PART 2: STRATIGRAPHY, PALEONTOLOGY, AND DEPOSITIONAL ENVIRONMENTS OF THE CLASSIC UPPER ORDOVICIAN–SILURIAN SUCCESSION IN NIAGARA COUNTY, NEW YORK

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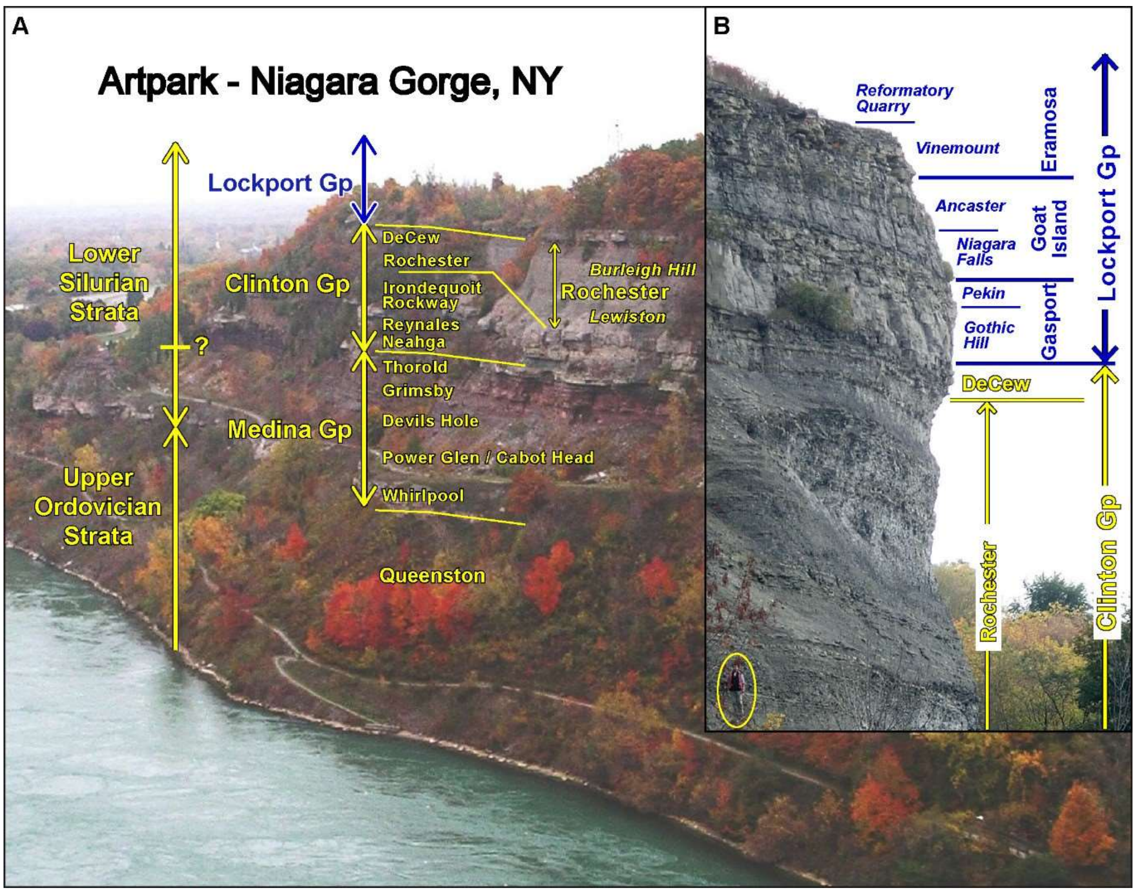

Stratigraphic succession at the north end of the Niagara Gorge near Lewiston, NY. Photo by Frank Brunton

