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LOWER SILURIAN MEDINA GROUP OF SOUTHWESTERN ONTARIO: SUMMARY OF LITERATURE AND CONCEPTS

By

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GENERAL TECTONIC AND STRATIGRAPHIC SETTING

Tectonic Setting

Southwestern Ontario overlies parts of three main tectonic elements: the Appalachian Foreland Basin, dominated by orogen-derived clastic sediments; the Michigan Intracratonic Basin, dominated by carbonate and evaporite sediments; and the Algonquin Arch which separates the former basins and hosts an interfingering succession of carbonates and clastics (Armstrong, 1992) (Fig. 1).

According to Sanford *et al.* (1985), the tectonic events in the Appalachian Orogen, and the lower Paleozoic depositional succession of southern Ontario were controlled by large-scale plate motions which resulted in periodic rejuvenation of basement blocks on deep-seated fracture systems and subsidence of intervening circular basins. This tectonic cycle (late Precambrian to late Paleozoic) began with creation of passive margin conditions and separation during the Late Proterozoic, as the south margin of Baltica rifted away from the east margin of Laurentia, and creation of passive margin conditions which widened to form the Iapetus Ocean during the Cambrian (McKerrow and Scotese, 1991). In the Early Ordovician, a transform boundary in the Iapetus converted to a southeast-dipping subduction zone, bounding a northwest-facing arc, and Iapetus began to narrow (McKerrow and Scotese, 1991). Newly-developed subduction to the northwest, beneath the margin of Laurentia, allowed the Bronson Hill-Tetagouche-Lush's Bight assembled island arcs to move northwestward to collide with Laurentia in the Llandoverian-Caradocian, an event referred to as the Taconian Orogeny (McKerrow and Scotese, 1991). Continued subduction to the northwest beneath Laurentia through the rest of the late Ordovician closed Iapetus Ocean, with the eventual collision of Baltica in the mid-Silurian (Salinian Orogeny) and of Avalonia in the early Devonian (Caledonian/Acadian Orogeny) (McKerrow and Scotese, 1991).

Compression of the passive margin by collision with an island arc system in the Early-Middle Ordovician Taconian Orogeny led to the foundering and collapse of the platform carbonates of the Trenton Group and produced the down-warped Appalachian Foreland Basin (Brett *et al.*, 1990; Diecchio, 1991; Waldron *et al.*,1998). Quinlan and Beaumont (1984) suggested that the emplacement of a thrust-load ~4 km thick over an area of approximately 500x500 km^2 modelled the general stratigraphy (Fig. 2). This loading, and subsequent rapid subsidence, led to progressive westward inundation of that drowned platform by abundant deep water, followed by shallower water, clastics derived from the Taconian uplift (Diecchio, 1991; Waldron et al., 1998). The waning phase of the main orogenic pulse resulted in deposition of the Upper Ordovician Juniata-Queenston clastic wedge(Diecchio, 1991), but the low-angle Cherokee Unconformity" at the Ordovician-Silurian boundary indicates a late Taconian pulse (Brett *et al.*, 1990; see Hamblin, 1999).

As suggested by Quinlan and Beaumont (1984), flexural interactions between the foreland Appalachian Basin and the intracratonic Michigan Basin resulted in the NE/SW-trending interbasinal Algonquin Arch. Howell and van der Pluijm (1990) concur with the concept of relating Arch uplift and episodic cratonic basin subsidence to orogenic phases in the Appalachians, and suggest that the post-Taconian Upper Ordovician/Lower Silurian stratigraphic sequence accumulated along the western margin of the east-tilting and rapidly subsiding Appalachian Foreland (Fig. 3). Tectonic tilting established a northwest dipping paleoslope in earliest Silurian time whereas foredeep depression by emplacement of thrusts in the

Appalachians promoted the Lower Silurian (upper Whirlpool Fm.) transgression and deeper facies to the east (Middleton, in Duke, 1987). Tectonic movements during the Taconic Orogeny at the craton margin had been transmitted through the craton by tilting of fault-bounded mega-blocks and expressed as uplift along Arches on dominant NE and NW trends, and as corresponding downwarp of intervening cratonic basins (Sanford *et al.*, 1985).

The "Tuscarora/Cherokee Unconformity", marking the Ordovician/Silurian boundary has been interpreted to represent the result of either a Late Ordovician glacio-eustatic sea level drop, or a tectonic phase of uplift (Dorsch *et al.*, 1994). In a tectonic setting dominated by orogenic subsidence, it is likely that tectonic mechanisms control most stratigraphic manifestations. Cant and Stockmal (1989) and Dorsch *et al.* (1994) suggested two orogen-related mechanisms which could create this unconformity after cessation of a phase of Taconian thrust loading: 1) migration of the peripheral bulge toward the orogen with associated uplift and erosion as it passes each point, creating a maximum lacuna in the distal-central foredeep, and conformity in the proximal foredeep, or 2) erosional thinning of the orogen leading to a reduction of the load and isostatic uplift, creating an unconformity over the whole foredeep with the maximum lacuna at the orogen itself. In the case of the "Tuscarora Unconformity" of Virginia, Dorsch *et al.* (1994) suggest the second alternative, isostatic basin-rebound, as the causative mechanism.

During the early Palaeozoic, the Algonquin Arch was a broad platform between the more rapidly subsiding Michigan Basin to the west and the Allegheny Trough to the east (Sanford *et al.*, 1985). Because the two basins experienced active subsidence at different times, the Arch migrated back and forth between them (Bailey and Cochrane, 1986). In fact, as stated by Sanford (1972), the Arch is really just the hinged eastern rim of the Michigan Basin, rather than an actual physical barrier, and facies changes which occur at that point are simply due to less continuous subsidence along that line. The Algonquin Arch also separates the northern Bruce basement mega-block (with simple uniform E-W fracture system) from the southern Niagara basement mega-block (with complex multiple sets of fractures cutting it into a maze of smaller blocks) (Sanford *et al.*,1985).

Stratigraphic Setting

The Precambrian surface slopes away from the Shield except for the mildly positive Algonquin Arch, and the Paleozoic succession of Southern Ontario (approximately 1500 m thick) dips away to the south, west and southwest (Roliff, 1954; Sanford and Quillian, 1959). During early Paleozoic time the Precambrian surface was likely similar to its present-day configuration, and irregularities on this surface are reflected far up into the stratigraphy (Sanford and Quillian, 1959). Lower Paleozoic strata onlap the Algonquin Arch from the Michigan Basin in the west and from the Appalachian basin in the south (Bailey and Cochrane, 1986). Upper Cambrian and Lower Ordovician marine depositional units originally thinned, but likely covered, the Algonquin Arch (Roliff, 1954; Poole *et al.*, 1968). However, these strata were eroded from the Arch crest during a phase of Early Ordovician uplift and subsequently overlapped by Middle and Upper Ordovician units (Cohee, 1948; Poole *et al.*, 1968). The geology of the Upper Ordovician deposits was extensively reviewed by Hamblin (1999).

There is an obvious unconformity between Ordovician and Silurian rocks (Cherokee Unconformity) to the west and northwest in the Michigan Basin, but the magnitude of that hiatus decreases eastward until at Niagara there is little firm evidence of significant erosion (Sanford, 1972), suggesting the dominance of down-to-the-east subsidence in the Appalachian Basin (Brett *et al.*, 1990). However, a regionally-recognizable unconformity is also present at this level in the central Appalachian Orogen (Dorsch *et al.*, 1994, 1995). The Lower Silurian sequence of the Michigan Basin is dominated by marine carbonates and fine grained clastics, whereas that of the Appalachian Basin is dominated by nonmarine coarse grained clastics derived from the east by erosion of the Ordovician Queenston-Juniata sandy wedge. In southwestern Ontario, at the crest of the Algonquin Arch (or "hinge line") these two facies styles intermix. As suggested by Bolton (1953) the two different depositional regions were separated only by a broad shelf, not a true physical barrier, although it did influence sedimentation patterns.

The early Llandoverian-age Medina Group (Fig. 4)(Cheel *et al.*, 1991) is the first of several major (third order) unconformity-bounded Sequences present in the Silurian (upper part of Tippecanoe Sequence of Sloss, 1963 and Wheeler, 1963) (Brett *et al.*, 1990). The bounding unconformities represent major drops in relative sea-level basinwide (Brett *et al.*, 1990), likely as a result of tectonic processes (Duke, 1991; Duke *et al.*, 1991). The Group records a brief lowstand, followed by transgression and subsequent highstand progradation of a clastic wedge over truncated Ordovician units (Brett *et al.*, 1990; Duke, 1991; Duke *et al.*, 1991). The Medina is approximately 60 m thick in Lake Erie, thinning northwest to 25 m over the Algonquin Arch (Poole *et al.*, 1972). Although the thickness is relatively constant, all components grade from more continental facies in the east to more open marine facies to the west (Brett *et al.*, 1991). The sub-Clinton Group unconformity, which increasingly bevels the Lower Silurian Sequence to the west (Brett *et al.*, 1995) and indicates broad uplift of the Algonquin Arch region following Medina deposition (Middleton, in Duke, 1987; Armstrong, 1989), again suggests that a phase of down-to-the-east subsidence in the Appalachian Basin was dominant at this time (Brett *et al.*, 1990).

Ordovician/Silurian Boundary

There is a sharp and obvious unconformity between Ordovician and Silurian rocks ("Cherokee Unconformity", equivalent to the Tippecanoe I/II boundary of Sloss, 1988) to the west and northwest in the Michigan Basin (Johnson *et al.*, 1992; Copper and Long, 1993; Rudkin *et al.*, 1998), but the magnitude of that hiatus decreases eastward until at Niagara there is little firm evidence of significant erosion or angularity (Sanford, 1972; Middleton, 1987), suggesting the dominance of down-to-the-east subsidence in the Appalachian Basin (Brett *et al.*, 1990), at least at that time. However, a major regional unconformity also occurs at this level within the Tuscarora Sandstone in the central Appalachians of Pennsylvania, Virginia and Tennessee, termed the "Tuscarora Unconformity" (Dorsch *et al.*, 1994, 1995), suggesting that tectonic uplift may have occurred there. Even where there is little lithological evidence for significant erosion, there appears to be a faunal hiatus (Middleton, 1987; Rudkin *et al.*, 1998). Middleton (1987) suggested that the latest Ordovician basin filled to just above sea level, after which there was slight erosion of the Queenston Formation and establishment of a northwest-dipping paleoslope by the beginning of the Silurian. Middleton (1987) and Brett *et al.* (1990) suggested the unconformity represents a late Taconian tectonic pulse with an alteration in paleoslope which did not involve any eustatic effects. Similarly, Dorsch *et al.* (1994, 1995) proposed that the "Cherokee/Tuscarora Unconformity" is related to isostatic flexural rebound of the foredeep and concomitant erosion between two distinct phases of thrust load-induced subsidence.

Alternatively, according to Johnson *et al.* (1992) and Rudkin *et al.* (1998), the unconformity at the top of the Ordovician in southern Ontario (and over much of the midcontinent; Frakes *et al.*, 1999) may relate to a Late Ordovician glacio-eustatic sea level drop.

