GEOLOGICAL SURVEY OF CANADA
COMMISSION GEOLOGIQUE DU CANADA

Open File 3729

UPPER ORDOVICIAN STRATA OF SOUTHWESTERN ONTARIO: SYNTHESIS OF LITERATURE AND CONCEPTS

By

A.P. Hamblin

Geological Survey of Canada (Calgary), 3303 - 33 Street N.W.
Calgary, Alberta T2L 2A7

APRIL 1999

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. This tectonic cycle (late Precambrian to late Paleozoic) began with 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) (Fig. 2). 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. 3). 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; Kerr and Eyles, 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).

Diecchio (1991) described two different basin styles in the Appalachian Foreland: a) deeply-subsided, more proximal basins (of primarily Middle Ordovician age and located in the eastern region), filled with very thick, deep-water siliciclastic facies, and b) shallower, more distal basins (of primarily Late Ordovician age and located in the western region), filled with thinner, shallowing-upward, shelfal clastic and carbonate successions. In the east, the onset of Taconian-derived clastic deposition is associated with rapid and profound deepening, whereas in the west, this effect is less extreme (Diecchio, 1991). In addition, the base of the orogen-derived clastic succession is older in the east than in the west, illustrating the progressive westward collapse of the carbonate shelf, and the progressive westward progradation of the easterly-derived wedge of sediment (Diecchio, 1991).

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 (essentially a "peripheral bulge") (Fig. 3). Howell and van der Pluijm (1990) concurred with the concept of relating Arch uplift and episodic cratonic basin subsidence to orogenic phases in the Appalachians, and suggested that the post-Taconian Upper Ordovician/Lower Silurian stratigraphic sequence accumulated along the western margin of the east-tilting and rapidly subsiding Appalachian Foreland. The northwest migration of the Appalachian structural front produced major clastic wedges with predominantly north-south facies tracts (Howell and van der Pluijm, 1990; Johnson *et al.*, 1992) (Fig. 4). Quinlan and Beaumont (1984) noted that Taconian timing, magnitude and distribution of downwarping were not uniform along the orogen and that the effects continued through the Lower Silurian. Their modelling suggests that circular form of the Middle Ordovician Intracratonic Michigan Basin was almost totally destroyed by the Late Ordovician Taconian down-to-the-east tilting as it, and the adjacent Algonquin Arch were incorporated into the Appalachian Foreland Basin (Fig. 4). That circular planform was then re-established during the Lower-Middle Silurian (Quinlan and Beaumont, 1984) (Figs. 3,4). Tectonic tilting established a northwest-dipping paleoslope in earliest Silurian time (Middleton, 1987). Tectonic movements during the Taconian 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).

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 non-related active subsidence at different times, the Arch migrated back and forth between them accordingly (Hutt *et al.*, 1973; Bailey and Cochrane, 1986; Brett *et al.*, 1990). In fact, as stated by Sanford (1972), Hutt *et al.* (1973) and Middleton (1987), the Arch is really just the hinged eastern rim of the Michigan Basin, a zone of greater stability, rather than an actual emergent 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 (up to approximately 1500 m thick) dips away to the south, west and southwest at an angle of less than 1^{o} (Roliff, 1954; Sanford and Quillian, 1959; Sanford, 1962; Hutt *et al.*, 1973) (Fig. 5). The sedimentary sequence of Southern Ontario underlies an area of over 100 000 km^2 (about one-third of which is offshore beneath lakes Erie, Ontario and St. Clair) (Hutt *et al.*, 1973). Strata range in age from Late Cambrian to earliest Carboniferous (Hutt *et al.*, 1973).

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 were subsequently overlapped by Middle and Upper Ordovician units (Cohee, 1948; Poole *et al.*, 1968). During the early Middle Ordovician transgression onto the Shield and Arch, deposition included basal shallow marine clastics (Shadow Lake Formation), thin-bedded micrite and fragmental limestone (Black River Group) and platformal coarse grained bioclastic and argillaceous limestones (Trenton Group) (Hutt *et al.*, 1973) (Fig. 6).

The creation of the Appalachian Foreland Basin, centred in New York and Pennsylvania, in the Middle Ordovician Taconian Orogeny led to the foundering of the Ordovician carbonate platform (Diecchio, 1991; Kerr and Eyles, 1991), and altered the predominant depositional patterns (Hutt *et al.*, 1973). The northwestward migration of the Appalachian structural front through time resulted in the progressive westward inundation of that foundered platform by the first influx of large volumes of orogen-derived, deep water clastics (Zerrahn, 1978; Diecchio, 1991; Kerr and Eyles, 1991; Johnson *et al.*, 1992). A similar tectonic evolution occurred in the northern Appalachians of western Newfoundland, the Gulf of St. Lawrence and Anticosti Island, and likewise led to drowning of the Middle Ordovician carbonate platform and blanketing by deep water, orogen-derived clastics (Diecchio, 1991; Fowler *et al.*, 1995). In southern Ontario, the Upper Ordovician depositional record is one of overall shallowing-upward from the black marine shale of the Collingwood Formation, to the grey shale of the Blue Mountain Formation, to the interbedded shale and siltstone of the Georgian Bay Formation, to the marine and nonmarine red siltstone and sandstone of the Queenston Formation (Hutt *et al.*, 1973; Johnson *et al.*, 1992) (Fig. 6). Zerrahn (1978) working in New York and Pennsylvania, and Diecchio (1991) working in Virginia, documented the rapid eastward and southeastward thickening of equivalents to these units, into the location of the main foredeep trough. In the western part of that trough the succession includes the Reedsville Fm., Oswego ss., and Juniata Fm, whereas in the eastern, most proximal part of the foredeep, the Middle-Upper Ordovician clastic succession is represented by the Martinsburg Formation (Diecchio, 1991). At the same time the units of southern Ontario appear to extend to the west and northwest into the area of the Michigan Basin (Johnson *et al.*, 1992) (Fig. 7).

Ordovician/Silurian Boundary

The Late Ordovician-Late Silurian succession of Southern Ontario (about 700 m of mixed carbonate and clastic deposits) dips gently to the southwest and represents much of the Tippecanoe Sequence of Sloss (1963). These strata record events along the hinge between the Appalachian Foreland and the Michigan Intracratonic Basins, leading up to and following the Latest Ordovician glacio-eustatic sea level drop (Rudkin *et al.*, 1998). 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. 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. 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 mid-continent) may relate to a Late Ordovician glacio-eustatic sea level drop, although Middleton (1987) and Brett *et al.* (1990) suggested this represents a late Taconian tectonic pulse with an alteration in paleoslope which did not involve any eustatic effects.

Climatic Setting

The area lay at about 15-20° S. paleolatitude in Middle Ordovician to Middle 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 Late Ordovician 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 beginning and the Late Ordovician glacial phase, predominantly in the Gondwanan continental fragments of Africa and South America, began to dominate world climates in the Caradocian (Middleton, 1987; Frakes *et al.*, 1993). According to Patskowsky *et al.* (1997), a mid Caradocian widespread increase in organic productivity and burial of organic carbon may have caused a draw-down of atmospheric pCO_2, precipitating global cooling. Although glaciation and mass extinction were concentrated in the final few million years of the Ordovician, there was a major decrease in faunal diversity in mid Caradocian time which may represent the initial response to the climatic shift from "greenhouse" to "icehouse" conditions (Patzkowsky *et al.*, 1997). 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).

STRATIGRAPHY

Nomenclature

The nomenclature used in this report is that currently endorsed by the Ontario Geological Survey (see Johnson et al., 1992). However, the stratigraphic units of southwestern Ontario have been studied intermittently for more than a century and most have been referred to by many different names. Because much of the published literature is pre-1975, many references include nomenclature now considered obsolete. In the formation descriptions below, these discontinued names are mentioned, so that correlation to the older literature is possible.

Lindsay Formation (Collingwood Member)

The name "Collingwood Formation" was first used by Raymond (1912) for the black or brown carbonaceous and fossiliferous shale with limestone interbeds overlying Trenton limestones. No type locality was designated but the well-developed fauna at Collingwood was mentioned. The type section is now considered to be the exposures in the vicinity of Craigleith Provincial Park on the shore of Georgian Bay. Caley (1936) also described the Collingwood Formation of Manitoulin Island and correlated it to the Eastview Formation of the Ottawa Valley.

Caley (1936) observed that, on Manitoulin, the shales rest on irregular surfaces of ferruginous limestone with Precambrian pebbles, or directly on Precambrian quartzite. Sproule (1936) also described the Collingwood as resting on an exposure surface of rotted limestone and directly on the eroded Precambrian surface on Manitoulin Island (also described by Copper and Long, 1993), and as resting with slight angular unconformity on limestones at Craigleith. Meanwhile, Liberty (1955) introduced the term "Craigleith Member of the Whitby Formation" for the same strata, with a type section at the road and stream cuts at Craigleith, suggesting that "Collingwood" might be a chrono-stratigraphic term, unsuitable for a lithologically-defined unit (Winder, 1961; Russell and Telford, 1983) and that the lower contact with the Trenton limestones was an unconformity. However, both Winder and Sanford (1972) and Russell and Telford (1983) observed that this same contact was gradational over a 2 m interval at the type section, clearly indicating to them that these strata are more closely related to the underlying carbonates. The contact is certainly gradational at Bowmanville Quarry on Lake Ontario. However, this contact is locally erosional in the Michigan and Manitoulin areas (Churcher *et al.*, 1991). In addition, Parks (1928) had recognized a sharp break between the black shales of the Collingwood and the overlying Blue Mountain Formation, later confirmed by Russell and Telford (1983). Therefore, Russell and Telford (1983) redefined the strata in question as the Collingwood Member of the Lindsay Formation, based on three key observations: the lack of a distinct break between the Lindsay and the Collingwood, the sharp drop in carbonate content and in organic content at the top of the Collingwood (Churcher *et al.*, 1991). The base of the Collingwood on Manitoulin Island is considered to be unconformable based on the sharp, irregular and erosional aspects of that surface (Copper and Long, 1993). It is possible that the contact is gradational toward the southeast, and unconformable toward the northwest.

The Collingwood Member (of probable Caradocian age, based on a conodont study by Barnes, quoted by Churcher *et al.*, 1991) comprises black or dark brownish, finely laminated, pyritiferous, calcareous and carbonaceous shale (or marlstone) with thin interbeds of fine grained, organic-rich limestone, especially near the base (Raymond, 1912; Caley, 1936; Sanford, 1961; Winder, 1961; Russell and Telford, 1983; Churcher *et al.*, 1991). According to Russell and Telford (1983), Obermajer (1997) and Rudkin *et al.* (1998) the unit is more shaley upwards and westwards. The upper contact with the overlying Blue Mountain Formation is sharp, but subtle, expressed by distinct declines in the contents of calcareous cement, organics, conodont abundance and diversity, and clay (Russell and Telford, 1983). Obermajer (1997) also mentions a prominent phosphatic lag marking the top of the member, although Churcher *et al.* (1991) mentioned that there is a gradational relationship to the east. A rich, well-preserved, but limited, fauna of trilobites (especially *Pseudogygites*), brachiopods, graptolites nautiloids and conularids is present (Winder, 1961; Russell and Telford, 1983; Obermajer, 1997; Rudkin *et al.*, 1998). The member is 6-18 m thick in outcrop (averaging about 2-4 m), and is exposed in a narrow belt from Manitoulin Island to Lake Ontario east of Toronto (Raymond, 1912; Winder, 1961; Obermajer, 1997). Sanford (1961) recorded a thickness of 60m in the subsurface near Lake Erie, but may have included additional strata. The type locality is at Craigleith and Sanford (1961) suggested a reference well in Louth Twp, Lincoln Co.

Rancourt (1998) divided the Collingwood into two informal sub-members: a) lower marlstones with abundant shelly limestone beds, predator/scavenger fossils and phosphatic nodules, and b) upper calcareous shale with no shelly limestone beds and minor phosphatic content. He also stated that the upper contact with the Blue Mountain is difficult to identify in core, but that there is a bed with abundant cephalopod fossils near that point.

Churcher *et al.* (1991) discuss the limited distribution of the Collingwood Member. To the east, it is limited by the present-day erosion surface, along a northwest-trending line from Bowmanville (east of Toronto) to Collingwood. Westward, in the subsurface, the unit appears to pinch out along a northwest-trending line from Port Colborne on Lake Erie to Port Elgin on Lake Huron. Thin, geographically-limited outliers apparently exist in a few wells west of this line, which Churcher *et al.* (1991) suggested must indicate that the unit was originally more widely distributed, but was mostly eroded during post-Collingwood exposure.

The Collingwood shale is considered to be a potential oil shale (Russell and Telford, 1983) with a strong petroliferous odour (Churcher *et al.*, 1991), and a rich, mature oil-prone source rock (Obermajer, 1997; Rudkin *et al.*, 1998).