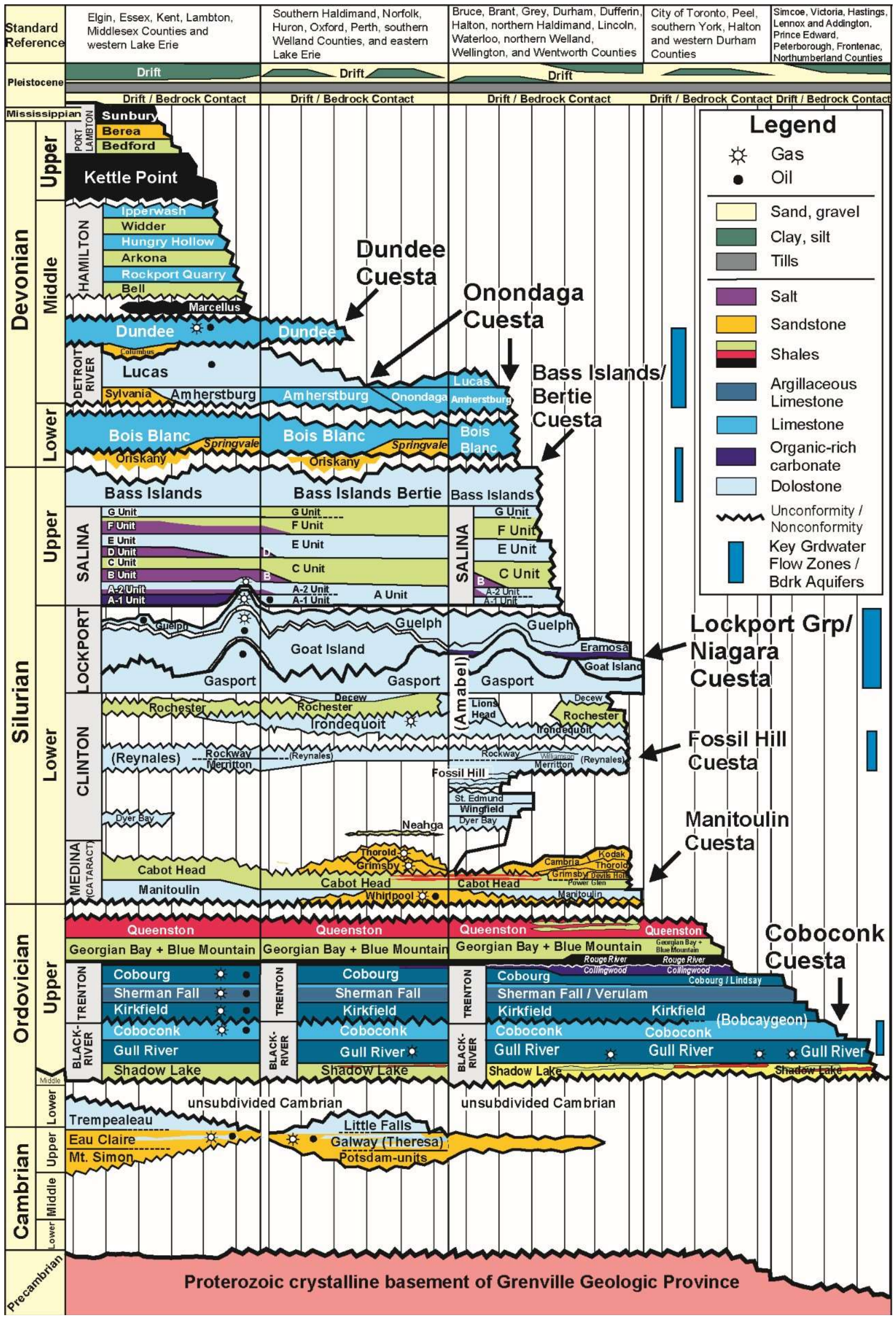

Figure A. Revised terminology of Paleozoic strata for south-central and southwestern Ontario (*modified after* Winder 1961; Beards 1967; Winder and Sanford 1972; Armstrong and Carter 2010; Brunton et al. 2017; Carter et al. 2017). Group names are in capitals, members in italics, and abandoned or geographically restricted formation names in brackets (e.g., Amabel Formation, which comprises: Irondequoit and Rochester/Lions Head fms of Clinton Group and Gasport Fm and lower member of Goat Island Fm of Lockport Group, and Reynales which is older than Rockway and Merritton fms, but has been used for these terms away from Niagara region; Brunton and Brintnell 2011; Brunton et al. 2012). The change in position of the Ordovician–Silurian boundary is discussed in Bergström et al (2011) and Schröer et al. (2016). Relative thicknesses of rock units are not to scale (Figure courtesy of Frank Brunton)

SILURIAN-EARLY DEVONIAN SEQUENCE STRATIGRAPHY, EVENTS, AND PALEOENVIRONMENTS OF THE NIAGARA PENINSULA AREA OF NEW YORK AND ADJACENT ONTARIO, CANADA*

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INTRODUCTION

Silurian and Devonian 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; Williams, 1919; Caley, 1940; Gillette,1947; Bolton,1957; Kilgour, 1963, Zenger,1965, 1971; Hewitt, 1971; Sanford, 1969; Sanford et al.,1985; Martini, 1971; Rickard, 1975; Brett, 1983 a, b; Brett et al., 1990a, b, 1995, 1998; Cramer et al., 2006, 2010; McLaughlin et al., 2008; Sullivan et al., 2014a,b).

Previous reports on the Silurian in the Niagara region have focused on identification of depositional sequences and depositional/fauna) 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. Ongoing research in southern Ohio, Indiana, and Kentucky has revealed striking similarities of sequences and events between this seemingly disparate area, some 600 to 800 km southwest of the main Niagara Escarpment. In this guide we review and update information on depositional sequences and events in western New York and Ontario.

The larger scale ("third order") sequences discussed herein are sharply bounded stratal packages, representing on the order of a 0.5 to 1 million years, 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 up-ramp 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. However, in detail the larger-scale sequences are composites, divisible into smaller (fourth-order sequence-like units that display similar patterns but are not separated by major unconformities; we have termed these units subsequences (see Brett et al., 1990a, b, 1995, 1998, for further details).

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), is now being applied to an outcrop scale to diverse depositional settings including foreland basins, such as the Appalachian (or Taconic) foreland basin of the Ordovician and Silurian (Brett et al., 1990 a,b; Witzke et al., 1996; Brett et al., 1998; Brett and Ray, 2005). Many distinct surfaces in the local stratigraphic record are interpretable as sequence boundaries or flooding surfaces. Moreover, several phenomena, which occur non-randomly in the geologic record, from phosphatic nodule horizons to reefs, fit in predictable ways into depositional sequences.

A second section of this paper considers, briefly the faunas and paleoecology of Silurian seas including bioherms and biostromes which typify some of the carbonates of the area. Another theme of this article is the recognition of widespread events, such as storm deposits, (tempestites), rapidly buried fossil horizons (obrution deposits), and

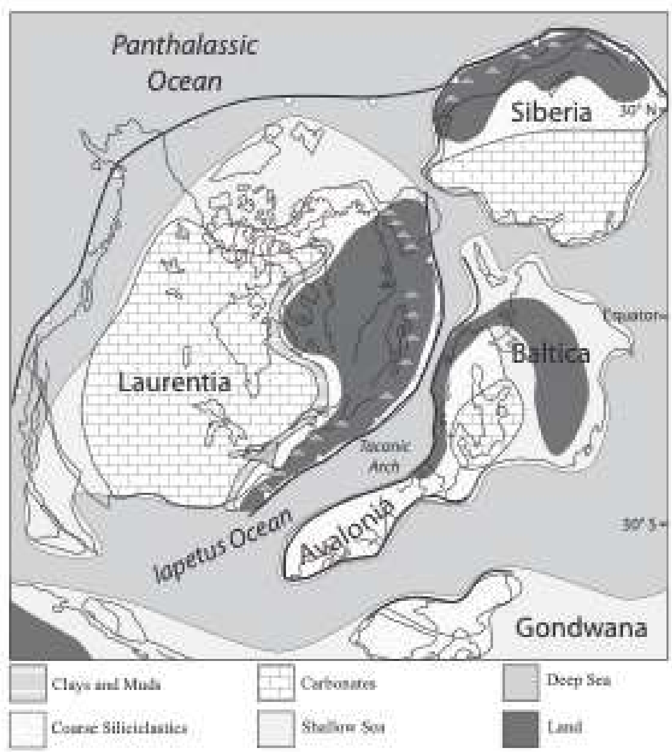

Figure 1 – Paleogeographic map of Laurentia during the Silurian with New York State highlighted. Modified from Scotese and McKerrow (1990), Cocks and Scotese (1991), and Brett and Ray (2005).

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.

REGIONAL GEOLOGICAL SETTING

Silurian strata of the Niagara Peninsula-western New York and in the Cincinnati Arch area were deposited along the northwestern rim of the Appalachian Basin, defined by the Algonquin-Findlay Arch, a relatively positive area intermittently uplifted by forebulge migration (Figs.1, 2). The Niagaran paleoenvironments were generally shallow, subtropical epeiric seas, situated 25-30° south of the equator (Witzke, 1990).

Siliciclastic sediments were derived from eastern and, possibly, northeastern source terranes that were uplifted during the Taconic orogeny. Ettensohn and Brett (2002) identified a third, Early Silurian or Medinan tectophase of the Taconic Orogeny; this phase of uplift produced a new episode of molasse deposition: the Tuscarora-Medina elastic 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, 199). These tectophases produced an initial pulse of quartz sands, conglomerates, and sandstones (upper Shawangunk-Keefer-Herkimer) in the proximal foreland basin, followed by a major influx of primarily fine-grained siliciclastics of the Vernon-Bloomsburg "delta": predominantly red molasse.

The ability to delineate and correlate thin sequence stratigraphic intervals al 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 (Figs. 4-12).

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).