Climatic Setting

The area lay at about 20°-30°S. paleolatitude in Early Silurian time during a phase when the Gondwanan continent was moving toward the South Pole (Ziegler *et al.*, 1979; Scotese and McKerrow, 1991) on the distal, northwest margin of the Appalachian Foreland Basin (Cheel, 1991). Laurentia was rotated about 45° clockwise from its present position (Middleton, 1987; Scotese and McKerrow, 1991), leaving this area in the southern tropical Trade Winds belt, where winds would blow from northeast to southwest along the paleoshorelines (Brogly, 1984). The climate was generally warm and seasonally arid, perhaps a dry subtropical area (Middleton, 1987). However, the Late Ordovician-Early Silurian Cool Mode (Frakes *et al.*, 1993) was ending and the Late Ordovician glacial phase, predominantly in the southern hemisphere Gondwanan continental fragments of Africa and South America (Sheehan *et al.*, 1997), had dominated world climates (Middleton, 1987; Frakes *et al.*, 1993; see Hamblin, 1999). Glaciation and mass extinction were concentrated in the final 0.5 to 1.0 million years of the Ordovician (Sheehan *et al.*, 1997) and concomitant with this climatic shift, a significant global eustatic sea level fall may have occurred, and affected deposition in Southern Ontario (Copper and Long, 1993; Rudkin *et al.*, 1998).

Biotic changes associated with the Late Ashgillian (Hirnantian/Gamachian) glaciation were related to intensification of climatic gradients and glacio-eustatic sea level changes (Sheehan *et al.*, 1997). Two pulses of extinction occurred: the first at the beginning due to a major sea level drop which eliminated much of the predominant epicontinental seaways and their "perched" faunas, and a second at the end due to a major warming which eliminated the widespread, but peculiar, Hirnantian cool-water fauna (Sheehan *et al.*, 1997). The faunal changes were diachronous and differed in timing between faunal groups, indicating a protracted environmental crisis, rather than instantaneous catastrophic annihilation (Finney *et al.*, 1999).

Stott (1998) suggested that the transition from Medina Group clastic sedimentation to the Clinton Group carbonate sedimentation reflects a climatic changeover from oceanic *Primo* state (cooler, more humid, with abundant clastic input) to *Secundo* state (warmer, dryer, with abundant carbonate precipitation).

MEDINA GROUP

Nomenclature

The modern use of the term Medina dates from the early 1900's when Grabau (1909) redefined it to include the Lower Silurian clastics overlying the Queenston red shale and overlain by the Clinton carbonates. Nomenclatural controversy raged for decades (refer to Winder, 1961) regarding the use of "Medina" (originally a New York term for nonmarine-sandstone-dominated facies to the southeast) versus "Cataract" (an Ontario-based term, defined by Schuchert, 1913, for marine shale- and carbonate-dominated facies to the northwest). These two geographically-based facies associations apparently are coeval (Cheel, 1991). However, much of the Ontario-based literature, including some petroleum industry material, employs usage of the term "Cataract" even for the hydrocarbon-bearing, Appalachian-derived sandy facies. The true Cataract facies to the northwest, as characterized by the type section at the cataract of the Credit River, are primarily marine carbonate and shale, have no proven hydrocarbon reserves, and only minor potential. In the subsurface of the Niagara area and to the west, drillers have always referred to the "Red Medina" and "White Medina" sandstones. Duke *et al.* (1991) reviewed the history of the nomenclature and concluded that "Medina Group" is the most useful formal rank in the Niagara and southwestern Ontario area. In addition, Duke (1991) and Duke *et al.* (1991) suggest that the upper contact of the Medina should be placed at the top, rather than the base, of the Thorold sandstone, thus including the Thorold in the Medina, rather than the overlying Clinton Group. This conclusion had previously been reached by Martini (1971) and Sanford (1972) based on simple lithology and facies association, and has been formalized in adjacent New York by Brett *et al.* (1995).

The Medina Group in Ontario includes, in ascending order, the Whirlpool, Power Glen or Cabot Head, Manitoulin, Grimsby and Thorold Formations (Fig. 4). In New York, Brett *et al.* (1995) also defined the Devil's Hole Sandstone between the Power Glen and the Grimsby, and the Cambria Shale as the uppermost unit, immediately beneath the sub-Clinton unconformity. Duke (1991) and Duke *et al.* (1991) argue that in the Niagara area most traditional formation definitions are based on diagenetic colour changes, rather than genetically significant subdivisions, and therefore are invalid: they introduced a scheme of informal correlatable sub-sequences based only on primary lithic properties. However the following formation descriptions provide a summary of the formal stratigraphic units, primarily in the Niagara region, as a framework for discussion. In south-central Ontario, to the northwest, the Medina (Cataract) includes the Whirlpool, Manitoulin and Cabot Head Formations. Further to the northwest, on the Bruce Peninsula, the Cataract (Medina) Group includes the Manitoulin, Cabot Head, Dyer Bay, Wingfield and St. Edmund Formations. The Medina represents a complex overall transgressive-regressive cycle: Whirlpool/Manitoulin/Cabot Head records a shorter, transgressive, fining-upward succession, whereas Grimsby/Thorold records a longer, regressive, coarsening-upward succession (Fisher, 1954; Benincasa, 1996). The change is marked by a phosphatic zone timeline (Fisher, 1954) (maximum flooding surface overlain by the Artpark Phosphatic Bed of Duke, 1991 and Duke *et al.*, 1991 and Brett *et al.*, 1995). Anastas and Coniglio (1992) attribute the latest Ordovician erosion and the subsequent earliest Silurian transgression to the combined effects of Gondwanan glaciation and Taconian tectonics.

Whirlpool Formation ("White Medina")

The Whirlpool Formation is a thin grey fine to medium grained sandstone unit present at the base of the Medina Group over most of southwestern Ontario. It can be defined in outcrop on the Escarpment from Niagara Gorge northward to near Collingwood, and in the subsurface as far west as a line from Pt. Bruce to Guelph to Collingwood (Caley, 1943; Winder, 1961; Bolton, 1957) and beneath Lake Erie as far west as Long Point (Armstrong, 1992). The term was first applied by Grabeau (1909) at the type locality at "The Whirlpool" in the Niagara Gorge. Additional good outcrops are known at Twentymile Creek, Stoney Creek, Hamilton, Duncan, and several small quarries in the Georgetown/Inglewood area northwest of Toronto (Caley, 1961; Rutka *et al.*, 1991). The lower contact is a mudcracked disconformity/unconformity resting on the Upper Ordovician Queenston formation (and representing the entire Gamachian stage), whereas the upper contact is sharply conformable with the Power Glen shales to the south and east, and with the Manitoulin dolostones to the north and west (Winder, 1961; Armstrong, 1992). The Whirlpool thins irregularly to the northwest from a maximum of 12 m at Niagara Gorge to 4 m at Hamilton, to 7 m at Orangeville to a pinch out at Duntroon (Caley, 1943, 1961; Bolton, 1957; Winder, 1961). In the subsurface to the west, near Brantford, only 0-1 m of quartz sandstone is present at the base of the Medina (Caley, 1943). Where present drillers refer these sandstones to the "White Medina". Fossils are very rare, except minor marine body fossils and trace fossils from the uppermost few metres (Rutka *et al.*, 1991), hence age determinations are imprecise and based primarily on stratigraphic considerations. The Whirlpool was commonly interpreted as a nearshore marine deposit approximately correlative to the Tuscarora sandstone of New York/Ohio (Rutka *et al.*, 1991).

The Whirlpool Formation comprises light grey to white, buff weathering, thick bedded, uniform, very fine to medium grained quartz arenite, in a general fining-upward trend, with minor silty mudstone interbeds at the top (Bolton, 1957; Rutka *et al.*, 1991). Grain size is generally coarser to the east, bedding is commonly lenticular, and thin lenses of grey shale rip-ups are present near the base (Bolton, 1957). Sand grains are typically of two kinds: well rounded and frosted, common near the base, mixed with clear subangular grains, and silica cement is prominent (Bolton, 1957; Caley, 1961; Winder, 1961). Much of the sediment is probably recycled from Upper Ordovician Queenston/Oswego/Juniata deposits to the southeast (Caley, 1961; Rutka *et al.*, 1991). Fisher (1954) gives results of petrographic analysis as 90% detrital quartz, 8% clay and 2% heavy minerals. Winder (1961) mentions the dominance of zircon in the lower part and collophane in the upper part. Fossils are uncommon, except for a few ichnofossils in the upper few metres (Caley, 1961; Rutka *et al.*, 1991). Some fossil fragments are abraded, rounded, phosphatized and the same size as quartz grains, suggesting multicyclic sediments derived from Upper Ordovician sources (Rutka *et al.*, 1991).

Middleton (1982) first noted that the Whirlpool can be grossly subdivided into a lower member typified by coarser grain size, large trough cross bedding (paleoflow to the northwest) and no fossils, and an upper member typified by thinner bedding, asymmetric ripple cross lamination and trace fossils. He suggested these units represented shoreline vs. shallow marine facies deposited during a marine transgression.

Rutka *et al.* (1991) provided a detailed description and interpretation of lower and upper members, as follows. The lower 2/3 of the Whirlpool comprises thick bedded very fine to medium grained, nonmarine sandstone in broad sheet-like, scour-based fining-upward channel units up to 14 m wide, which display unidirectional paleoflow indicators to the northwest. Fossils are absent except for a depauperate terrestrial/semi-aquatic microflora. The thickness of the unit, the thickness of stacked fining-upward sequences, grain size, channelization, occurrence of trough cross bedding, all decrease to the northwest, whereas occurrence of ripple cross lamination increases to the northwest. This unit pinches out north of Orangeville. The remainder of the Whirlpool, and the entire formation north of Orangeville, comprises thinly interbedded fining-upward, very fine sandstone and siltstone with abundant symmetrical wave ripples, hummocky cross stratification, minor marine body fossils and a conspicuous Skolithos/Cruziana ichnofauna. Ripple crests are oriented NW/SE, interpreted to be approximately parallel to shoreline. The lower-upper contact is a sharp erosional surface with shale rip-ups, symmetrical and interference ripples. Also conspicuous are broad shallow scours which open to the northeast, and were infilled by sediment toward the northeast. Similarly Cheel (1991) and Cheel and Middleton (1993) describe in detail the lower unit with large nonmarine braided fluvial channels which flowed to the northwest, the upper shallow marine interbedded sandstone and siltstone with bioturbated HCS sandstones and the irregular intervening surface of transgression characterized by broad shallow scours, shale clast lags, vertical burrows and symmetrical wave ripples (crest orientation NNW/SSE, interpreted as parallel to shoreline orientation during northeast toward southwest transgression).

Rutka *et al.* (1991) interpreted the lower Whirlpool as a sandy braidplain, at least 350 km downslope by 200 km wide, with a northwest-dipping paleoslope (ie. away from the Taconian highlands) where a complex of small, flashy discharge braided streams flowed. The upper Whirlpool was interpreted as a marine transgressive unit with transgression proceeding toward the southwest, and scour currents flowing to the northeast down the offshore paleoslope. The observations and conclusions require that a major tectonic reorientation of the entire region must have occurred during Whirlpool time, likely due to emplacement of a Taconian tectonic load in the Appalachian area to the east, causing the original NW-dipping paleoslope to tilt and convert to a NE-dipping one. The upper Whirlpool is gradationally overlain by Power Glen marine shale in the southeast (closest to the area of maximum subsidence) and sharply overlain by Manitoulin Formation marine limestone to the northwest (the distal shallow margin of the foredeep).

