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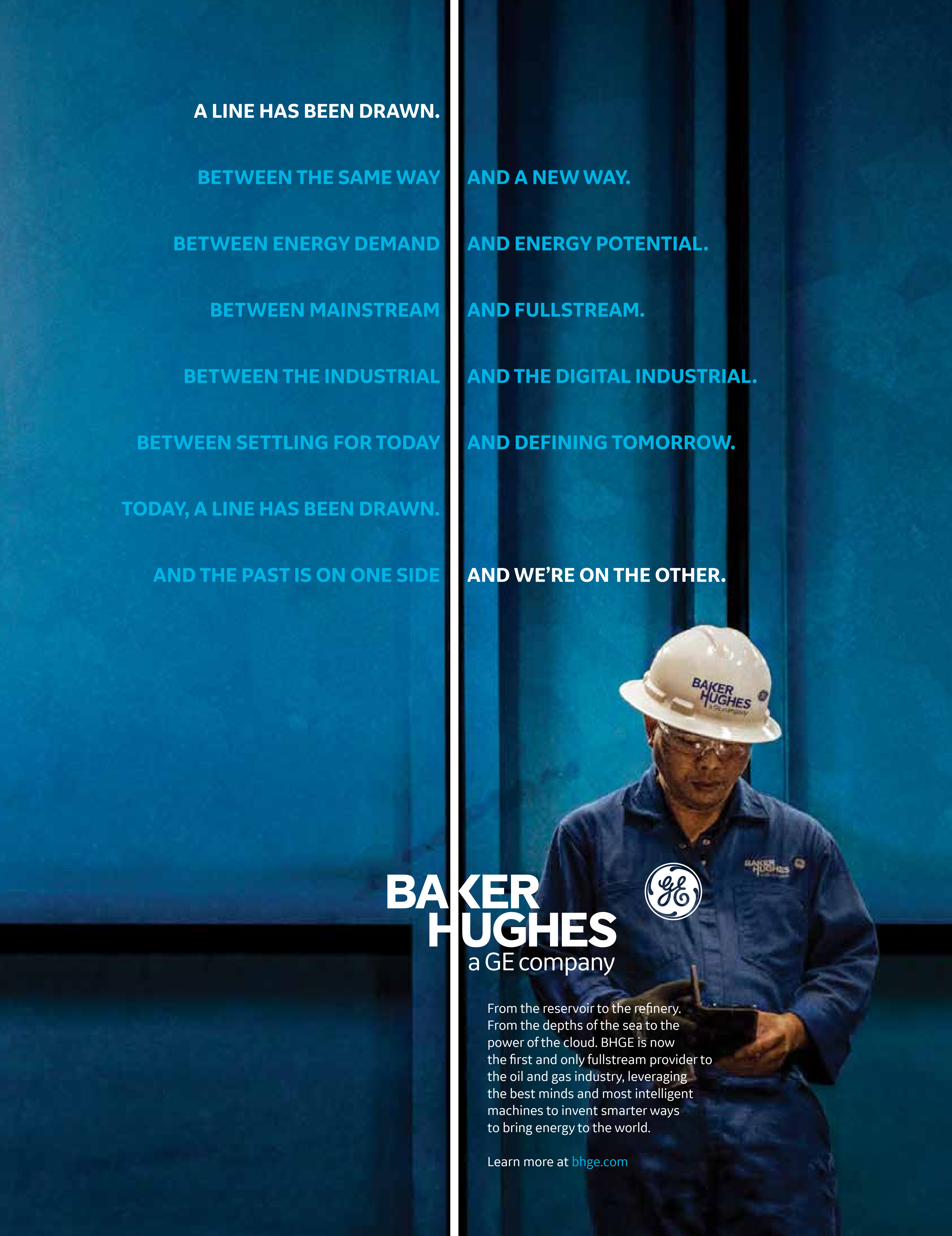
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BETWEEN THE SAME WAY AND A NEW WAY.
BETWEEN ENERGY DEMAND AND ENERGY POTENTIAL.
BETWEEN MAINSTREAM AND FULLSTREAM.
BETWEEN THE INDUSTRIAL AND THE DIGITAL INDUSTRIAL.
BETWEEN SETTLING FOR TODAY AND DEFINING TOMORROW.
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DEL Communications Inc.