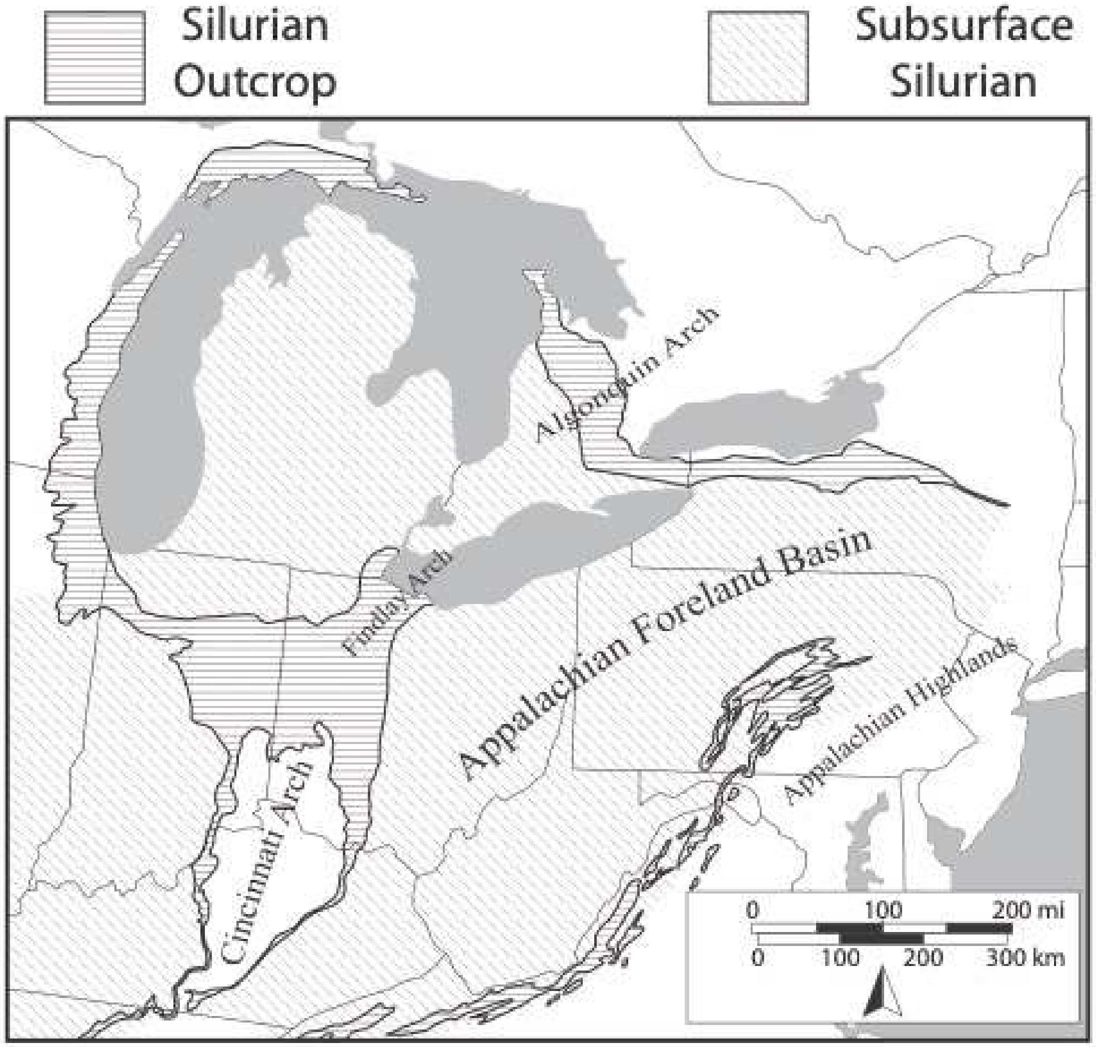

Figure 2. Geological setting of middle Silurian rocks in New York, Ontario, Michigan, and adjacent areas, showing position of the Algonquin-Cincinnati Arch system that separates Appalachian and Michigan basins. Silurian outcrop is highlighted with horizontal lines; subsurface distribution of Silurian strata is highlighted in diagonal lines. Modified from Berry and Boucot (1970) andTelford (1978).

