GEOLOGICAL SURVEY OF CANADA

OPEN FILE 5730

Hydrocarbon Potential of the Paleozoic succession of southwestern Ontario: Preliminary conceptual synthesis of background data

A.P. Hamblin[1]

2008

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ABSTRACT

The hydrocarbon potential of the lower Paleozoic succession of southwestern Ontario was first realized in 1858 with the first commercial oil well in North America. Development continues today, at a modest level, for oil and gas in a wide variety of carbonate and clastic plays of many different ages and styles. Most discoveries and production in these understudied rocks are from step-outs to known fields, and there are few wildcats, little testing of new concepts and little modern stratigraphic analysis. Most zones still have excellent potential for further discoveries in this shallow, low-risk setting. The location in the heart of major markets is a significant positive factor. New geological study of structural controls, stratigraphic architecture and correlation, lateral predictability of reservoir geometry, trap mechanism for basin-centred gas plays, and generation of new play concepts would likely result in major increases in exploration success and economic impact.

SUMMARY DATA - PALEOZOIC OF SOUTHWESTERN ONTARIO

Age:	Upper Cambrian to Upper Devonian
Depth to Target:	Up to 1500 m
Hydrocarbon Shows:	Oil and gas shows in hundreds of wells, and over 300 oil and gas pools known to date
First Discovery:	Oil first discovered in 1858 near Oil Springs, representing the earliest commercial hydrocarbon discovery in North America, and gas first discovered in 1885 near Leamington
Discovered Resources:	Most recent preliminary regional assessment, now out of date, estimated undiscovered oil potential of 159 x 10^6 m^3, and undiscovered gas potential of 79,000 x 10^6 m^3. Recent assessment of Middle Ordovician hydrothermal dolomite play yielded estimates of 6,313, 671 m^3 recoverable oil (43% undiscovered) and 7,960 X 106 m^3 recoverable gas (85% undiscovered).
Basin Type:	Michigan Intracratonic Basin and Appalachian Foreland Basin
Depositional Setting:	Wide range of shallow marine deposits, including platform, reefal and bioclastic carbonates and shallow marine to shoreline clastics
Reservoirs:	Upper Cambrian nearshore-shoreline sandstones, Middle Ordovician fractured and hydrothermally-dolomitized limestones, Upper Ordovician mudstones, Lower Silurian nearshore sandstones, Middle/Upper Silurian reefal dolostones, Middle Devonian shelfal limestones, Upper Devonian mudstones
Regional Structure:	Michigan Intracratonic Basin to the northwest is separated from the Appalachian Foreland Basin to the southeast by the more stable hinge line of the Algonquin Arch
Traps and Seals:	Stratigraphic traps involve unconformity, shale interbed and diagenetic seals, whereas structural traps involve seals related to faulting, minor drape folding over underlying structures, and salt dissolution
Source Rocks:	Middle Ordovician Trenton Group, Middle/Upper Ordovician Collingwood Mbr/Blue Mountain Fm, Middle Silurian Eramosa Mbr, Upper Silurian Salina A-1 Mbr, Middle Devonian Marcellus Fm, Upper Devonian Kettle Point Fm
Total Number of Wells:	~21,000 well penetrations with records
Seismic Coverage:	Modest industry coverage

Pipelines: Excellent access near natural gas transmission lines in most of southwestern Ontario, but areas north of Highway 401 corridor are less well-served

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INTRODUCTION/OVERVIEW

The Lower and Middle Paleozoic strata of southwestern Ontario, up to about 1500 m thick, include a diverse assemblage of lithologies deposited in portions of both the Michigan and Appalachian basins. The sedimentary succession of Southern Ontario underlies an area of over 130,000 km^2 (1/3 offshore beneath lakes Ontario, Erie and Huron). Within this small area, plays include both stratigraphic and structural traps, in both clastic and carbonate reservoirs. These rocks form part of the oldest petroleum province in North America and represent the cradle of the modern energy industry. The first commercial oil well in North America was drilled in 1858 near the town of Oil Springs (Hutt et al., 1973). In addition, the first offshore drilling in the world occurred here in Lake Erie. Although these successions have been the subject of successful exploration for nearly 150 years, activity has remained at a relatively low level and confined to established plays and areas: potential for under-explored or new play concepts and areas still exists. Whereas reserves and production rates are generally modest by global standards, their high quality, shallow depth, low operating costs and location in the midst of a rapidly-expanding prime North American market make them eminently profitable.

An estimated 50,000 wells have been drilled in the search for hydrocarbons to date, although records are available for only about 26,000. To the end of 2006, 149 oil and 198 gas pools have been discovered and 13.7 million m^3 (86 million bbl) of oil and 35.9 billion m^3 (1.2 Tcf) of gas have been produced (T. Carter, Ontario Ministry of Natural Resources, pers. comm., 2007). In 2006, Ontario produced approximately 780,000 barrels of oil, valued at $57 million, from 1200 active wells, and 12 billion cubic feet of natural gas valued at $98 million from 1300 active wells. Ordovician reservoirs currently dominate oil production in Ontario and accounted for 70% of Ontario production in 2006, compared to less than 4% in 1982. Silurian sandstone and reef traps beneath Lake Erie accounted for 65% of the natural gas production in 2006 from 540 active wells located on the lake bottom. Approximately 80 new wells are drilled each year in Ontario. Cambrian, Ordovician and Devonian strata contain numerous oil pools, whereas gas is dominant in Silurian strata. A recent provisional assessment suggests significant oil and gas potential still exists in this region. As a result of a recent GSC-funded Targeted Geoscience Initiative project, the release of an updated guide to the subsurface units (Armstrong and Carter, 2006) and a full resource assessment of the most active oil play (Golder Associates Ltd, 2005) provide a cogent starting point for further study of the hydrocarbon potential.