Blue Mountain Formation

The name "Blue Mountain Formation" was first proposed by Parks (1928) for the bluish grey, sparsely fossiliferous shale exposed along the shore of Georgian Bay, west of Camperdown. Previously, Foerste (1912) had used the term "Sheguiandah Formation" for equivalent beds on Manitoulin Island, but that name has never been extended regionally. In the Ottawa Valley, Wilson (1937) proposed the Billings Formation for similar shales, with a type locality designated near Ottawa, but with a major reference section on the Rouge River east of Toronto. For several decades the name Billings Formation was used to denote all the dark grey shales above the Trenton and below the "Dundas" shale and limestone unit throughout southern Ontario (eg. Caley, 1943, 1945, 1961). In southwestern Ontario, this name has been superseded, as described below. In the Ottawa Valley, the term is still used in its original form to refer to the shale unit between the Eastview Formation (Collingwood equivalent) below, and the Carlsbad Formation (Dundas or Georgian Bay Formation equivalent) above (Wilson, 1964). Due to the excessively recessive nature of the soft shales, outcrops of this unit are rare and generally of poor quality, which has led to a lack of understanding.

Liberty (1969) proposed a new stratigraphic nomenclature for the Upper Ordovician, orogen-derived, grey shale-dominated succession, based on the contention that the previous terms had been bio- rather than lithostratigraphic in nature. His Nottawasaga Group incorporated the former Collingwood, Gloucester, Blue Mountain, Dundas and Meaford formations and was divided into two new formations: Whitby Formation of Caradocian age, and Georgian Bay Formation of Caradocian-Ashgillian age (Liberty, 1969; Liberty and Bolton, 1971). The Whitby Formation included 3 members, in ascending order: the lower Craigleith Member (Collingwood equivalent) black petroliferous shale, with a type section at Craigleith; the middle Rouge River Member (of restricted geographic extent) brown, slightly petroliferous shale, with a type section on Rouge River east of Toronto; the upper Thornbury Member (Blue Mountain equivalent) bluish grey shale, with a type section on East Meaford Creek near Camperdown (Liberty, 1955). A well on the C.N.E. grounds in Toronto was designated as the reference well.

Sanford (1961) reverted to the Blue Mountain terminology of Parks (1928) in his subsurface work to denote this unit, and suggested a reference well in Louth Twp, Lincoln Co. The work of Russell and Telford (1983) established that the contact between the Collingwood below and the blue grey shales above is a sharp, but subtle, surface where there is a distinct decrease in the contents of clay, calcite, organics and conodonts. Obermajer (1997) mentions a phosphatic lag and suggests the surface is a disconformity. Rancourt (1998) mentions a cephalopod fossil bed at the contact. Russell and Telford (1983) concluded that the name "Blue Mountain" should be reinstated for the noncalcareous shales between the Collingwood and the overlying Georgian Bay Formation.

The Blue Mountain Formation (of probable upper Caradocian age, based on a conodont studies by Tarrant (1977) and by Barnes, as quoted by Churcher *et al.*, 1991) generally comprises uniform, soft, laminated, non-calcareous bluish grey to dark grey shale with few fossils (Winder, 1961; Caley, 1961; Johnson *et al.*, 1992). The formation is 35-75 m thick (Caley, 1943,1945,1961; Obermajer, 1997), generally thinning to the north (Sanford, 1961). The bulk of this thickness, especially west and north of Toronto, is the bluish grey, non-calcareous shale which Liberty (1955) referred to as the "Thornbury Member". The lower 2-15 m are typically dark brownish and more organic-rich (Sanford, 1961; Barker, 1985; Obermajer, 1997) and this may represent the "Rouge River Member" of Liberty (1955). The lower contact has been discussed above, although Churcher *et al.* (1991) and Johnson *et al.* (1992) suggest that the Collingwood is absent over much of the Michigan Basin and southern Ontario, and hence, the contact between the Lindsay carbonates and the base of the Blue Mountain is marked by a phosphatic erosional lag. This unit is a thin bed of phosphatic nodules, shell fragments and pyrite suspended in a sparry calcite cement, which apparently extends eastward only to the point where the Rouge River facies begins to appear (Churcher *et al.*, 1991). The upper contact with the Georgian Bay Formation is gradational, placed where medium grey colour and calcareous content increase, and at the first calcareous siltstone hard bands greater than 5 cm thick (Churcher *et al.*, 1991; Johnson *et al.*, 1992).

The Blue Mountain Formation includes fairly organic-rich brownish to black shale in its lowest 10-15 m, is within the oil window, and is considered to be a significant potential oil source rock (Obermajer, 1997).

Georgian Bay Formation

The name Georgian Bay Formation was coined by Liberty (1964) for the grey shales with interbedded limestones which occur between the Blue Mountain below, and the Queenston above. This lithostratigraphic term was introduced to replace the long-standing, but purely biostratigraphic, terms of "Dundas" and "Meaford" formations which had originated with Parks (1924) and Foerste (1924) respectively. The type locality was designated as East Meaford (Workman's) Creek, where about 120 m are exposed, and the shore of Georgian Bay between Boucher Point and Meaford (Winder, 1961). The latest mapping program (Armstrong, 1987, 1988, 1989) in the Bruce Peninsula area utilizes Georgian Bay nomenclature.

The original Dundas Formation (Parks, 1924), 125-200 m thick, included five members, in ascending order: Rosedale (blue shale with few limestone beds), Danforth (blue shale with many limestone and sandstone beds), Humber (blue shale with upward increase of sandstone and limestone beds), Credit (grey shale with many fossiliferous limestone beds), Christie (grey shale with numerous fossiliferous limestones, may be a northern equivalent to the Credit). The original Meaford Formation (Foerste, 1924), 30-35 m thick, included four members, in ascending order: Erindale (grey shale with numerous thin limestones and sandstones), Streetsville (grey limestone with thin shales and a thin *Stromatocerium* reef), Vincent (sandy limestone with thin shales and a bryozoan reef, may be a northern equivalent to the Streetsville), Meadowvale (grey shale with thin limestones and sandstones and a thin *Columnaria* reef at the base). Caley (1943, 1945, 1961) continued to use the Dundas and Meaford terminology in surface and subsurface studies, for the lower grey shale with thin limestone and sandstone beds and the upper grey sandy limestone and calcareous sandstone, respectively. Sanford (1961) identified them throughout the subsurface of southwestern Ontario and designated a reference well in Lincoln Co.

Liberty (1969) proposed a new stratigraphic nomenclature for the Upper Ordovician, orogen-derived, grey shale-dominated succession, based on the contention that the previous terms had been bio- rather than lithostratigraphic in nature. His Nottawasaga Group incorporated the former Collingwood, Gloucester, Blue Mountain, Dundas and Meaford formations and was divided into two new formations: Whitby Formation of Caradocian age, and Georgian Bay Formation of Caradocian-Ashgillian age (Liberty, 1969; Liberty and Bolton, 1971). The Georgian Bay Formation comprises 125-250 m of grey thinly interbedded shale, siltstone, calcareous sandstone and sandy fossiliferous limestone which gradationally overlies the Blue Mountain and is gradationally overlain by the Queenston. The formation generally thins to the northwest (Stanley and Pickerill, 1993). The shale is recessive and the sandstone/limestone beds, which represent about 20% of the rock (Czurda *et al.*, 1973) are noticeably resistant and laterally continuous, and are referred to throughout the literature as the "hard bands". Conodont studies by Tarrant (1977) suggested that the lower Georgian Bay was Caradocian, and the upper is Ashgillian age (ie. Late Maysvillian-Richmondian age; Rudkin *et al.*, 1998). Brachiopods, bryozoans, bivalves, gastropods, nautiloids, trilobites and a well preserved trace fauna of the *Cruziana* ichnofacies are ubiquitous (Rudkin *et al.*, 1998).

Liberty (1969) identified two members, although they are not exactly equivalent to the former Dundas and Meaford. The lower member consists of 100-150 m of non-bituminous blue grey shale with thin, laterally-extensive interbeds of sandstone, limestone and dolostone which increase upward in thickness and number. The upper member, which can be traced to the northwest into the Kagawong beds of Manitoulin Island, is 10-15 m of crystalline and arenaceous limestone with thin shaley partings and several thin biostromal beds. All contacts are gradational. Byerley and Coniglio (1989) recognized the lower and upper members, and divided the upper into two informal sub-members: the lower Sextant Falls and the upper Lookout sub-members. Both the sand and carbonate content increase upward, and the carbonate content increases to the northwest (Johnson *et al.*, 1992). The lower contact is arbitrarily chosen at the lowest hard band thicker than 5 cm, and the upper contact is chosen arbitrarily at the change from grey to red colour (Tarrant, 1977), although this is acknowledged to be a diagenetic front and therefore may not be a regionally definable surface.

On Manitoulin Island, Foerste (1912) described the Wekwemikonsing Formation, 60-70 m of dark grey fissile shale with thin crystalline limestone interbeds, especially near the base and top (Caley, 1936). This is approximately equivalent to the lower portion of the Georgian Bay Formation (Dundas Formation, Caley, 1936). In addition, equivalents to the Meaford Beds are recognized as 15 m of coral/stromatoperoid biostromes overlying the Wekwemikonsing (Copper and Long, 1993). In the Ottawa Valley equivalents to the Dundas and Meaford include the Carlsbad Formation (grey shale with minor limestone and sandstone beds), and the Russell Formation (interbedded grey shale and dolomitic limestone) (Wilson, 1964).

Queenston Formation

The name "Queenston Formation" was first proposed by Grabau (1908, 1909), for the strata which occupied the lower 325 m of Hall's original "Medina Sandstone" of New York (Sanford, 1961) with a type locality designated as the Niagara River at Queenston. Sanford

(1961) designated a reference well in Crowland Twp., Welland Co. As a lithostratigraphic unit this distinctive red arenaceous shale is easily recognized throughout southern Ontario, including in a small downthrown fault block in the Ottawa Valley (Wilson, 1964; Johnson *et al.*, 1992). It outcrops all along the base of the Niagara Escarpment from Queenston to Owen Sound and is recognizable in the subsurface to the west (Winder, 1961; Johnson *et al.*, 1992). It conformably overlies the Georgian Bay Formation where the base is defined at an abrupt colour change, but there is a sharp, regionally extensive, erosional disconformity at the top (Winder, 1961; Middleton, 1987; Brett *et al.*, 1990).

The Queenston Formation comprises dark maroon to brick red, micaceous and arenaceous, very uniform, thin bedded shale with greenish bands, mottlings and fractures (Caley, 1961; Liberty, 1955; Liberty and Bolton, 1971). The shales are slightly to non-calcareous and very sparsely fossiliferous (Johnson *et al.*, 1992). Thin grey to bluish green, rippled, calcareous siltstones and bioclastic/biostromal limestones represent about 20 % of the rock (Donaldson, 1989; Brogly, 1984) and are especially common near the base and middle, toward the north (Liberty, 1955; Caley, 1961; Liberty and Bolton, 1971; Brogly, 1984; Johnson *et al.*, 1992; Rudkin *et al.*, 1998). To the north, several of these distinctive beds apparently can be traced into the Kagawong Formation of Manitoulin Island (Sanford, 1961; Liberty and Bolton, 1971). These limestone beds contain ooids, brachiopods, ostracods, bryozoans, bivalves, nautiloids, algae and vertical burrows (Brogly, 1984; Rudkin *et al.*, 1998). These fossils indicate an Ashgillian (Richmondian) age (Rudkin *et al.*, 1998). The red colour, although very distinctive and the main basis for definition of the formation, is likely diagenetic, resulting from oxidation of original grey shale (Liberty, 1955; Liberty and Bolton, 1971). Therefore the definition of the unit as different from the underlying Georgian Bay Formation is quite arbitrary, accounting for thickness changes over short lateral distances. On the Bruce Peninsula, Armstrong (1988, 1989) found that the red colour is subordinate to grey and green colours, rendering it difficult to differentiate between the Queenston and the Georgian Bay formations. In addition, the greenish bands and fractures result from a second diagenetic bleaching phase of the reddened shale (Caley, 1945). Cross bedding, wave and current ripples, casts of evaporite crystals and desiccation cracks are common (Caley, 1961; Brogly, 1984; Johnson *et al.*, 1992), particularly near the top, where mudcracks filled with the overlying Whirlpool sandstone are present at the erosional surface (Caley, 1961). Gypsum, in the form of nodules and thin laminae which may parallel or crosscut bedding are common (Rudkin *et al.*, 1998). The formation thins to the north and west from about 335 m at Lake Erie to about 200 m near Hamilton to 140 m at Halton to 45 m on Bruce Peninsula (Liberty, 1955; Sanford, 1961; Brogly, 1984; Johnson *et al.*, 1992).