Power Glen Formation

The Power Glen Formation is a thin grey mudstone unit present between the Whirlpool and Grimsby Formations in the Niagara area. It can be defined in outcrop along the Escarpment from Niagara Falls to Stoney Creek (Bolton, 1953, 1957). Bolton (1953) first proposed the term to denote shale at the approximate stratigraphic location of the Manitoulin, with a type section at Decew Falls. The lower and upper contacts are conformable (Winder, 1961), and the unit was thought to grade eastward into the red sandstones of the Grimsby and westward into the dolostones and shales of the Manitoulin and Cabot Head formations (Caley, 1940; Bolton, 1953). However Duke (1991) points out that the grey fossiliferous shales of the Power Glen are very different from the red barren siltstones of the Cabot Head to the north. The Power Glen attains maximum thickness of 15 m at the type section , and thins slightly to the east to 10 m at Niagara, and drastically to the west to pinch out near Stoney Creek (Bolton, 1957).

The Power Glen Formation comprises greenish grey to dark grey fissile calcareous to arenaceous mudstone with thin grey fine-grained calcareous sandstone and minor ferruginous oolitic limestone (Bolton, 1953, 1957). The amount of sandstone increases upward and to the south and east (suggesting the detrital source in that direction), and the presence of beds of ferruginous rip-ups increases upward (Bolton, 1957). The base of the unit is gradational with thin bedded fossiliferous sandstone and shale overlying the Whirlpool, whereas the top is likewise conformable but represented by a sharp colour change (Bolton, 1957). Duke (1991) described a prominent 1-2 m thick white quartz sandstone at the top of the Power Glen in western New York (his Devil's Hole Sandstone, now formally-defined in New York by Brett *et al.*, 1995) interpreted to represent Whirlpool-like sediments derived from the southeast during a brief relative sea level drop. To the west in Ontario, this interval is represented by the Ball's Falls dolostone/dolomitic shale/phosphatic lenses, interpreted as a marine condensed section (Duke, 1991; Duke *et al.*, 1991; Brett *et al.*, 1995). The Power Glen is sparsely fossiliferous, including a shallow marine assemblage of brachiopods, pelecypods, gastropods, bryozoans: Bolton (1957) noted that most shells are transported and occur as single valves lying convex-up in the bedding, and bryozoan fragments lie in bedding with an east-west orientation.

Manitoulin Formation

The Manitoulin Formation is a thin, but widespread carbonate unit present in the northern and western portions of southern Ontario. It can be defined in outcrop, along the Escarpment, from Stoney Creek to Manitoulin Island (Bolton, 1953, 1957; Armstrong, 1987, 1988, 1989). The unit conformably overlies the Whirlpool Formation, where that is present, or to the north, it unconformably overlies the Queenston Formation (Cherokee Unconformity) (Bolton, 1953, 1957; Anastas and Coniglio, 1992; Armstrong, 1992). The Manitoulin and Whirlpool may be, in part, time equivalent (Armstrong, 1992). The Manitoulin Formation is overlain conformably by the Cabot Head (Bolton, 1953, 1957). Southeastward, toward the Niagara region, the Manitoulin grades to shale (into the Power Glen Formation; Caley, 1961; Middleton, 1982) and ultimately pinches out into a single phosphate pebble bed (maximum flooding surface; Cheel, 1991). Westward into the subsurface, it is present in the Hamilton (Caley, 1961), Brantford (Caley, 1941) and London (Caley, 1943) areas. It is also present in outcrop in the Lake Timiskaming outlier, far to the north (Armstrong, 1992). In outcrop, the thickness increases to the northwest into the Michigan Basin from 1 m at Stoney Creek to 4 m in the Hamilton area to 9 m near Orangeville to 12 m on Bruce Peninsula to 15 m on Manitoulin Island (Bolton, 1953; Middleton, 1982; Anastas and Coniglio, 1992; Armstrong, 1988,1989). The age is Early Llandoverian (Anastas and Coniglio, 1992).

The Manitoulin Formation comprises grey thin bedded fossiliferous fine crystalline dolostone (Bolton, 1953, 1957). It tends to be thicker bedded and more massive and cleaner at the base, but more argillaceous and with thin shale partings toward the top (Bolton , 1953, 1957). Middleton (1982) suggested that the original lithology was and bioclastic calcarenite. To the north, white chert lenses are common, especially near the top (Bolton, 1953, 1957; Armstrong, 1989) and on Manitoulin Island bryozoan bioherms are present in the upper part (Bolton , 1957; Anastas and Coniglio, 1992), the earliest and largest Silurian bioherms in North America (Armstrong, 1992). Low angle stratification, trough crossbedding and bioturbation are common (Middleton, 1982; Anastas and Coniglio, 1992). Armstrong (1989) observed hardgrounds near the top. Fossils include abundant bryozoans, brachiopods and corals (Bolton, 1953, 1957). The unit is interpreted as shallow marine carbonate deposition, on a storm-dominated shelf (Leggitt, 1985; Anastas and Coniglio, 1992), beyond the area of clastic input (Bolton, 1953). Deposition began earlier in the northwest and spread southward as regional transgression proceeded, until the Manitoulin rested directly on the partly-equivalent Whirlpool (Bolton, 1957; Anastas and Coniglio, 1992).

Cabot Head Formation

The Cabot Head Formation is a thick green, grey and red shale with thin calcareous siltstone beds present throughout southwestern Ontario. It can be defined in outcrop from the Hamilton area in the south to Manitoulin Island in the north, and throughout the subsurface to the west (Bolton, 1957; Winder, 1961). The name was first applied by Grabeau (1913) at the type section at Cabot Head on the Bruce Peninsula. In outcrop the unit commonly appears as a steep, poorly exposed talus slope between the resistant Manitoulin below and the vertical cliffs of the Lockport/Amabel above (Caley, 1941). Additional good outcrops are present along the Escarpment at Stoney Creek, Hamilton, Dundas and the Limehouse RR cut (Caley, 1961) and as far north as the Lake Timiskaming outlier (Armstrong, 1992). The lower boundary of the unit is conformable and gradational, whereas the upper contact is gradational with the Grimsby in the Hamilton area, but sharp with the Clinton Group carbonates to the north (Caley, 1941; Winder, 1961; Armstrong, 1989). This latter relationship was interpreted as an erosional bevelling unconformity in south-central Ontario by Armstrong (1989), Brett *et al.* (1991) and Duke (1991). The Cabot Head generally thickens to the north, ranging from about 23 m at Hamilton to 40 m at Owen Sound to 25 m on Bruce Peninsula, but only 15 m on Manitoulin Island (Winder, 1961). In the subsurface it ranges 5-25 m thick (Caley, 1941). The Cabot Head is generally poorly fossiliferous, although in some areas the bryozoan *Helopora fragilis* is very abundant, and minor rhynconellid brachiopods are present (Caley, 1941, 1961; Bolton, 1953, 1957). The fauna is similar to that of the Manitoulin and Power Glen formations and bryozoan fragments are commonly oriented northwest/southeast along bedding planes (Bolton, 1957). The unit is usually interpreted as the result of shallow marine mudstone deposition (Bolton, 1953, 1957).

The Cabot Head Formation comprises alternating beds of green, grey and red mudstones with common thin calcareous siltstone to silty dolostones, and minor argillaceous limestones (Caley, 1941). Carbonates are more common to the west and north (Winder, 1961). Regionally, the lower portions include greater amounts of red shale, whereas upper portions are typically green shale with carbonate beds (Caley, 1941, 1961). However in the Niagara area the unit grades upward into the interbedded red sandstone and shale of the Grimsby, and this facies marks the northwestern limit of shoreline-related deposition (Caley, 1941; Bolton, 1957). To the northwest, the upper part of the Cabot Head is laterally equivalent to the Grimsby Formation (Armstrong, 1992). Sandstone:shale ratios in the Cabot Head indicate that the clastic detritus was predominantly derived from the Taconian source area to the southeast (Sanford, 1969), but Armstrong (1992) suggested some craton-derived input in the northern area.

Middleton (1982) pointed out that the strata between the Whirlpool and top of Medina Group remain relatively constant across most of southern Ontario, with no major breaks, but the facies expressed vary at the expense of one another according to depositional environment. The Manitoulin passes eastward and upward into Cabot Head/Power Glen shallow marine (pro-delta?) shale and these shales pass eastward and upward into the Grimsby/Thorold shoreline-related facies (Middleton, 1982). Duke (1991) suggested that in the Niagara area there is no true Cabot Head: the lower grey shales are attributable to the Power Glen, and the upper red, sandier shales are attributable to the lower Grimsby.

Grimsby Formation ("Red Medina")

The Grimsby Formation is a relatively thin sequence of interbedded red sandstone and mudstone present in the southern and eastern parts of southern Ontario. The unit is predominantly sandstone in the Niagara to Hamilton area, but becomes more shaley, greener and more marine to the north as its thickness decreases (Bolton, 1953). Armstrong (1992) suggested that the Grimsby passes laterally to the northwest into the upper Cabot Head. The Grimsby Formation can be defined in outcrop from Niagara as far north as Hamilton, and in the subsurface of southern Ontario as far west as London and beneath Lake Erie where drillers refer to the "Red Medina" (Winder, 1961). The name was first applied by Williams (1914) to the type section in Fortymile Creek in the Escarpment at Grimsby. Other important outcrops occur at Rochester, N.Y., Niagara Gorge, Stoney Creek, Webster's Falls, Hamilton, and Dundas (Caley, 1961; Martini, 1972). The contacts with the under- and overlying Cabot Head/Power Glen and Thorold formations are generally conformable, although the upper contact is traditionally drawn at a distinct colour change from red to white sandstone (Bolton, 1953; Caley, 1961). Bolton (1953, 1957) suggested that the Grimsby represented the uppermost unit of the Medina Group, but Martini (1971), Sanford (1972) and Duke (1991) all advocated the inclusion of the overlying

Thorold in the group. The formation attains a maximum thickness at Niagara Gorge of about 14 m, thinning to the west and north to 6-8 m in the Hamilton/Stoney creek area, to 4 m at Dundas, and only 1 m near Orangeville (Bolton, 1953, 1957; Caley, 1961). Maximum thickness in the subsurface is 20 m (Winder, 1961). The unit is typified by a very sparse fauna of pelecypods, brachiopods, bryozoans and trace fossils, hence age determinations are imprecise and based primarily on stratigraphic considerations.

The Grimsby Formation comprises a generally coarsening-upward succession of red medium bedded very fine to fine sandstone with interbedded red silty mudstone and minor rip-up conglomerate beds (Bolton, 1953, 1957; Caley, 1961). Brett *et al.* (1995) defined the 0-2 m thick Artpark Phosphate Bed marking the top of the Devil's Hole/Power Glen and base of the Grimsby in the Niagara area. The proportion of sandstone increases upward so that the upper half is primarily thick bedded fine cross bedded sandstone, but decreases to the north and west where the sandy facies pinches out (Bolton, 1953). Sandstones are well sorted, subround to rounded, equant, clear quartz with hematite rims and minor heavy minerals (Bolton, 1957). Fisher (1954) gives a composition of 92% quartz, 4% hematite, 3% clay, and trace calcite and feldspar. Several greenish concretion beds occur in the middle of the unit and calcareous cement is more prominent toward the northwest (Bolton, 1957; Caley, 1961). Sandstones are typically manifest as broad, thin lenticular beds with abundant trough and ripple cross lamination (Caley, 1961; Martini, 1971).

