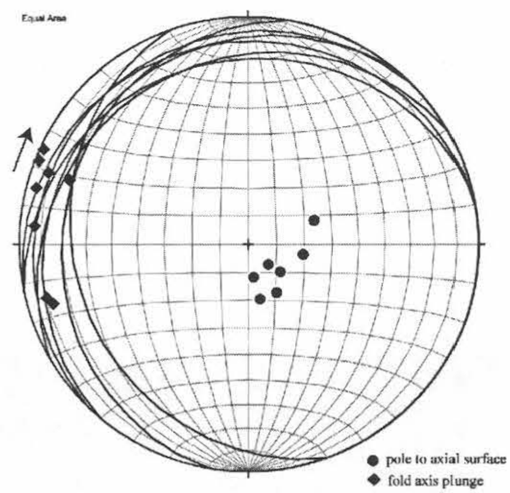


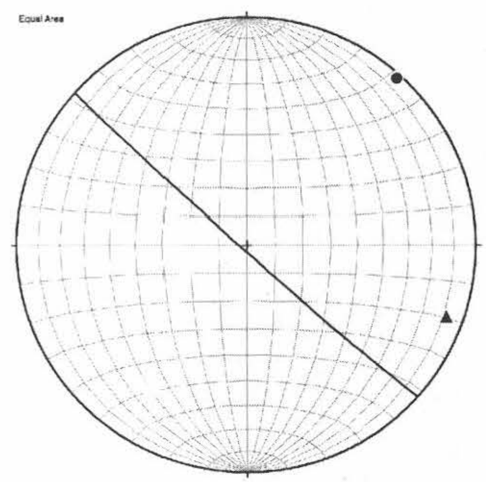
Figure 17. Outcrop of DeCew Dolostone at South Haul Road, Niagara Gorge, Lewiston, Niagara County, NY. A) General view of deformation. Note contorted beds of dolomitic shale intraclasts. B) Detail of overturned fold within lower DeCew.



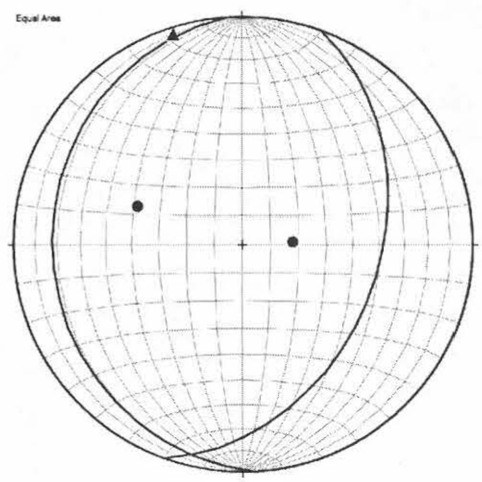
Haul Road (east side) fold axes. Axes bearing 285, 300, 330 have a NE-over-SW asymmetry (arrows indicate relative motion of upper plate).



Haul Road (west side) fold axial surfaces and axes. Arrows indicate relative motion of upper plate.



Haul Road (west side) open F2 axial surface and axis



Haul Road (west side, north end) fold axial surfaces and axes

Figure 18. Stereoplots of folds in the DeCew Member exposed along the Haul Road, Niagara Gorge. The upper left panel displays the bearing of fold axes (diamonds) observed along the east side of the Haul Road. Bearings with arrows indicate folds with asymmetry; the arrow indicates the sense of relative motion inferred from the asymmetry (relative motion of the upper plate). Note the apparently conflicting senses of motion. The upper right panel displays the disposition of axial surfaces (great circles), poles to the axial surfaces (solid circles), and bearing of fold axes (diamonds) observed along the southwest side of the Haul Road. Arrow indicates same as in the upper left panel. The lower left panel shows the axial surface of a later, open F2 fold that folds the folds in the upper panels. The lower right panel displays the disposition of axial surfaces (great circles), poles to the axial surfaces (solid circles), and bearing of fold axes (diamonds) of folds observed at the northern tip of the outcrop on the west side of the Haul Road.

such horizons have been identified in the Silurian Rochester Shale in the Niagara region. Sandstone beds full of eroded mudstone clasts and lingulid shell fragments in the Grimsby Formation may represent storm deposits in peritidal settings. The shale clasts may have been derived from banks of tidal channels by strong storm surge currents..

Among more distal events, several other types of tempestites have proved to be regionally extensive and traceable. For example, thick calcisiltites with hummocky cross stratification have been traced for tens of kilometers in the Rochester Shale. Large scale hummocky to swaly bedding locally in the DeCew Formation similarly reflect storm deposition of carbonate silts and fine sands. Bimodal cross-stratification of crinoidal sand and gravel in the Gasport Limestone may record superposition of tidal currents on storm surges (see Fig. 19).

Obrution Deposits

Another type of tempestite-related feature that provides very useful local markers are obrution or "smothered bottom", deposits. These are recognized taphonomically and may be traceable, at least locally. Excellent examples are provided by layers of beautifully preserved crinoids, trilobites, and other fossils (*Homocrinus* beds) that have been studied in detail from the lower Rochester Shale (Taylor and Brett, 1996). These rapidly buried surfaces have been correlated for tens of kilometers along outcrop strike of the Niagara Escarpment. The series of beds display much the same unusual characteristics over this area. Such evidence indicates that the smothering mud blanket was very extensive following a particular storm, resulting in mass mortality and burial on a regional scale.

LoDuca and Brett (1997) described laterally extensive horizons of extraordinarily preserved fossil green algae, annelid worms, and other non-skeletonized fossils from shaly dolostones in the base of the Goat Island Formation. Here rapid burial in organic-rich carbonate silts below an oxycline may have promoted preservation of soft bodied organisms as carbonized films.

Bioherms and Stromatolites

Organic buildups, including small coral-stromatoporoid or algal mud mounds, thrombolites, stromatolites, and larger scale reef structures, also appear to occur in very laterally extensive zones; these can be considered as "mounding events". For example, throughout western New York and Ontario, small fistuliporoid bryzoan-algal? mounds occur consistently near the top of the Irondequoit Limestone and project up to a meter into the overlying Rochester Shale (Cuffey and Hewitt, 1989). Nearly identical mounds occur at the top of the age-equivalent "Cryptothyrella bed" of the Bisher Dolostone of Ohio and its extension in the middle Osgood Limestone of Indiana (Brett and Ray, 2006).