MESSAGE FROM THE MINISTER OF NATURAL RESOURCES AND FORESTRY JOHN YAKABUSKI

Our government was elected on a promise to cut red tape, create jobs and promote economic growth. We recognize the important role the oil and natural gas industry continues to play in driving Ontario's economy.

Since the province's first oil well began production in 1858, approximately 93 million barrels of oil and 1.35 trillion cubic feet of natural gas have been produced in Ontario, almost all of it in the southwestern part of the province. Because of the continuous search for new oil and gas pools, other industries – such as salt solution mining and underground hydrocarbon – now also contribute to our province's economy.

My ministry is committed to helping industry keep pace with changes in the sector. In 2018, the province amended Ontario Regulation 245/97 under the Oil, Gas and Salt Resources Act to include the regulation of compressed air energy in salt caverns. An existing cavern in Goderich is the first in Canada to use new, innovative technology which involves compressing air into a cavern at times of low energy demand, storing it until the demand is higher and releasing it to power turbines. The Ontario Petroleum Institute's work in promoting the viability of Ontario's hydrocarbon sector is reflected in new, external investors exploring similar opportunities in our province.

We all know that the oil and gas exploration and production sector has experienced challenges and a decline in activity in recent years. We also know that Ontario's petroleum sector is evolving to meet growing energy demands. This is evident in the transition from drilling traditional exploration wells to the use of hydrocarbon storage wells. I am aware of your concerns for the future of the industry. That is why we are committed to continuing to work with your industry representatives to remove unnecessary administrative burdens and improve regulatory processes. It is part of our government's commitment to reduce barriers and ensure Ontario is open for business and open for jobs.

The OPI-MNRF Hydrocarbon Sector Working Group is an excellent example of the benefits we gain from maintaining an open dialogue on these issues. This collaborative approach between industry and government has resulted in improved processes, and this past year there was an increase in industry outreach and information sessions that kept you informed of regulatory efficiencies and key developments.

The oil and natural gas industry has experienced many successes, challenges, and changes over the last century and a half. Here in Ontario, the industry has a track record of successful operations, and of developing new technologies and applications that have been shared around the world.

My ministry looks forward to continuing to work with the OPI as this important industry continues to evolve.

PRESIDENT'S MESSAGE
DALE HOLLAND

It is my pleasure as president of the OPI to welcome you to the 2019 Ontario Oil & Natural Gas magazine. The OPI is pleased to again, in collaboration with DEL Communications, have an opportunity through the magazine to provide the most up-to-date information on the Ontario industry to our members and readers in general.

The OPI, under the direction of the board of directors, has worked diligently to fulfil the fundamental objectives of the Institute to encourage responsible exploration of the oil, gas, hydrocarbon storage and solution-mining, maintain close liaison with government agencies which regulate the industry, disseminate information relevant to member needs, promote the legislative goals of the membership and inform and educate the general public on the significance of the industry to the province of Ontario.

The last few years have been difficult for our industry and made more difficult when prices began to decline in 2014. The impacts have been felt by many companies and individuals across the industry. It's encouraging to see promise in 2019 with higher oil prices, natural gas holding its own and a rebound in drilling starts in recent months in North America.

In Ontario, we, too, have been challenged in recent years with a decline in new exploration that resulted in fewer drilling starts in the province. The OPI's focus has been on encouraging new exploration and to that extent we have concentrated on advocating to the Government of Ontario to support natural resource development as well as to promote Ontario throughout North America as an exploration and development opportunity that shows the province's energy patch as a "potential profitable business opportunity".

The OPI has developed good working relationships with various provincial government ministries, most notably the Ministry of Natural Resources and Forestry which regulates the industry, as well as the Ministries of Energy, Environment and Climate Change, Finance and Economic Development.