In addition, annual underground storage of hydrocarbons in depleted former natural gas reservoirs is of vital importance to Ontario's economy, and allows the immediate and local marriage of supply with demand. Both natural gas and liquified hydrocarbons are stored underground within depleted former natural gas reservoirs of the Paleozoic bedrock. Data supplied by T. Carter (2004, pers. comm.) indicate a total of 30 reservoirs have been converted to storage of natural gas with a cumulative storage capacity of 236 billion cubic feet. Twenty-nine of the storage pools are located in Lambton County or northern Kent County and utilize Guelph Formation pinnacle reef reservoirs. One small pool is located in the Niagara peninsula and utilizes a reservoir in Lower Silurian Whirlpool sandstone. In 2003 there were 285 wells used for injection/withdrawal of natural gas into/from storage reservoirs and an additional 73 wells were used for observation. Further unevaluated storage and/or waste disposal potential exists within pinnacle and patch reefs, and possibly in deeper Cambrian sandstone reservoirs, or Ordovician hydrothermal dolomite reservoirs.

Although this area has a long history of exploration, and the potential for further discoveries is modest by world standards, the importance to the regional economy, and its effect on national interests, is pre-eminent.

GEOLOGICAL SETTING

Southwestern Ontario overlies parts of three main tectonic elements: 1) the Appalachian Foreland Basin, dominated by southeastern- (orogen-) derived, clastic sediments; 2) the Michigan Intracratonic Basin, dominated by carbonate and evaporite sediments; and 3) the Algonquin Arch, a basement hinge-line of lesser subsidence, which separates those basins and hosts an interfingering succession of carbonates and clastics (Brigham, 1971; Armstrong, 1992; Sanford, 1993a) (Fig. 1). During the first 120 m.y. of Phanerozoic time (Sauk Sequence) the cratonic margins were largely passive, flexural cratonic downwarps were rare and great thicknesses of uniform sandstones and carbonates were deposited near the margins (Sanford, 1993a). However, in the succeeding 150 m.y. (Tippecanoe and Kaskaskia sequences), the Appalachian margin became a site of active plate convergence, foreland basin subsidence and sediment derivation from orogenic sources. Meanwhile, the cratonic interior witnessed the emergence of flexure-dominated syndepositional arches and basins (Sanford, 1993a).

Precambrian rocks form the basement to the Paleozoic strata and are exposed in outcrop northeast of Lake Simcoe, marking the southern margin of the Canadian Shield. They consist of complexly deformed and metamorphosed plutonic, volcanic and sedimentary rocks of the Central Gneiss Belt and the Central Metasedimentary Belt of the Grenville Province and represent the eroded roots of a major mountain chain formed by the Grenville Orogeny at approximately 1000-1100 Ma (Carter et al., 1996). The Grenville orogeny was a major episode of compressional thermal metamorphism and northwest-directed thrusting and imbrication of the entire crust. The basement gneisses now comprise large blocks or "domains" separated by narrow zones of intense deformation. Nearly 400 m.y. of erosion reduced these mountains to a surface with local relief of less than 50 metres except where it is broken by faults. The basement geology has had a controlling influence on reservoir and trap development for some hydrocarbon plays in Ontario, in particular those associated with faults and fractures (Carter et al, 1996). During the Late Proterozoic, the south margin of Baltica rifted away from the east margin of Laurentia, creating the passive margin conditions which widened to form the Iapetus Ocean during the Cambrian. In the Early Ordovician, Iapetus began to narrow and newly-developed subduction to the northwest beneath the margin of Laurentia allowed the assembled island arcs to move northwestward to collide with Laurentia in the Early-Middle Ordovician, an event referred to as the Taconian Orogeny. This led to the foundering and collapse of the platform carbonates at the cratonic margin and produced the down-warped Appalachian Foreland Basin (Brett et al., 1990). Subsequent rapid subsidence led to progressive westward inundation of that drowned platform by deep-water and shallower-water clastics derived from the Taconian uplift. Continued subduction 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).

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. During the early Palaeozoic, the Algonquin Arch was a broad platform between the more rapidly subsiding Michigan Basin to the west and the Appalachian Basin to the east (Brigham, 1971; Sanford et al., 1985): facies changes which occur at that point are simply due to less continuous subsidence along that line. Because the two basins experienced active subsidence at alternating times, the hinge-line migrated back and forth between them. The Appalachian Basin subsided most strongly and accumulated the thickest strata during Late Cambrian, Late Ordovician-Middle Silurian and Late Devonian times; conversely, the Michigan Basin did so in Late Cambrian, and Late Silurian-Middle Devonian times (Brigham, 1971). 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; Sanford, 1993a).