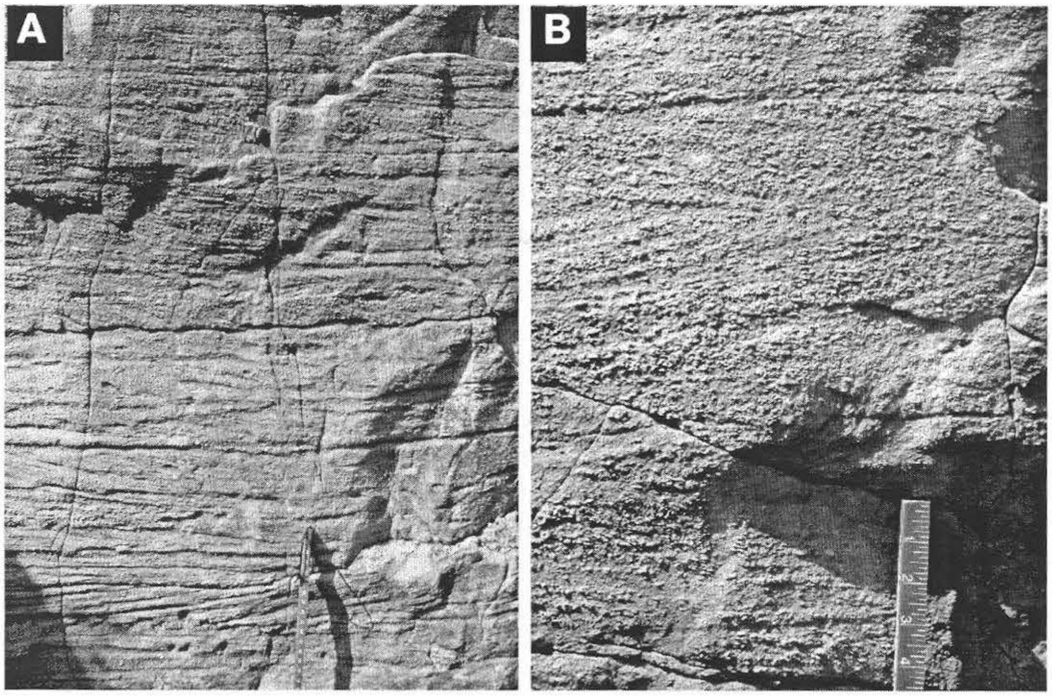


Figure 19. Outcrop of Gothic Hill Member grainstone at South Haul Road, Niagara Gorge, Lewiston, Niagara County, NY.

Larger, stromatoporoid-tabulate bioherms occur at two horizons in the Lockport Group of western New York and Ontario: the upper grainstones of the lower or Gothic Hill Member of the Gasport Limestone and extending upward up to 6m into the overlying thin-bedded argillaceous Pekin Member (Crowley, 1973; Brett et al., 1995); and in possible channel fills along an erosion surface at the top of the Gasport and extending upward into thin bedded middle Goat Island Formation (Brett et al., 1995). Not only are these horizons persistent over substantial distances in the New York-Ontario outcrop belt, similar thrombolitic mounds are present in probably correlative horizons in the McKenzie Shale in Pennsylvania to West Virginia (Brett et al., 1990). A comparable interval of bioherms has been recently recognized in the coeval upper Bisher in southern Ohio and Kentucky.

Finally, very persistent zones of large stromatolites and thrombolites (non-laminated algal mounds) occur at several horizons, especially near the base of the Guelph Formation (Brett et al., 1990, 1995) and in the lower Fiddlers Green Formation of the Bertie Group (Ciurca, 1990).

Of particular importance is the observation that mounds of varying type (stromatolites, thrombolites, coral-stromatoporoid bioherms) developed contemporaneously in different environments along an onshore to offshore gradient. What these features appear to have in common is that they are in laterally persistent horizons and occur either immediately above unconformities or on the flooding surfaces at the tops of skeletal sands. We suggest that the non-random distribution of such organic buildups in the stratigraphic record reflects the dynamic interaction of sea-level and organism growth. Mounding commonly appears to be associated with transgressing or deepening successions, in particular, during times of rapid deepening, as at maximum flooding surfaces. During these intervals rapid deepening created accommodation space and reef- or mound-forming organism may have built upward to keep pace with this increasing water depth. At the same time sequestering of sediments in coastal areas may have favored growth of algae and clonal organisms by reducing water turbidity and nutrient influx. Hence, widespread mound horizons are a signature of rising sea-level. In some cases the mounds were able to keep pace with deepening but in others they failed to keep up and were drowned. This explains the common burial of bioherms by thin, shaly sediments of deeper water facies.

SUMMARY

The Silurian strata of the Niagara Peninsula-western New York and their counterparts in the Cincinnati Arch region of southern Ohio and Kentucky, are richly fossiliferous, and display recurring depth-related benthic assemblages that aid in interpretation of relative sea-level fluctuation, as well as ecological-evolutionary history. Many fossil assemblages are exceptionally well preserved, reflecting event deposition, primarily widespread storm deposits. These fossils have also permitted relatively refined biostratigraphy.

Despite their classic status, these strata have only recently been considered from the standpoint of modern sequence and event stratigraphy (Duke and Fawcett 1987; Brett et al. 1990; Goodman and Brett, 1994; Brett et al., 1998). Newer approaches to refining our understanding of stratigraphy and facies relationships in these classic strata. These include identification and tracing of distinctive event beds, such as the DeCew seismite horizon and a hierarchy of disconformity bounded cycles of sequences. About nine large scale, 3rd-order, unconformity-bound stratal sequences, and more than 25 smaller 4th order subsequences, have been recognized within the Medina to Bertie groups (Llandovery to Ludlow Series) of the Ontario Peninsula-New York area (see Brett et al., 1990, for details. These sequences and many of their component subsequences can be correlated regionally into exposures on the east flank of the Cincinnati Arch in south-central Ohio and Kentucky (Dennison and Head, 1975; Brett et al., 1990; Brett and Ray, 2006). The persistence of similar patterns for over 700 km along the cratonic rim of the Silurian foreland basins demonstrates the existence of elongate belts of rather uniform facies parallel to the trend of the Algonquin-Findlay arch. Similarity of facies patterns was enhanced by the orientation of this belt, which during the Silurian lay approximately along the same latitude; but it also reflects allocyclic controls , including climatic and sea-level oscillations. Furthermore, some of the major events of relative sea-level fall and rise appear to be correlative with those recognized in other basins (see Johnson et al. 1985, 1998, for example), suggesting an underlying eustatic mechanism.

Nonetheless, detailed examination of regional patterns, within unconformity bound sequences permits recognition of far-field tectonics resulting from orogenesis in the Taconic mobile belt. During the Early Silurian these include a progressive eastward translation of the foreland basin axis and shoreline belts, by approximately 500 km, and the rise of the Findlay-Algonquin arch system, probably as a result of forebulge migration. This gentle differential uplift resulted in truncation of Llandovery sequences to the west-northwest in western New York-Ontario, as well as in west-central Ohio and Kentucky. During late Llandovery and Wenlock time the foreland basin and forebulge appear to roll back to the west. This abrupt reversal in basin axis migration, coupled with the influx of K-bentonites and the appearance of widespread seismites records renewed orogenic activity related to a little known medial Silurian (Salinic) tectophase.