The Grimsby has classically been considered as a coarsening-upward prodelta to deltaic deposit (in a regional sense), with the Taconian source area to the southeast (Bolton, 1957; Martini, 1971, 1972; Middleton, 1982). In the Ontario area the deposits are intertonguing marine and nonmarine, with abundant channelling the Niagara area, but progressively more marine with less sandstone and channelling toward the northwest (Martini, 1971, 1972; Middleton, 1982; Duke, 1991; Duke *et al.*, 1991). The Grimsby passes southeast into more proximal facies of the Tuscarora Formation of the Taconian Foreland of Pennsylvania (Middleton, 1982; Duke, 1991). Martini (1971, 1972) interpreted the Grimsby in terms of an overall regressive cycle from open marine prodelta to distal reworked delta top/interdeltaic environments, with complex interfingering of these facies due to interaction of sparse sediment input, slow subsidence rate and a shallow basin. He identified two major paleocurrent systems of channel paleoflows offshore to the northwest, and marine longshore paleoflows oriented northeast/southwest. Interstratification of the two was interpreted as evidence of the intertonguing of marine and nonmarine influences in the Niagara area (Martini, 1971).

Duke (1991) and Duke *et al.* (1991) interpreted the Medina in modern sequence stratigraphic terms. They identified three regionally-correlatable shallowing-upward marine parasequences in the Grimsby (the overlying Thorold represents another), forming a progradational stacking pattern (highstand systems tract). Within this format, they identified 1) shallow marine fine grained host sediment facies association, 2) estuarine/tidal channel sandstone dominated channel facies association, 3) laterally extensive shallow marine storm-dominated sheet sandstone facies association (Duke, 1991; Duke *et al.*, 1991). Abundant paleocurrent data essentially confirms the conclusions of Martini (1971) that tidal channels flowed approximately northwest through north-south oriented shorelines where strong northward wave-driven components forced alongshore drift parallel to shoreline.

Thorold Formation ("Clinton Sand")

The Thorold Formation is a thin light grey fine-grained sandstone unit present in the southern and eastern parts of southern Ontario. The formation is predominantly sandstone in the Niagara to Stoney Creek area, but predominantly muddy to the north (Bolton, 1953; 1957). It can be defined in outcrop in the Niagara Peninsula as far west as Dundas, and in the subsurface of southwestern Ontario as far west as Elgin County and beneath Lake Erie (Winder, 1961). The name was first applied by Grabau (1913) at the type section on the old Welland Canal at Thorold. Distribution is similar to that of the Grimsby, with excellent exposures at Niagara Gorge, fifteen Mile Creek, Decew Falls, Grimsby Beach roadcut and Websters Falls (Caley, 1961). The boundaries of the unit are generally sharp (Winder, 1961), although the traditional formation is essentially defined based on the colour contrast between it and the underlying Grimsby. In the subsurface, drillers generally lumped the Thorold with the overlying Clinton Group strata (Caley, 1961), following the ideas of Bolton (1953; 1957) that the Thorold represents the initial transgressive deposits of the Clinton, rather than the final regressive phase of the Medina. Sanford (1969) and Armstrong (1992) stated that these sandstones grade laterally and vertically into the dolostones of the Reynales Formation, suggesting the linkage with the Clinton. However, Duke (1991) and Duke *et al.*, (1991) presented convincing arguments that colour changes are diagenetic and cross lithological boundaries, and that the Thorold is simply the uppermost cycle of the Medina Group. Brett et al. (1995) formally included the Thorold in the Medina Group of adjacent New York.

In the Niagara peninsula the Thorold is overlain by the thin Neahga shale, and the Reynales dolostone, but to the north the Neahga pinches out and the Thorold is sharply overlain by the Reynales (Armstrong, 1992). Brett *et al.* (1995) interprets this relationship, and the northwesterly pinch-out of the Thorold, as erosional truncation at the sub-Clinton unconformity. Thickness is a maximum of 4.5 m at Clappisons Corners, about 2.5 m at Niagara and thins to the north to zero just north of Dundas (Bolton, 1957; Caley, 1961). The unit is typically barren, except for trace fossils and *Lingula*, hence age determinations are imprecise and based primarily on stratigraphic considerations.

The Thorold Formation comprises light grey to white or greenish grey thin bedded fine-grained quartz sandstone, with minor greenish grey mudstone. The entire unit thins and becomes more mud dominated toward the north, whereas to the east in New York state, it becomes coarser and eventually grades into the Oneida Conglomerate (Bolton, 1957). Sandstones are about 70% clear, subround to subangular, very fine to fine quartz, with minor feldspar, about 20% argillaceous matrix, and silica cement (Caley, 1961; Bolton, 1957). Ripple cross lamination and small-scale trough cross bedding are common (Caley, 1961; Bolton, 1957). A thin bed of red and green shale rip-ups is commonly present at the base (Bolton, 1957), interpreted by Duke (1987, 1991) as an erosion surface. The upper contact is commonly marked by a phosphatic pebble bed, the Densmore Creek Phosphate Bed of Brett *et al.* (1995), interpreted by Duke (1987, 1991) as a marine flooding surface at the Medina/Clinton unconformable sequence boundary.

Middleton (1982) described a regional distribution of four ichnofacies: 1) lagoonal/tidal flat facies to the east in New York, 2) *Skolithos* shallow nearshore facies in the Niagara area, 3) mixed *Skolithos/Cruziana* deeper marine and storm-influenced facies in the Hamilton area, 4) *Cruziana* deeper marine facies to the west and north. G. Pemberton, in Duke (1987), provided more detailed information on the ichnofacies of the Hamilton area, as follows. The bulk of the sediments are fine sandstones and siltstones with a resident fauna of lower energy *Cruziana* ichnocoenese, including a high diversity/low density fauna of mobile carnivores and deposit feeders in a relatively offshore setting. Interspersed, are thin hummocky cross stratified sandstones with higher energy *Skolithos* ichnocoenese, including a low diversity/high density, periodically introduced fauna of suspension feeder dwelling burrows in a shallower, higher energy setting.

Neahga Formation/Cambria Shale

In the Niagara Peninsula the Thorold Formation is overlain by a thin greenish to dark grey shale, the Neahga Formation, which thins westward from 2 m at Niagara River to 0 at Grimsby (Winder, 1961; Armstrong, 1992). Bolton (1957) described the lower contact with the Thorold in the following words: "undulates slightly, with short tongues of argillaceous limestone extending downwards into the Thorold" and " a thin transition zone of calcareous sandstone", which appear to indicate a conformable transition. In adjacent New York, Brett *et al.* (1995) defined the Cambria Shale, a thin fossiliferous red shale with minor sandstone which conformably overlies the Thorold, but is erosionally truncated at the Niagara River by the sub-Clinton unconformity. It appears that there is some confusion in the Niagara area of Ontario between these two units, one a part of the clastic-dominated Medina (Cambria), and one a part of the carbonate-dominated Clinton (Neahga). However, west and north of Grimsby, only the Neahga Formation (Clinton Group) is present. The Cambria Shale may represent a minor transgressive event, poorly preserved in Ontario.

Dyer Bay/Wingfield/St. Edmund formations

These units, which conformably overlie the Cabot Head to the northwest, are not included in the Medina Group, but are included in the coeval Cataract Group to the northwest. They appear to be partially correlative to the Grimsby/Thorold part of the section. They are only present on Manitoulin Island and the Bruce Peninsula, and are erosionally truncated by the overlying Fossil Hill Formation (Clinton Group) toward the south (Armstrong, 1989, 1992) over the crest of the Algonquin Arch. These units may have originally extended southward over the crest of the Arch and have been laterally equivalent to the uppermost portion of the Cabot Head Formation (Armstrong, 1992). The Dyer Bay Formation is thin bedded fossiliferous dolostone conformably overlying the Cabot Head, the Wingfield Formation is grey and green shale with thin dolostone beds and mudcracks, and the St. Edmund Formation comprises thin bedded dolostone with mudcracks (Armstrong, 1987, 1988, 1989, 1992). Together, these units total about 15-50 m of thickness. These may represent transgressive Michigan Basin carbonate-dominated facies, deposited on the northwest side of the Algonquin Arch at about the same time as the upper Medina Group.

SEDIMENTOLOGY AND SEQUENCE STRATIGRAPHY

Facies Assemblages

Duke (1991) and Duke *et al.* (1991) presented a facies assemblage and sequence stratigraphic analysis of the Medina Group, based on outcrop data from western New York and southern Ontario, as follows.

1) The *Host Sediment Facies Association*, including various laterally extensive shallow marine bioturbated mudstones, bioclastic limestones, storm-emplaced very fine sandstones and phosphatic lags. These facies are of more proximal aspect to the east and are locally incised by

channels of the following association.

2) The *Channel Facies Association*, including erosively-based, fining-upward sandstone-dominated meandering estuarine/tidal channel fills, tens of metres wide by up to 4 m thick, which commonly stack into multistoried complexes. These include larger-scale fine to medium grained sandstone bodies with trough cross bedding and lateral accretion surfaces, and smaller-scale very fine to fine grained sandstone or mudstone bodies with horizontal lamination.

3) The *Sheet Sandstone Facies Association*, including laterally extensive shallow marine tide dominated shoal or shoreface fine to medium grained sandstones. These include laterally amalgamated trough cross bedded tidal channel, laminated or bioturbated shoreface sandstones.

The New York region is dominated by shoreline-attached coarse grained channel and sheet sandstone facies with minor open marine sediments. The Hamilton-Niagara region has vertical alternation between dominant Host facies and subordinate Channel/Sheet sandstone facies, and the Hamilton region is dominated by open marine fine grained Host Association facies with rare small channel sandstones (Duke, 1991; Duke *et al.*, 1991) (Fig. 5). This regional proximal(east)-to-distal(west) trend of depositional facies is consistent throughout the Medina Group. Brett *et al.* (1990) noted that the transgressive-regressive succession of the Medina Group can be traced eastward into the much thicker, and predominantly nonmarine, Tuscarora Sandstone of New York..

Castle (1998) presented a similar analysis of facies assemblages in the Medina, based on a NE/SW regional depositional strike and NW depositional dip, from dominantly fluvial updip to dominantly offshore marine facies downdip (Fig. 6), as follows.

1) The Whirlpool (transgressive reworked channels and shoreface), unconformably overlying the Upper Ordovician, thickening to the east, and grading upward into the Cabot Head shale and northward into the marine dolostone of the Manitoulin. The lower portion represents nonmarine channel deposition in Ontario and New York and shoreface deposits in Pennsylvania, whereas the upper portion represents marine deposits throughout.

2) The Cabot Head (marine shelf) includes marine shales with interbedded thin sandstones, and transitional base and top. There is a distinct maximum transgression surface in the middle, recognized by higher Gamma Ray values on subsurface logs.

3) The Grimsby/Thorold formations (marine shelf, shoreline, fluvial/estuarine), arranged in stacked coarsening-upward sandstone sequences with a proximal-distal range of facies from East (fluvial/estuarine Tuscarora in Pennsylvania which displays northwestward paleoflow according to Yeakel, 1962) to West (shelf and shoreline e complexes of Ontario/Lake Erie/Ohio). In the west, those coarsening-upward sequences are 3-10 m thick and represent wave-dominated shelf sedimentation, from below wave base to shoreline. In the east, where the Grimsby is thickest and sandiest, coarsening-upward sequences are 20-30 m thick and represent proximal shelf, shoreline and tidal deposits.

Benincasa (1996), in a regional subsurface study of eastern Lake Erie, interpreted the Grimsby-Thorold in terms of nearshore estuarine processes, influenced by tides, on a prograding shelf. The lower half of the Grimsby was dominated by subtidal channel complexes incised into the underlying Cabot Head shales. The upper half was dominated by discrete tidal channels and mudflats, overlain by Thorold nonmarine deposits. Sedimentation occurred in association with a NNE-SSW paleoshoreline, turning to a or NW-SE orientation through time.