The OPI is extremely proud of its involvement through the Ontario Oil, Gas and Salt Resources Trust with the Oil, Gas and Salt Resources Library (Library). As a resource centre for the industry, the Library is an excellent example of how innovation and technology has enhanced the industry's ability to take full advantage of the information available throughout the sector, providing its members and clients a full suite of services.

The industry will continue to face its fair share of challenges as we strive to contribute to the economy, collaborate on energy development, and be environmentally responsible in support of managing climate change. I'm confident that we will meet these challenges as we have those in the past and thrive as an industry in the years ahead.

I would like to take this opportunity to express my appreciation to the OPI board of directors for their volunteer service and commitment to fostering a stable future of Ontario historic oil, natural gas and salt solution mining industries.

Dale Holland, President

Ontario Petroleum Institute

LAMBTON COUNTY CELEBRATES 145TH ANNIVERSARY OF ITS INTERNATIONAL DRILLERS

BY PATRICIA MCGEE

Setting off for the jungles of Java in 1873 in a quest for oil, the brave and skilled drillers of Lambton County were just the beginning. Over the next 70 years, more than 500 drillers from the Petrolia-Oil Springs area would take their tools and expertise to 87 far-flung countries around the globe.

In Lambton County, they were long-known as the Foreign Drillers, the men who went "to foreign fields", not "overseas". They are now called The International Oil Drillers and, on the 145th anniversary of the first drillers to set sail, the County of Lambton is celebrating them with the launch this summer of a new virtual exhibit called "The Canadians are Coming".

This undated photo of oil drillers of Bill McCrae and Bill McEwan in Singapore was so iconic of the International Drillers that it was made into a postcard. Photo courtesy of The Oil Museum of Canada.

More than 500 artifacts from the drillers and photos of the drillers will be on the Internet for the world to see. The exhibit showcases items they sent home or brought home through the decades: quivers for poiso- dart arrows, teeth of a tiger and wooden shoes inlaid with mother of pearl, to name a few.

The International Drillers were not born out of a thirst for adventure or a longing to sail the Seven Seas. They left Lambton County to work. The intense drilling of thousands of wells in Oil Springs and Petrolia between 1858 and 1873 meant that there was little left to be drilled. By this time, the entire world was awakening to the new energy of petroleum. It was eager to find and produce it with the expertise of the Lambton drillers.

And experts they were. When John Henry Fairbank reported for the 1890 Royal Commission on the Mineral Resources of Ontario, 90 per cent of Canada's oil, products and technology manufactured in Petrolia. "It is owing to that, and the skill of our drillers that Petrolia men are in demand all over the world."

"We have drillers now in Germany, Austria, India, Burmah, Mexico and Australia. They are in demand in Pennsylvania… The cause of the demand is that they have superior tools and possess superior intelligence. Our manufacturers of tools have succeeded in getting the greatest possible strength within the smallest limit, and the training here makes the men perfect in their department…"

"Our men become great experts at. By handling the pole they can tell what is going on down below 1,000 feet as well as if they were there."

William Henry McGarvey was the most outstandingly successful International Driller with 2,400 employees. Once the mayor of Petrolia, he revolutionized the oil industry of Galicia (now Poland and the Ukraine) in 1883 by introducing the pole drilling system known as the Canadian rig. It could reach a depth of 1,000 metres where prodigious amounts of oil lay. Before his arrival with the Canadian drillers, almost all shafts had been dug by hand and could only reach 150 metres. Steam engines, used in Oil Springs in the early 1860s, were an unknown luxury. By 1900, Galicia's Boryslaw basin was the fourth largest oil producer in the world.