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STOP DESCRIPTIONS

Figure 20 shows stop locations for the trip on a simplified geologic base map (Rickard and Fisher, 1970). Abbreviations used in the text and figures for inferred sequence stratigraphic units are as follows: for subsequences (fourth order sequences): RLS = relative lowstands (regressive deposits); RHS = relative highstands; MFS = marine flooding surface; SDS = sea level drop surface; CI, condensed interval, and for sequences: SMT = shelf margin systems tract (lowstand deposit); TST = transgressive systems tract; CS = condensed section; EHS = early highstand; LHS = late highstand; SB = sequence boundary; TS = transgressive surface. The sequences referred to in the previous text are abbreviated as S-I through S-VIII in the following.

ROAD LOG FOR SILURIAN SEQUENCES, CYCLES, AND EVENTS

Total Mileage	Incremental Mileage	Description
0.0		I-290; take exit to Millersport Highway Junction NY 263 (Millersport Highway); turn left (northeast) onto Millersport Highway
9.5	9.5	Junction NY 78 (Transit Road); turn hard left (north) on Transit
10.0	0.5	Bridge over Tonawanda Creek; enter Niagara County
		Pass Niagara Wine Cellar
14.7	4.7	Pass Summit St/Lincoln Road these mark the approximate city of Lockport Limit and northern edge of ridges of Barre Moraine and possibly the Albion Moraine, which converges with it here
15.8	1.1	Cross Erie/NYS Barge Canal. Proceed north on North Transit crossing NY Rte 31
16.6	0.8	Turn left (west) on Outwater Drive and proceed to loop on Lockport Escarpment at Outwater Park.
17.4	0.7	Pull off in parking area adjacent to small overlook area

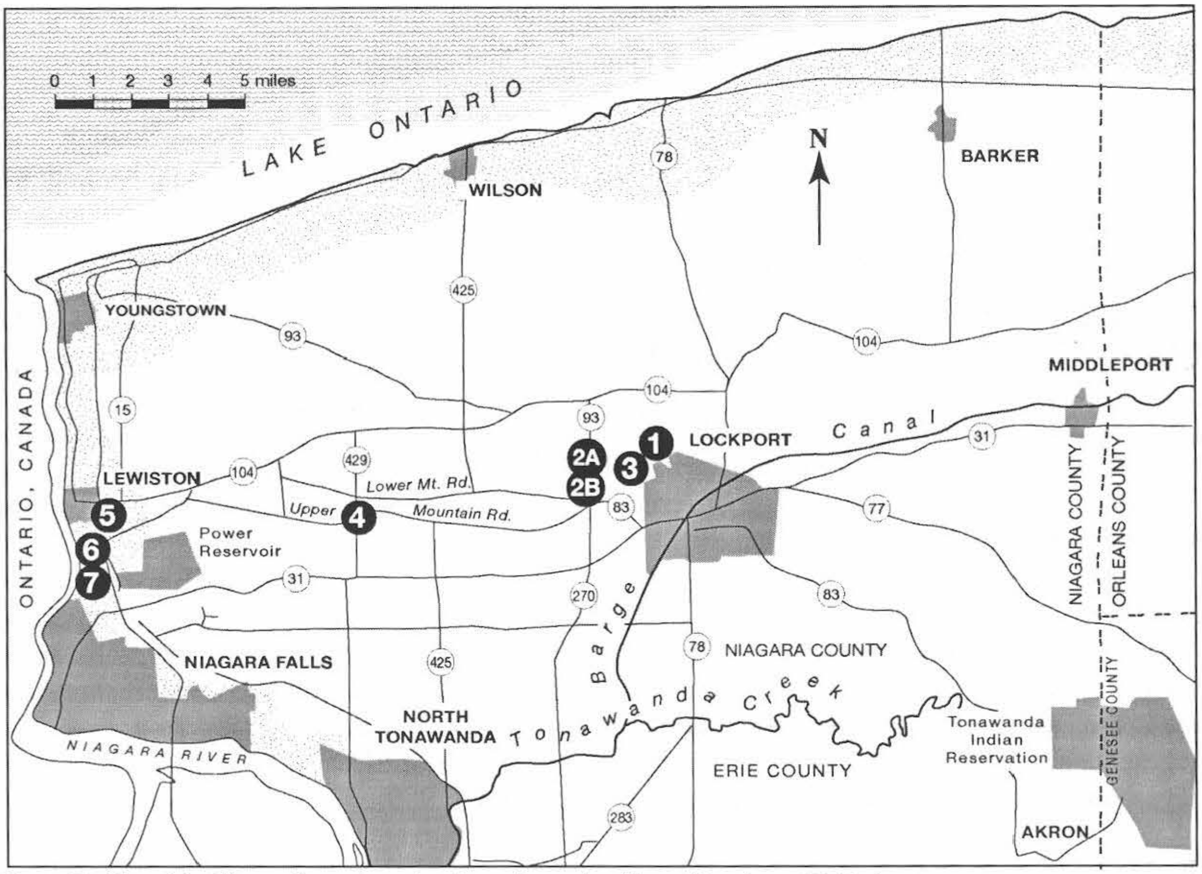

Figure 20. Map of the Niagara County area showing major roads, cities and locations of field trip stops.

OPTIONAL STOP CRAIN STREET QUARRY AND OUTWATER PARK (brief stop). View off Lockport (Niagara) Escarpment. View off Niagara Escarpment; spillways (occupied by East and West Jackson Roads) of ancient Lake Tonawanda into proglacial Lake Iroquois. Note Lake Ontario (about 18 km to north).

Walk back from overlook into old quarry at brink of escarpment to observed glacially polished surface of Pekin Member, Gasport Formation with small bioherms with well preserved stromatoporoids, favositids, and colonial rugose corals; pelmatozoan holdfasts are attached directly to bioherm surfaces. Patches of cross-bedded reef-flank debris are present at margins of bioherms.

		Retrace route to Transit Road.
18.1	0.7	Junction Transit Road; turn left (north); proceed north over escarpment.
18.2	0.1	Turn right (east) on Glenwood Drive. Adjacent hummocky deposits of cemetery may relate to Albion ice margin (moraine).

18.5	0.3	Take sharp left onto Gooding-Plank Street.
19.3	0.8	Junction West Jackson Street (on left) and Gooding-Plank Road at Lockport wastewater treatment plant. Pull off and park on Gooding near intersection.

STOP 1: ROAD CUT ON GOODING STREET BELOW SOMERSET RAILROAD VIADUCT (QUEENSTON SHALE—MEDINA GROUP)

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

About 6 m (20') of upper red mudstones and siltstones of the Queenston Formation (upper Ordovician. Ashgillian) are exposed at this locality. The Queenston has been interpreted as either very shallow marginal marine or non-marine red beds. The Cherokee unconformity in this area is the basal surface of Whirlpool Sandstone, which is nearly planar. It is also a megasequence boundary separating the early or Creek phase of Sloss' (1963) Tippecanoe megasequence from the later Tutelo phase) see Dennison, (1989).