Donaldson (1989) noted a general trend toward upward increase of siltstone and calcarenite beds to the middle of the formation, with subsequent decrease upward to the top. Brogly (1984) suggested the presence of three lithologically-distinct informal members in the Hamilton-Milton area, based on similar observations: the lower Streetsville member (60-70 m of red mudstone and oolitic limestone), the middle Bronte Creek member (30-40 m of red mudstone with abundant siltstone beds) and the upper Milton member (50-60 m of dominantly red mudstone).

The age of the Queenston has always been difficult to establish due to the paucity of fossils. Foerste (1912, 1916) acknowledged this difficulty, but noted that there were Richmondian (Ashgillian age) fossils in underlying beds and several fossiliferous limestones near the base, similar to those present below, at several locations (confirmed by Caley, 1961).

Conodont studies by Tarrant (1977) also suggested an Ashgillian age. From the beginning Grabau (1908, 1909, 1913) was able to physically correlate these strata with the latest Ordovician Juniata Sandstone of New York. Apparently, the youngest Ordovician stage (ie. Gamachian) is not present, suggesting a significant hiatus before subsequent Lower Silurian deposition (Churcher *et al.*, 1991; Johnson *et al.*, 1992).

On Manitoulin Island Foerste (1912) described the grey limestones of the Kagawong Formation which conformably overlay the Georgian Bay Formation and are sharply overlain by the lower Silurian Manitoulin Formation. Foerste (1912) regarded the Kagawong as equivalent to the Queenston of southern Ontario, and to the Vaureal Formation of Anticosti. The unit consists of grey to brown, thin bedded arenaceous or dolomitic limestone with minor grey shale and several distinctive coral biostrome beds (Caley, 1936). It is 25-30 m thick and is sparsely fossiliferous (Winder, 1961) with bryozoans and brachiopods (Johnson *et al.*, 1992). Copper and Long (1993) pointed out that the uppermost Gamachian stage of the Ordovician is missing here, and paleokarst features are present suggesting significant erosion at the top of the Kagawong.

SEDIMENTOLOGY

Facies

Russell and Telford (1983) interpreted the Collingwood Member as an areally restricted, anoxic facies representing the final phase of the underlying Trenton carbonate platform package. It has been generally accepted that the Collingwood was deposited in relatively shallow water, because of the presence of limestone coquina beds which might represent storm deposits at or near fairweather wave base (Churcher *et al.*, 1991; Rancourt, 1998). However, there are no ripples or mudcracks known (Tarrant, 1977). Harris (1985) also concluded that deposition was in shallow water which deepened to the southeast into the Appalachian Basin, but that the water was stratified with respect to oxygen due to its location close to the equator. This conclusion was based on the lack of a diverse sessile infauna or epifauna, the assemblage being dominated by nektoplanktonic and poorly-developed benthic species (Harris, 1985). Churcher *et al.* (1991) concluded that the Collingwood was deposited near the peak of regression, and was then subject to a period of erosion before the Blue Mountain transgression. They suggested that this phase of erosion was due to uplift during the Taconian Orogeny, plus a eustatic sea level drop associated with the Late Ordovician glacial period in North Africa (Churcher *et al.*, 1991). Conversely, Liberty (1969) suggested that the Collingwood Member of the Lindsay Formation (his lower Craigleith Member of the Whitby Formation) represented the initial transgressive facies, equivalent to the Utica facies of New York. Rancourt (1998) suggested that upwelling of deep phosphate-rich waters shut down the carbonate factory and resulted in algal blooms which depleted the oxygen content and created a stressed environment.

The Blue Mountain Formation includes two distinctly different facies; the localized lower dark brown shales of the Rouge River Member, and the upper grey, more normal shales of the Thornbury Member. Churcher et al. (1991) suggested that the Blue Mountain represents the beginning of marine transgression and input from the Taconian sediment source. Russell and Telford (1983) acknowledged that the Rouge River likely represents a restricted marine facies, but that the bulk of the Blue Mountain was deposited in open marine conditions.

The sedimentology of the Georgian Bay Formation has received considerable attention in recent decades. Tarrant (1977) noted the common presence of shallow water fossils, symmetrical ripples and ripple cross lamination, interpreting deposition in a shallow marine setting. He also noted the upward increase in number and thickness of hard bands, suggesting that this represents shallowing-upward due to delta progradation from an Appalachian source (Tarrant, 1977). These rocks interfinger northward with shallow marine fossiliferous limestones, but subdivision has proven difficult due to outcrop limited to certain areas, lack of precise biostratigraphy and lateral facies changes (Johnson *et al.*, 1992). Although based on a single small outcrop, the work of Flach (1985) provided the first detailed sedimentological observations on a portion of the Georgian Bay Formation. His 40 m measured section displayed an upward increase in number and thickness and lateral discontinuity of calcarenite/siltstone beds with abundant ripple cross lamination and tool marks. Flach (1985) made a number of important new observations: 1) "limestone" hard bands are actually composed of quartz silt/abraded fossil fragments set in a sparry calcite cement (ie. detrital calcarenites, rather than normal limestones), 2) hard bands are graded and have sharp erosive bases with lags, fine-upward and have a sequence of sedimentary structures from horizontal lamination to ripple cross lamination (analogous to Bouma Sequences), 3) the shales and hard bands have different mineralogies and fabrics suggesting different derivation, and 4) the hard bands have abraded shallow marine fossils whereas the shales have only a few non-shallow fossils. He concluded that the hard bands represent material derived from the shallow shelf and redeposited by turbidity-like flows onto basinal shales and document a shallowing-upward of a distal submarine fan setting over a pelagic basin plain (Flach, 1985).

Kerr and Eyles (1991) continued and extended these concepts with further work on 10 outcrops and 3 cores. They too observed a general coarsening- and shallowing-upward succession to shorelines interpreted to be oriented NNE/SSW, but noted that numerous smaller coarsening-upward and fining-upward sequences are present. They also found that hard bands were composed of approximately equal parts quartz (35%), shallow water fossil fragments (30%) and sparry cement (35%), with framework grains generally in the coarse silt size range. They distinguished a mudstone/minor sandstone facies assemblage of grey-blue, poorly calcareous, bioturbated shale with thin rippled sandstones, coquina beds and isolated sandy gutter casts. This facies assemblage was interpreted to represent fine terrigenous mud from the Taconian uplift deposited below fairweather wave base in a basinal setting, with minor storm-introduced coarser beds (Kerr and Eyles, 1991). In addition, they distinguished a facies assemblage of thicker laterally-extensive calcareous sandstones with erosive bases, fossil lags, horizontal lamination passing upward into hummocky cross stratification and wave ripples. *Cruziana* and *Skolithos* trace fossils are abundant (Stanley and Pickerill, 1993). This facies assemblage was interpreted to represent tempestites deposited above storm wave base in the overall progradational succession (Kerr and Eyles, 1991).

Byerley and Coniglio (1989, 1991) also performed sedimentological studies of 50 measured sections of the Georgian Bay Formation in the Bruce Peninsula-Manitoulin Island area. They identified four lithofacies: shales at the base, interbedded limestone and shale, argillaceous limestone, and dolostone at the top, interpreted as the deposits of a shallowing subtidal setting with upward increasing storm influence. Scoured surfaces, load structures, graded beds, megaripples, amalgamated beds, hardgrounds, and hummocky cross stratification are ubiquitous (Byerley and Coniglio, 1989). Carbonate facies are particularly abundant in the upper portion, including skeletal grainstones, packstones, and wackestones with local development of bryozoan/stromatoperoid/coral biostrome floatstones. Dolomitization, leaching of allochems and development of late stage saddle dolomite and gypsum are common. They noted that biostromes in the lower member are transported/reworked deposits, whereas those in the upper member are parautocthonous and *in situ* accumulations (Byerley and Coniglio, 1991). Hardgrounds of two different types were identified in the upper member in this area: high-relief digitate hardgrounds resulting from bioturbation and boring, and planar corrasion surfaces resulting from erosion (Byerley and Coniglio, 1989, 1991).

From the beginning (Grabau, 1909), the Queenston Formation has always been thought of as the distal portions of a large deltaic complex (the "Queenston Delta", lateral equivalent to the Juniata Formation of New York), derived from the Taconian Orogen, but has been the subject of few modern studies. Deposits are considered to be nonmarine to the southeast and marine to the northwest (Johnson *et al.*, 1992). Tarrant (1977) recovered conodonts from a limestone bed in the middle of the formation and pointed out that it intertongues with biostromal reefs to the northwest, suggesting important marine influence. In southern Ontario, there is no evidence of sandy distributaries, but the rocks do contain graded marine siltstone beds, mudcracks, oolites, evaporites and vertical escape burrows (Brogly, 1984). Brogly (1984) concluded that the Queenston was the result of deposition on a broad supratidal mudflat, the terrigenous equivalent of a coastal sabkha (Middleton, 1987), and that the mud was derived from a river system somewhere to the northeast, now eroded away. Donaldson (1989) described and interpreted several facies from one core of the Queenston. These are 1) interlaminated mudstone and bioturbated calcarenites of intertidal mudflat origin, 2) sharp-based graded calcarenites (commonly with lags of intraclasts) with evaporative nodules and cross lamination interbedded with bioturbated mudstone, representing storm beds on a supratidal mudflat, 3) bioturbated silty mudstone with minor calcarenite deposited in a supratidal setting (Donaldson, 1989).

Brogly *et al.* (1998), working with 7 outcrops and 6 cores in the Hamilton-Brampton area, defined 14 facies in three facies associations as follows. Continental facies dominate to the southeast and marine facies dominate to the northwest, and they are arranged into two generally regressive successions.

1) Dark grey shale interbedded with thin calcareous siltstone to very fine sandstone and fossiliferous limestone is common in the lower Queenston(and middle part to the north and west), and is very similar to the underlying Georgian Bay Formation. Ripples, flaser bedding, hummocky cross stratification, mudcracks and trace fossils are common. These are interpreted to represent shallow marine deposits with storm graded beds.

2) Red mudcracked shale with interbedded grey shale and thin calcareous siltstone, sandstone and bioclastic limestone typifies the middle portion of the formation. Lags of rip-up conglomerate, gypsum nodules, halite hoppers and trace fossils are common. These sediments are interpreted as coastal deposits affected by storms and fluctuating water levels, and represent a transition between the more marine beds beneath and the more supratidal ones above.

3) Massive red shale with mudcracks, shale troughs, and local lenticular bioclastic siltstone dominates the upper portion of the formation in most outcrops. These strata, the most common in outcrops, represent subaerial muddy coastal plain deposition in a sabkha setting (Gulf of California model) at the continental/nearshore interface.

The apparent erosional gap (disconformity, with paleokarst features on Manitoulin Island) at the top of the Queenston is commonly related to the known late Ashgillian glaciation in North Africa and is assumed to represent a major eustatic drawdown (Copper and Long, 1993). This surface is also marked by desiccation cracks filled with overlying sandstone in the Niagara area, and in places, there are rip-ups of Queenston material in the basal part of the overlying Manitoulin Formation (Rudkin *et al.*, 1998).

Paleocurrents

There are no published paleocurrent data for the Collingwood Member, or the Blue Mountain Formation. However, Zerrahn (1978) reported early work on oriented fossils from the equivalent strata of western New York, indicating flow from east to west.

Flach (1985) made 11 paleocurrent measurements from one outcrop in the lower part of the Georgian Bay Formation, yielding paleoflow to the NW or WNW. Kerr and Eyles (1991) produced the largest published paleocurrent data set for the Georgian Bay Formation, from 10 outcrops in the Toronto and Meaford areas, including the trends of 110 gutter casts and 51 ripple crests. They found much variation, but ripples were oriented 24°/204°, implying paleoshorelines oriented approximately NNE/SSW. However, gutters were oriented 16°/196°, interpreted by Kerr and Eyles (1991) to represent shore-parallel flows typical of mid and outer shelf areas. Byerley and Coniglio (1989), working to the north, found similar results with unidirectional southward flows based on gutter casts and current ripples, and wave ripple crests (indicating the trend of the paleoshoreline) oriented north-south. Zerrahn (1978) reported data (24 measurements) from equivalent strata from western New York indicating offshore flow to the northwest.

Paleocurrent data for the Queenston Formation are extremely sparse, because to date Brogly (1984) and Brogly et al. (1998) are the only modern outcrop-based studies. The former study included 22 measurements of ripple crests from 4 outcrops, which were oriented at an average trend of 119°, and 5 measurements of ripple cross lamination from 2 outcrops, with paleoflow to 222°. This meagre data set implies paleoflow to the southwest from shorelines oriented NNW/SSE (Brogly *et al.*, 1998), but more data are required to make any reasonable interpretations. Zerrahn (1978) reported data (165 measurements) from equivalent strata in western New York, indicating flow of paleochannels to the north or northwest.