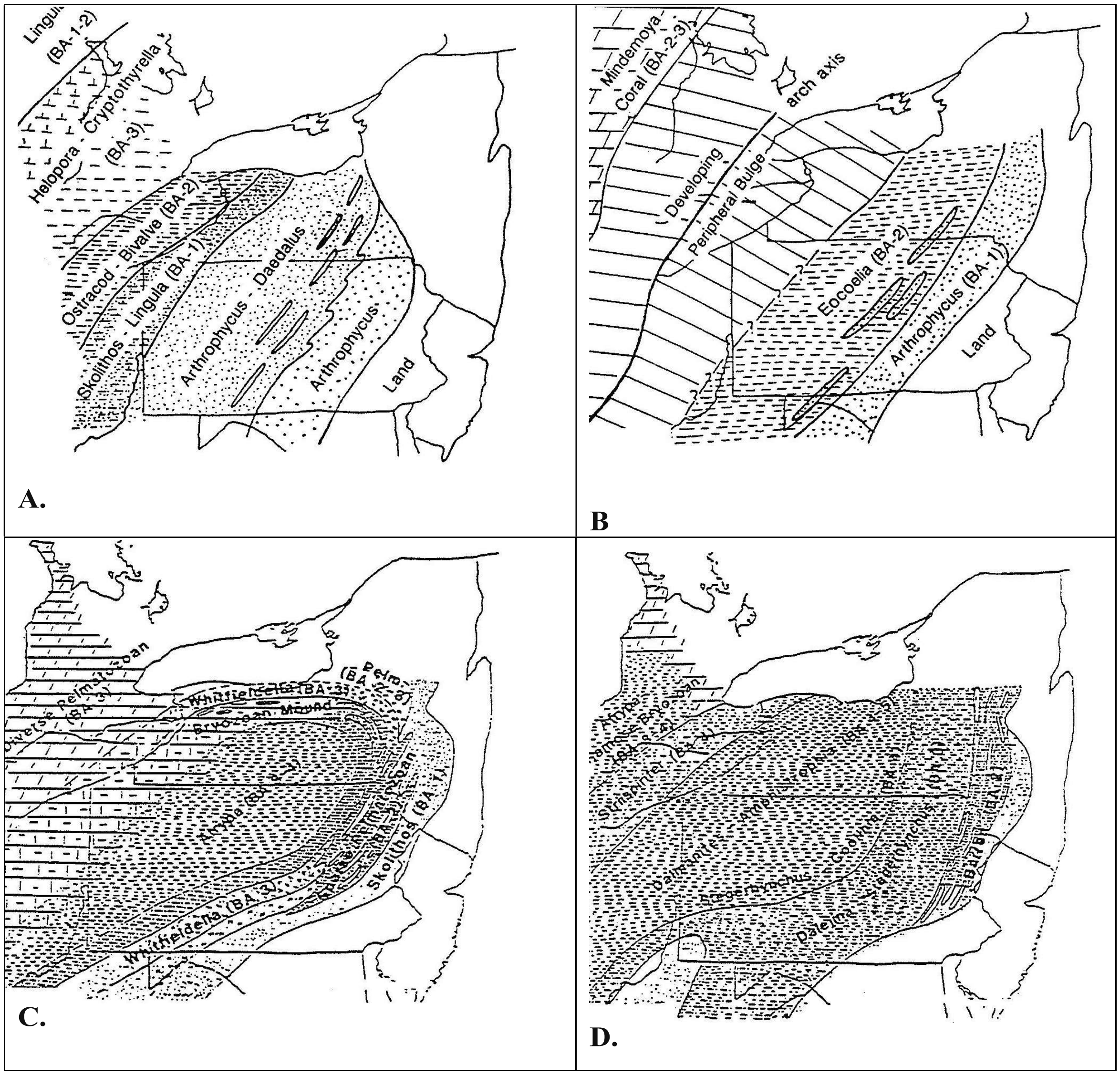

Figure 3. Paleogeographic map for Pennsylvania, New York, and Ontario during early and late Llandovery time. (A) Early Silurian (Rhudannian), Sequence I, Medina Group; note position of basin center in southern Ontario. (B) Mid Telychian time, during deposition of Sequence III, the Sauquoit-Otsquago-upper Rose Hill succession in central New York and Ontario. Note development of regional uplift (forebulge) along the Algonquin Arch (C) Early Wenlock time (Lower *K. ranuliformis* Zone), Note position of basin axis in western New York State during deposition of Irondequoit Limestone. (D) Mid Wenlock time (*O. sagitta rhenana* Zone), relatively deep water occupies basin center during deposition of Rochester Shale.

SEQUENCE STRATIGRAPHY AND LATERAL CHANGES OF SILURIAN SEQUENCES IN SOUTHERN ONTARIO-WESTERN NEW YORK

SUMMARY OF SILURIAN-EARLY DEVONIAN SEQUENCES

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) depositional sequences (Figs. 4-11). 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).

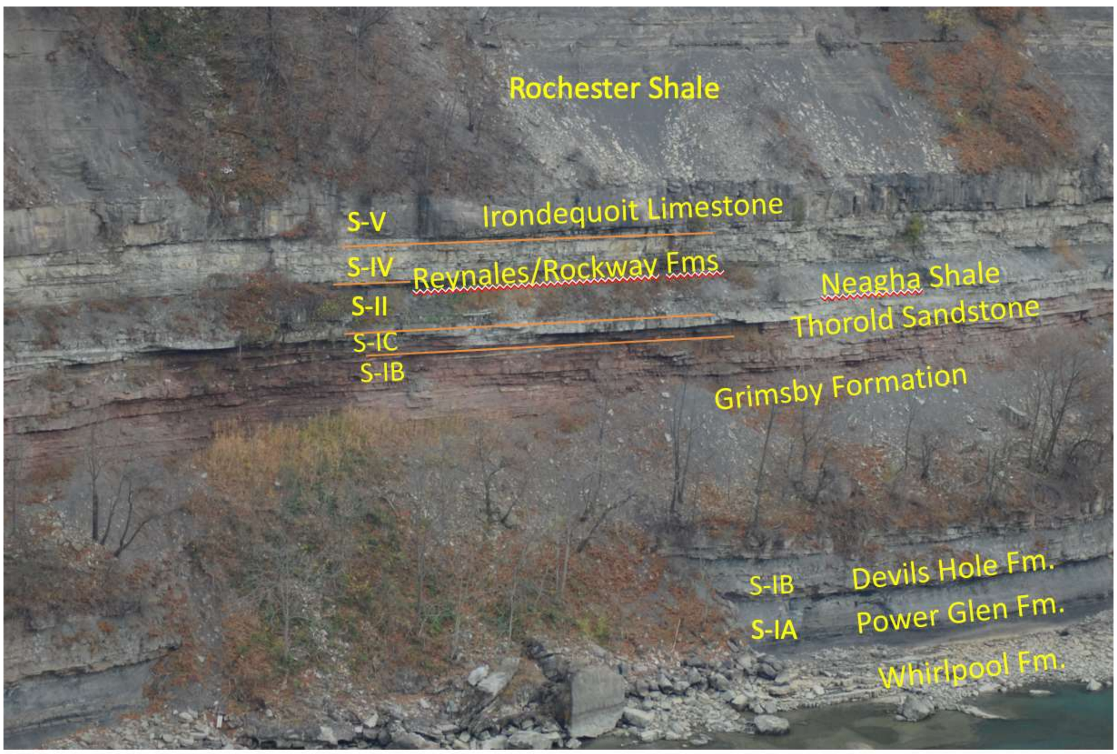

Figure 4. Lower Silurian sequences exposed in the east wall of Niagara Gorge; thin orange lines denote sequence bounding erosion surfaces; note that S-III and most of S-II are missing at a cryptic mid Llandovery unconformity. Photo taken from Canadian side of gorge.

Silurian sequences are bounded by unconformities, three of which, the S-I to S-II, S-II to S-IV, and S-V- and S-VI-boundaries, are regionally angular (Figs. 5,6). The magnitudes 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. 2-3). The I-II and II-IV boundaries are merged west of St. Catharines, Ontario, forming a compound unconformity (Figs. 6, 7). Conversely, the basal sequence I unconformity (Cherokee unconformity) decreases westward (Figs. 5, 6, 7). Varying east to west facies changes within each of the sequences along the Niagara Escarpment reflect differential subsidence and elevation of the Algonquin 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 (upper Hirnantian-lower Llandovery (Rhudannian)

The stratigraphically lowest interval (S-1) 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) whitish gray, trough cross bedded quartz arenite, Power Glen Shale (I 0-15 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, 6).

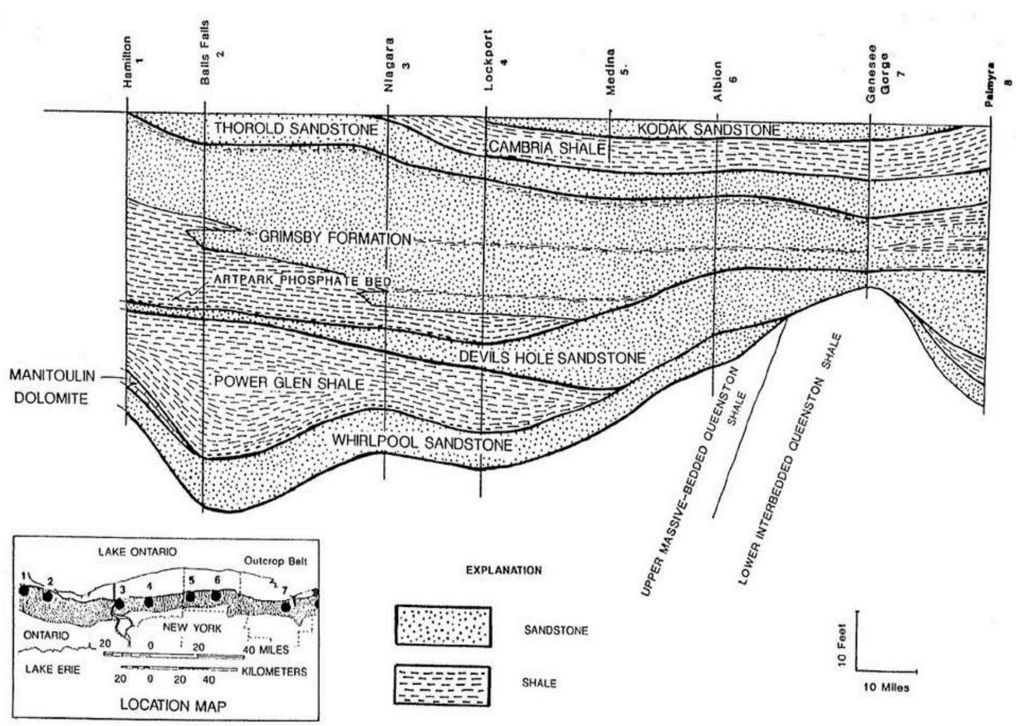

Figure 5. Regional cross-section of Medina Group (sequence I) in western New York and southern Ontario.