There were other amazing accomplishments too. The International Drillers made their mark in all continents but Antarctica. Fred Webb drilled Colombia's first oil well in 1905. In 1908, six of the Lambton drill-

William O. Gillespie, shown in white hat, toured the pyramids in 1910 with British friends. Earlier, he worked as a driller in Australia and fell ill. After five months recovering in Petrolia, he worked as an oil driller in Egypt from 1910 to 1913, when he headed off to drill in Burma. Photo courtesy of The Oil Museum of Canada.

ers worked the first oil well of the Middle East, in Persia (Iran). Charles McAlpine drilled the first oil well in Sarawak (Malaysia) on the island of Borneo in 1910, a spot known to this day as Canada Hill. William Gillespie's 24-year career took his knowledge of the Canadian rig with him to Cuba, Sumatra, Borneo, Egypt, Sudan and Australia.

Harrowing tales were not unknown. In 1914, Albert Huggard and 20 other drillers were fatally poisoned at a banquet in Madagascar. Caught in First World War political upheaval, McGarvey died under house arrest in Vienna. His brother was shot. Charles Wallen and family made a terrifying five-month escape in the Russian Revolution of 1917.

Most men returned to Petrolia between their stints of being years away at several different countries. But some began to take their families with them and had children born in foreign lands. In 1924, Victor Lauriston penned an article for Maclean's magazine where he gushed his amazement: "To Petrolia, travel is mere commonplace; as much of the everyday texture of life as eating and sleep. The return of a Petrolia driller from Persia after a journey of 13,000 miles by land and sea, the departure of a Petrolia driller for Burma or Australia, causes no excitement. World travellers come and go every day – in Petrolia."

The actual artifacts and photos of the exhibit can be seen at the Oil Museum of Canada in Oil Springs, as well as the collections of letters and amazing photos. In a salute to the drillers, the nearby Fairbank Oil Nature Trail has a collection of colourful hand-carved signs of their many destinations.

For more info, visit:

Oil Museum of Canada:
https://www.lambtonmuseums.ca/oil/

Fairbank Oil Nature Trail:
http://www.fairbankoil.com/ ■

HOW TO FIND OIL IN ONTARIO

BY ALLAN PHILLIPS, CLINTON-MEDINA GROUP

Ontario was the birthplace for both conventional and unconventional oil production in North America in the decade before Confederation. Looking back over the last 150-plus years, there have been three peaks in oil production in Ontario. Figure 1 is a plot of annual oil production versus time and illustrates the first peak to occur in the late 1800s, the second in the 1950s to 1960s and the latest in the 1980 to 1990s. By looking back at the history behind these three periods of peak oil production we can better understand what were the driving forces that lead to these booms and apply them to the next oil boom in Ontario.

The early years: 1854-1895

In 1854, Charles Nelson Tripp and his brother Henry incorporated International Mining and Manufacturing Company to mine the surface seeps of oil that had solidified at the surface to form the Enniskillen Gum Beds. The "ashphaltum" was distilled to make lighting oil but the venture was destined for failure, as they were unable to get their product out of the backwoods of Lambton County to market. As a result, Tripp was forced to sell 400 acres of his companies lands in the Enniskillen Gum Beds to a group of investors lead by James Miller Williams. In the summer of 1858, J.M. Williams and Company dug a well into the clay under the gum beds. The well was seven by nine feet square and cribbed with logs. Oil was struck at 14 feet and a well was later dug to a depth of 49 feet.

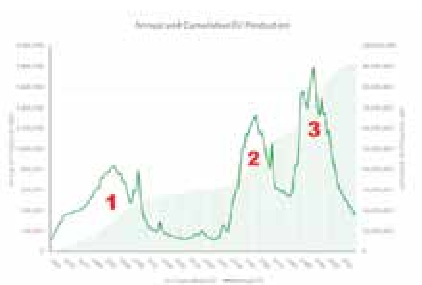

Figure 1: Annual and cumulative Ontario oil production 1863-2016 (data complied by Ontario Oil, Gas and Salt Resources Library Staff).