Paleocurrents

A large body of paleocurrent data was assembled by Duke (1991) and Duke *et al.* (1991), from their own and others data, for the New York to Hamilton area. Straight-crested ripples trend north-south, approximately parallel to Medina shorelines; ripple cross lamination and sole marks indicate flow offshore to the west and northwest; trough cross bedding in channels indicate predominant flow to the northwest, but upward in the sequence (more proximal) there are significant flow reversals in individual tidal channels and shoreface sheet sandstones; trough cross bedding and lateral accretion surfaces in shoreface sheet sandstones indicate strong northward alongshore wave-driven components and migration of tidal channels. The direction of offshore progradation was clearly toward the west-northwest, at an oblique angle to the trend of the Escarpment outcrop belt (Duke, 1991; Duke *et al.*, 1991).

Yeakel (1962) assembled an enormous body of paleocurrent data from the correlative fluvial Tuscarora sandstone in Pennsylvania, Maryland and Virginia, one of the earliest and most comprehensive such studies. The result of several thousand individual measurements of, primarily, trough crossbedding is a clear paleoflow pattern to the northwest.

Sequence Stratigraphy

The first-order Tippecanoe Sequence (Sloss, 1963) of the Appalachian Basin is a direct result of the evolution of the Orogen during Middle Ordovician to Early Devonian time. The second-order Taconian Foreland Basin succession is represented by the clastic-dominated series of, primarily regressive, wedges of marine to nonmarine synorogenic molassic sediments of Upper Ordovician to Lower/Middle Silurian age, deposited over 20-25 m.y. (see Hamblin, 1999). The Lower Silurian Medina Group correlates with the earliest Silurian relative sea level highstand and represents the distal extension of a third -order sequence of Llandoverian (Rhuddanian) age, bounded below and above by major sequence-bounding unconformities in Ontario.

Within the Medina Sequence, Brett *et al.* (1990) proposed five Sub-sequences or Cycles (about 1.0-1.5 Ma in length) bounded by sharp, but non-erosive disconformities, which can be correlated regionally. Each comprises a basal sandstone followed by transgressive marine shale, followed by a stack of progradational parasequences (Brett *et al.*, 1990). In Ontario, these include 1) Whirlpool/Power Glen, 2) upper Power Glen (Devil's Hole) Sandstone/lower Grimsby, 3) upper Grimsby, and 4) Thorold units (Brett *et al.*, 1990). Conversely, Duke (1991) and Duke *et al.* (1991) suggest that the Medina Sequence can be divided into seven depositional cycles: 1) Whirlpool fluvial lowstand deposits, 2) Power Glen transgressive marine, 3) Ball's Falls marine condensed section, 4)/5)/6) superimposed Grimsby progradational parasequences of a highstand systems tract, 7) Thorold progradational parasequence. These units are more clearly recognizable in the field. According to Duke (1991) and Duke *et al.* (1991) Medina sedimentation began with braided fluvial deposits over the Cherokee Unconformity, followed by transgression and thinning- and fining-upward storm-dominated marine sediments overlain by episodic progradation of a major thickening- and coarsening-upward succession of tide/wave-dominated shorelines. Each cycle terminated in increasingly shallower water and cycles are separated by transgressive phosphatic lags or bioclastic carbonates. The subsequent sequence-bounding sub-Clinton Group unconformity bevels the Medina Sequence increasingly to the west, implying that down-to-the-east subsidence was prominent (Brett *et al.*, 1990).

Castle (1998) provided further detail on the sequence stratigraphic architecture of the

Medina in Ontario/New York/Pennsylvania. He suggested that the Whirlpool sandstone represents channel deposition in valleys incised into the underlying sequence-bounding unconformity, and extends so far northwestward into the foreland basin because sediment supply greatly exceeded accommodation space. The boundary between lower fluvial and upper marine Whirlpool represents a regionally-correlative transgressive surface. The Cabot Head, which thins to the southeast (toward the sediment source), represents a transgressive systems tract associated with relative sea level rise to a maximum flooding surface and condensed section, which marks the boundary between the transgressive and "highstand" systems tracts. The Grimsby regressive system records progradation of a marine shelf/shoreline complex toward the west or northwest in stacked coarsening-upward sequences. A general upward shift from dominantly estuarine to dominantly fluvial deposits in the correlative, and more proximal, Tuscarora to the east reflects this progradation (Castle, 1998).

Within the upper Grimsby, Castle (1998) identified another flooding surface represented by argillaceous hematitic sandstone with *Skolithos* and *Daedelus* (correlative to base of Cambria shale in New York; Castanea Member of Tuscarora in Pennsylvania). He suggested a final flooding surface at the top of the Medina Group/base of the Clinton Group (Neahga shale) marked by an extensive phosphate pebble horizon (Densmore Creek bed of Brett *et al.*, 1990, Brett *et al.*, 1995).

Brett *et al.* (1990), Duke (1991) and Duke *et al.* (1991) offered a regional tectono-stratigraphic interpretation of the Medina, as follows. A peripheral bulge migrated westwards from the Appalachian area in the latest Ordovician/earliest Silurian creating the post-Queenston rapid sea level fall Type 1 Cherokee Unconformity, on which stable cratonic platform the lowstand systems tract (lower Whirlpool) was deposited, onlapping progressively older units eastward. As that bulge migrated back, due to increased tectonic load and rate of foredeep subsidence, it allowed the development of a transgressive systems tract (upper Whirlpool/Power Glen/Ball's Falls) on its northwest side. Increased sediment supply from the Taconian thrust stack led to large scale progradation of a highstand systems tract composed of stacked parasequences or cycles while the foredeep continued to subside. In a foreland setting sea level fluctuations almost certainly result from tectonic, rather than eustatic, effects. Continued down-to-the-east subsidence led to bevelling of the Medina Sequence (over an ancestral Algonquin Arch), regional transgression and subsequent deposition of the Clinton Group carbonates.

PETROLEUM GEOLOGY

Historical Background

In the early 1800's a series of "gum beds" were noted locally in Enniskillen Township and Lambton County which later proved to be seeps from shallow Devonian reservoirs (Powell *et al.*, 1984). However, the first scientific reports were not completed until those of Hunt and Murray of the GSC in the early 1850's. To exploit the Lambton County seeps, the Tripp Brothers registered the first oil company in North America (perhaps the world) in 1854, as the "International Mining and Manufacturing Company" (Powell *et al.*, 1984). This organization was purchased by James Miller Williams in 1856, who proceeded to set up the world's first fully integrated oil company. The culmination of these efforts occurred in 1858 when Williams dug/drilled 18 m through the "gum beds" into a Devonian reservoir to complete North America's first oil well at Oil Springs. Many wells in the following years were drilled in the surrounding area with very high initial flow rates, and in 1862 oil was also discovered at Petrolia. By 1900 there were 2500 producing wells within an area of only 80 km^2 of Lambton Co. (Hutt et al., 1973). However, extreme overproduction, spillage and, in particular, the aggressive marketing of the Pennsylvania oil fields (discovered one year after Miller's well in 1859) led to plummeting prices and a decrease in activity (Hutt *et al.*, 1973; Powell *et al.*, 1984; Harper, 1998). However, the industry has continued to thrive through the succeeding 125 years. Due to several oil spills and growing environmental concerns, the provincial government placed a moratorium on all offshore oil exploration or production in 1970 (Hutt et al., 1973).

In 1884 Eugene Coste drilled the first successful natural gas well in Canada at Medicine Hat, Alberta and ushered in a new era in hydrocarbon exploitation. The same man also made the first discoveries of commercial quantities of gas in Ontario with the drilling of the Coste #1 well near Leamington, Essex Co., and the Coste #2 well near Port Colborne (Hutt et al. 1973) both of which produced from Silurian reservoirs. Due to proximity to ready markets in the eastern United States, rapid development of these gas resources led to further discoveries along the northern shore of Lake Erie (Hutt et al. 1973). Today, exploration for gas continues both onshore and offshore.

The Lower Silurian clastic units of the Medina (Cataract) Group in southwestern Ontario have proven oil and gas reserves (about 54% of Ontario gas in 1980; Barker and Pollack, 1984), and represents one of the oldest exploration targets in conventional hydrocarbon exploration in the province (Sanford, 1989, pers. comm.). Minor production of gas from the Medina in the Lake Erie/Niagara region began as early as 1885 (beginning with the Whirlpool Formation in Welland Co., Sanford, 1969)(Sanford, 1962; Bailey and Cochrane, 1986; Carter and Colquhorn, 1987), but the first significant commercial production was from the Grimsby in Norfolk County in 1906 where the Dominion Natural Gas Co. obtained flows of 150 Mcf/d (MacDougall, 1973). In 1918 discoveries at Long Point proved that the Medina sandstone reservoirs extended into the Lake Erie offshore, although gas production did not begin until 1957 (MacDougall, 1973). All gas produced is dry and sweet (Caley, 1961). In addition minor oil production has been obtained, from the Whirlpool. All hydrocarbon reservoirs discovered to date occur in Whirlpool, Grimsby and Thorold formations in the Hamilton/Niagara/eastern Lake Erie areas (especially the onshore/offshore of Norfolk County) near the updip edge of sandstone deposition/preservation along the southern flank of the Algonquin Arch (Sanford, 1962; MacDougall, 1973; Bailey and Cochrane, 1986). According to Caley (1961) most of the gas production listed as "Clinton" has actually been derived from reservoirs in the Thorold Formation. North of Hamilton the Whirlpool is the only potential reservoir unit, and it thins progressively northward. Pools are present in Brant, Elgin, Oxford, Norfolk, Welland, Haldimand, Kent and Middlesex Counties.

Regional Factors

The Silurian succession of southwestern Ontario is thermally immature to marginally mature, whereas deeper Cambro-Ordovician rocks are mature (Barker and Pollack, 1984). Silurian rocks fall into a range of C.A.I.= 0-1.5, indicating the beginning of the oil and wet gas generating window (Legall et al., 1981). Silurian gases are generally wet and Carbon and Hydrogen isotopes suggest they were sourced from the thermally mature, but old, sources (Barker and Pollack, 1984; Barker *et al.*, 1984). Because the maturity of the gases is greater than that of the enclosing rocks, the hydrocarbons were likely generated outside the boundaries of Ontario (Barker *et al.*, 1984). However, there is no clear distinction between gases from the Michigan

Basin and the Appalachian Basin (Barker *et al.*, 1984).

Regionally, all Medina hydrocarbons are reservoired in the area where the strata dip southward at 4.5-5.0 m per km, down the monoclinal flank of the Algonquin Arch into the Appalachian Foreland Basin (Barker and Pollack, 1984; Legall *et al.*, 1981; Caley, 1961). Very few, and very small, structures are present at this stratigraphic level, with no significant structural closures (Caley, 1941, 1961). Traps are likely all stratigraphic due to facies or diagenetic traps (Sanford, 1962; Caley, 1961; Legall *et al.*, 1981). In fact, each sandstone unit forms a single large stratigraphic trap, within which there are local variations of porosity and permeability (Bailey and Cochrane, 1986). Medina reservoir facies pinch out depositionally, or are erosionally truncated, to the north and west (MacDougall, 1973).