Recent studies based on carbon isotopes and chitinozoans suggest that the Whirlpool Sandstone and its partial lateral equivalent in Ontario, the lower Manitoulin Dolostone are of latest Ordovician (Hirnantian) age (Bergström et al., 2011; Farnam and Brett, in review). The basal sequence boundary with the underlying red mudstones of the Queenston Formation, long known as the "Cherokee unconformity" actually represents a composite erosion surface of early Hirnantian age associated with a major glacioeustatic lowstand. Detailed subsurface studies of Castle (1998) and Waid (unpublished data) indicate that the Whirlpool shows large variations in thickness possibly related to fillings of paleovalleys.

The Medina represents a large-scale depositional sequence with lowstand (non-marine) transgressive (foreshore to shoreface) Whirlpool Sandstone (Middleton et al., 1991), overlain by maximal 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 subsequences at the bases of the Whirlpool, Devils Hole, Thorold, and Kodak transgressive quartz arenites (Figs. 4, 6).

Sequences II-V: 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. 6-11).

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 phosphatic dolostone) and Reynales Limestone (0-3 m of calcisiltite, phosphatic nodular packstone and bryozoan-brachiopod-echinoderm grainstone, and minor shale) (Figs. 4). Waid and Over (2016) obtained a suite of conodonts including *Pranognathus tenuis* in the basal Densmore Creek phosphatic bed of the Neahga Shale as well as in the Budd Road phosphatic bed of the Reynales Formation This indicates that both units are of early Aeronian (*P. tenuis* Zone) age. To the northwest. in the Bruce Peninsula, up to 20 m.

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 shale possibly a feather edge of Williamson Shale (Telychian)western New York suggest westward deepening patterns (LoDuca and Brett, 1994).

Middle Clinton Unconformity: Upper Llandovery (Telychian)

Middle Clinton Group strata (Sequence III) are absent in the Niagara region, and a major regionally angular unconformity separates the lower Clinton Reynales Formation from the overlying Sequence S-IV (Figs. 6-8). A major change in depositional topography of the Appalachian foreland occurred during the mid-Llandovery (early Telychian); 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 (Fig. 7; Lin and Brett 1988; Ettensohn and Brett, 1998). This substantial regionally angular unconformity suggests another period of broad regional uplift centered on the Algonquin Arch (Fig. 7). Stott and Von Bitter (1999) documented a complex pattern of local uplift/erosion and minor basins in the southern Georgian Bay area 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 (Figs, 5-7; Ettensohn and Brett, 1998).

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, 7).

The thin, condensed Merritton Dolostone overlies the major mid Clinton unconformity (Figs. 6, 8); it is unknown in western New York State, although it is possibly equivalent in age (mid Telychian) to the Westmoreland Hematite of central New York (Fig. 6). 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. The Rockway falls in the *Pterospathodus amorphognathoides* Superzone; it also displays the rising limb of the Ireviken excursion (Cramer et al., 2006).

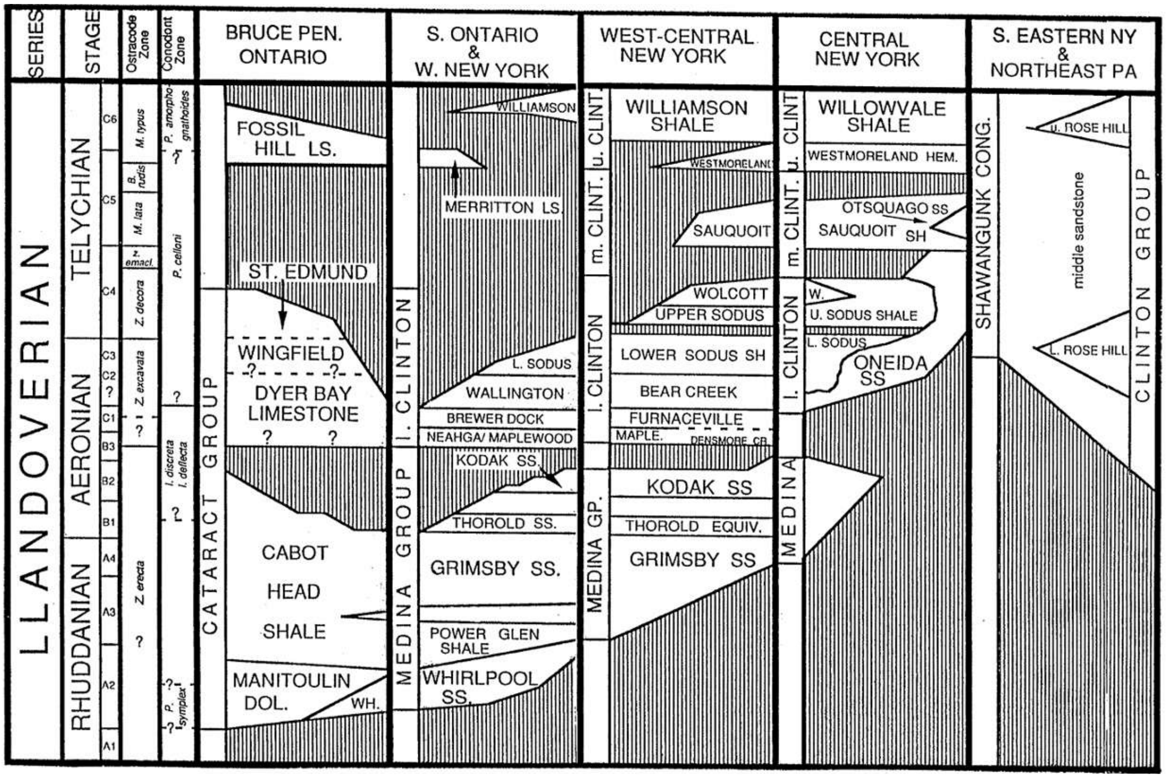

Figure 6. Correlation chart for lower Silurian (Llandovery) stratigraphic units (Sequences S-I through IV): Abbreviations: BC: Bear Creek shales; Dol: dolostone; Sh: shale; SS: sandstone; WH: Whirlpool Sandstone; WOL: Wolcott Limestone.