The Medina Group (Sequence I of the Silurian System), consists of an Early Silurian (early Llandovery, Rhuddanian), siliciclastic wedge derived from tectonic source areas to the southeast (Figs. 5, 21). The lowest Silurian unit, white Whirlpool sandstone is about 3.5 m (11.5') thick at this location. Basal beds of the Whirlpool Sandstone are quartz arenites with northwest dipping cross strata, which have been interpreted as non-marine, braided stream deposits (Middleton et al., 1987). Large-scale channel-like structures occur in, or at least at the top of, these sands. Shale drapes within such channels at Lockport have yielded marine acritarchs (M. Miller, unpublished data) indicating that the channels were backfilled by very shallow marine sands and minor muds during a rise of sea level. Hence the irregular channeled surface that separates lower Whirlpool braided fluvial facies from upper Whirlpool hummocky cross-stratified, sparsely fossiliferous beds is a transgress surface. The Whirlpool Sandstone thus is interpreted to contain either a lowstand (or shelf margin) systems tract and a transgressive deposit. A thin bed containing phosphatic pebbles and fossil grains occur with the Whirlpool-Power Glen contact. This phosphatic pebble bed may mark a marine flooding surface, or surface of maximum starvation associated with relatively increased rates of sea level rise. This surface marks the change from shallow shelf sands of the upper Whirlpool into deeper shelf muds and storm sands of the upper Whirlpool into deeper shelf muds and storm sands of the Power Glen Formation, herein interpreted as highstand deposits. The Power Glen exhibits subtle small-scale parasequences.

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

Greenish to reddish sandy shales and reddish sandstones occur near the top of the Power Glen suggesting a minor upward shallowing trend. However, the top of the unit (as defined herein) is sharply demarcated at the base of a massive white to pink mottled sublitharenitic sandstone about 2.5 meters (7.7') thick, the Devil's Hole Sandstone (Brett et al. 1995) seen at Niagara Gorge (Stop 6). The basal and upper beds of the sandstone contain lingulid brachiopods and probable *Lingula* burrows.

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

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

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

Return to vehicles, turn left and proceed west on West Jackson Street.

20.7	1.4	Junction Niagara Street and West Jackson Street. Turn or continue west on Niagara Street.
22.2	1.5	Overpass over Lockport Junction Road (Route 93).
22.25	0.05	Access road to Route 93 on left; turn left onto road.
22. 3	0.05	Pull off along berm on left side of road and park. Proceed on foot directly down embankment along Route 93 to road cut.

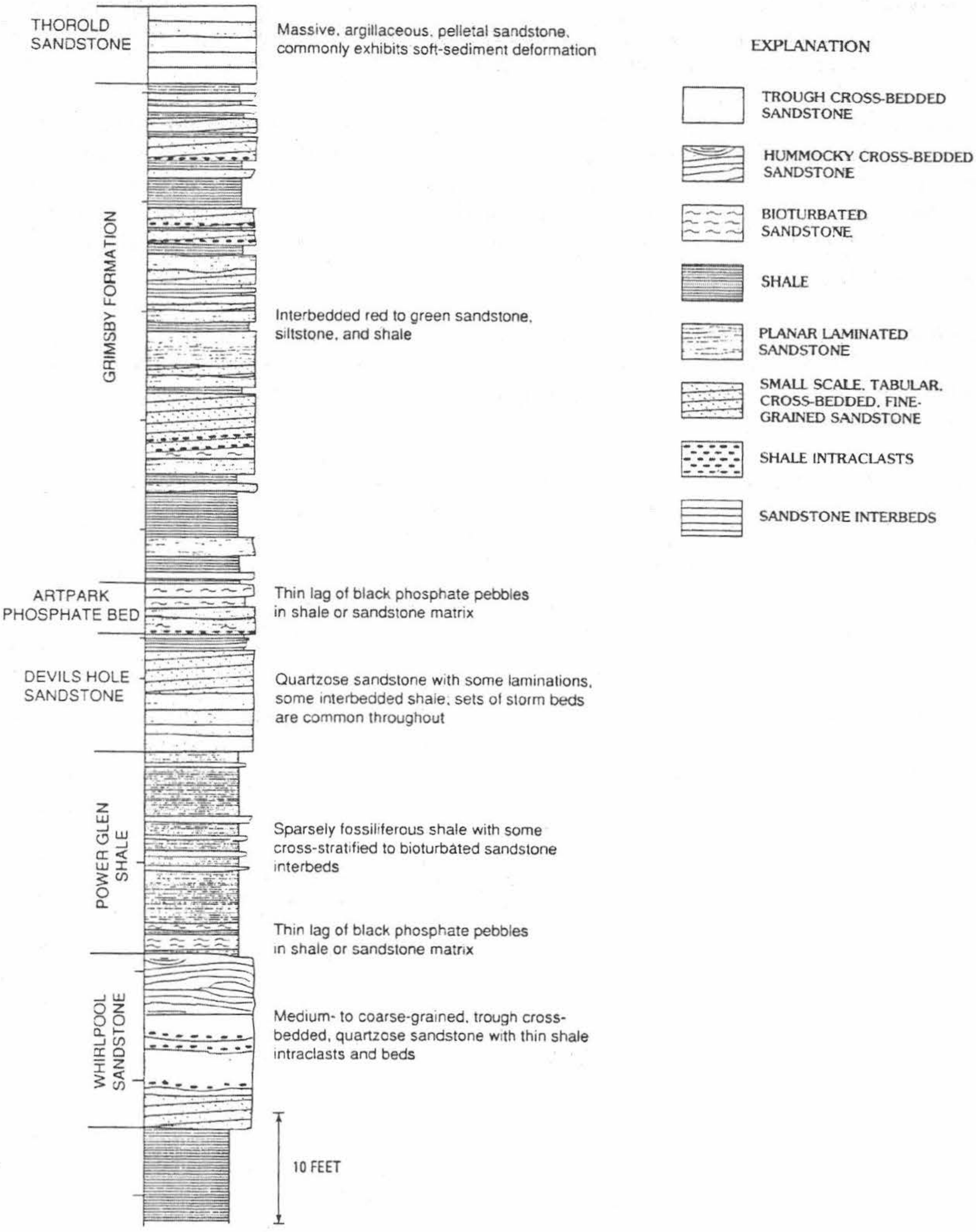

Figure 21. Generalized stratigraphic column for the Lower Silurian Medina Group in Niagara County, NY, showing revised terminology. From Brett et al. (1995).

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

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

The Thorold, in turn, is overlain by 1.7 to 1.8 m of dominantly red silty shale of the (Cambria Member) uppermost Medina Group. This shale bears distinctive fine, white mottling due to bioturbation. Although previously assigned to the Grimsby Formation, this is a distinctive, ostracode-bearing shaly unit that <u>overlies</u> the Thorold Sandstone and is traceable regionally at least as far as east as the Rochester area. Brett et al. (1995) termed this unit Cambria Shale Member of the Thorold Formation, using this section as the type locality.