Although the Medina reservoirs have produced large quantities for very long periods, the reservoirs are generally very fine grained, with low primary porosity and permeability (Sanford, 1962). Diagenetic, differential cementation trapping, due top permeability pinchouts are the most prominent factor (Caley, 1961), making prediction difficult (MacDougall, 1973). Gas seeps are known from Escarpment outcrops only a few km from subsurface production, suggesting that compartmentalization of reservoirs is pronounced and that, in spite of seeps, little volume has leaked away (Caley, 1961). Most successful wells produce from several Medina formations (Caley, 1961) and Sanford (1969) suggested that all Medina pools really belong to a single large field. Gases are 90% methane, with Nitrogen and traces of others (Barker and Pollack, 1984).

Reservoirs and Traps

Stratigraphic, erosional truncation and porosity/permeability pinchout mechanisms play parts in trapping gas in Silurian units (Powell *et al.*, 1984; Barker and Pollack, 1984). Whirlpool sandstones have primary porosity of about 10%. About one-fifth of wells have production from this unit and there are still under-explored areas in Lake /Erie (Caley, 1961; Sanford, 1969). Significant porosity and production is limited to the area of greater thickness in eastern and central Lake Eire and immediately adjacent onshore counties of Haldimand-Norfolk and Niagara (Bailie and Cochrane, 1986) (Fig. 7). There is no production from the Manitoulin, Power Glen and only minor shows from thin sandstone beds which are commonly referred to the Cabot Head (but, in fact, are lower Grimsby) (Sanford, 1969; Bailey and Cochrane, 1986). The entire updip portion of the Grimsby is gas-charged and virtually all wells initially produce some amount of hydrocarbon (Bailey and Cochrane, 1986). Most Grimsby commercial production is from linear north-south trending lenticular sandstone bodies, oriented approximately parallel to shorelines (MacDougall, 1973). The thicker Grimsby is particularly heterogenous with multiple laterally discontinuous (isolated elongate bar and channel bodies) reservoir bodies throughout (MacDougall, 1973; Holm, 1984). Thorold reservoirs are also linear, trending north-south or NNW/SSE, but are thinner, more uniform and generally manifest as a single reservoir unit (MacDougall, 1973). MacDougall (1973) quotes several reservoir characteristics for the Grimsby (Sw=30-40%, Porosity=10-18%, permeability=1-50md), and for the Thorold (Sw=25%, Porosity=10-17%, k=1-100md). Holm (1984), studying the Grimsby reservoirs, found that sandstones are primarily fine-grained subangular to subrounded quartz with abundant quartz overgrowths and hematitic rims. There is subordinate feldspar, lithics and calcite. He also observed porosities of 10-15%, permeabilities of <1.0-20 mD, but very variable (Holm, 1984).

The Medina Group of southern Ontario, western New York and eastern Ohio is one of the largest stratigraphic gas traps in the United States (Keltch *et al.*, 1990). Pool and field limits are not easily definable, and the entire region is essentially one vast stratigraphic trap (Bailey and Cochrane, 1986). Successful exploration in these very subtle traps requires a detailed knowledge of the depositional systems, the reservoir characteristics and geometries, and good well control (Keltch, *et al.*, 1990).

Castle and Byrnes (1998) describe Medina sandstones in Pennsylvania as quartz arenites, subarkoses and sublkitharenites with cements of quartz, hematite and chlorite and minor detrital clays of illite. Porosity tends to have a very irregular distribution and is mostly secondary (Laughrey, 1984). In Ohio, porosity averages 8% (up to 16%), permeability averages 0.5 mD (up to 5.0 mD), water saturation averages 20% (up to 60%), and reservoir areas average 1x5 km (770 ha) (Keltch *et al.*, 1990). Laughrey (1984) provided a very detailed description of reservoir facies and characteristics in Pennsylvania. In New York Seyler (1982) and Metzger (1982) describe Whirlpool linear NE/SW trending reservoirs with multicyclic quartz which are prolific producers. In this case primary porosity is reduced to 5% by silica overgrowths, but secondary moldic porosity (after dissolution of quartz and original calcite cement) provides adequate reservoir quality. Grimsby sandstones are also productive (Metzger, 1982). In Pennsylvania one of the most active plays has been exploration of the Grimsby channel-dominated deltaic setting with SW/NE-oriented shorelines (Piotrowski, 1981), as well as Whirlpool linear bodies as in New York (Pees, 1986). Castle and Byrnes (1998) described low-permeability Medina gas reservoirs in northwestern Pennsylvania where low *average* porosity (6%, but with values up to 18%) and permeability (0.1 mD, but with values up to 1048 mD) are due to authigenic cements, but good flow rates can be attained from certain facies because there is very little detrital clay. They found that medium-grained sandstones in the Medina which have preserved primary and dissolution secondary porosity totalling 6-8% have the highest gas permeability, contain 90% of the flow capacity, contain most of the storage capacity and are considered to be the carrier beds for draining the reservoir (Castle and Byrnes, 1998). Sandstones with thick intervals of 3-6% porosity produce adequate volumes of gas at a slower production rate, but strata with less than 3% porosity are unlikely to produce significant volumes (Castle and Byrnes, 1998).

In a provisional assessment of natural gas potential in southwestern Ontario, the largest reserves and the largest remaining potential was estimated to reside in stratigraphic trap pools of the "Clinton-Cataract" strata (Osadetz *et al.*, 1996). This play includes the gas-producing formations of the Medina Group in southwestern Ontario: the Whirlpool, Grimsby and Thorold.

Other Commodities

In addition, Whirlpool sandstone has been extensively quarried in the past in the Hamilton to Inglewood portion of the Escarpment, but only a few small operations remain today (Caley, 1961; Cheel, 1991). The thin bedded marine facies of the upper Whirlpool makes good flagstone, but irregular bedding makes for difficult quarrying and quality control (Caley, 1961). Most brickwork use clay from the Upper Ordovician Queenston Formation, although Cabot Head shales could be used if their volumes and access were suitable (Caley, 1961).

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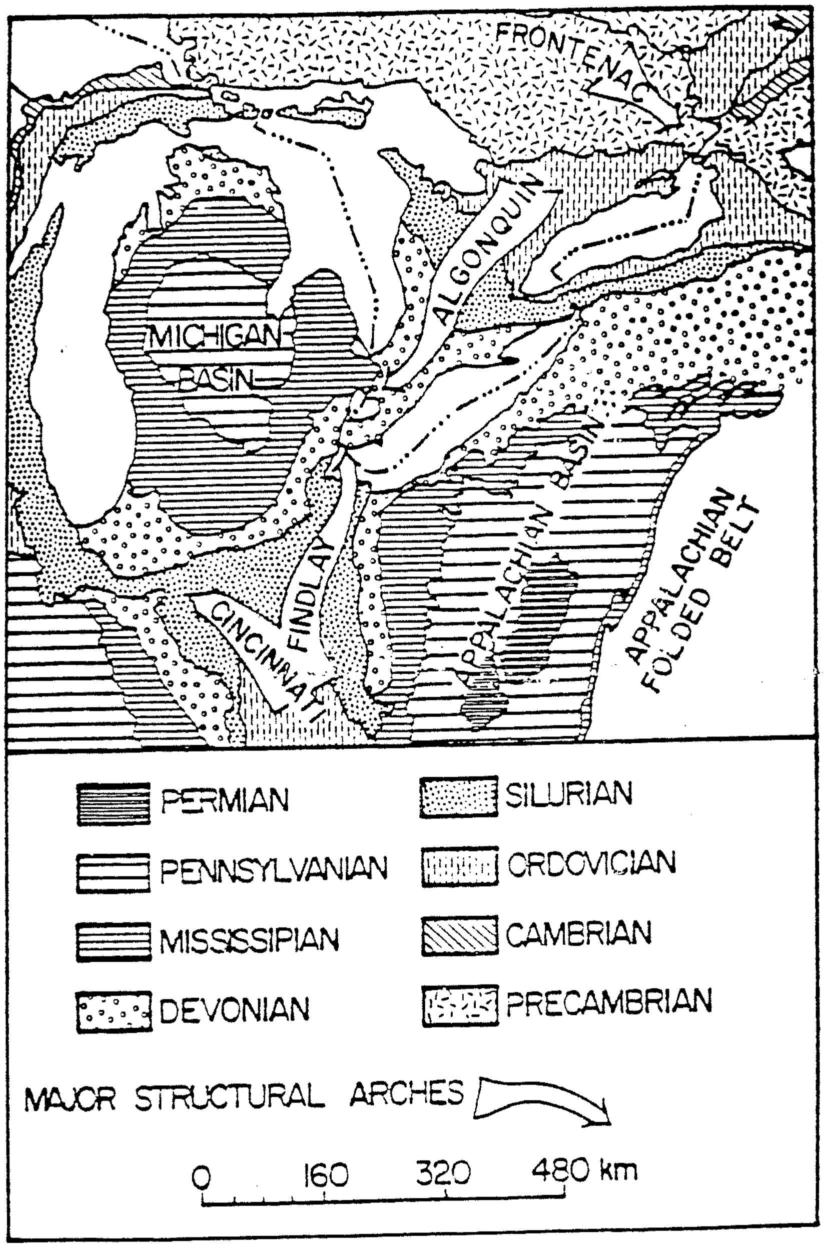
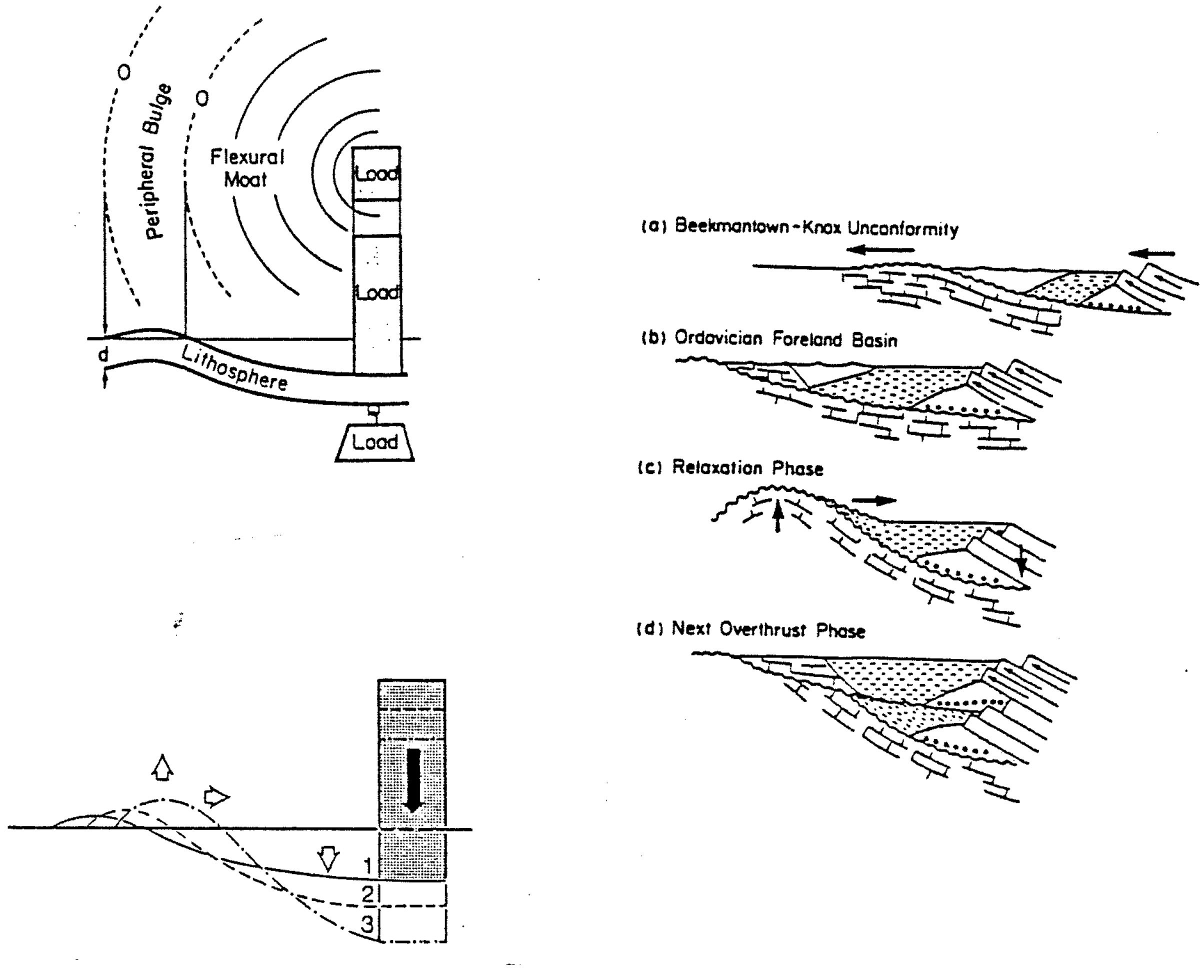