PETROLEUM GEOLOGY

History

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 Co. 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 the aggressive marketing of the Pennsylvania oil fields discovered in 1859 led to plummeting prices and a decrease in activity (Hutt *et al.*, 1973; Powell *et al.*, 1984). However, the industry has continued to thrive through the succeeding 125 years. By 1996, total cumulative production stood at $11.7x10^6$ m^3, with currently 75% of oil production from Ordovician platform carbonates, 25% from Silurian pinnacles and Devonian anticlinal structures, with minor amounts from Cambrian reservoirs (Obermajer *et al.*, 1998). 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 1889 drilling of the Coste #1 well, to Silurian carbonates, near Leamington, Essex Co., and the Coste #2 well, to Silurian clastics, near Port Colborne (Hutt *et al.*, 1973; Obermajer *et al.*, 1998). 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. To the end of 1996, total cumulative production was $30.8x10^9 m^3$, of which 90% is now from Silurian carbonates and clastics in the Niagara and Lake Erie areas (Obermajer *et al.*, 1998).

Although most oil and gas production from Ordovician rocks in Ontario derives from structurally-influenced traps in the Middle Ordovician Trenton-Black River carbonates (Sanford, 1961; Armstrong, 1992), Upper Ordovician strata may contain source rocks and reservoir rocks (Caley, 1941) and, in fact, have yielded a number of shows of non-commercial natural gas through the years (Liberty, 1955; Caley, 1961; Sanford, 1961; Liberty and Bolton, 1971). Even today, only a small proportion of wells in southern Ontario penetrate below the base of the Silurian. Although the hydrocarbon potential of these rocks has generally been ignored in recent decades, Collingwood and Blue Mountain rocks have always been known to be very petroliferous, and gas pockets of near-commercial quantities (but short-lived flow) are common and well known throughout the outcrop area of the Georgian Bay Formation (Sanford, 1961; Liberty and Bolton, 1971). Perhaps the influential comments of Caley (1961) have discouraged concerted exploration: he stated that the Upper Ordovician has reasonable source rocks but poor migration possibilities due to its shaliness and lack of faulting, plus reservoirs that appear to be thin and discontinuous.

The Collingwood shales have been known to be petroliferous since the earliest reports of the Geological Survey of Canada (Murray, 1845) and were the object of early attempts to process oil shales (Liberty, 1955; Verma, 1979). A wood-fired plant for the distillation/extraction of oil from the outcrops of these shales was established in the vicinity of Craigleith in 1859, yielding about 7 gallons/ton of rock or about 250 gallons (1140 litres) per day (Verma, 1979; Harris, 1985). This petroleum was primarily used for illumination and lubrication, but the enterprise was short-lived, overcome in 1863 by the lower cost of conventional "free oil" supplied by the newly discovered fields at Petrolia and Oil Springs (Verma, 1979; Johnson *et al.*, 1983). An extensive program to evaluate the oil shale potential of the Collingwood, including shallow and deep core drilling and detailed geochemistry, was pursued by Ontario Geological Survey in the mid-1980's (refer to Churcher *et al.*, 1991, and references therein).

Sanford (1961; 1962) and Caley (1961) mentioned several wells drilled in 1922-1927 in Caledon Twp. (Peel Co.) yielding flows of 40-475 Mcf/d from the Georgian Bay, and a well in Crowland Twp. (Welland Co.) drilled in 1955 which was produced as a commercial well with gas flow from siltstone and silty limestone near the top of the Georgian Bay Formation. Caley (1961) also described significant gas shows from the Georgian Bay Formation in wells in Chingacousy Twp. (Peel Co.), Vaughn Twp. (York Co.), Etobicoke Twp. (York Co.) and near Cooksville. In addition, Caley (1961) mentioned two wells which struck gas at the base of the Queenston Formation near Milton in Halton Co.

It appears that the historical record suggests further hydrocarbon potential for the Upper Ordovician rocks of southern Ontario.

Regional Factors

The Upper Ordovician succession of southwestern Ontario is thermally mature to marginally mature and deeper Cambro-Ordovician rocks are mature (Powell et al., 1984). Regionally the succession lies in the area where strata dip south or southeast into the Appalachian Basin at about 4.5-5 m/km (Caley, 1961; Legall et al., 1981). These rocks represent up to 25% of the sediment volume (Legall et al., 1981). Known hydrocarbon source rocks occur in the lower portion of the succession (see below). Minor gas shows have been common throughout the drilling history of these rocks, although to date no sustained commercial production has been achieved. Few structures occur at this stratigraphic level with few closures (Caley, 1961), although production from underlying carbonates is associated with dolomitization along faults (Legall et al., 1981). Reservoir facies may be thin and may require secondary enhancement of porosity/permeability. Most trapping possibilities in the Upper Ordovician may be stratigraphic and diagenetic, or related to underlying platform reservoirs.

Reservoirs and Petrography

The Georgian Bay Formation hard bands are predominantly coarse grained calcareous siltstone to fine sandstone in the south, and more dominantly siltstone in the north. Early reports (eg. Parks, 1925) suggested that these beds were laterally discontinuous, but in contrast, later workers (eg. Liberty and Bolton, 1971) found that even very thin beds could be traced laterally over hundreds of metres to the full extent of available outcrops in these near-horizontal strata (in the Toronto area the beds strike at 115° and dip at less than 0.5° to the southwest; quoted by Parks, 1925).

The hard bands of the Georgian Bay represent about 20% of the rock and are up to about 25 cm thick. Czurda et al. (1973), using only whole rock methods of Chittick apparatus and XRD analyses, found that these beds are 60% calcite/8-14% quartz/26% clays at Toronto, but 55% quartz/ 30-35% calcite/10% clays at Meaford, implying an increase in quartz content to the north. However, no visual examination of the grains was performed. In the same study, shales at Toronto were found to have 55-60% illite/15-18% quartz/10-15% chlorite/4%calcite/3-5% vermiculite/2-4%pyrite, whereas those at Meaford have 40% quartz/35-45% illite/10-15% chlorite/4%calcite/3-5% vermiculite/2-4% pyrite. However, Flach (1985) performed visual point counts on thin sections of hard bands from Toronto and found that quartz ranges 25-55%, increasing upward, and calcite ranges 10-40% and is composed exclusively of abraded fossil fragments (ie. clastic components) and sparry cement. The quartz and fossil grains are angular, low sphericity, poorly sorted and form an original open framework (Flach, 1985). Clays represented 15-50% of these rocks. The beds were classed as detrital calcareous siltstones and should not be confused with normal chemical limestones.

Byerley and Coniglio (1991) concluded that the common hardgrounds, biostromes and storm beds are widespread but of limited use for regional correlation due to local complexity and variability of the facies mosaic. However, widespread development of skeletal grainstones, packstones and floatstones with dolomitization and secondary porosity may create favourable reservoirs in this unit, particularly toward the top and toward the north (Byerley and Coniglio, 1989, 1991).

Working in the Toronto area, Kerr and Eyles (1991) found that the clastic grains are 45-50% calcite fossil fragments, 35% quartz, 13% feldspar, and minor rock fragments. Grains are generally well sorted, subround to round, of moderate to high sphericity and range 0.0175-0.10 mm (av. 0.55 mm; coarse silt). These epiclastic grains represent about 60-65% of the rock, the rest being 30-35% sparry calcite cement. The carbonate detritus is primarily angular fossil fragments in the coarse silt size including echinoderms, brachiopods, bivalves, ostracods and gastropods. The amount of fossil fragments decreases upward. Diagenetic processes observed by Kerr and Eyles (1991) included dissolution of fossil fragments, precipitation of sparry cement and fracturing of fossil fragments. Although not mentioned by any of these authors, dissolution of the abundant calcareous cement would create significant secondary porosity. Donaldson (1989) noted that sandstones in the upper Georgian Bay have 20% quartz and 15% K-feldspar.

In studies of the Queenston Formation, Brogly (1984) and Donaldson (1989) found that siltstones and sandstones are common in the lowermost and middle parts of the unit and include 15% quartz and 10% K-feldspar as angular to subangular, low to medium sphericity grains. The sand grains appear to be frosted, but under SEM study, they are covered with V-shaped pits and therefore were deposited in a subaqueous environment rather than an aeolian setting (Brogly, 1984). Brogly *et al.* (1998) also found that grain size decreases from southeast to northwest, consistent with the dispersal pattern. Broken and abraded shell fragments of coarse silt to fine sand size were abundant in the limey beds of the middle and lower parts of the formation (up to 85% of any bioclastic bed), including trilobite, brachiopod and bryozoan fragments, and sparry cement is also common. A series of oolite beds are present near the base (with a few at the top) of the Queenston. Hence, the "limestone" beds are really bioclastic calcarenites of detrital origin, rather than normal limestones. Both Brogly (1984) and Donaldson (1989) also noted a minor evaporite association of nodular, and bedded, dolomite/gypsum/anhydrite in the middle and upper portion (with a few occurrences of halite inclusions). Brogly *et al.* (1998) found that most of the clay content of the Queenston was illite and chlorite, and that calcium content increases upward and form southeast to northwest.

Hydrocarbon Source Rocks and Maturity

Legall et al. (1981) investigated the thermal regime of Paleozoic strata of southwestern Ontario (including 735 Ordovician samples) and delineated two stratigraphically-bound thermal facies: 1) strata between the surface and the Middle Ordovician Trenton Group with a maximum burial temperature of 60°, and 2)Cambrian to Lower/Middle Ordovician strata with a maximum burial temperature of 60-90 ° (ie. All within oil window). Barker *et al.* (1984) and Powell *et al.* (1984) reviewed the source rock data for oil discoveries of southern Ontario to that date and found that Cambrian and Ordovician oils are derived from a typical marine source and correlate geochemically to the organic-rich limestones and marls of the Middle Ordovician Collingwood Member of the Lindsay Formation. Their data indicate that the Collingwood is rich (TOC up to 11%), mature and has fair to excellent yields (Powell *et al.*, 1984). Snowdon (1984) found that the Collingwood has good to excellent source rock potential, being both rich (TOC = 2.0 - 9.7%)

and moderately mature (early oil window), with a dominance of Type II organic matter. In addition, the T_{max} increases from north to south, suggesting that the maturity increases from north to south (Snowdon, 1984). Russell and Telford (1983) suggested that the Collingwood, with an average of 6% TOC, increasing upward and Fischer Assay results of 40 litres oil/ton, should be considered a significant potential oil shale. They found that the richest shales are present in the Craigleith area, decreasing in richness toward the north on Manitoulin and toward the south at Lake Ontario. Barker and Pollock (1984) studied the natural gases of southern Ontario (primarily produced from Silurian reservoirs) and found that they are generally wet (~85% methane, 8.5% other hydrocarbons, 6.0% nitrogen and 0.5% helium), likely all derived from mature to overmature marine sources present deeper in the basins and the result of considerable migration distances.

Barker (1985) provided geochemical analyses of shales from the Collingwood and Blue Mountain formations, based on samples from cores recovered in the Ontario Geological Survey study of oil shale potential. The results suggest that the Collingwood generally contains 0.5-9.7% TOC, with the upper 2-10 m being the richest at 4-9%, and that the Blue Mountain generally contains 0.5-6% TOC, with the lower 10-15 m being richest at 1-5%. Summary data provided by Churcher et al. (1991) indicate that TOC's measured in the Collingwood range from 0.9-11.2%, averaging 4.3%, and generally increase from Toronto (av. 3.5%) to Manitoulin (av. 5.5%).

Recent source rock and thermal maturity studies on Paleozoic strata of southwestern Ontario, including the Upper Ordovician, were conducted by Obermajer *et al.* (1995), Obermajer (1997) and Obermajer *et al.* (1998). Obermajer *et al.* (1995, 1998) found that Cambro-Ordovician oils were derived from marine clastic sources, deposited under normal water salinities but in dysoxic conditions, with good to excellent potential. They suggested that these oils were sourced either from discontinuous organic-rich laminae within the Middle Ordovician Trenton Group carbonates, or from the Upper Ordovician Collingwood Member and Blue Mountain Formation. The Blue Mountain was shown to be thermally mature, whereas the Collingwood is marginally mature, but was positively correlated with some Cambro-Ordovician production (Obermajer *et al.*, 1995). The oils themselves, primarily sampled from Trenton-Black River reservoirs, are mature to supermature (implying greater burial temperatures than the Paleozoic succession of Ontario has experienced), suggesting the oils were generated outside the area of the present reservoirs (Obermajer *et al.*, 1998). This probably indicates long-distance migration from deeper in the Appalachian Basin.

Obermajer (1997) conducted an extensive analysis of source rock quality and thermal maturity, including 47 samples of the Collingwood Member (6 from outcrop) and 226 samples of the Blue Mountain Formation (none from outcrop), most of which proved to have good to excellent hydrocarbon potential. Both units can be characterized as oil prone source rocks, with normal marine Type II kerogen, dominated by bituminite and alginite. The presence of both *Tasmanites* and *Gloeocapsomorpha prisca* were noted.