The oil rises within the well to a depth of 10 feet. The well produced at a maximum rate 1,500 gallons (37 barrels) in 10 hours with the use of a hand pump (Gale, 1860). By the end of 1860, oil well digging had given way to spring pole drilling and almost 100 wells had been drilled most of them into bedrock (Gray, 2008). On Jan. 16, 1862 along the banks of Black Creek, Hugh Nixon Shaw struck oil at about 200 feet and the well flowed over an estimated 100,000 barrels of oil before flow could be stopped. This well kicked off the oil boom in the Oil Springs area spreading to Petrolia, Bothwell and beyond. While early conventional oil drilling was taking place in and around the Enniskillen Gum Beds in Lambton County, another oil play was being developed further north near Collingwood on the south shore of Lake Huron (Figure 2).

William Darley Pollard had built a plant on a quarry site to distill the local bituminous Ordovician age shale bedrock in cast iron retorts. The operating capacity of the facility was designed to produce 1,000 gallons a day of lamp and lubricating oils from 30 to 35 tons of shale (Dabbs, 2007). North America's first unconventional oil shale operations soon fell on hard times. The conventional oil boom in Lambton County could produce oil cheaper and was closer to market and the Craigleith Shale Oil Works was shut down in 1863.

Over the next 40 years, wildcat or random drilling for shallow oil production continued over the fairway from Sarnia through Petrolia and Oil Springs to Bothwell. Once oil was discovered with a wildcat well hundreds of closely spaced wells would be drilled (Figure 3). A vast majority of these early wells were not gushers like the Shaw well. It was common practice to place explosives in the well to enhance oil flow rates. Nitroglycerine was placed in a canister by the "shooter" and lowered the canister to the zone of oil production. The canister of explosives was detonated and would shatter the rock in the well to increase the flow of oil. Intense drilling and oil production activity continued in this area from 1858 into the early 1900s. Productivity from individual wells was low but the shear number of wells was high.

Figure 2: Canada West (now Ontario) in the late 1850s. Early oil development was taking place around the Enniskillen Gum Beds near Sarnia and at the Craigleith Shale Oil Works near Collingwood (Phillips, 2016).

Post-Second World War era: 1950s to 1960s

The manufacturing boom that followed the Second World War saw the demand for oil and gas increase worldwide. Union Gas had been supplying local natural gas to their customers in southwestern Ontario. Much of the gas was coming from Silurian age gas pools in Kent and Lambton Counties. These shallow reservoirs drilled in the early 1900s were depleting and no longer providing sufficient volumes and the search was on to find more gas reserves. Two gas pools discovered in the 1930s were now depleted and they had been converted to gas storage reservoirs. In the early 1940s, Union Gas was injecting gas from outside the province into the depleted reservoirs of the Dawn 47-49 and Dawn 59-85 Pools. This practice signifies the early beginnings to the Dawn Hub that would grow to become the second largest natural gas storage hub in North America.

This search for additional gas pools had two major players, Union Gas and Imperial Oil, who were active in Lambton County in the 1940s to 1950s. They had made several significant Silurian Guelph and Salina oil

Figure 3: Tripods set up over wells drilled along Black Creek in the Oil Springs Oil Pool. The tripods are used to lift and lower drilling tools in and out of the well (Photo courtesy of the Oil Museum of Canada Archives).

and gas discoveries and new technology would be brought in to help in their search. The Silurian age rocks in the Ontario portion of the Michigan Basin included reef hydrocarbon reservoirs overlain with thick salt layers. Gravity surveys had been successful in mapping subsurface salt layers in the Gulf Coast and the technology was brought into this area in the early 1950s. Figure 4 shows gravity data acquired over the Waubuno Reef Pool in Moore Township, Lambton County south of Sarnia (Pohly, 1966). Sharp local variations in salt thickness near the carbonate buildup results in a gravity anomaly. An east west cross-section across the Waubuno Reef shows about 67 metres (220 feet) of salt thinning. The Salina A2 Salt is absent over the reef and there is thinning of the Salina B and Salina D Salts over the reef (Figure 5).