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 (Fig. 2). Lower/Middle Paleozoic strata onlap the Algonquin Arch from the Michigan Basin in the west and from the Appalachian basin in the south (Armstrong, 1992; Sanford, 1993a). Strata range in age from Late Cambrian to earliest Carboniferous, comprising a succession of carbonate and clastic deposition which recorded the subsidence and filling of the Appalachian and Michigan basins on the southeastern margin of the North American Precambrian craton. The area resided at about 20°-30°S. paleolatitude in Lower Paleozoic time on the distal, northwest margin of the Appalachian Foreland Basin during a phase when the Gondwanan continent was moving toward the South Pole. The climate was generally warm and seasonally arid, perhaps a dry subtropical area. However, the Late Ordovician glacial phase, predominantly in the southern hemisphere Gondwanan continental fragments of Africa and South America, temporarily dominated world climates.

The concept of major, broadly-distributed rock-stratigraphic units of interregional scope, delimited by a small number of interregional unconformities (as introduced by Sloss) has provided a unifying tool for organizing the Paleozoic strata of cratonic North America. In Southern Ontario, components of the Sauk, Tippecanoe and Kaskaskia Sequences are preserved and present hydrocarbon potential (Fig. 3). During the Sauk Sequence, Upper Cambrian and Lower Ordovician marine depositional units overlapped the basal unconformity and originally covered the Algonquin Arch. However, these strata were eroded from the Arch crest during a phase of Early Ordovician uplift and erosion (the Knox Unconformity, which ended the Sauk). Preserved deposits now include a Late Cambrian overall transgressive sequence of basal Potsdam/Mount Simon sandstone, Theresa/Eau Claire sandy dolostone and Little Falls/Trempeleau dolostone (Armstrong, 1992; Johnson et al., 1992), and these units have significant hydrocarbon production and potential (Sanford, 1993b). No evidence of Lower Ordovician deposits remains in southwestern Ontario, although they are present in the Ottawa Lowlands.

The Tippecanoe Sequence is represented by a thick and complex assemblage of Middle Ordovician to Late Silurian clastics and carbonates which record the establishment and later collapse of the cratonic margin platform carbonates (Middle Ordovician), the tectonic creation and filling of the Appalachian Foreland Basin (Late Ordovician to Early Silurian) and the subsidence and expansion of the intracratonic Michigan Basin (Middle to Late Silurian) (Armstrong, 1992; Johnson et al., 1992). A transgressive-regressive sequence of Middle Ordovician marginal platform carbonates is represented by the basal clastics of the Shadow Lake, followed by Black River limestones and Trenton limestones (very important petroleum targets). This was followed by tectonic collision, subsidence of the Appalachian foreland and filling by Upper Ordovician-Lower Silurian clastics and minor carbonates in a transgressive-regressive sequence (including important source and reservoir rocks). Within this sequence, there is an obvious unconformity between Upper Ordovician rocks and Lower Silurian Medina Group rocks (Cherokee Unconformity, separating Tippecanoe I and II). 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 sandy wedge. In southwestern Ontario, at the crest of the Algonquin Arch (or "hinge line") these two facies styles intermix. Middle and Upper Silurian facies are dominated by carbonates and evaporites related to the subsidence, expansion and filling of the intracratonic Michigan Basin. These units include the Clinton, Lockport, Guelph and Salina carbonates (major hydrocarbon reservoirs).

The Kaskaskia Sequence is represented by a thick and complex assemblage of Lower-Middle Devonian to Early Carboniferous carbonates with minor clastics which record the establishment of platform carbonates (Lower-Middle Devonian), and the tectonic creation and filling of another Appalachian foreland basin (Late Devonian-Early Carboniferous) (Armstrong, 1992; Johnson et al., 1992). Thin, discontinuous Lower Devonian Oriskany sandstones, bounded by unconformities and of uncertain affinity present a challenging exploration target. Lower Devonian Springvale sandstone and Bois Blanc cherty limestone are bounded by unconformities. Also unconformity-bound, the Detroit River and Dundee (Onondaga) platform carbonates have a long history of hydrocarbon production, including the earliest major fields. Thick shales and minor limestones of the Middle Devonian Hamilton Group mark the renewed subsidence of the Appalachian Basin associated with the Acadian Orogeny and provide minor potential. The thick Kettle Point organic-rich shales and thin Port Lambton Group are present at or near surface over parts of the Michigan Basin area of southwestern Ontario.

EXPLORATION HISTORY/DISCOVERIES TO DATE

Exploration and production of hydrocarbon resources in southwestern Ontario has a long and distinguished history, stretching back over 150 years (see also Bailey and Cochrane 1984a, 1984b, 1985, 1986, 1990 for further details). In the early 1800's a series of “gum beds” were noted locally in Lambton County which later proved to be oil seeps from shallow Devonian reservoirs. To exploit the Lambton County surface seeps (for ship caulking, asphalt and fuel), the Tripp Brothers registered the first oil company in North America (perhaps the world) in 1854, as the “International Mining and Manufacturing Company”. They achieved international recognition at the Paris Exposition of 1855 for their superior asphalt. This organization was then 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 commercial oil well at Oil Springs (Sanford, 1993b). He immediately constructed a small refinery and began producing refined kerosene for oil lamps. Over the next four years, 400 wells had been drilled, but the flow of oil from very shallow reservoirs was waning, until Hugh Shaw spent six months drilling deeper and brought in the world’s first “gusher” in 1862. By 1900 there were 2500 producing wells within an area of only 80 km^2 of Lambton Co. However, extreme overproduction, spillage and, in particular, the aggressive marketing of the Pennsylvania oil fields (discovered one year after Williams’ well) led to plummeting prices and a decrease in activity. The industry has continued to thrive at a low level through the succeeding century. Due to several small oil spills and growing environmental concerns, the provincial government placed a moratorium on all offshore oil exploration or production, in all of the Great Lakes, in 1970. Exploration for natural gas on Lake Erie is still permitted.