Samples of the Collingwood fell into two families: a) in Georgian Bay area the TOC = 4-7% (max. 11.3%) and T_{max} = 436-444°C (marginally mature) and HI = 500-600; b) in Toronto area the TOC = 0-2.5% (max. 4.3%) and T_{max} = 444-453°C (thermally mature, in the oil window) and HI = 200-400 (Obermajer, 1997). These data imply that the Collingwood source rocks are richer in the Georgian Bay area than in the Toronto area. In addition, the PI increased toward the Toronto area, suggesting that some generation of hydrocarbon has already occurred there.

Samples of the Blue Mountain yielded TOC = 0.7-2.7% with the highest values in the brownish to blackish shales of the lowest 15 m, T_{max} = 439-448°C (thermally mature, in the oil window) and HI = 200-350, with a PI = 0.1-0.23, increasing slightly to the west (Obermajer, 1997). These data suggest that the lower Blue Mountain is a significant source rock, although less rich than the Collingwood.

Other Commodities

The Blue Mountain Formation provides a local source of pottery clay, although thick Quaternary cover limits its economic use (Johnson *et al.*, 1992). Slabs of limestone from the Georgian Bay Formation provided good building stone in the past, with a large quantity extracted particularly from the Cooksville Quarry (Caley, 1941). Shales of the Georgian Bay were a main source of brick and tile clay, such as that extracted from the famous Don Valley Brickpits (Caley, 1961; Czurda *et al.*, 1973) or from the Meaford area, and are present over a large urban area, although this material required a considerable amount of processing due to the ubiquitous presence of calcareous beds (Johnson *et al.*, 1992). In addition, rock from the Georgian Bay is extensively used in the concrete/aggregate industry (Czurda *et al.*, 1973). The red shales of the Queenston Formation have been the most widely-used and long-regarded as the finest quality material for the brick/clay/tile industry due to the ease of mining and crushing, homogenous texture, consistency of chemistry, uniform colour, and a tendency toward good plasticity when mixed with water (Caley, 1941; Caley, 1961; Liberty and Bolton, 1971; Johnson *et al.*, 1992). However, the zone of outcrop and shallow subcrop of the Queenston, where economic extraction is attractive, is generally in areas of significant environmental sensitivity along the foot of the Niagara Escarpment (Johnson *et al.*, 1992).

LIST OF FIGURES

REFERENCES

Armstrong, D.K. 1987. Paleozoic geology of the northern Bruce Peninsula. *In* Summary of Field Work and other Activities, R.B. Barlow, M.E. Cherry, A.C. Colvine, B.O. Dressler and O.L. White (eds.), Ontario Geological Survey Miscellaneous Paper 137, p. 392-395.

Armstrong, D.K. 1988. Paleozoic geology of the central Bruce Peninsula. *In* Summary of Field Work and other Activities, A.C. Colvine, M.E. Cherry, B.O. Dressler, P.C. Thurston, C.L. Baker, R.B. Barlow, and C. Riddle (eds.), Ontario Geological Survey Miscellaneous Paper 141, p. 446-453.

Armstrong, D.K. 1989. Paleozoic geology of the southern Bruce Peninsula. *In* Summary of Field Work and other Activities, A.C. Colvine, M.E. Cherry, B.O. Dressler, O. L. White, R.B. Barlow, and C. Riddle (eds.), Ontario Geological Survey Miscellaneous Paper 146, p. 222-227.

Armstrong, D.K. 1992. Paleozoic and Mesozoic sedimentation: tectonic influences on a "stable" craton. *In* Geology of Ontario, P.C. Thurston, H.R. Williams, R.H. Sutcliffe and G.M. Stott (eds.), Ontario Geological Survey, Special Volume 4, part 2, p. 907-1008.

Barker, J.F. 1985. Geochemical analyses of Ontario oil shales. Ontario Geological Survey, Open File Report 5568, 77p.

Barker, J.F., Russell, D.J., Johnson, M.D. and Telford, P.G. 1983. Oil shale assessment project, volume 3, organic geochemical results 1981-82. Ontario Geological Survey, Open File Report 5460, 36p.

Barker, J.F., Macqueen, R.W. and Waldron, J. 1983. Source, correlation and thermal maturation history of hydrocarbon deposits of southern Ontario. Ontario Geological Survey, Open File Report 5570, 11p.

Barker, J.F., Macqueen, R.W. and Waldron, J. 1984. Source, correlation and thermal maturation history of hydrocarbon deposits of southern Ontario. *In* V.G. Milne (ed.), Geoscience Research Grant Program 1983-1984, Ontario Geological Survey, Miscellaneous Paper 121, p. 42-46.

Barker, J.F. and Pollock, S.J. 1984. The geochemistry and origin of natural gases in southern Ontario. Bulletin of Canadian Petroleum Geology, v. 32, p. 313-326.

Brett, C.E., Goodman, W.M. and LoDuca, S.T. 1990. Sequences, cycles and basin dynamics in the Silurian of the Appalachian Foreland Basin. Sedimentary Geology, v. 69, p. 191-244.

Brett, C.E., Goodman, W.M. and LoDuca, S.T. 1990. Silurian sequences of the Niagara Peninsula. *In* R.J. Cheel (ed.), Sedimentology and depositional environments of Silurian strata of the Niagara Escarpment, Ontario and New York. Geological Association of Canada, Field Trip Guidebook B4, p. 3-26.

Brogly, P.J. 1984. The depositional environment of the Queenston Formation in southern Ontario. Unpublished B.Sc. thesis, McMaster University, Hamilton, Ontario, 80p.

Brogly, P.J., Martini, I.P. and Middleton, G.V. 1998. The Queenston Formation: shale-dominated, mixed terrigenous-carbonate deposits of Upper Ordovician, semi-arid, muddy shores in Ontario, Canada. Canadian Journal of Earth Sciences, v. 35, p. 702-719.

Byerley, M. and Coniglio, M. 1989. Stratigraphy and sedimentology of the Upper Ordovician Georgian Bay Formation, Manitoulin Island and Bruce Peninsula.. *In* Geoscience Research Grant Program Summary of Research 1988-1989, V.G. Milne (ed.), Ontario Geological Survey Miscellaneous Paper 143, p. 227-237.

Byerley, M. and Coniglio, M. 1989. Stratigraphy and sedimentology of the Upper Ordovician Georgian Bay Formation, Manitoulin Island and Bruce Peninsula.-- evaluation of hardgrounds, biostromes and storm beds for regional correlation. *In* Geoscience Research Grant Program Summary of Research 1990-1991, V.G. Milne (ed.), Ontario Geological Survey Miscellaneous Paper 156, p. 3-15.

Caley, J.F. 1936. The Ordovician of Manitoulin Island, Ontario. Geological Survey of Canada, Memoir 202, p 21-91.

Caley, J.F. 1941. Paleozoic geology of the Brantford area, Ontario. Geological Survey of Canada, Memoir 226, 176p.

Caley, J.F. 1943. Paleozoic Geology of the London area, Ontario. Geological Survey of Canada, Memoir 237, 171p.

Caley, J.F. 1945. Paleozoic Geology of the Windsor-Sarnia area, Ontario. Geological Survey of Canada, Memoir 240, 227p.

Caley, J.F. 1961. Paleozoic geology, Toronto-Hamilton area, Ontario. Geological Survey of Canada, Memoir 224, 284 p.

Cheel, R.J. (ed.). 1991. Sedimentology and depositional environments of Silurian strata of the Niagara Escarpment, Ontario and New York. Geological Association of Canada, Field Trip Guidebook B4, 99p.

Churcher, P.L., Johnson, M.D., Telford, P.G. and Barker, J.F. 1991. Stratigraphy and oil shale resource potential of the Upper Ordovician Collingwood Member, Lindsay Formation, southwestern Ontario. Ontario Geological Survey, Open File Report 5817, 98p.

Copper, P. and Long, D.G.F. 1993. Upper Ordovician-Early Silurian geology of the Manitoulin area, Ontario (Caradocian-Llandoverian). Third Canadian Paleontology Conference, Field Trip Guidebook, Sudbury.

Czurda, K., Winder, C.G. and Quigley, R.M. 1973. Sedimentology, mineral facies and petrofabric of the Meaford-Dundas Formation (Upper Ordovician) in southern Ontario. Canadian Journal of Earth Sciences, v. 10, p. 1790-1804.

Cohee, G.V. 1948. Cambrian and Ordovician rocks in Michigan Basin and adjoining areas. American Association of Petroleum Geologists Bulletin, v. 32, p. 1417-1448.

Diecchio, R.J. 1991. Taconian sedimentary basins of the Appalachians. *In* Advances in Ordovician geology, C.R. Barnes and S.H. Williams (eds.) Geological Survey of Canada, Paper 90-9, p. 225-234.

Donaldson, W.S. 1989. The depositional environment of the Queenston shale, southwestern Ontario. Unpublished B.Sc. thesis, University of Western Ontario, London, 106p.

Duke, W.L. 1987. Sedimentology, stratigraphy and ichnology of the Lower Silurian Medina Formation in New York and Ontario. Society of Economic Paleontologists and Mineralogists, Eastern Section Annual Fieldtrip Guidebook, 185p.

Duke, W.L. 1991. The Lower Silurian Medina Group in New York State and Ontario. *In* R.J. Cheel (ed.), Sedimentology and depositional environments of Silurian strata of the Niagara Escarpment, Ontario and New York. Geological Association of Canada, Field Trip Guidebook B4, p. 35-61.

Duke, W.L., Fawcett, P.J. and Brusse, W.C. 1991. Lower Silurian Medina Group, Ontario and New York: storm- and tide-influenced sedimentation in a shallow epicontinental sea, and the origin of enigmatic shore-normal channels encapsulated by open shallow-marine deposits. International Association of Sedimentologists, Special Publication 14, p. 339-375.

Flach, G.A. 1985. A facies interpretation of the Mid-Upper Ordovician Georgian Bay Formation at the Don Valley Brick Pit, Toronto, Ontario. Unpublished BSc thesis, University of Waterloo, Waterloo, Ontario, 43p.

Foerste, A.F. 1912. The Ordovician section in the Manitoulin area of Lake Huron. Ohio Naturalist, v. 13, p. 43.

Foerste, A.F. 1916. Upper Ordovician formations in Ontario and Quebec. Geological Survey of Canada, Memoir 83, 279p.

Foerste, A.F. 1924. Upper Ordovician faunas of Ontario and Quebec. Geological Survey of Canada, Memoir 138, p. 51.

Frakes, L.A., Francis, J.E. and Syktus, J.I. 1993. Climate models of the Phanerozoic. Cambridge University Press, Cambridge, 350p.

Grabeau, A.W. 1908. A revised classification of the North American Siluric System. Science, v.

27, p. 622.

Grabeau, A.W. 1909. Physical and faunal evolution of North America during Ordovicic, Siluric, and Early Devonic time. Journal of Geology, v. 17, p. 209-252.

Grabeau, A.W. 1913. Early Paleozoic delta deposits of North America. Geological Society of America Bulletin, v. 24, p. 399-528.

Harris, D. 1985. Graphic logs of oil shale intervals - Ordovician Collingwood Member and the Devonian Kettle Point and Marcellus Formations. Ontario Geological Survey, Open File Report 5527, 225p.

Howell P.D. and van der Pluijm, B.A. 1990. Early History of Michigan Basin: subsidence and Appalachian tectonics. Geology, v. 18, p. 1195-1198.

Hutt, R.B., MacDougall, T.A. and Sharp, D.A. 1973. Southern Ontario *In* The Future Petroleum Provinces of Canada. R.G. McCrossan (ed.), Canadian Society of Petroleum Geologists, Memoir 1, p. 411-441.

Johnson, M.D. 1983. Oil shale assessment project, deep drilling results, Toronto region. Ontario Geological Survey, Open File Report 5477, 17p.

Johnson, M.D., Russell, D.J. and Telford, P.G. 1985. Oil shale assessment project, volume 1, shallow drilling results 1981/82. Ontario Geological Survey, Open File Report 5458, 36p.

Johnson, M.D., Russell, D.J. and Telford, P.G. 1985. Oil shale assessment project, volume 2, drillholes for regional correlation 1981/82. Ontario Geological Survey, Open File Report 5459, 20p.

Johnson, M.D., Russell, D.J. and Telford, P.G. 1985. Oil shale assessment project drillholes for regional correlation 1983/84. Ontario Geological Survey, Open File Report 5565, 49p.

Johnson, M.D. Armstrong, D.K., Sanford, B.V., Telford, P.G. and Rutka, M. A. 1992. Paleozoic and Mesozoic of Ontario. *In* Geology of Ontario, P.C. Thurston, H.R. Williams, R.H. Sutcliffe and G.M. Stott (eds.), Ontario Geological Survey, Special Volume 4, part 2, p. 907-1008.