Union Gas and Imperial Oil would go on to make several Silurian Guelph and Salina discoveries in the 1950s and 1960s using gravity and later early seismic surveys. A handful of these discoveries would contain oil including Warwick, Grand Bend, Wanstead, Talford, Brigden and Sutorville. The biggest oil discovery would come as a result of the ongoing search for Silurian gas reservoirs. The operators would borrow a technique from the mining industry to help in their exploration efforts. In areas where they had little or no well control, they would drill a series of stratigraphic tests using a diamond drill hole rig. The drill core would provide the geologists with critical data on formation tops, thickness and lithology changes that were helpful as reef proximity indicators. Hydrocarbon reservoir quality assessments could be made by gauging any hydrocarbon or water shows encountered while drilling. Union Gas was looking to follow up recent Silurian Salina A1 and A2 gas discoveries at Zone, Wardsville and Townline Gas Pools when they drilled Union Gas DDH No. 28 just north of McIntyre Line in Lot 6 Concession IV, Aldborough Township. Drilling was terminated in the Salina A2 Unit at 1,561 feet (475.8 metres) on Dec. 17, 1948. The Silurian section they were targeting showed little promise, but they did encounter oil shows in the shallow Devonian section between 260 to 380 feet (79.2 to 115.8 metres). This encouraged a local producer James Beattie to drill an offset well about 1,000 feet (304.8 metres) to the northwest on John Graham's farm. The Richfield Oil & Gas No.1 – J.D. Graham No. 1 Aldborough 2-7-6-IV discovery well in the Rodney Oil Pool was completed on May 18, 1949 with an initial oil production rate of five barrels of oil a day. As a result of the modest oil production rates, only 13 wells were drilled into the oil pool in the next three years. The span from 1953 to 1956 saw significant development with over 100 wells drilled into the Rodney Oil Pool (Felmont Oil Report, 1957). Production jumped from 1,147 bbls. (182.4 m3) in 1949 to 354,903 bbls. (56,423.4 m3) in 1955 (Felmont Oil Report, 1957). A successful water flood scheme has since been implemented and production continues today.

The most recent oil boom: 1980s to 1990s

The early 1980s proved difficult in the Canadian oil industry with high inflation, a global economic downturn and Canadian oil prices depressed below $30 a barrel as a result of the National Energy Program. Despite these challenges, two groups who were active in Ontario asked the local seismic contractor Cangeo Ltd. to shoot two programs in 1982 that were outside of the traditional oil fairway. E.P. Rowe Oil acquired a line of seismic along Maple Line in Dover Township, Kent County just north Dover Gas Pool. A drilling location was selected based on the seismic interpretation and Rawlings Drilling cable tool rig was brought in the drill Rowe/Ram No.1 Dover 7-5-V. In early February 1983, they encountered gas and oil in the Ordovician Black River carbonates. The well flowed at a rate of 49.0 m3/d (308 bopd) after acid stimulation. Pembina Exploration also acquired a line of seismic in 1982 along Mersea Road B in Mersea Township, Essex County just southeast of the city of Leamington. The partnership of Consumers' Gas, Pembina Exploration and Onexco spudded the Consumers' et al 33683 Mersea 1-15-B well using Underwater Gas Developers air rotary rig. The well was completed in the Trenton carbonates and flowed at an initial rate of 4.8 m3/d (30 bopd) after acid stimulation. These two discovery wells would kick off the recent Trenton-Black River oil boom in Ontario.

The Ordovician Trenton-Black River carbonates had seen some modest oil production in Ontario prior to these two discoveries in 1983. Smaller oil pools at Malden, Colchester and Gosfield South discovered in the 1950s to 1960s were northeast extensions of the historic Lima-Indiana Trend extending under Lake Erie from Ohio on the crest of the Findlay Arch. It was the Dover Gas Pool discovered in 1917 by Union Gas that was the model used by geologists and geophysicists in their search for new pools in southwestern Ontario. Figure 6 is the schematic developed by Bruce Sanford in the early 1960s to illustrate this complex and unique hydrocarbon reservoir. The Dover Pool was discovered and developed prior to the invention of modern well logging technology, therefore cable tool drill cuttings and drillers records were tools available to develop this model. Comparing Sanford's model in Figure 6 to seismic line BPM-023 (Figure 7) the similarities between the two start to become apparent. The syncline or

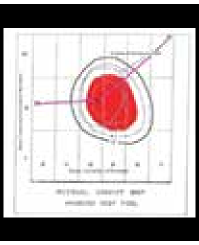

Figure 4: Residual gravity anomaly (red) over the Waubuno Pool in Moore Township, Lambton County, Ontario. Purple line is cross-section in Figure 5 (after Pohly, 1966).