The Upper Ordovician Collingwood shales have been known to be petroliferous since the earliest reports of the Geological Survey of Canada and were the object of early attempts to process oil shales. A wood-fired plant for the distillation/extraction of oil from the outcrops of these shales was established at Craigleith in 1859. 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. An extensive program to evaluate the oil shale potential of the Collingwood was pursued by Ontario Geological Survey in the mid-1980's.

Oil seeps from the Ordovician Trenton-Black River strata were noted on Manitoulin Island as early as 1860, and several small gas and oil pools were discovered in the early 20th Century, but concerted exploitation of this hydrothermal dolomite (HTD) play occurred in the 1980's after seismic surveys identified the linear fault-related dolomitization trends (Golder, 2005). This play is now the most important and prolific in Ontario.

In 1884 Eugene Coste drilled the first successful natural gas well in Canada at Medicine Hat, Alberta and also made the first discoveries of commercial quantities of gas in Ontario in 1885 with the drilling of the Coste #1 well near Leamington, Essex Co., and the Coste #2 well near Port Colborne both of which produced from Lower Silurian sandstone 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. In 1918 discoveries at Long Point proved that the Medina sandstone reservoirs extended into the Lake Erie offshore, although gas production from the lake did not begin until 1957. Gas production from the Silurian pinnacle reef play dates from 1899. Today, exploration for gas continues both onshore and in the Lake Erie offshore (there is currently a moratorium on exploration in lakes Huron, Superior and St. Clair).

SOURCE ROCKS, MATURATION, GENERATION AND MIGRATION

Most of the Paleozoic of southwestern Ontario is within the oil window. The Cambrian/Lower Ordovician succession of southwestern Ontario is thermally mature (C.A.I. = 2-2.5, 60-90° maximum burial temperature), but the Middle Ordovician to surface section is marginally mature (C.A.I. = 1.5, maximum burial temperature 60°) (Barker and Pollack, 1984). Produced oils in southwestern Ontario fall into three stratigraphically-distinct families, from oldest and most mature to youngest and least mature: Cambro/Ordovician, Silurian, Devonian (Obermajer et al., 1998).

Cambro-Ordovician oils were likely derived from mature marine clastic sources formed under dysoxic to anoxic conditions, and likely of Ordovician (possibly Cambrian) ages, generally located in the same stratigraphic intervals as their reservoirs (e.g. organic-rich laminae in the Trenton, Collingwood marl with up to 11% TOC, or Blue Mountain shale) (Obermajer et al., 1998; 1999). There is presently no known source for Cambrian- or Ordovician-reservoired gas in the Ontario section and long-distance migration from deeper in the Appalachian Basin is likely (Barker and Pollack, 1984). In nearby New York and Ohio, Cambrian sandstone units include thin source rock intervals in the oil window with TOC = 3-5%. The Collingwood and Blue Mountain formations include rich, immature to mature, potential source rocks, which may prove to have potential for *in situ* production of shale gas (Hamblin, 2006).

The Silurian succession of southwestern Ontario is thermally immature to marginally 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. Geochemically-unique Silurian oils were derived from less mature carbonate/evaporite sources, likely of Middle Silurian ages, deposited under hypersaline conditions in a strongly reducing environment, local to the individual reservoirs and with short migration paths (e.g. Eramosa Mbr of the Guelph Fm; Obermajer et al., 1998; A-1 Mbr of the Salina Fm; Obermajer et al., 2000). 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). Because the maturity of the gases is greater than that of the enclosing rocks, the hydrocarbons were likely generated outside the boundaries of Ontario. However, there is no clear distinction between gases from the Michigan Basin and the Appalachian Basin.

Devonian oils are reservoired at very shallow depths (less than 150 m) on the Michigan Basin side of the Algonquin Arch. They were derived from the least mature marine clastic source formed under dysoxic to anoxic conditions, likely of Middle to Upper Devonian age, in either the Michigan or the Appalachian Basins, or a mixture of both (e.g. Marcellus, Kettle Point or a source outside Ontario) (Obermajer et al., 1997; 1998). Interestingly, despite their occurrence at such shallow depths, these Devonian oils are not biodegraded (Obermajer, 2007, pers. comm.). The Kettle Point is a rich, but immature, potential source rock, which may prove to have potential for *in situ* production of shale gas (Hamblin, 2006).

RESERVOIR FACIES

Productive facies in southwestern Ontario encompass a wide range of shallow marine carbonate and clastic lithologies (Powell et al., 1984). The Cambrian Sauk succession is a transgressive sequence of nonmarine/marginal marine sandstone, passing upward into shallow marine sandy dolostone and argillaceous dolostone. Basal sandstones of the Mount Simon/Potsdam are feldspathic porous arkoses of fluvial and tidal origin, and are overlain by porous sandy ooilitc dolostone of the Eau Claire/Theresa, of shallow marine origin.