Kerr, M and Eyles, N. 1991. Storm-deposited sandstones (tempestites) and related ichnofossils of the Late Ordovician Georgian Bay Formation, southern Ontario, Canada. Canadian Journal of Earth Sciences, v. 28, p. 266-282.

Legall, F.D., Barnes, C.R. and Macqueen, R.W. 1981. Thermal maturation, burial history and hotspot development, Paleozoic strata of southern Ontario - Quebec, from conodont and acritarch colour alteration studies. Bulletin of Canadian Petroleum Geology, v. 29, p. 492-539.

Liberty, B.A. 1955. Stratigraphic studies of the Ordovician System in central Ontario.

Proceedings of the Geological Association of Canada, v. 7, p. 145.

Liberty, B.A. 1964. Geology of Central Ontario. American Association of Petroleum Geologists, Field Guidebook, 93p.

Liberty, B.A. 1969. Paleozoic geology of the Lake Simcoe area, Ontario. Geological Survey of Canada, Memoir 355, 201p.

Liberty, B.A. and Bolton, T.E. 1971. Paleozoic geology of the Bruce Peninsula area, Ontario. Geological Survey of Canada, Memoir 360, 163p.

Middleton, G.V. 1982. Brief guide to the sedimentology of the Hamilton area. McMaster University Technical Memo 82-1, 26p.

Middleton, G.V. 1987. Geologic setting of the northern Appalachian Basin during the Early Silurian. *In* Sedimentology, Stratigraphy and Ichnology of the Lower Silurian Medina Formation in New York and Ontario, W.L. Duke (ed.), Society of Economic Paleontologists and Mineralogists, Eastern Section Annual Field Trip, p. 1-15.

Obermajer, M. 1997. Thermal maturity and petroleum potential of the Paleozoic strata in southwestern Ontario. Unpublished PhD thesis, University of Western Ontario, London, Ontario, 329p.

Obermajer, M., Fowler, M.G., Goodarzi, F. and Snowdon, L.R. 1995. Oil families and source rocks of southwestern Ontario. Geological Survey of Canada, Open File 3058, p. 401-405.

Obermajer, M., Fowler, M.G. and Snowdon, L.R. 1998. A geochemical characterization and a biomarker re-appraisal of the oil families from southwestern Ontario, Canada. Bulletin of Canadian Petroleum Geology, v.46, p. 350-378.

Parks, W.A. 1924 (abst.). Upper Ordovician at Toronto, Ontario. Geological Society of America Bulletin, v. 35, p. 103.

Parks, W.A. 1928. Faunas and stratigraphy of the Ordovician black shales and related rocks in southern Ontario. Transactions of the Royal Society of Canada, 3rd Series, v. 22, sec. 4, p. 53.

Patzkowsky, M.E., Slupik, L.M., Arthur, M.A., Pancost, R.D. and Freeman, K.H. 1997. Late Middle Ordovician environmental change and extinction: Harbinger of the Late Ordovician or continuation of Cambrian patterns? Geology, v. 25, p. 911-914.

Poole, W.H., Sanford, B.V., Williams, H. and Kelley, D.G. 1968. Geology of Southeastern Canada, *In* Geological Survey of Canada, Economic Geology Report, Number 1, Geology and Economic Minerals of Canada, R.J.W. Douglas (ed.), p. 227-303.

Powell, T.G., Macqueen, R.W., Barker, J.F. and Bree, D.G. 1984. Geochemical character and origin of Ontario oils. Bulletin of Canadian Petroleum Geology, v. 32, p. 289-312.

Qunilan, G.M. and Beaumont, C. 1984. Appalachian thrusting, lithosphere flexure and the Paleozoic stratigraphy of the eastern interior of North America. Canadian Journal of Earth Sciences, v. 21, p. 973-995.

Roliff,W.A. 1954. The pre-Middle Ordovician rocks of southwestern Ontario. Proceedings of the Geological Association of Canada, v. 6, part II, p. 103-109.

Raymond, P.E. 1912. Paleontological Division: Invertebrate. Geological Survey of Canada, Summary Report 1911, p. 354.

Rudkin, D., Stott, C., Tetrault, D., and Rancourt, C. 1998. Ordovician and Silurian rocks and fossils of the southern Georgian Bay area, Ontario. Eighth Canadian Paleontology Conference, Field Trip Guidebook, Collingwood.

Russell, D.J. and Telford, P.G. 1983. Revisions to the stratigraphy of the Upper Ordovician Collingwood Beds of Ontario - a potential oil shale. Canadian Journal of Earth Sciences, v. 20, p. 1780-1790.

Sanford, B.V. 1961. Subsurface stratigraphy of Ordovician rocks in southwestern Ontario. Geological Survey of Canada, Paper 60-26, 54p.

Sanford, B.V. 1962. Sources and occurrences of oil and gas in the sedimentary basins of Ontario. Proceedings of the Geological Association of Canada, v. 14, p. 59-89.

Sanford, B.V. and Quillian, R.G. 1959. Subsurface stratigraphy of Upper Cambrian rocks in southwestern Ontario. Geological Survey of Canada, Paper 58-12, 33p.

Sanford, B.V., Thompson, F.J. and McFall, G.H. 1985. Plate tectonics - a possible controlling mechanism in the development of hydrocarbon traps in southwestern Ontario. Bulletin of Canadian Petroleum Geology, v. 33, p. 52-71.

Sanford, J.T. 1972. Niagaran-Alexandrian (Silurian) stratigraphy and tectonics. *In* Niagaran Stratigraphy: Hamilton, Ontario, R.T. Segall and R.A. Dunn (eds.), Michigan Basin Geological Society , Fieldtrip Guidebook, p. 42-55.

Scotese, C.R. and McKerrow, W.S. 1991. Ordovician plate tectonic reconstructions. *In* Advances in Ordovician Geology, C.R. Barnes and S.H. Williams (eds.) Geological Survey of Canada, paper 90-9, p. 271-282.

Sloss, L.L. 1963. Sequences in the cratonic interior of North America, Geological Society of America Bulletin, v. 74, p. 93-114.

Snowdon, L.R. 1984. A comparison of ROCK EVAL pyrolysis and solvent extract results from the Collingwood and Kettle Point oil shales, Ontario. Bulletin of Canadian Petroleum Geology, v. 32. P. 327-334.

Sproule, J.C. 1936. A study of the Cobourg Formation. Geological Survey of Canada, Memoir 202, p. 93-118.

Stanley, D.C.A. and Pickerill, R.K. 1993. Shallow marine *Paleodictyon* from the Upper Ordovician Georgian Bay Formation of southern Ontario. Atlantic Geology, v. 29, p. 115-119.

Stromquist, J.K., Dickhout, R. And Barker, J.F. 1984. Oil shale assessment project, volume 4, analytical geochemistry of selected potential oil shales (Ontario and New Brunswick). Ontario Geological Survey, Open File Report 5461, 46p.

Tarrant, G.A. 1977. Taxonomy, biostratigraphy and paleoecology of Late Ordovician conodonts from southern Ontario. Unpublished MSc thesis, University of Waterloo, Waterloo, Ontario, 240p.

Verma, H.M. 1979. Geology and fossils of the Craigleith area. Ontario Geological Survey, Guidebook No. 7, 61p.

Waldron, J.W.F., Jamieson, R.A., Stockmal, G.S. and Quinn, L.A. 1998. Loading the Laurentian margin: correlating foreland basin subsidence with eclogite metamorphism (Abst.). Atlantic Geology, v. 34, p. 79.

Wilson, A.E. 1937. Erosional intervals indicated by contacts in the vicinity of Ottawa. Transactions of the Royal Society of Canada, 3rd Series, v. 31, sec. 4, p. 46.

Wilson, A.E. 1964. Geology of the Ottawa-St. Lawrence Lowland, Ontario and Quebec. Geological Survey of Canada, Memoir 241, 66p.

Winder, C.G. 1961. Lexicon of Paleozoic names in southwestern Ontario. University of Toronto Press, 161 p.

Ziegler, A.M., Scotese, C.R., McKerrow, W.S., Johnson, M.E. and Bambach, R.K. 1979. Paleozoic paleogeography. Annual Review of Earth and Planetary Science, v. 7, p. 473-502.

Table 1. Ontario Geological Survey Coreholes with Upper Ordovician strata, southwestern Ontario (most stored at OGS, Sudbury)

CORE NAME	GENERAL LOCATION	O.G.S. OPEN FILE REPORT	LO. SIL. ABOVE QNSTN	UPP. ORD. ABOVE LINDS
Nobleton #1	R.M. York (Aurora)	5458 (1983)		32 m
S.I.S. #1	MetroToronto (Scarb)	5458 (1983)		44 m
S.I.S. #2	R.M. Durham (Ajax)	5458 (1983)		13 m
S.I.S. #3	R.M. Durham (Ajax)	5458 (1983)		34 m
S.I.S. #4	MetroToronto (Don VallQ)	5458 (1983)		118 m
Clgd #1	Grey Co. (Clarksburg)	5458 (1983)		25 m
Clgd #2	Grey Co. (Clarksburg)	5458 (1983)		87 m
Clgd #3	Grey Co. (Clarksburg)	5458 (1983)		28 m
Clgd #4	Grey Co. (Clarksburg)	5458 (1983)		8 m
Clgd #4b	Grey Co. (Clarksburg)	5458 (1983)		30 m
Clgd #6a	Grey Co. (Collingwood)	5458 (1983)		44 m
Clgd #7a	Grey Co. (Collingwood)	5458 (1983)		38 m
Clgd #16	Grey Co. (Thornbury)	5458 (1983)		50 m
Clgd #17	Grey Co. (Meaford)	5458 (1983)		50 m
Corbetton#1	Dufferin Co. (Shelburne)	5459 (1983)	27 m	302 m
SIS #13	Grey Co. (Banks)	5459 (1983)	42 m	8 m
SIS #14	Grey Co. (Gibraltar)	5459 (1983)	8 m	
OGS 83-1	Milton (Dufferin Q)	5477 (1983)	31 m	403 m
OGS 83-2	Mississauga (Clarkson)	5477 (1983)		270(234) m
OGS 83-3	Pickering (Ontario Hydro)	5477 (1983)		23 m
OGS 82-1	Lambton Co. (Courtright)	5565 (1985)	53 m	190 m
OGS 82-2	Kent Co. (Chatham)	5565 (1985)	51 m	262 m
OGS 82-3	Elgin Co. (Pt. Stanley)	5565 (1985)	36 m	358 m
OGS 82-4	Bruce Co. (Wiarton)	5565 (1985)	51 m	201 m