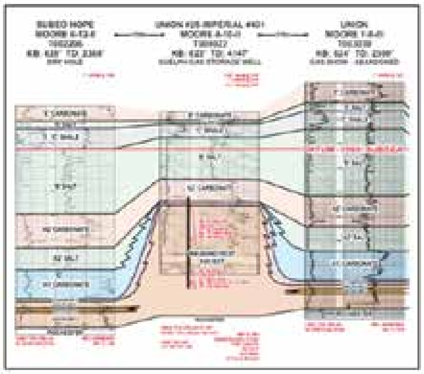

Figure 5: East to west cross-section across the Waubuno Pool in Moore Township, Lambton County, Ontario. Note dramatic thinning of the Salina salt layers (green) over the reef buildup. Hydrocarbons are trapped in the porous reef buildup.

sag at the top of the Trenton (orange marker on the seismic line) with a sharp break on the left side and subtle roll on the right. The continuous markers in the interval between the Trenton and Cambrian events (Trenton-Black River interval) change character in the sag and are indications of the lithology change from regional limestone to a porous and fractured dolomite reservoir.

These two Trenton-Black River oil discoveries and subsequent followup development success lead to a massive land acquisition rush in Essex and western Kent Counties in the early to mid-1980s. A number of seismic contractors were active acquiring 2D seismic and later 3D seismic over a large portion of this oil fairway. Several additional oil pools would be discovered in the 1980s and developed into the 1990s using vertical wells. In the late 1990s, horizontal drilling technology evolved and became the preferred development drilling choice of most operators.

How to find oil in Ontario

Based on this historic perspective what are the key takeaways that will help in the discovery of new oil reserves in Ontario?

- James Williams' concept of digging in proximity to surface oils shows lead to the first conventional oil production in North America. Surface oil shows are rare but there are numerous subsurface oil shows in the drilling records at the Ontario Oil, Gas and Salt Resource Library. Using these records to high-grade

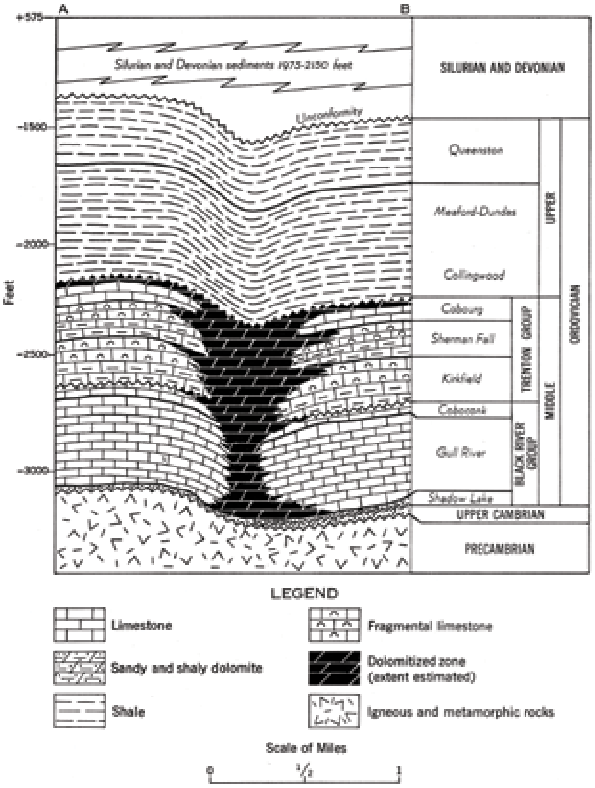

Figure 6: Schematic cross-section across the Dover Gas Pool showing dolomitized zone (black) in the regional limestone Trenton-Black River section. The sag at the top of the Trenton

areas for future exploration is an excellent starting point.