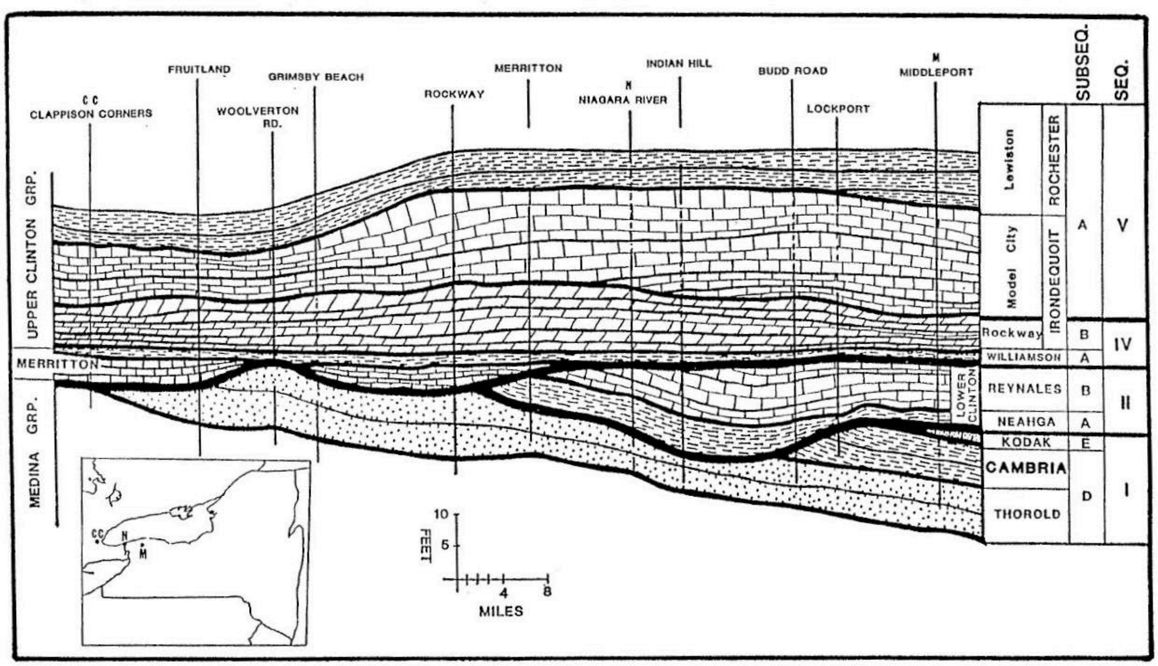

Figure 7. Regional cross section of upper Medina (Sequence S-I), lower Clinton (Sequence S-II), and upper Clinton (Sequences S-VI and S-V) through western New York and Ontario outcrop belt (see inset). Modified from Kilgour (1963).

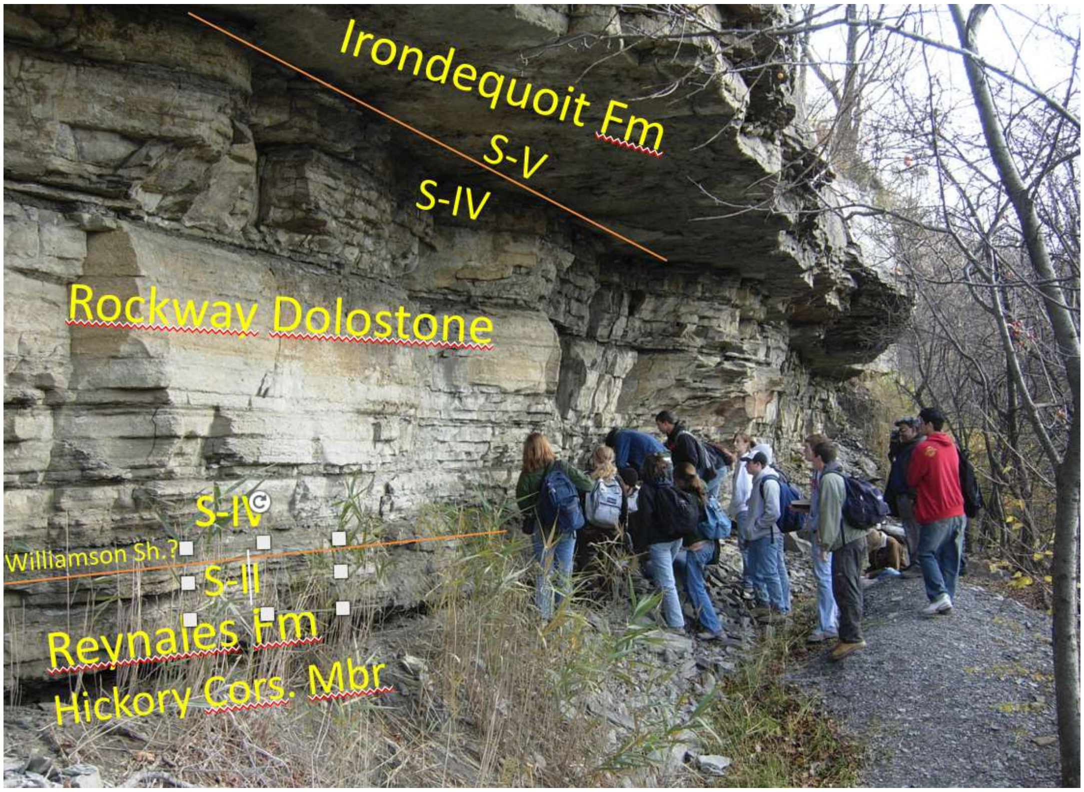

Figure 8. Sequences S-II, S-IV, and S-V (base) at Niagara gorge near Lewiston-Queenston Bridge. Note cryptic paraconformity above Reynales Formation, marked by phosphatic pebbles below the "Williamson Shale" tongue.

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 bryozoan-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. 4, 9-12).

The lateral equivalents of these units in the Bruce Peninsula are assigned to the Amabel Formation of the Albemarle Group (Bolton, 1957; Armstrong and Goodman, 1990). The Irondequoit and lower Rochester belong to the *Kockella ranuliformis* Zone; upper Rochester and DeCew belong to the *Ozarkodina sagitta rhenana* Zone (Cramer et al. 2006). Chemostratigraphic studies of Cramer et al. (2006) indicate the peak of the global Ireviken $\delta^{13}C_{carb}$ excursion within Sequence V, Rochester Shale and Decew Dolostone.

The Rochester Shale is divided into two members (Brett, 1982,1983a, b), which form two subsequences. The lower- Lewiston Member- (SVA) is highly fossiliferous along most of the Niagara Escarpment, with over 200 species of bryozoans, brachiopods, mollusks, crinoids, blastozoans, trilobites, and graptolites. Bryozoan-brachiopod rich limestone beds form the base of the overlying sequence VB. They pass upward into sparsely fossiiferous dolomitic shale. In turn this unit is overlain by the sparsely fossiliferous hummocky-swaley laminated sandy dolostone of the DeCew Formation (S-VC).