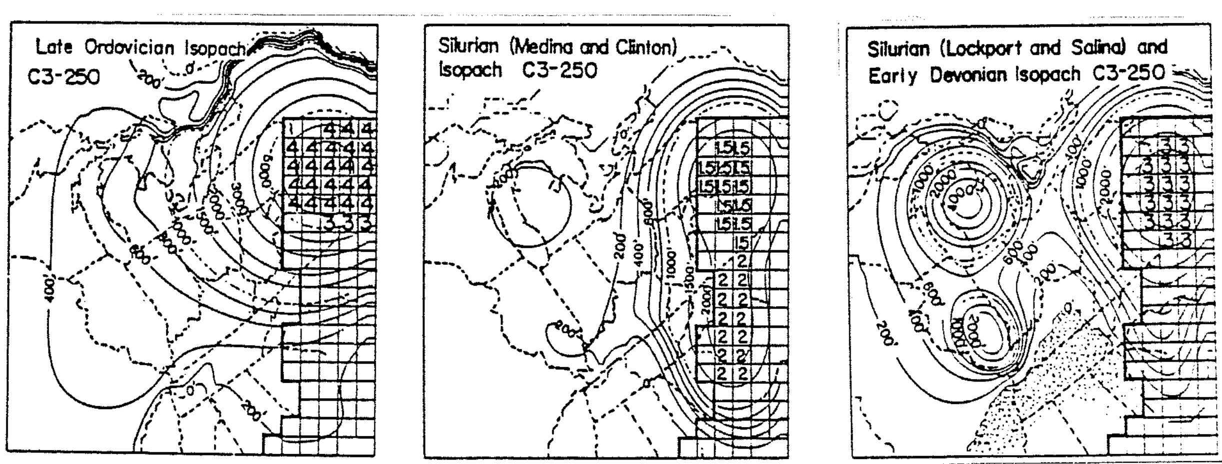
(from Sanford, 1961)

FIGURE 1.

A)

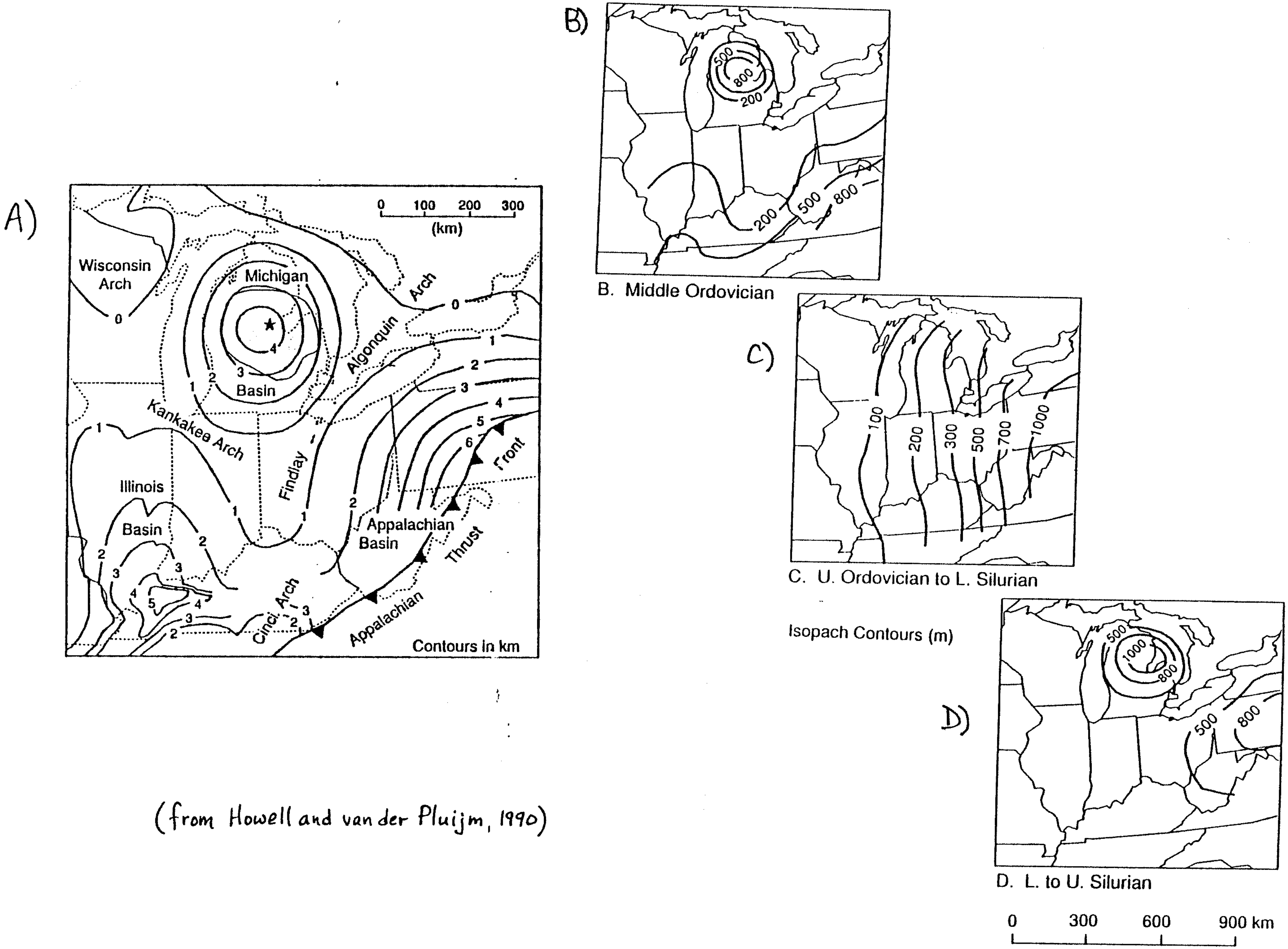


B)



(from Quinlan and Beaumont, 1984)

FIGURE 2.



(from Howell and van der Pluijm, 1990)

FIGURE 3.

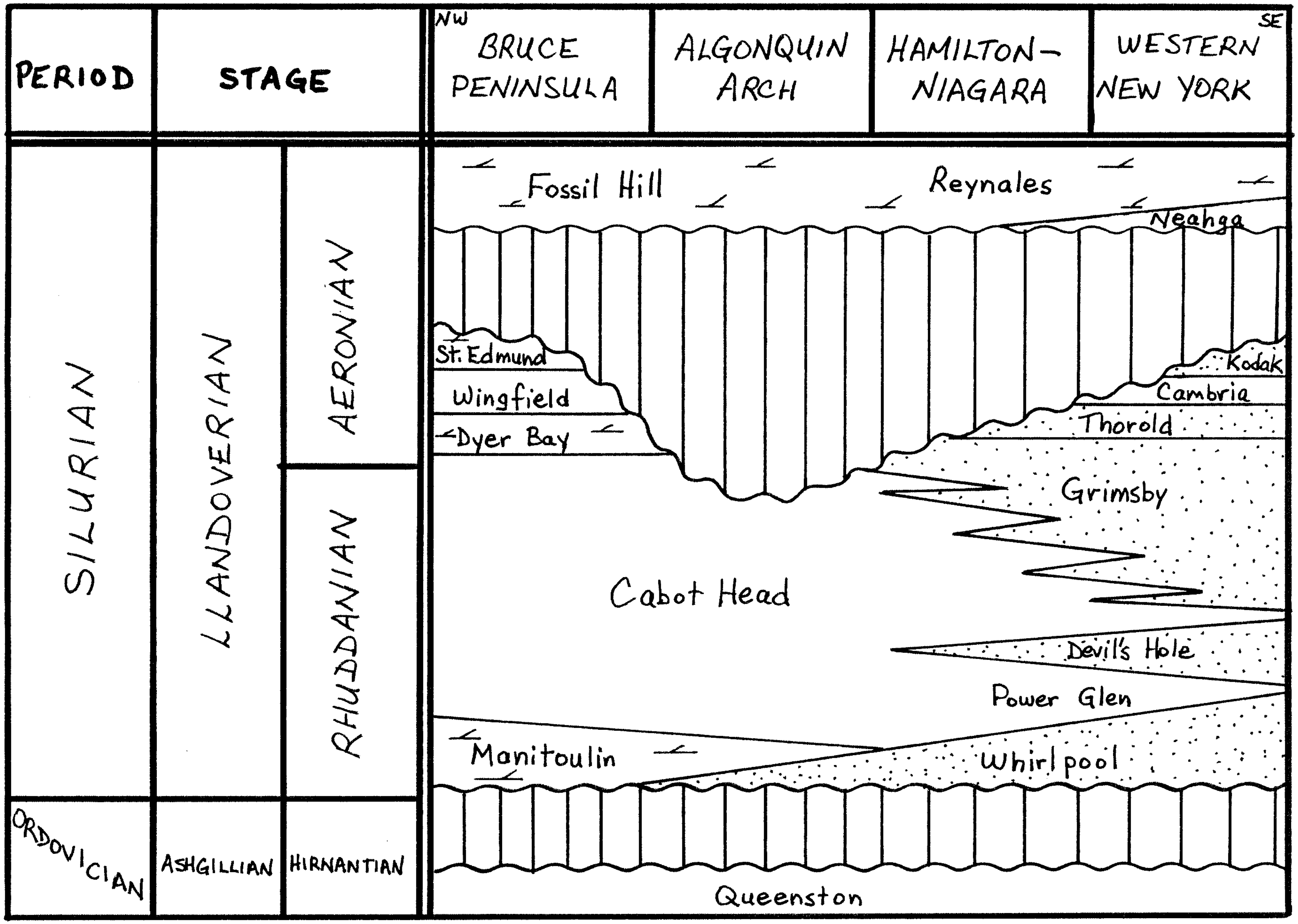
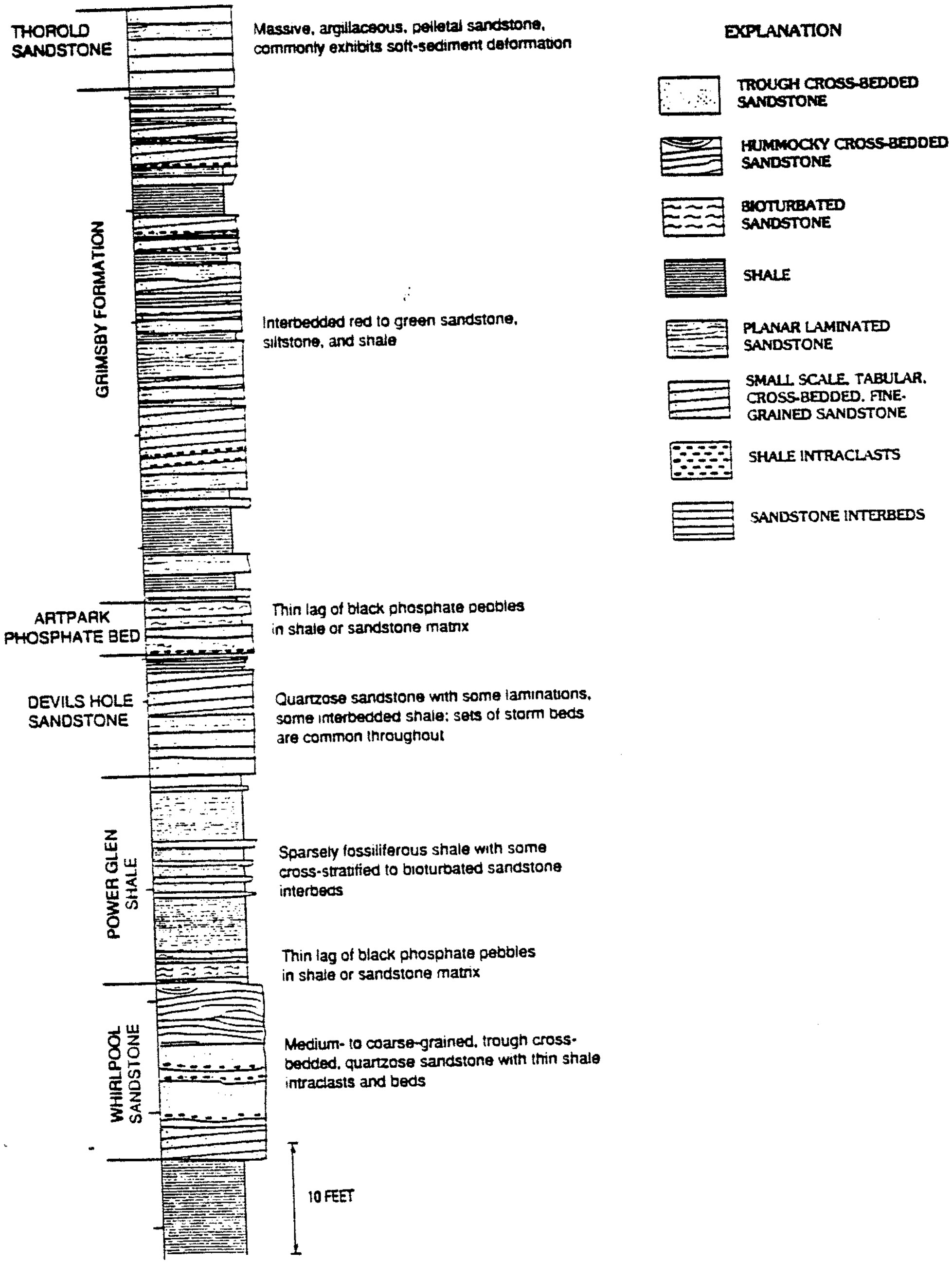