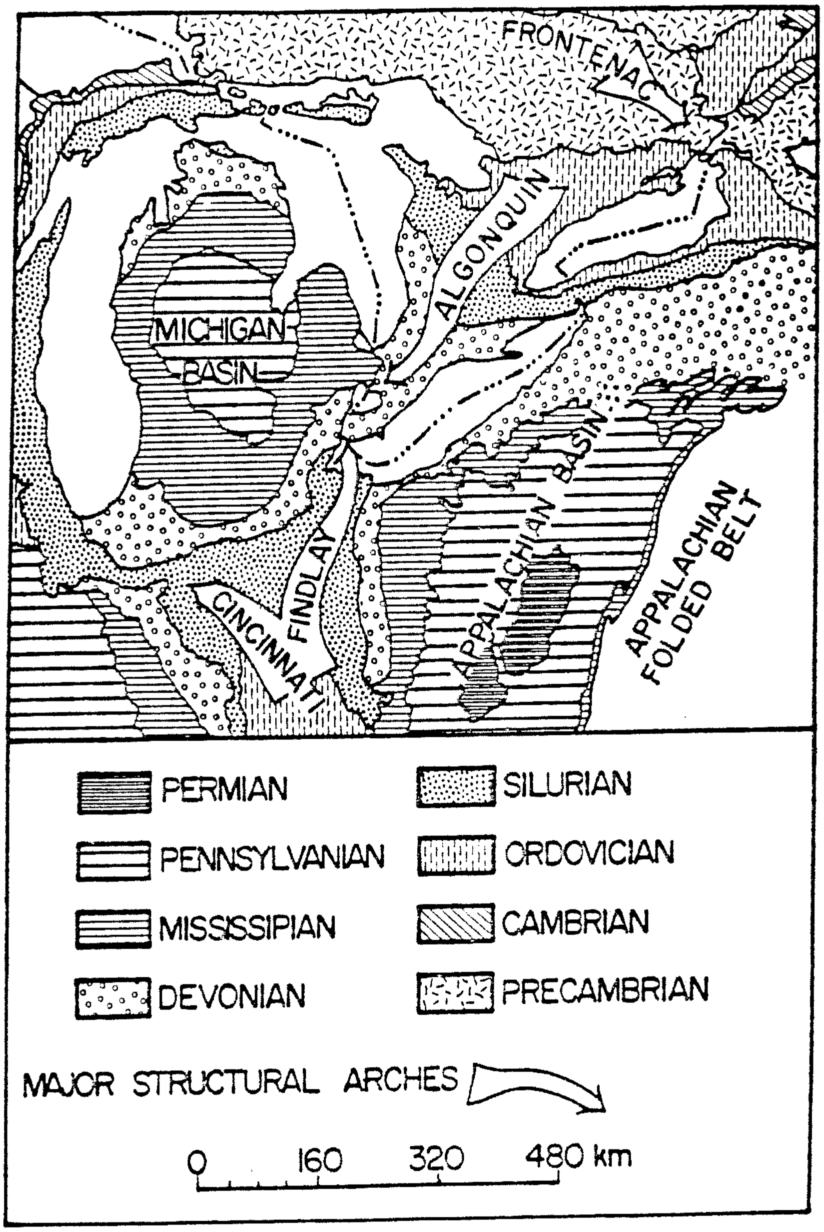
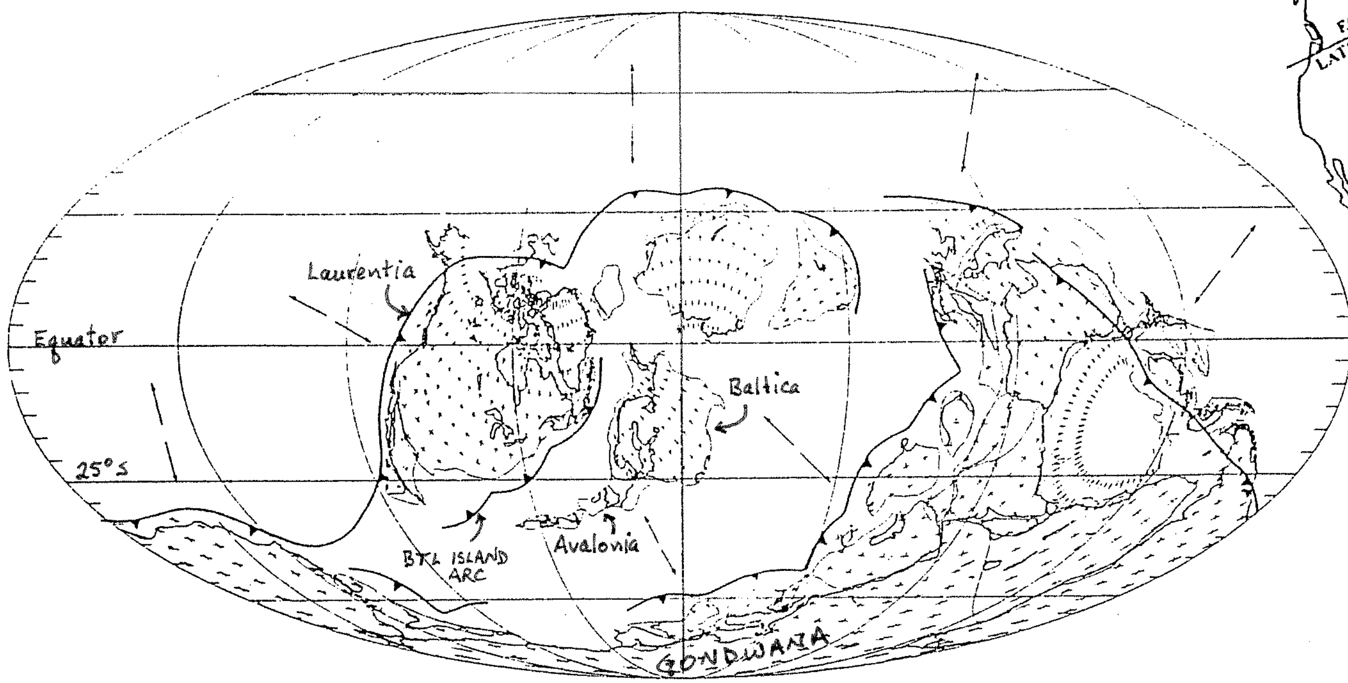

FRONTENAC
ALGONQUIN
MICHIGAN
BASIN
FINDLAY
CINCINNATI
APPALACHIAN BASIN
APPALACHIAN
FOLDED BELT
PERMIAN
PENNSYLVANIAN
MISSISSIPIAN
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN
PRECAMBRIAN
MAJOR STRUCTURAL ARCHES
0
160
320
480 km

Figure 1



Late Ordovician (Ashgill)

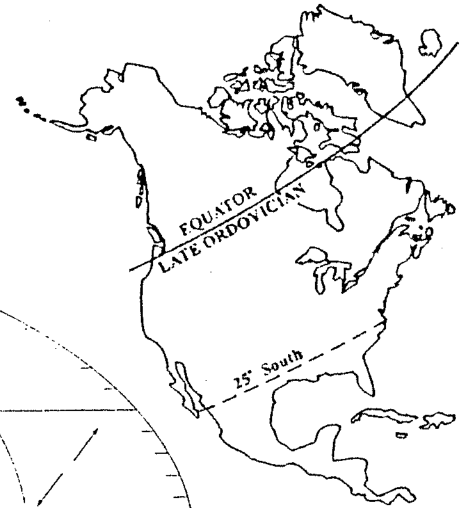
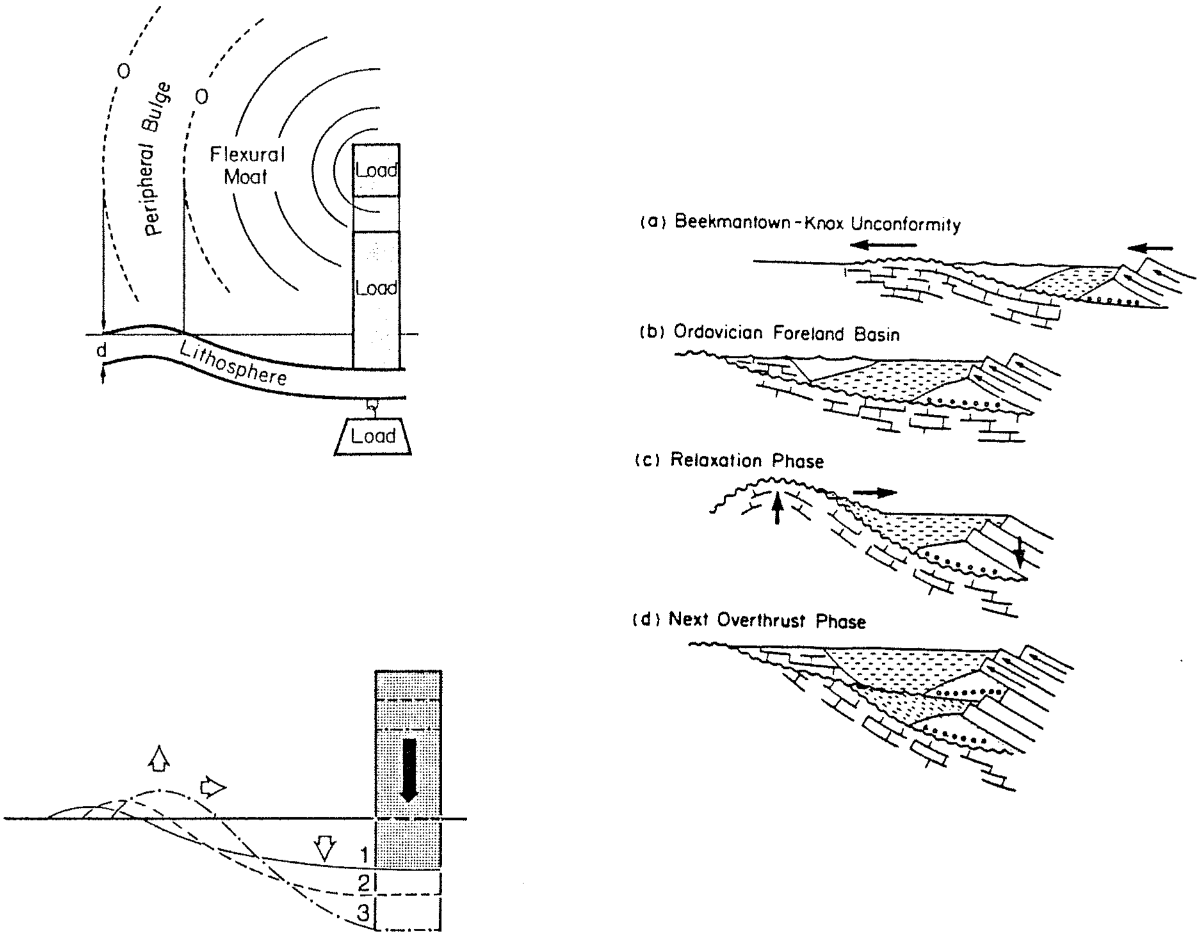


Figure 2.

(from Scotese and McKerrow, 1991)

A)



B)

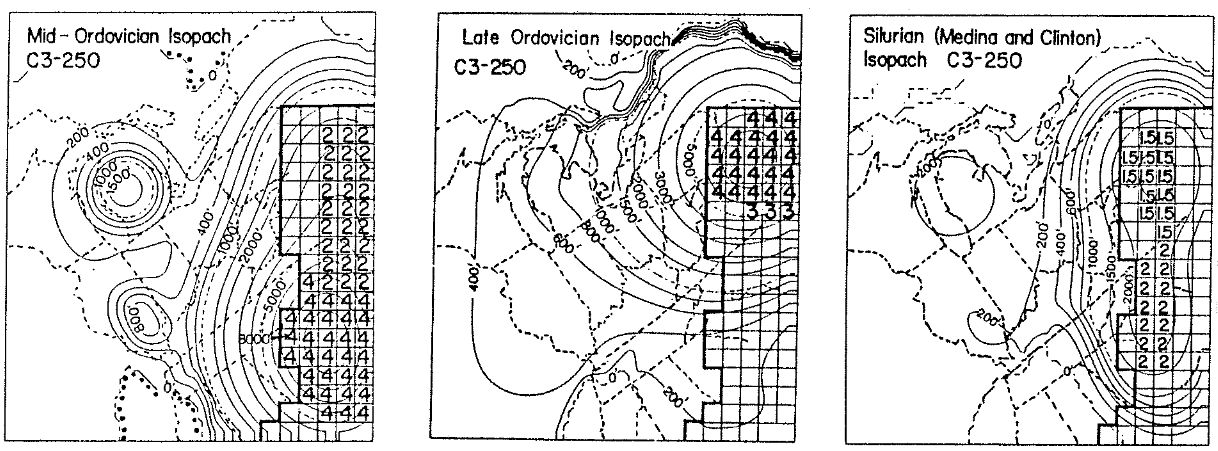
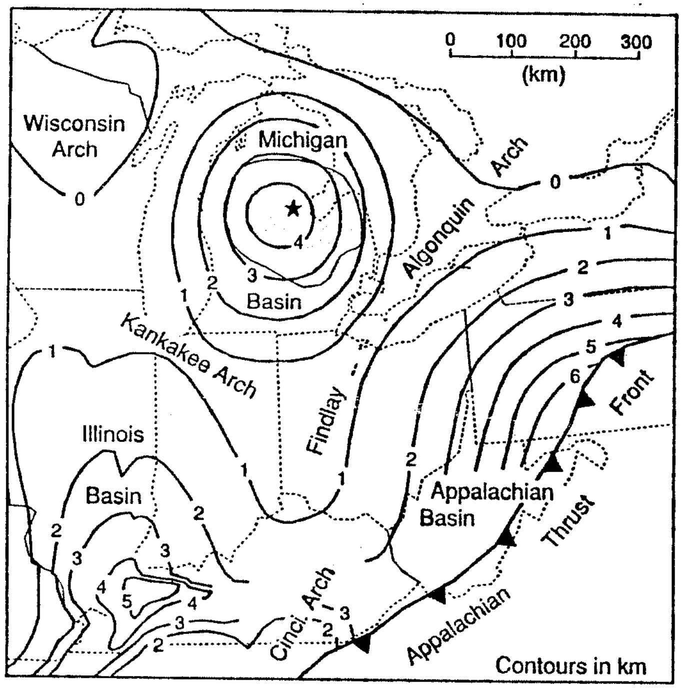


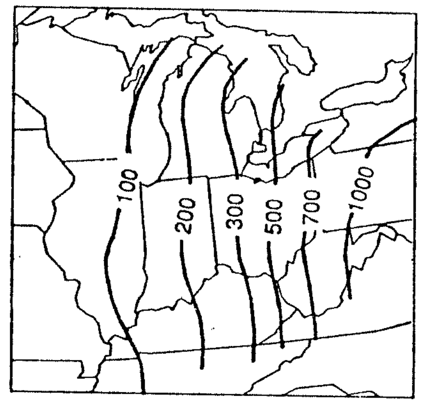
Figure 3.
(from Quinlan and Beaumont, 1984)

A)



B)

C)



(from Howell and van der Pluijm, 1990)

Figure 4.