Ordovician reservoirs of the Tippecanoe Sequence occur as narrow, linear, cross-cutting “chimneys or ribbons” of hydrothermal dolomite closely associated with vertical faults and fractures that formed conduits for fluid movement (Golder, 2005). Within, and adjacent to, these vertical dolomite zones, coarse grained bioclastic strata are often preferentially dolomitized in the widespread Black River-Trenton carbonate platform. These facies were originally deposited in storm-dominated shoal-shelf environments, in shoaling-upward sequences. Subsequent faulting, solution enhancement and diagenetic high-temperature hydrothermal dolomitization (preferentially focussed on coarser more porous bioclastic fabrics) created the main reservoir facies, situated around the fracture loci (Carter et al., 1996). In addition, the emerging concept of shale gas suggests that the fractured organic-rich mudstones of the Collingwood Member and the Blue Mountain Formation may themselves form viable reservoirs (Hamblin, 2006). Further study and exploration will be required to evaluate this concept.

Regionally, all Lower Silurian Medina hydrocarbons are reservoired in the area where the clastic strata dip southward, down the monoclinal flank of the Algonquin Arch into the Appalachian Foreland Basin. Traps are likely all stratigraphic, due to facies or diagenetic mechanisms: 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. Whirlpool linear NE/SW trending reservoirs, characterized by multicyclic quartz, are prolific producers in eastern and central Lake Erie and immediately adjacent onshore counties. Most Grimsby and Thorold commercial production is from linear north/south- or east/west-trending lenticular sandstone bodies, oriented either parallel or perpendicular to shorelines, apparently representing either offshore bars or incised tidal channels (MacDougall, 1973). The thicker Grimsby is particularly heterogeneous with multiple, laterally-discontinuous (isolated elongate bar and channel bodies) reservoir bodies throughout but Thorold reservoirs are thinner, more uniform and generally manifest as a single reservoir unit.

Middle and Upper Silurian reservoirs include widespread crinoidal/bryozoan bioclastic facies in the Reynales/Irondequoit formations, abundant and geographically small (but seismically-visible) pinnacle reefs (with reef heights up to 140 m) within the Guelph and Salina A-1 units, patch reefs in the Guelph Formation, and fault/reef drape structural traps in the Salina A-1 and A-2 units (Bailey and Cochrane, 1990). Reservoir facies typically involve a diverse coral or stromatoporoid framework with crinoidal and mud-mound facies, often dolomitized. The pinnacle reef gas reservoirs, when depleted, also form major gas-storage reservoirs.

Devonian reservoirs of the Kaskaskia Sequence are localized in the Lucas and Dundee formations (primarily on the Michigan Basin side of the Algonquin Arch) which are characterized by shallow subtidal to shelfal marine fossiliferous grainstones and laminated lime mudstones. Reservoir facies include dolomitized limestones, fractured limestones with dissolution porosity and minor calcareous sandstones, usually localized in large structural domes formed by collapse over dissolution features in the underlying salts of the Salina Group, or by drape over underlying Silurian pinnacle reefs (Bailey and Cochrane, 1985). In addition, the emerging concept of shale gas suggests that the fractured organic-rich mudstones of the Kettle Point Formation may themselves form viable reservoirs (Hamblin, 2006). Further study and exploration will be required to evaluate this concept.

POROSITY AND PERMEABILITY

As expected in a diverse assemblage of lithologies and depositional settings housed within two major basins of different tectonic origins and evolutions, the reservoir quality is extremely variable (following data provided by T. Carter, pers. comm.):

1) Middle/Upper Cambrian sandstone and dolostone reservoirs of the Appalachian Basin (including the Mount Simon-Potsdam basal sandstones and the Eau Claire-Theresa sandy dolostones, and immediately overlying Middle Ordovician Shadow Lake sandstone) have porosities (primary and secondary) of 8-20% and permeabilities of 1-300 md.

2) Middle Ordovician carbonate reservoirs of the Michigan Basin, within the various formations of the Black River and Trenton groups, are dominated by structural fracture and secondary dolomitization porosity which are extremely variable. High initial flow rates suggest good reservoir quality with secondary porosity ranging 3-6% and permeability averaging 1-10 md (and locally exceeding 3000 md). Production commonly drops off rapidly, but continues to drain matrix porosity.

3) Lower/Middle Silurian sandstone reservoirs of the Whirlpool, Grimsby and Thorold formations (Medina Group) in the Appalachian Basin, have porosities ranging generally from 6 to 18% (typically 10-15%) and permeabilities of 1-100 md (typically 5-10 md) throughout Ontario and the northeastern US. In many reservoirs, primary porosity is occluded by authigenic silica cement, but well-connected secondary porosity of 3-8% allows adequate production.

4) Middle/Upper Silurian carbonate reservoirs (primarily in the Michigan Basin) of the Guelph and Salina formations have vuggy and dolomitization porosities ranging 3-25% (averaging about 9%) and permeabilities ranging 5-170 md (averaging 20 md).

5) Middle Devonian carbonate reservoirs of the Michigan Basin include platform dolostones and limestones of the Lucas and Dundee formations. Lucas sucrosic dolomites have about 13% porosity and 4 md permeability. Sandy units between the carbonates have 18% porosity and 425 md permeability. Crinoidal limestones of the Dundee have 8-10% of vuggy and dolomitization porosity and about 3 md permeability. However, both characteristics can be much enhanced by pervasive fracturing, caused by subsidence and collapse of these carbonates over Salina salt dissolution features.