The upper portion of the Cambria Member is pale purplish to greenish gray sandstone and sandy shale that was formerly termed Thorold Sandstone. In actually, this is simply a leached sandy zone in the Cambria Shale. The Kodak Sandstone and about 1 m of Cambria Shale have been removed here at the sequence I/II unconformity. Sandstones contain small *Skolithos* burrows and intercalated green shale beds, especially the topmost layer, contain prolific leperditiid ostracodes. The greenish color extends down about 30

to 50 centimeters below the upper contact where sandstones are mottled pale purple and green. This discoloration is probably associated with the top unconformity and deposition of overlying reducing sediments (Duke and Fawsett, 1987).

Here the top of the Medina Sandstone is an erosion surface overlain by a thin (3 to 5 centimeter) dark gray, phosphatic sandy dolostone (Densmore Creek Bed) with prolific *Hyattadina* brachiopod valves. A thin laminated siltstone rests on the bed at the contact with the greenish gray Neahga Shale, which at this locality is about 1.0 meter thick.

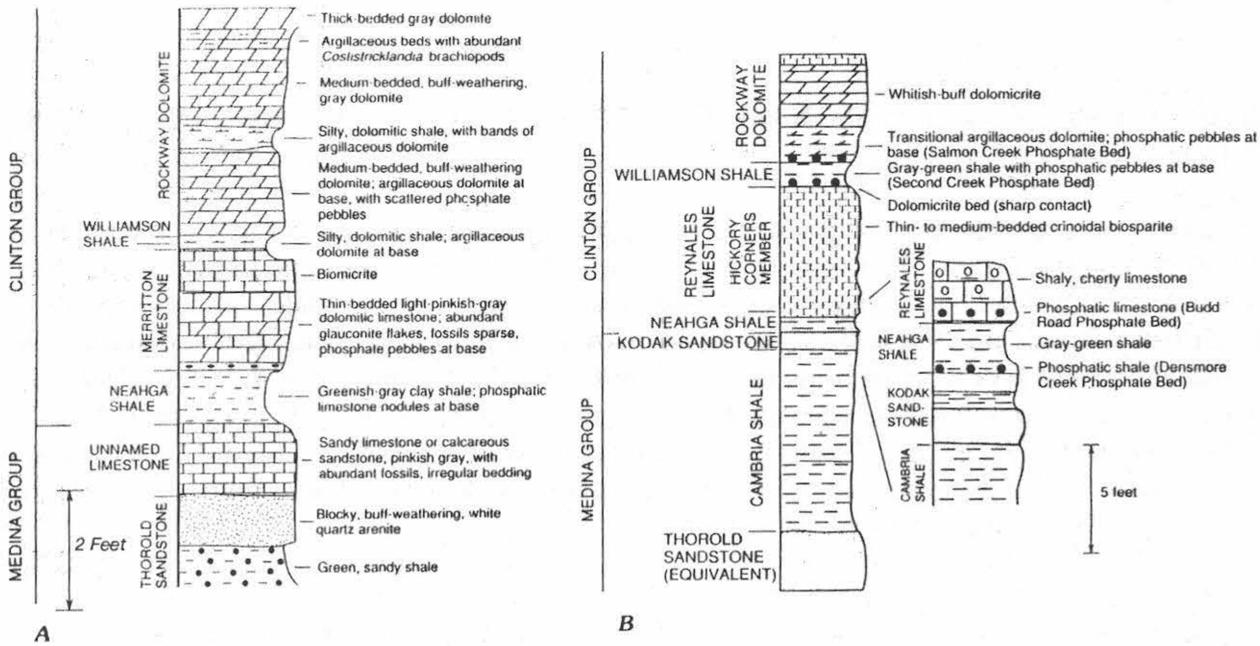

Figure 22. Detailed stratigraphy of the uppermost Medina Group (Sequence I), lower Clinton Group (Sequence II) and upper middle Clinton Group (Sequence IV) at outcrops separated by about 40 km. A) Western section; railway cut at Merritton (near St. Catharines), Ontario. B) Eastern section; Lockport, New York area. Note the loss of Cambria Shale between the two sections; also gradation of Densmore Creek phosphatic bed into unnamed limestone; truncation of the Reynales Limestone and intercalation of Merritton Limestone between Lockport and Merritton. Adapted from Brett et al. (1995).

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

Reboard vehicles and continue on exit lane

22.4	0.1	Junction with Lockport Junction (Townline) Road (Route 93); turn right (south) and proceed up escarpment
22.7	0.3	Pull into small parking area at gap in guard rail (for driveway) to left (Note; this parking is not suitable for large groups)

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

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

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

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

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

Reboard vehicles and turning left out of the driveway, continuing south along Route 270/93.

22.9	0.2	Upper end of road cut.
23.2	0.3	Junction Upper Mountain Road (Rte. 270/93). Turn right (<u>west</u>) on Upper Mountain Road.
23.9	0.7	Junction Thrall Road on right. Exposures of fossiliferous Rochester Shale along Thrall Road were described as Stop 2 in Brett (1982).
28.1	4.2	Junction Rt. 425.
30.1	2.0	Pekin Village; fire department on left.
30.2	0.1	Junction Old Pekin Road (one way). <u>Turn right and proceed down</u>

hill.

30.3 0.1 Junction Rt. 427; turn left (south) and move quickly toward right shoulder of Rt. 427

30.4 0.1 Pull off on wide area of right shoulder of Rt. 427 and park

STOP 3. "PEKIN BIOHERM" CUT ON RT. 427

Location: Cuts on both sides of NY 427, just north of underpass beneath Upper Mountain Road, Pekin, Niagara County, NY (Cambria 7.5' Quadrangle).
Description: This classic cut in the brow of Niagara Escarpment has recently been widened, and provides an excellent, but very fresh exposure of the upper Gasport (Pekin Member of Brett et al., 1995) and the lower portion of the overlying Goat Island Formation (Fig, 19). The large, massive mound exposed particularly on the west side of Rt. 427 was originally described as a Gasport bioherm and was considered to show reefal succession (Crowley and Poore, 1974). However, recent excavations have revealed that the mass of stromatoporoid bearing rock is almost entirely within the Goat Island Formation and is separated from older Gasport deposits (including a formerly exposed small bioherm, now destroyed by blasting) by a major erosion surface. The contact between the gray, thin bedded argillaceous dolostones of the Pekin Member of the Gasport and overlying massive, dolomitic crinoidal grainstone of the Goat Island (Niagara Falls Member of Brett et al., 1995), a sequence boundary, appears sharp. but horizontal in the northeastern portion of the cut. However, this contact abruptly descends to near road level just north of the Upper Mountain Road overpass. Here a mass of biohermal lithology overlies the unconformity. On the freshly blasted west side of the cut the irregular contact between the dark gray Pekin and light pinkish biohermal Goat Island is now very clear. The erosion surface separating the units has a relief of over 2 meters. The Goat Island "bioherm" appears to have developed in low areas on the unconformity. It consists of a mixture of crinoidal grainstones and light gray dolomicrite, rich in stromatoporoids, many of which are tumbled onto their sides or even inverted, indicating storm disturbance. This biohermal mass built up in "channels" along a sequence boundary during initial transgression.