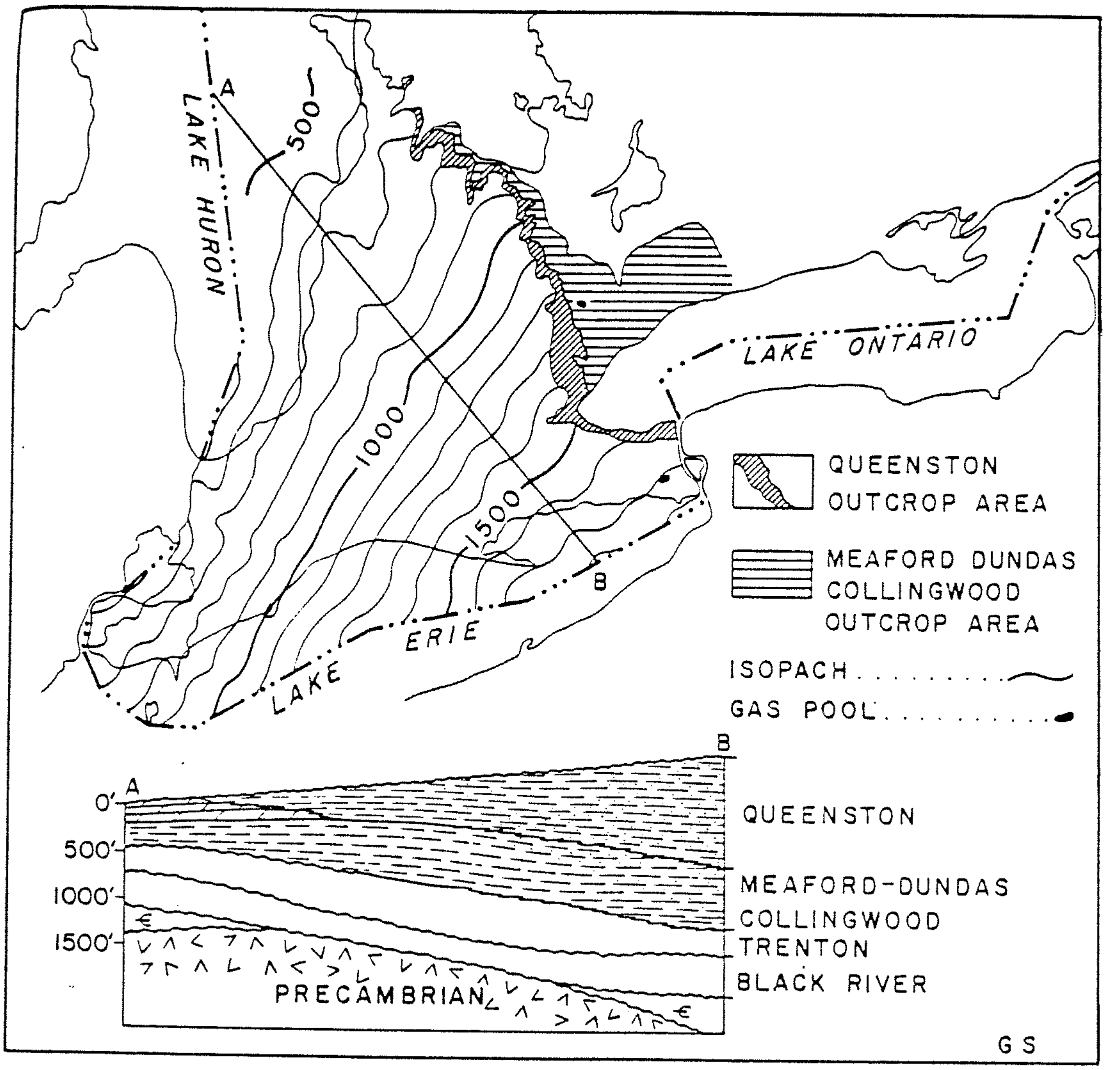
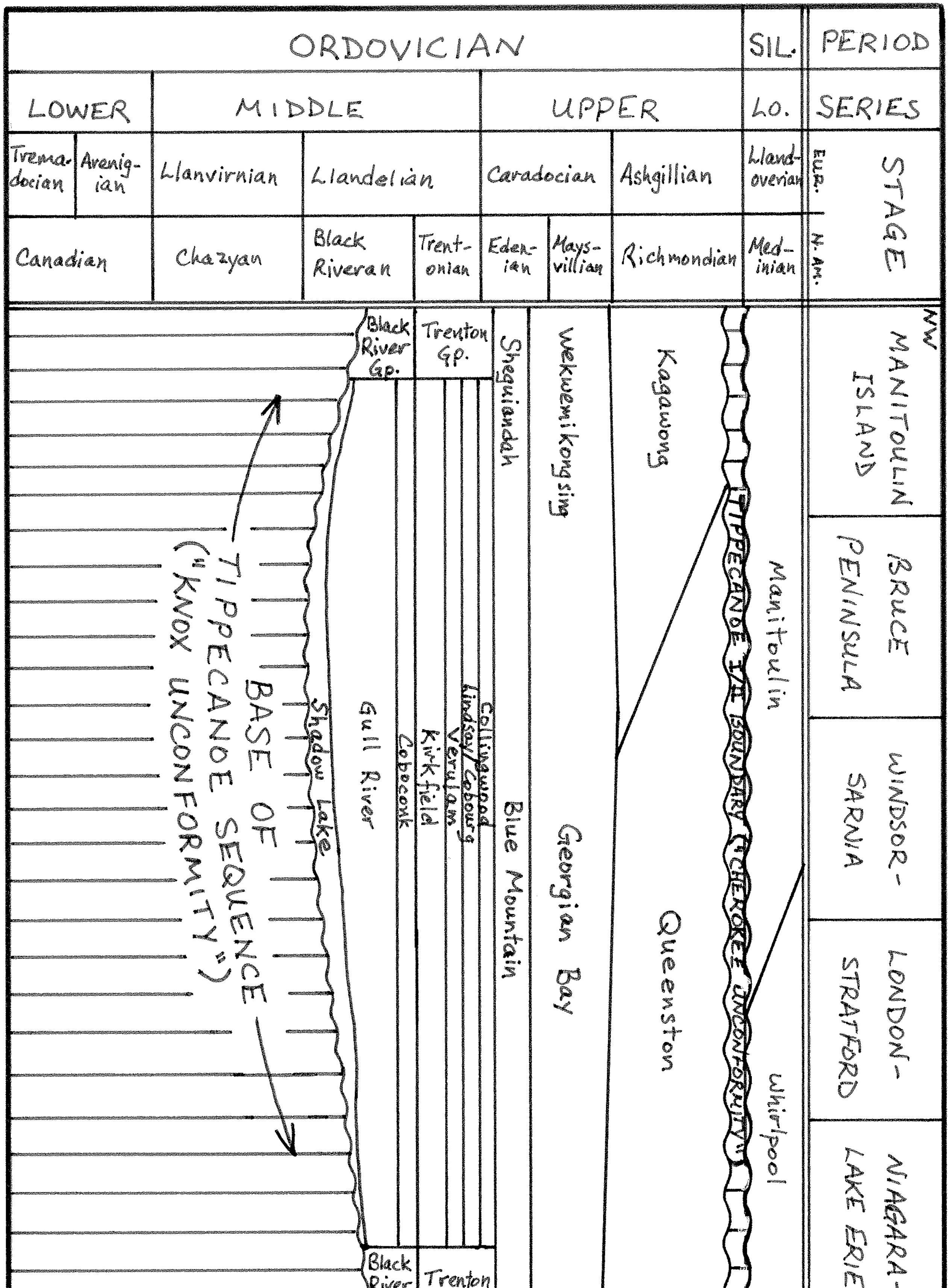


Figure 5.
(from Hutt et al, 1973)



ORDOVICIAN
SIL.
PERIOD
LOWER
MIDDLE
UPPER
Lo.
SERIES
Trema-docian
Arenig-ian
Llanvirnian
Llandelian
Caradocian
Ashgillian
Llandoverian
EUR.
STAGE
Canadian
Chazyan
Black Riveran
Trent-onian
Eden-ian
Mays-villian
Richmondian
Med-inian
N. AM.
NW
MANITOULIN ISLAND
BRUCE PENINSULA
WINDSOR-SARNIA
LONDON-STRATFORD
NIAGARA-LAKE ERIE
SE
Black River Gp.
Trenton Gp.
Sheguiandah
Wekwemikongsing
Kagawong
Manitoulin
Whirlpool
Queenston
Georgian Bay
Blue Mountain
Collingwood
Lindsay/Cobourg
Verulam
Kirkfield
Coboconk
Gull River
Shadow Lake
TIPPECANOE I/II BOUNDARY ("CHEROKEE UNCONFORMITY")
BASE OF TIPPECANOE SEQUENCE ("KNOX UNCONFORMITY")
Black River Gp.
Trenton Gp.

Figure 6.

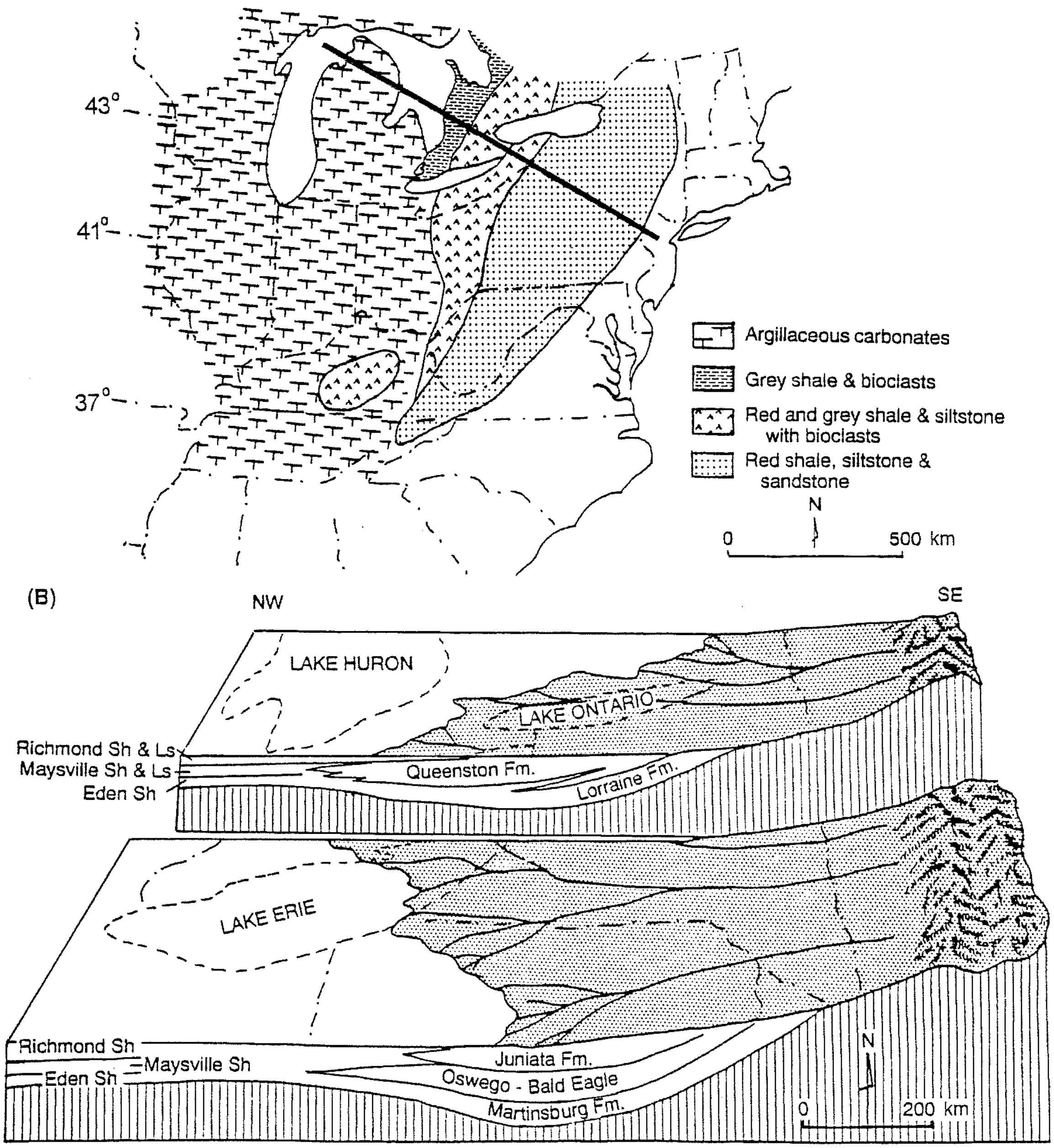


Figure 7.

(from Brogly et al., 1998)