Putative identification of the DeCew horizon in south-central Ohio and even northern Kentucky has important implications for event stratigraphy. The DeCew has previously been interpreted as a seismite, i.e., seismically deformed sediment bed (McLaughlin and Brett, 2006). Recently, several authors have begun to recognize zones of widespread deformation that may be attributable to seismic shocking (Pope et al., 1997; Ettensohn, 1998). These intervals are typified by beds of ball-and-pillow deformation that extend for tens to hundreds of square kilometers (Schumacher, 1992; Pope et al., 1997; McLaughlin and Brett, 2004,2006; see Figures 18, 19). Careful observation of these deformed intervals demonstrates that they resemble beds known to have been deformed seismically, e.g., by liquefaction of muds and foundering of overlying coarser sediments ("seismites," *sensu* Seilacher, 1991). The larger deformed masses show overturned folds and flame structures, but most deformed zones do not show consistent orientation of fold axes (Pope et al. 1997). Such evidence is consistent with deformation induced by liquefaction rather than by slumping.

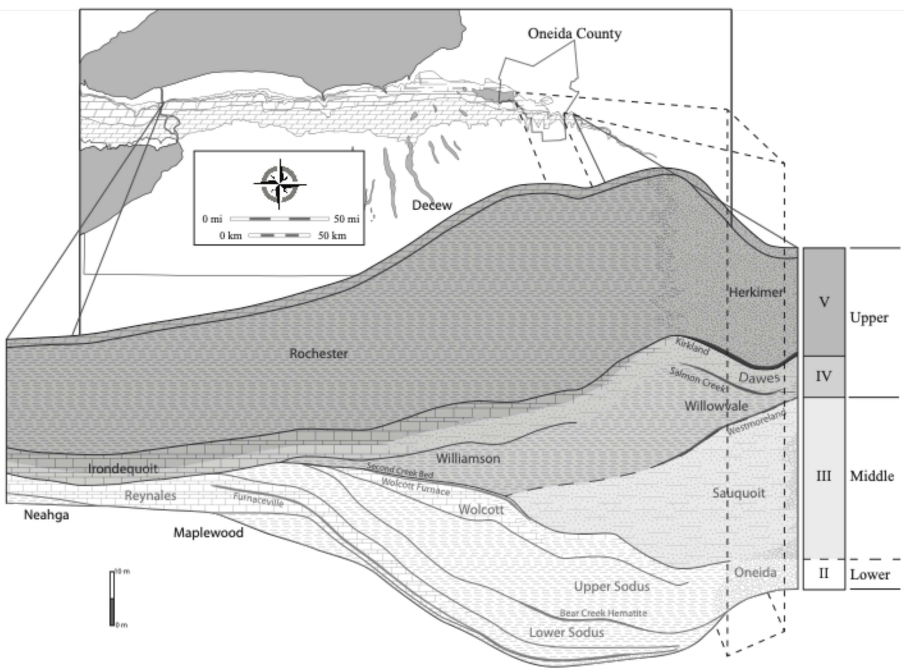

Figure 9. Regional cross section, showing litho– and sequence stratigraphic relationships of the Clinton Group. Cross section modified from Gillette (1947) and Brett and others (1998). Map modified from Fisher and others (1970); from Sullivan et al. (2012).

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. 10-12). Tabulate-stromatoporoid bioherms typically extend upward from lower crinoidal grainstones into the argillaceous Pekin Member (Figs. 10,11, 13); 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). 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.

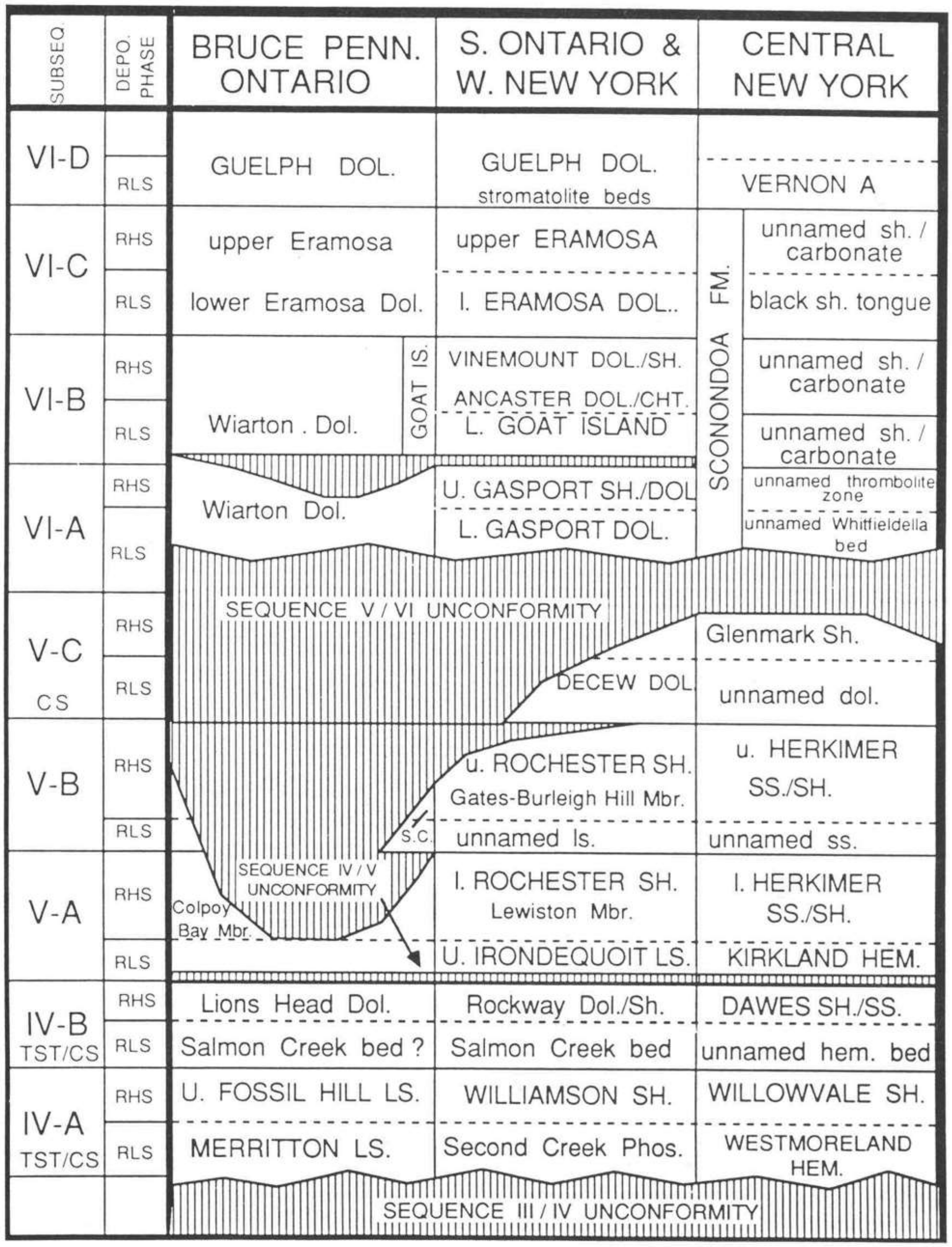

Figure 10. Correlation chart for stratigraphic units in the upper Clinton Group (Sequences S-IV, V) and Lockport Groups (Sequence S-VI) in Ontario and New York State. Formation names in all capitals; members in lower case. From Brett (1990).