Reboard vehicles and proceed south on Rt. 429 through the underpass beneath Upper Mountain Road; prepare to turn right

30.6 0.2 Junction Grove Road; turn right

30.7 0.1 Junction Upper Mountain Road; turn left; Pekin, NY; note dolostone church on right

35.8 5.1 Dangerous curve on Upper Mountain Road at junction of Blackman Road; bear right continuing on Upper Mountain Road; view out to Lake Ontario

36.3 0.5 Leave Tuscarora Indian Nation

38.3	2.0	Junction Military Road at stoplight. Go straight onto Upper Mountain Road extension ; crossing I-190; avoid ramps to Lewiston-Queenston Bridge and Robert Moses Parkway
38.8	0.5	Exit ramp to Rte. 104 (Lewiston Road)West to Niagara Falls
39.0	0.2	Bear right onto Lewiston Road (Rte 104W); proceed south. Good view of Niagara Gorge to right
39.5	0.5	Pass forebay on left; driving over sluiceways of Robert Moses Power Plant
40.0	0.5	Pass Niagara University on left; Hyde Park Blvd at light
40.1	0.1	Junction Hyde Park Blvd. (NY Rt. 61) at light; bear left onto Hyde Park
40.3	0.2	Cross railroad track and prepare to make immediate right
		Junction South Haul Road; access for Robert Moses Power Plant; turn right
40.4	0.1	Pass by fisherman's parking area (cars can be left here; we will continue on South Haul Road to the bottom of the gorge and allow passengers to disembark and return uphill on foot); ahead through underpass beneath Robert Moses Parkway are excellent views of the Niagara Gorge and a complete stratigraphic section from the mid Silurian Lockport Group down to the unconformable contact between the Silurian Whirlpool Sandstone and the underlying Ordovician Queenston Shale
41.0	0.6	Fishermen's access at bottom of Niagara Gorge, just outside gates for Robert Moses Power Plant; passengers will disembark and proceed back up the South Haul Road; vehicles will return back up the road to park

STOP 4: NIAGARA GORGE: SOUTH HAUL ROAD

Location: Large road cuts in east wall of Niagara Gorge along South Haul access road for Robert Moses Power Plant, and ascending for about 1 km south to a tunnel beneath Robert Moses Parkway (Fig. 21). Parking is available in a fisherman's access parking lot just west of Rt. 62 (Hyde Park Boulevard) immediately south (uphill) from the tunnel. Lewiston, Niagara County, New York (USGS Lewiston 7.5' Quadrangle). Note: Access to the Haul Road exposure is strictly controlled by the Robert Moses Power Project and requires advance permission.

Description: This outstanding outcrop of Lower to mid Silurian strata shows important contrasts with sections of the comparable interval near Hamilton. The section begins near the Power Plant with about 8 m of the Upper Ordovician Queenston Shale (Fig. 21). Its sharp contact with the overlying Whirlpool Sandstone is the Cherokee Unconformity (Silurian Sequence I boundary).

The units of the Silurian succession are described in ascending order, as follows:

Medina Group (Fig. 21).

Whirlpool Sandstone: (4.5 m)- White, trough cross bedded, quartz arenite facies which record a non-marine to marine transition. Excellent profiles of channels are visible.

Power Glen Shale: (~ 8 m)- Dark gray, friable shale, with very minor sandstone interbeds

Devils Hole Sandstone: (2 m)- Pale gray, massive, quartz arenite with a distinctive, meter-thick phosphatic, sandy dolostone, Artpark Phosphate Bed near the top (IC).

Grimsby Formation: (15 m)- Greenish gray to maroon shales and mudstones with bundles of thin reddish and white mottled sandstones (Fig. 21).

Thorold Sandstone: (2 m)- White, cross-bedded quartz arenite. The Thorold has a sharp, erosive base which marks the base of the next Medina subsequence (IC). A thin (2-10 cm), sandy phosphatic bed, the Densmore Creek Bed (Brett et al., 1995) rests sharply on the Thorold (and on a Cambria Shale remnant north of the Power Plant), marking the base of the Neahga Shale. Clinton Group (Fig. 18)

Neahga Shale: (2 m)- Dark greenish gray, very friable shale (base sharp (II SB).
Reynales Formation (Hickory Corners Member): (~50 cm)- Medium gray, nodular, burrowed, bryzoan-rich wacke- to packstone. Conodonts indicate a mid Llandovery age for the Reynales (see LoDuca and Brett, 1994); this unit represents an erosional remnant of the Reynales.

Rockway Formation: (3 m)- Buff-weathering, argillaceous dolostone with thin dolomitic shales shows prominent rhythmic bands (10-50 cm) of sparsely fossiliferous argillaceous dolostone interbedded with thin gray shales. The Rockway shows a sharp upper contact(S-IV-V SB).

Irondequoit Formation: (2.5 m)- Massive, pinkish-gray, crinoidal pack-and grainstone. Clasts of fine-grained dolostone, derived from the underlying Rockway occur in the basal thin bed of the Irondequoit (Fig. 23). Its sharp upper contact (MFS) is marked by a 30 cm thick shell bed.

Rochester Shale: (18 m)- Medium dark gray mudstone with thin calcisiltites and lenticular fossil rich limestones; 1.5 m of bryzoan-rich limestone beds underlie the sharp top (MFS) of the Lewiston Member . The upper Rochester (Burleigh Hill Member) also displays a sharp contact (SSB) with the enterolithic DeCew Dolostone beds.

DeCew Formation: (3m) -Dark gray, buff weathering, laminated dolostone (calcisiltite). Here and, especially in weathered exposures in the adjacent Devils Hole Park section, the DeCew displays spectacular soft-sediment deformation with isoclinally folded beds (seismite?).

Lockport Group (Fig. 24): The sequence V-VI boundary at the DeCew-Gasport contact is well exposed near the entrance to the "tunnel" beneath the Robert Moses Parkway at the top of the cut; basal Gasport shows rip-up clasts of DeCew Dolostone (Fig. 17).

Gasport Formation: (5 m)-Pinkish gray thin bedded to massive dolostone, divided into a lower pinkish gray dolomitic crinoidal grainstone (Gothic Hill Member) and a 2.5 m upper argillaceous, bioturbated dolostone (Pekin Member) Weathered surfaces of the Gothic Hill grainstones display probable bipolar cross- stratification . The sharp upper contact is a subsequence boundary.