PERIOD
STAGE
NW
BRUCE PENINSULA
ALGONQUIN ARCH
HAMILTON–NIAGARA
WESTERN NEW YORK
SE
SILURIAN
LLANDOVERIAN
AERONIAN
RHUDDANIAN
ORDOVICIAN
ASHGILLIAN
HIRNANTIAN
Fossil Hill
Reynales
Neahga
St. Edmund
Wingfield
Dyer Bay
Kodak
Cambria
Thorold
Grimsby
Cabot Head
Devil's Hole
Power Glen
Manitoulin
Whirlpool
Queenston

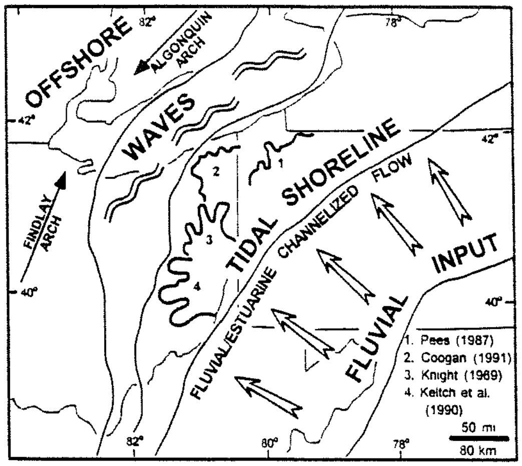
FIGURE 4.



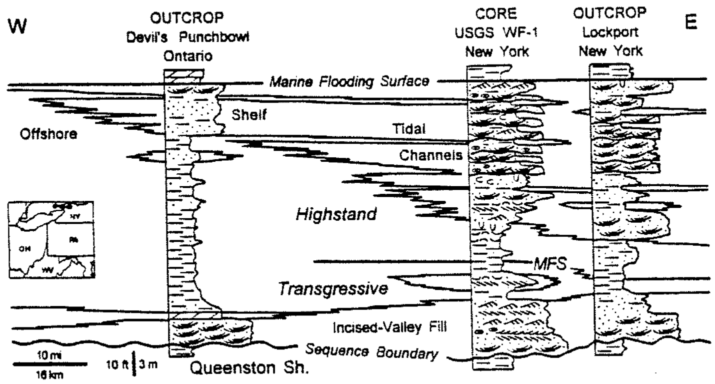
(from Brett et al., 1995)

FIGURE 5.

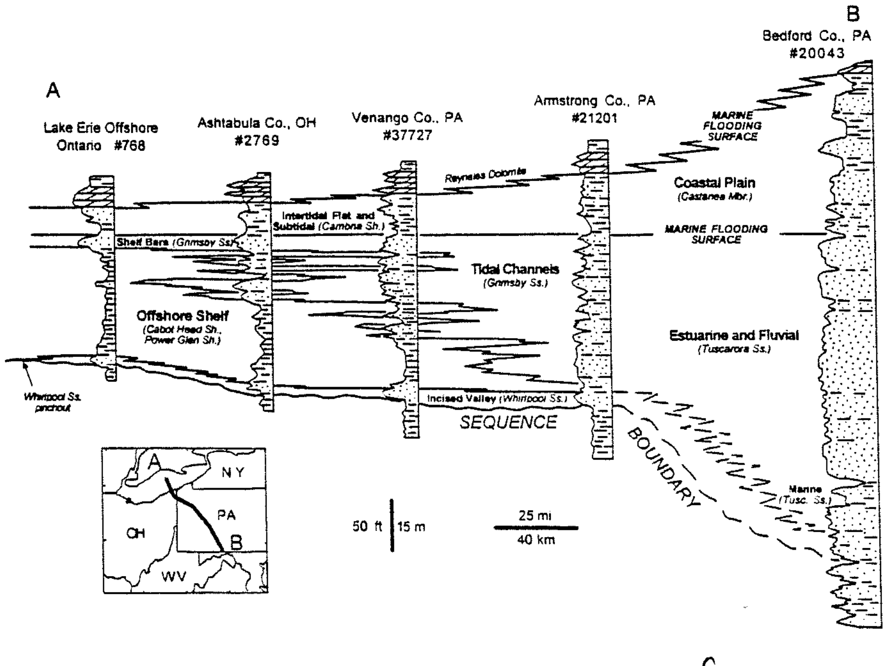
A)



B)



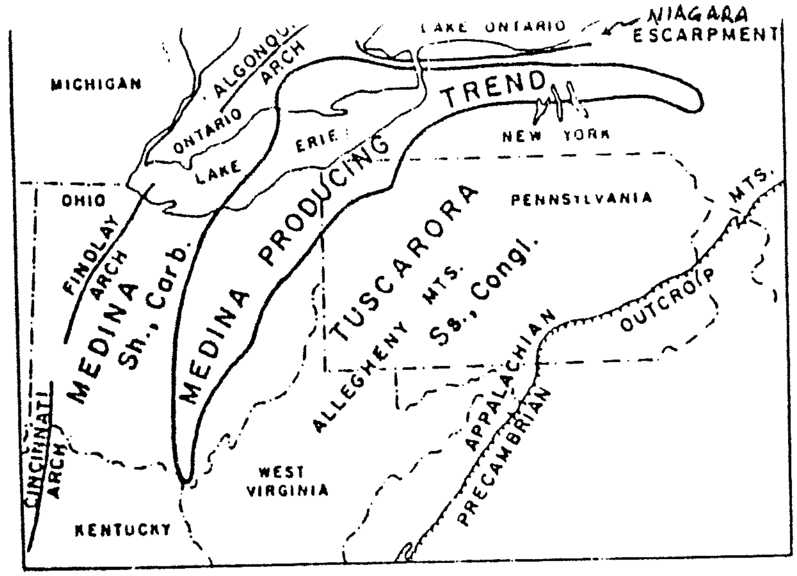
C)



(from Castle, 1998)

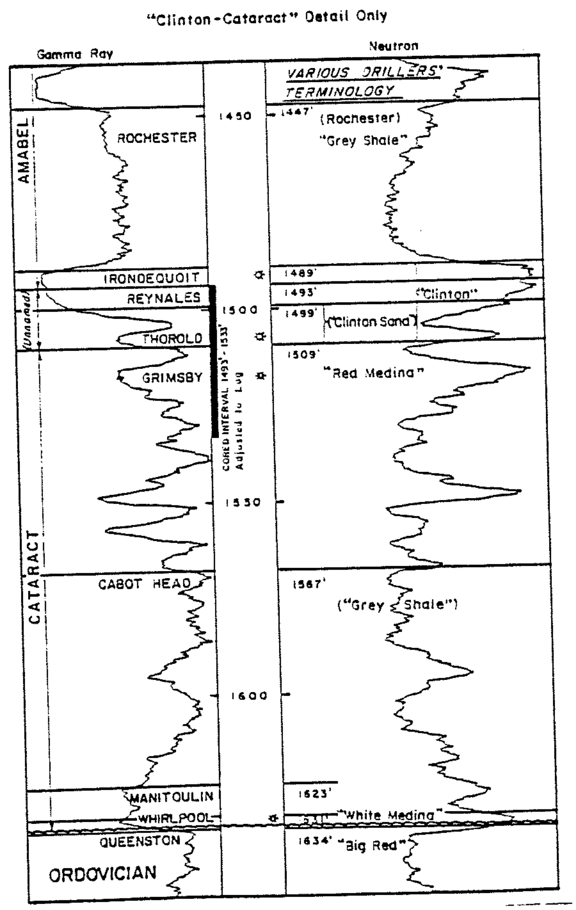
FIGURE 6.

A)



(from Martini, 1971)

B)



(from MacDougall, 1973)

TYPE WELL FOR "CLINTON-CATARACT" GEOLOGICAL CONTACTS

Consumers - Pan Am 13047

Norfolk - Lake Erie

Latitude: 42° 30' 54·7" North

Longitude: 80° 27' 25·6" West

FIGURE 7.