Figure 11. Silurian sequences in the Niagara Gorge near Whirlpool Bridge, Niagara Falls, NY; photo taken from Canadian side of gorge.

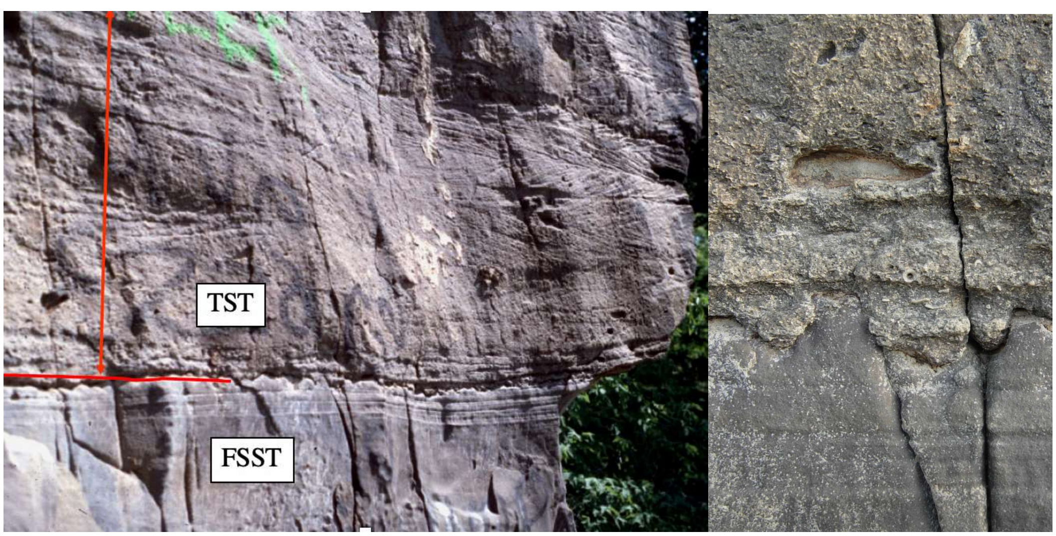

Figure 12. Sequence S-V/S-VI sequenced boundary (SB) Clinton-Lockport Group contact. DeCew Formation, falling stage systems tract (FSST) of DeCew Dolostone over lain at marked unconformity by herringbone (bimodal) cross-bedded crinoidal grainstone of Gasport Formation. On enlarged view note stylolitized SB contact and rip up clast (3 cm across) of DeCew in basal Gasport; Devils Hole, Niagara Falls, NY.

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. 429 roadcut at Pekin, 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 (Figs.10, 13, 15). 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 Wiarton dolostones (Fig. 10).

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 (Figs.1 0 , 13).

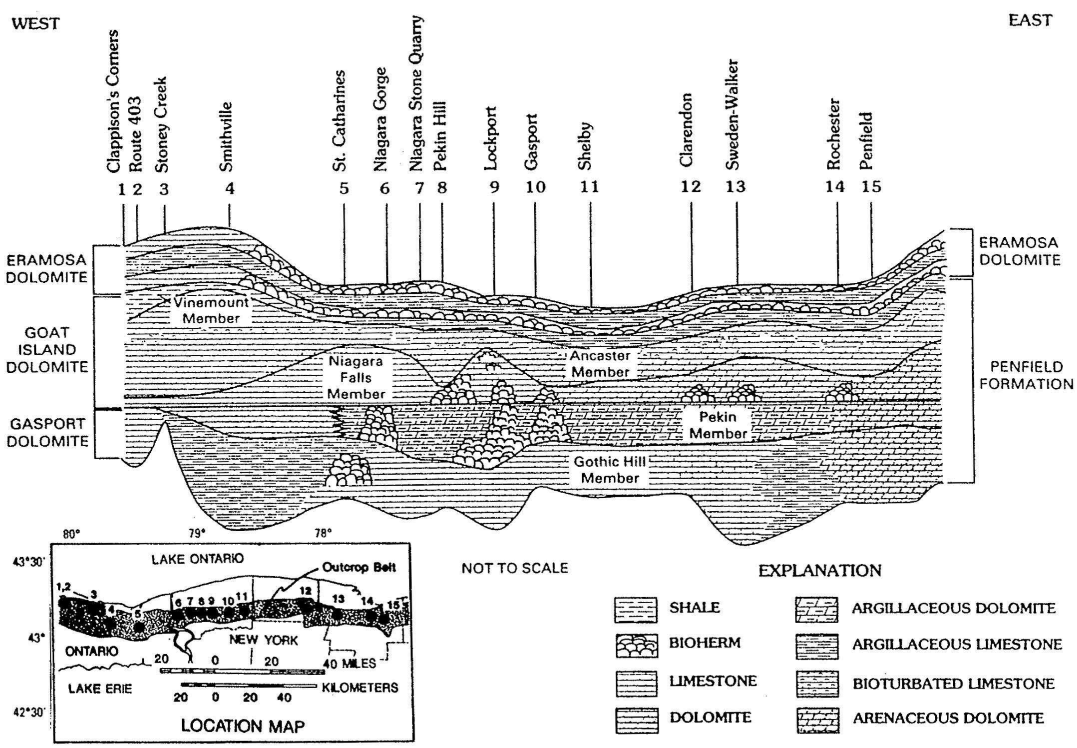

Figure 13. Regional stratigraphic cross section of the Lockport Group between Clappisons Corners (near Hamilton) Ontario and Rochester, NY. Datum is contact of Gasport and Goat Island formations. Modified from Brett et al. (1995).

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

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 (Figs. 14,15). 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, 1997). 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; Fig. 14).

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 elastic wedge, that was shed from tectonic regions (Salinic Orogeny) in the mid-Atlantic region. Near its type are, 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. Large domal stromatolites (~1m across) overgrowing thrombolites. Guelph/basal Salina Group boundary; Robert Moses Access Road, Lewiston, NY

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 (Fig. 15).

The Syracuse and Camillus formations, each about 30 m thick, comprise gray to green-maroon mudstones, buff dolostones and evaporites (Fig. 15). Key salt-gypsum horizons within the Syracuse have been traced in subsurface through Ontario from the Appalachian foreland into the Michigan Basin (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 (Fig. 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 (Ciurca, 1973; Copeland and Bolton, 1985), and other fossils that are suspected to represent a brackish water estuarine biofacies that bordered hypersaline shallow seas (Vrazo et al., 2016, 2017; Fig. 17). 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.