Goat Island Formation : (~10 m)- Buff weathering dolomitic, crinoidal grainstones, buff, thin bedded dolostone with white chert, and dark brownish gray, argillaceous, banded dolostone; the basal unit (Niagara Falls Member) is massive crinoidal grainstone with scattered *Cladopora* corals and stromatoporoids; abundant vugs appear to be solution cavities in a stromatoporoid-rich zone. The Lancaster Member is poorly developed here, thin (-2.5 m) and only sparingly cherty. Argillaceous and bituminous gray dolostones of the Vinemount Member form the uppermost unit on the access road. This member is much less shaly than at its type area near Hamilton.

Return to vehicles and proceed

41.6	0.6	<u>Turn right</u> out of fisherman's parking lot
41.7	0.1	Junction Hyde Park Boulevard; again, proceed straight across onto University Road
42.4	0.7	as road curves to right; <u>turn left</u> onto unnamed access road; note jungle of high tension wires ahead
42.8	0.4	T-intersection with Robert Moses Power Vista back entrance road; <u>turn right</u>
42.9	0.1	<u>Pull off and park</u> along road cuts just before underpass beneath I-190

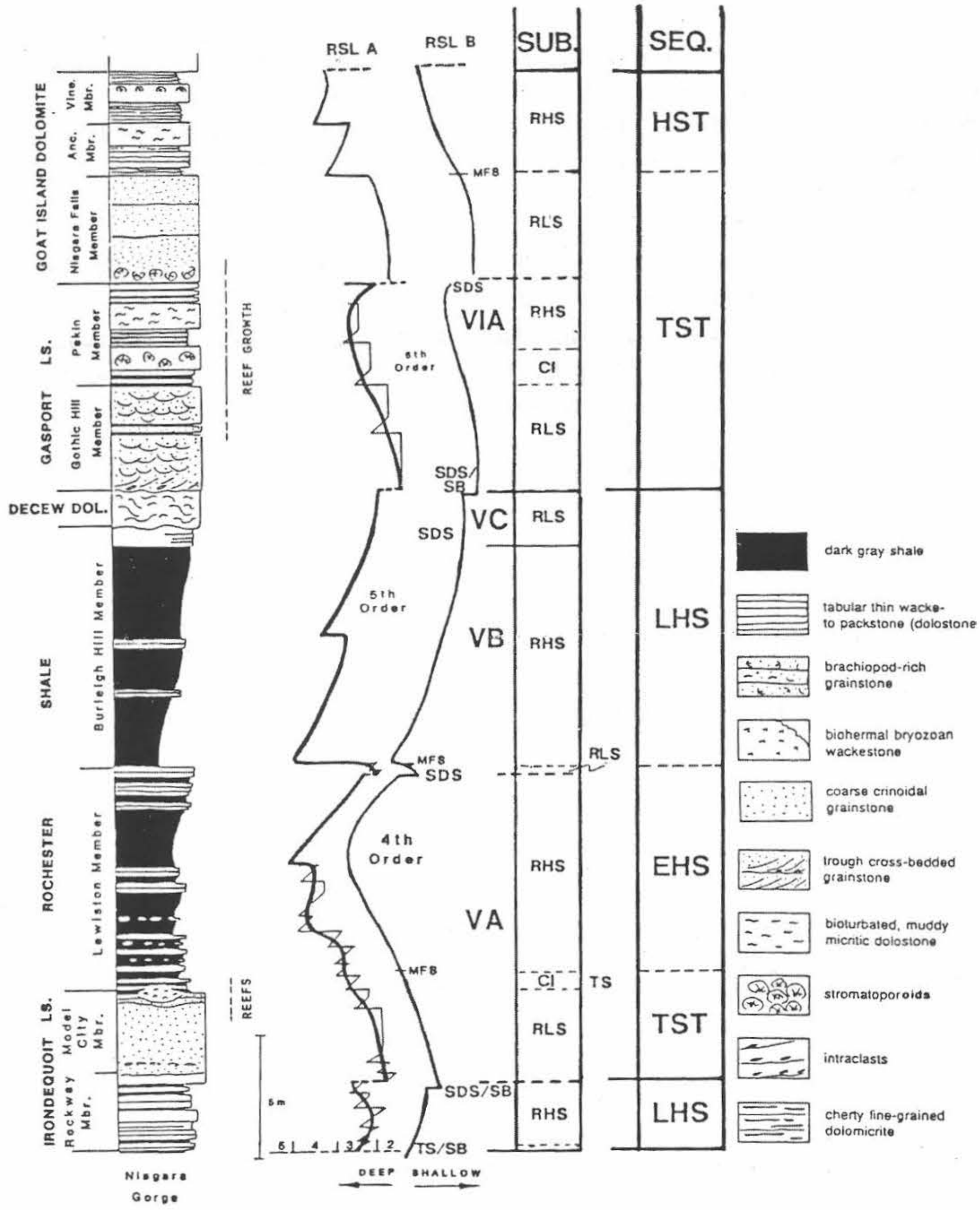

Figure 23. Stratigraphy, sequence stratigaphic interpretation and inferred sea level curve for the upper part of the Clinton Group (SequenceV) and the lower Lockport Group (Sequence VI) in Niagara County. Sequence stratigraphic abbreviations: CS: condensed section; EHS: early highstand systems tract; LHS: late highstand (or falling stage) systems tract; SB: sequence boundary; TST: transgressive systems tract. Adapted from Brett et al. (1990).