TRAPS, SEALS AND TIMING

Structural, stratigraphic, erosional truncation, and porosity/permeability pinchout mechanisms all play parts in trapping oil and gas in Cambrian units. Porous Cambrian units pinch out updip against the Precambrian surface and are top-sealed by the overlapping Shadow Lake Formation. Structurally-based mechanisms related to basement block faulting during various phases of rejuvenation of the Algonquin Arch, and erosional paleotopography are important controlling factors (Sanford et al., 1985; Carter et al., 1996).

Vertical seals for Ordovician hydrothermal dolomite reservoirs are formed by the thick, regionally-distributed shale and marlstone of the abruptly-overlying Collingwood Member and/or Blue Mountain Formation. This abrupt contact, identifiable over all of southwestern Ontario, marks the initiation of rapid subsidence and creation of the Appalachian Foreland Basin associated with the Middle to Late Ordovician Taconian Orogeny. Lateral seals for these reservoirs are formed where the porous hydrothermal dolomites grade into the non-porous regional limestones of the Trenton and Black River groups.

Stratigraphic, erosional truncation, porosity/permeability pinchout and hydrodynamic mechanisms play parts in trapping gas in Lower Silurian units (Barker and Pollack, 1984). Diagenetic, differential cementation trapping, due to permeability pinchouts, is the most prominent factor, making prediction difficult. Gas seeps are known from Niagara 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. The Medina Group of southern Ontario, western New York and eastern Ohio is one of the largest stratigraphic (basin-centred) gas traps in North America. Pool and field limits are not easily definable, and the entire region is essentially one vast stratigraphic trap. Most successful wells produce from several Medina formations.

Middle/Upper Silurian carbonate platform facies (Clinton Group) and isolated biohermal reservoirs (Albemarle Group) are primarily trapped by regionally-distributed thick, impermeable, encasing Salina salt and anhydrite deposits. Secondary (especially dolomitization) porosity is common in a number of reservoirs. Middle Devonian reservoirs are trapped beneath the thick terrigenous mudstones of the Hamilton Group which abruptly and unconformable overlie them. These shales represent the initiation of rapid subsidence and re-creation of the Appalachian Foreland Basin associated with the Middle to Late Devonian Acadian Orogeny.

POST-ACCUMULATION PROCESSES

Due to the extended and complex geological history of these rocks during and since deposition, diagenetic processes which create and destroy porosity and permeability were widespread in the Lower Paleozoic strata of southwestern Ontario. Whereas primary intergranular porosity is preserved in many units, secondary porosity is common in a number of reservoirs. Post-depositional dolomitization was a vitally important process in development and enhancement of porosity and subsequent migration of hydrocarbons in southwestern Ontario, particularly in Ordovician hydrothermal dolomite reservoirs and in Middle Silurian reef and structural reservoirs. In the case of Ordovician hydrothermal dolomites, the extensive regional fault and fracture network acted as conduits for localization of fluid flow and associated dolomitization. Dolomitization in Middle Silurian strata was the result of seawater flux through the regional platform carbonates, caused by evaporative drawdown in the Michigan Basin, with localized flow through pinnacle and patch reefs.

A regional network of faults and fractures have broken the Paleozoic bedrock into a complex series of fault blocks (Sanford et al, 1985). Fault displacements range up to 100 metres (Brigham, 1971) and controlled the formation of classic fault traps in both the Cambrian and the Middle Silurian A-1 and A-2 units. Fault and fracture conduits also resulted in differential post-depositional subsurface dissolution of the Salina Group salts. Subsequent collapse over the dissolution cavities created large structural traps and fracture porosity in the overlying Devonian carbonates (Brigham, 1971).

EXPLORATION PLAYS

The definition of play type and area, and the resulting predictive concepts which subsequently emerge, are the primary objectives of geological basin analysis. In southwestern Ontario, the combination of updip pinchouts, numerous unconformities, internal facies and porosity/permeability variation, subtle structural drape and faulting/folding with accompanying dolomitization all provide a myriad of opportunities for entrapment of oil and gas. As expected in a diverse assemblage of lithologies and depositional settings housed within two major basins of different tectonic origins and evolutions, the known hydrocarbon plays in southwestern Ontario (see Sanford, 1993b) are equally varied:

1) Middle/Upper Cambrian-Middle Ordovician shallow marine sandstone and dolostone reservoirs of the Appalachian Basin (including the Mount Simon-Potsdam basal sandstones and the Eau Claire-Theresa sandy dolostones, and immediately overlying Middle Ordovician Shadow Lake sandstone) occur around the edges of the plunging Algonquin Arch as stratigraphic pinch-out traps against the underlying Precambrian surface. They are also present over upturned basement blocks, sealed by a regionally-extensive unconformity and Middle Ordovician shale.

2) Middle Ordovician shallow marine carbonate reservoirs of the Michigan Basin, within the various formations of the Black River and Trenton groups, occur as narrow, linear, vertically-oriented, fault-related hydrothermal dolomitization zones, and associated horizontal bioclastic horizons, encased in non-

porous platform limestone (Golder, 2005). There is commonly a structural depression of 10-20 m over the dolomitized zone, displacement of the underlying Precambrian basement surface and a change in character of seismic records coincident with the transition from limestone to dolomite (Carter et al., 1996). Dolomitization and distribution of porosity is very heterogeneous, both laterally and vertically, but reservoir development is most common near the tops of either the Trenton or Black River groups. Extensive use of horizontal drilling has enhanced production in this play and reduced the risk associated with this reservoir heterogeneity.

3) Lower/Middle Silurian sandstone reservoirs of the Appalachian Basin produce from areas near the northern stratigraphic shale-out of the Whirlpool, Grimsby and Thorold formations (Medina Group), both onshore and in Lake Erie, apparently trapped by local variations in porosity and permeability. Sandstones were deposited in fluvial, shoreline and shallow marine settings. These reservoirs represent the earliest 19^{th}C gas discoveries and a century of co-mingled production, lack of understanding of trap mechanisms and poor records have obscured realistic pool designations. Some aspects of trapping may relate to high mobile-water saturations and the associated basin-centred gas accumulations to the southeast in the US., and the entire area is essentially a continuous regional stratigraphic trap. Dolostones of the immediately overlying Irondequoit Formation (Clinton Group) are also productive.

4) Middle/Upper Silurian carbonate reservoirs (primarily in the Michigan Basin) include pinnacle reefs in the Guelph and Salina A-1 units, incipient reefs in the Guelph Formation, patch reefs in the Guelph Formation, and structural traps related to faulting and reef-drape in the Salina A-1 and A-2 units. All reservoirs are sealed by surrounding thick evaporite deposits of the Salina Formation and many of these pools have been subsequently converted to gas storage.

5) Middle Devonian carbonate reservoirs of the Michigan Basin include shallow marine platform dolostones and limestones of the Lucas and Dundee formations (associated with salt solution fracturing and subtle structural drape over Guelph reefs), and sandy limestones which occur at the unconformable contact between these two units. Minor production has been obtained from thin carbonate units in the Hamilton Group. These reservoirs represent the original 19^{th}C discoveries which yielded spectacular initial flow rates from shallow depths (i.e. less than 150 m).

Possible new conceptual plays might include 1) the extension of the Cambrian play around the full extent of the edges of the Algonquin Arch and even up onto the Arch erosional surface, 2) concerted exploration of the basal Middle Ordovician Shadow Lake sandstone where it overlaps the Cambrian and may be in communication with the Cambrian, 3) definition and exploration of the Upper Ordovician shoreline-related sandstones and carbonates at the tops of shallowing-upward sequences in the Georgian Bay and Queenston formations (Hamblin, 2003), 4) attempts to lend predictability to the Lower Devonian discontinuous Oriskany and Springvale sandstones, and 5) shale gas produced from Upper Ordovician and Upper Devonian organic-rich mudstone units (Hamblin, 2006).

RECENT RESERVE/RESOURCE ESTIMATES

The last comprehensive assessment of Ontario's remaining hydrocarbon resources was completed in the early 1980's, although several potential gas supply estimates were conducted in 1996 and 2001 based on that information (e.g. Osadetz et al., 1996). Since that time, an additional 3000 petroleum wells have been completed in southern Ontario, and Ordovician strata now dominate oil production. New technologies and techniques have been developed, there has been a dramatic improvement in the quality of surface and subsurface data available and new geological concepts and interpretations have evolved. Currently, a new assessment of the Ordovician Trenton-Black River HTD play has been completed, funded through federal "Targeted Geoscience Initiative 2" monies (Golder, 2005).

The most recent regional assessment indicated that, as of the early 1980's:

1) Middle/Upper Cambrian sandstone and dolostone reservoirs (including Middle Ordovician Shadow Lake sandstone) had remaining proven oil reserves of 909,000 m^3 and remaining proven gas reserves of 457 billion m^3 from 19 pools, with remaining oil potential of 17.71 million m^3 and remaining gas

potential of 6.27 billion m^3 (located in both the Appalachian and Michigan Basins, and predominantly offshore in Lakes Huron and Erie).
2) Middle Ordovician carbonate reservoirs had remaining proven recoverable oil reserves of 30,813 m^3 and remaining proven recoverable gas reserves of 50, 952 m^3 reflecting production from only two pools, with remaining oil potential of 5.44 million m^3 and remaining gas potential of 9.70 billion m^3 (70% located in the Michigan Basin area and a significant portion offshore in Lakes Huron and Erie). These estimates have now been superseded by a new assessment (Golder, 2005) focussed on this single play, yielding the following potential: recoverable oil resources of 6,313,671 m^3 including 2,733,296 m^3 (i.e. 43%) of undiscovered potential, and recoverable gas resources of 7,960,106 m^3 including 6,799106 m^3 (i.e. 85%) of undiscovered potential.
3) Lower/Middle Silurian sandstone reservoirs had remaining proven recoverable gas reserves of 5.54 billion m^3 from an unknown and poorly-defined number of pools with co-mingled production spanning a century, and remaining gas potential of 21.52 billion m^3 (located predominantly in the Lake Erie offshore).
4) Middle/Upper Silurian carbonate reservoirs had remaining proven recoverable oil reserves of 310,000 m^3 and remaining proven recoverable gas reserves of 9.5 billion m^3 in 148 oil and gas pools, with remaining oil potential of 36 million m^3 and remaining gas potential of 22 billion m^3.
5) Middle Devonian carbonate reservoirs had remaining proven recoverable oil reserves of 430,000 m^3 in 25 pools, with remaining oil potential of 10.86 million m^3 (located primarily in offshore lakes Huron and Erie).