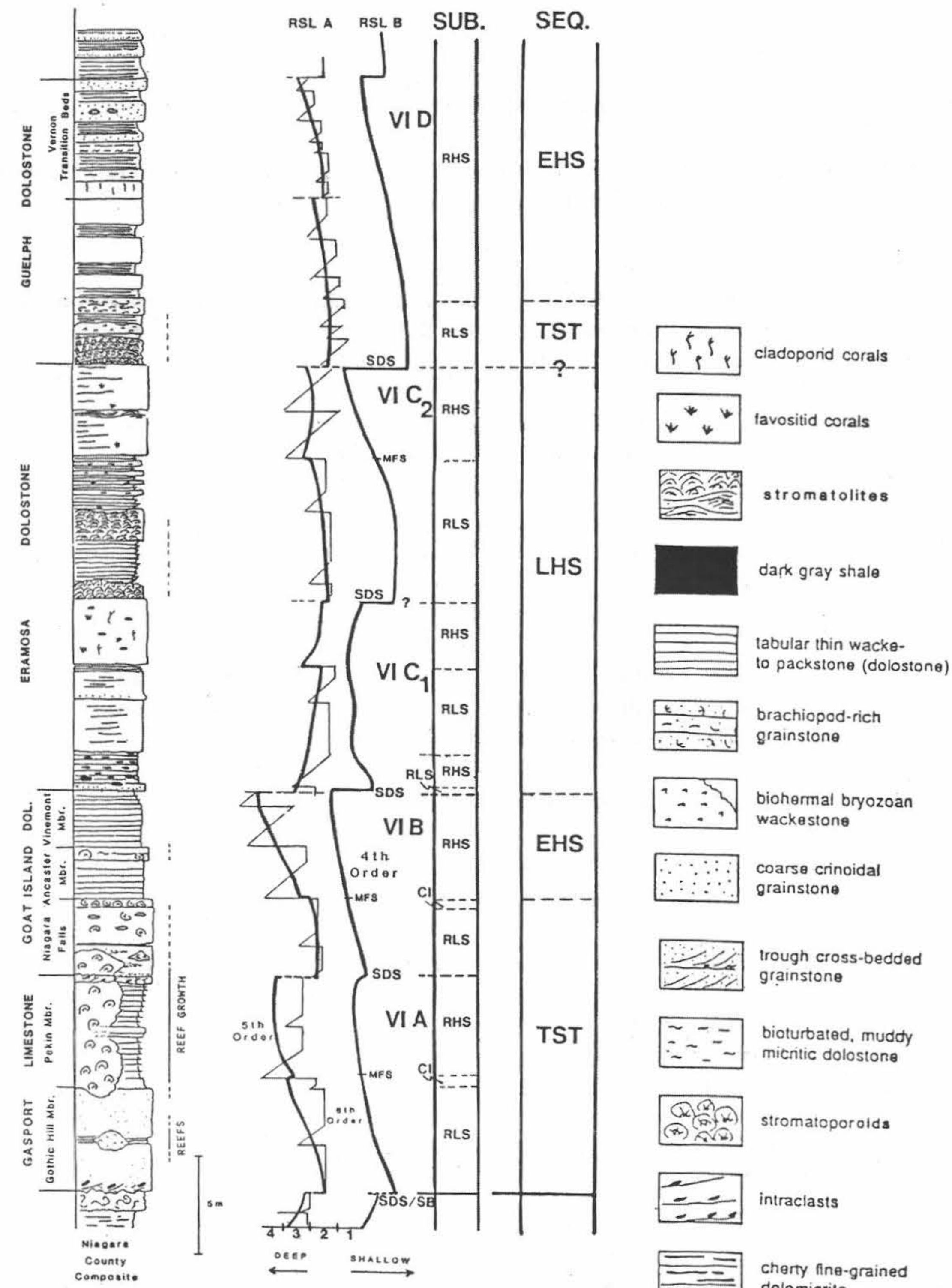

Figure 24. Stratigraphy, sequence stratigaphic interpretation and inferred sea level curve for the upper part of the Clinton Group (SequenceV) and the lower Lockport Group (Sequence VI) in Niagara County. Sequence stratigraphic abbreviations: CS: condensed section; EHS: early highstand systems tract; LHS: late highstand (or falling stage) systems tract; SB: sequence boundary; TST: transgressive systems tract. Adapted from Brett et al. (1990).

STOP 5 : ROBERT MOSES ACCESS ROAD AND FOREBAY

Location: Access road to the Robert Moses Power Plant, and adjacent forebay canal just west of Military Road and 1.2 km north of Route 31, Lewiston, Niagara Co., NY (Lewiston 7.5' Quadrangle).

Description: Higher units of the Lockport Group are visible along the forebay and consist of the upper Eramosa (new usage in New York) and lower Guelph formations (Fig. 24). Large algal bioherms characterize the uppermost units of the Eramosa Formation in the forebay. Exposures in the small road cut at the underpass of the access road beneath the lanes of I-190 show exceptionally large (2 m high) stromatolites, and some non-laminated thrombolites the stromatolitic interval at the base of the Guelph is traceable with subsurface data at least to Hamilton (Fig. 24).

Pull forward under the I-190 overpass and proceed to Military Road

43.1	0.2	Junction Military Road; turn left (north)
43.6	0.5	Crossing east end of Robert Moses forebay area; Pump Generating Power Plant to right; note small thrombolitic mounds in Eramosa Formation exposed in forebay cuts to left
44.5	0.9	Junction Upper Mountain Road at stoplight
45.2	0.7	Junction NY 104; turn right (north)
45.5	0.2	Brow of Niagara Escarpment; on clear days good views of the mouth of Niagara River and Lake Ontario to the north; cuts to right in Gasport-Goat Island formations
45.9	0.4	Skip Exit for Rt. 18F east, but stay right
46.4	0.5	Exit for Rt.104-18F west; bear right onto exit lane
46.6	0.2	Merge right onto Rt, 18F; Center Street, Lewiston, NY
47.1	0.5	Portage Road; turn right and proceed to entrance for Artpark
47.3	0.2	Entrance to Artpark Road
48.0	0.7	Parking Lot B; bear right and then turn left immediately once in parking lot; proceed up to left on small road labeled "Narrow"

near Clay Studio

48.2 0.2 Fishermen's parking area; pull in and park; proceed south on foot to entrance of Niagara Gorge

STOP 6. NIAGARA GORGE, LEWISTON (ARTPARK)

Location: Sections in east wall of Niagara Gorge along old haulage road extending from north end of Niagara Gorge at Niagara Escarpment just south of Artpark, off Fourth Street, southward to the Lewiston-Queenston bridge, Lewiston, Niagara County, NY (Lewiston 7.5' Quadrangle)

Description: The north-facing cuesta (Niagara Escarpment) stands 76 m above the adjacent Lake Ontario plain. Niagara Falls was initiated here about 12,000 BP.

Exposures of the Upper Ordovician Queenston Shale and its unconformable contact with basal Silurian Whirlpool Sandstone are visible along a short path, adjacent to the river, immediately south of the Artpark theater. Outcrops of the Lower Silurian stratigraphic units above the Whirlpool Sandstone are accessible along an old haulage road that leads southward from the Artpark Visitor Center into the gorge. At the entrance to the gorge (edge of Niagara Escarpment) an isolated "butte" of Lower Silurian strata (Power Glen-lower Grimsby; type locality of the Artpark Phosphate bed) between the path and the river, represents a remnant of a promontory in the gorge wall that was breached during excavation for the power plant. A 0.5 m layer of mottled sandstone with prominent ball-and-pillow structures, about 5.5 m above the base of the Grimsby, is well exposed in the cliffs about 200 to 700 m north of the Lewiston-Queenston Bridge. Caution is required in this exposure, as rock falls are common. Abundant fallen debris also provides an excellent look at varied lithologies of the upper Medina, as well as Clinton and Lockport units.

Reboard vehicles and retrace route to parking lot B

48.4 0.2 Bear right out of parking lot onto exit road and proceed to exit from park

49.1 0.7 Proceed straight through onto Portage Road

49.5 0.4 Junction Rt. 18F; turn right (east)

49.7 0.2 Junction Rt. 104 West/Robert Moses Parkway; turn right

49.8 0.1 Fork; bear left onto entrance for Rt. 104; IF going to Canada DO NOT go onto Robert Moses Parkway

NOTE: If time permits we will take a short side trip to optional stop for Whirlpool State Park; approximately 4 miles south of Robert Moses Parkway.

END FIELD TRIP