These data, most now 20 years out of date, do not reflect the current position at all, and need to be re-analysed. Pool boundaries and trap mechanisms in the Lower/Middle Silurian play have never been adequately defined, and assessment has never been scientifically analysed. Additionally, at the time the Ordovician carbonate play (deeper than most well penetrations) accounted for about 15% of oil production and 1% of gas production, whereas today, with much more deep drilling, the comparable values are 70% and 10%. The recent assessment of this play (Golder, 2005) has highlighted the considerable upside of this region, even in a well-exploited play, aside from the potential of the other, poorly-understood, plays.

A provisional assessment, published by GSC in 1996, of oil and natural gas potential in southwestern Ontario (Osadetz et al., 1996) suggested that there is significant, under-estimated potential in the region. This study suggested a total undiscovered potential of 158.94 million m^3 of oil in 9 plays and 78.74 billion m^3 of gas in 9 plays. Within these totals, the most prospective oil plays are “Ordovician structural” and “Guelph Pinnacle” (comparable to plays 2 and 4 above), whereas the most prospective gas plays are “Clinton-Cataract Stratigraphic” and “Guelph Platform” (comparable to plays 3 and 4 above). For gas, the largest reserves and the largest remaining potential by far was estimated to reside in stratigraphic trap pools of the “Clinton-Cataract” strata (Osadetz et al., 1996), which includes the gas-producing formations of the Medina Group (Whirlpool, Grimsby and Thorold) and of the Clinton Group (Reynales, Irondequoit).

LEVEL OF CERTAINTY/RISK

With over 300 oil and gas pools, thousands of individual producers and a modest, but long, history of successful exploration, Lower Paleozoic strata in southwestern Ontario are certain to contain additional undiscovered resource. Low reservoir pressure and relatively modest pool size are challenges to be recognized. Conversely, shallow depth, location in the middle of a prime North American market, and laterally extensive mappable reservoir trends ensure good rates of success and economic feasibility in the better-known units. Those units less well-studied need further detailed stratigraphic analysis to yield similar results. Most production is from step-outs from known fields, and there have been few true wildcats and little testing of new concepts. More unconventional thinking might allow new conceptual plays to emerge. The risk for successful exploration in these strata could be relatively low if more detailed research brought the status of knowledge to the level of productive horizons in WCSB.

POTENTIAL FOR NEW DISCOVERIES

The last complete geological analysis and statistical assessment of Lower Paleozoic oil and gas resources of southwestern Ontario (now 20 years out-of-date) and a recent provisional assessment indicated the following conclusions. For gas, Lower Silurian sandstones, Middle Ordovician carbonates and Upper Cambrian sandstones/carbonates still have excellent potential for further discoveries. There is considerable remaining untested potential for natural gas resources in the Ordovician hydrothermal dolomite play: exploration to date has focussed only on the oil play in these strata, with only 1700 well penetrations in an area of 130,000 km^2. The recent assessment of this play suggested considerable undiscovered potential for both oil and gas. For oil, Middle Devonian carbonates, Middle Ordovician carbonates, Upper Silurian carbonates and Upper Cambrian sandstone/carbonate reservoirs still have excellent potential for further discoveries. These are all established plays, with variable levels of knowledge.

However, the units where fresh geological work would have the greatest impact in suggesting novel play concepts or new geographic areas, and perhaps lead to greater potential returns, are the less well-known Upper Cambrian sandstones/carbonates, Middle Ordovician basal clastics, Upper Ordovician clastics, and Lower Devonian basal clastics. In most areas, there is very little well penetration below the traditional producing target of that region.

KNOWLEDGE GAPS

Whereas geological understanding of the Middle Ordovician, Middle-Upper Silurian, and Devonian carbonate targets is already at a modest to high level, new geological study of the lesser known and under-explored units and concepts would greatly improve understanding, prospects and exploration efficiency in these strata. In general, analysis of facies, stratigraphic architecture and lateral predictability of reservoir geometry would be most valuable in encouraging more focussed industry attention. In particular, the extent and reservoir quality of Cambrian units around the edges of the Algonquin Arch and into the Michigan Basin, analysis of the potential of the basal Ordovician sandstone, the geometry and reservoir quality of the shallowing-upward sequences and shoreline reservoirs of the Upper Ordovician succession, the predictability and potential of the basal Devonian sandstone, the potential for production of shale gas from Ordovician and Devonian mudstones, the origin of natural gas in southwestern Ontario, and the trap mechanism for the gas reservoirs/basin-centred play are all subjects which would help drive new exploration efforts. Perhaps most crucial, a reassessment of the subtle structural geology of southern Ontario would be particularly beneficial, given the direct relationship between structure and traps for many reservoir intervals. In particular, clarification of the distribution, magnitude and importance of basement faults (affection Cambrian and Ordovician strata), reef drape (affecting Silurian and Devonian strata) and salt dissolution (affecting Silurian and Devonian strata) would be critical.

CONCLUSION

It is clear from recent discovery rates, and the most recent numerical assessment, that a major step forward in conceptual and stratigraphic/structural analysis of Middle Ordovician hydrothermal dolomite reservoirs resulted in a major increase in exploration success during the 1980's and 1990's. Similar efforts in other units could yield similar surges in activity and additions to Canada’s reserves from these under-studied rocks.

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FIGURES