- Hugh Shaw was dubbed "that insane Yankee" for drilling his well deeper. Conventional wisdom at Oil Springs was to just drill into the surface clay or just into bedrock. His well continued deeper and he brought in the first gusher. A vast majority of the wells drilled to date in Ontario only penetrate the upper layers with very few drilled to deeper targets (> 500 metres).
- William Pollard's oil shale operation at Craigleith proved that the bituminous shales in Ontario could yield oil. Today, oil is being produced from equivalent Ordovician shale reservoirs elsewhere in the Michigan and Appalachian Basins. Modern horizontal drilling and completion technology has resulted to the current shale boom sweeping North America.
- Union Gas and Imperial Oil's used of new exploration technology to reduce the risk in exploration drilling and it paid huge dividends in the 1950 to 1960s. Gravity surveys were the key to finding a significant number of reef pools in Lambton, Kent and Huron Counties. Embracing new technology in the search for new oil reserves will result in future discoveries.
- James Beattie and Richfield Oil & Gas saw opportunity in a dry hole drilled by a competitor. Union Gas was focused on Silurian gas reserves in the Guelph and Salina section. Their diamond drill core at Rodney had oil shows up hole in the Devonian section. A local producer familiar with this oil zone recognized the significance. The Ontario Oil, Gas and Salt Resource Library has an extensive collection of drill core and cuttings samples collected over the last century. Opportunity knocks for those that are willing to make the effort and follow James Beattie's lead.
- The early 1980s ushered in challenging economic times in the Canadian oil patch, not unlike today. The successful operators then jointed forces and formed joint ventures to explore areas where they had common lands under lease. This allowed them to pool their limited exploration capital and expertise resulting in significant oil discoveries.
- Seismic technology developed in the 1960s evolved and became an important oil and gas exploration tool in the 1970s to 1980s. It was used primarily in Lambton County and offshore Lake Erie chasing Silurian reef reservoirs. The Rowe-Ram and Consumers'-Pembina-Onexco groups used seismic to successfully discover new Ordovician Trenton-Black River oil reservoirs in the early 1980s. Applying existing exploration technology to new play types with the help of a sound geologic model could open up many more opportunities in southwestern Ontario.

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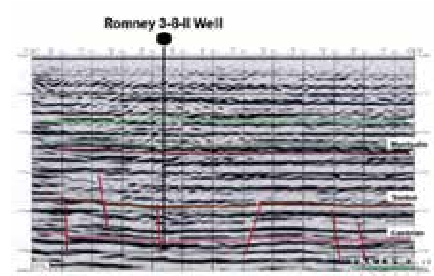

Figure 7: Seismic line BPM-023 through the Consumers' et al 34011, Romney 3-8-II (T006944) discovery well in the Lakeshore Oil Pool (from Coulter & Waugh, 2002).

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THE ONTARIO ADVANTAGE

The Ontario Advantage – the best of both worlds. In today's volatile energy market with fluctuating prices, and transportation challenges affecting market access existing in certain regions it would benefit companies to have assets in different jurisdictions where they have the option of chasing larger plays when the commodity prices are higher, or smaller more economic plays when prices are lower.

Ontario is an attractive place today because it offers companies the option to develop a successful oil and gas field in a jurisdiction that generates excellent paybacks at 50$USD/bbl for oil and 4$USD/MMbtu for gas, an available transportation network and immediate access to the market.

"Ontario does not have heavier grades of crude oil, so superior oil prices are the norm. Natural gas prices are routinely at or above Henry Hub prices with ample gas infrastructure in place leading to lower tie-in costs and higher natural gas prices. As a result, with reasonable royalties and leasing costs for freehold acreage, and lower operating costs it means the netbacks in Ontario are among the highest in North America," says Ian Colquhoun, consulting geologist.

Western Canada used to turn to Ontario when they experienced dry spells, because Ontario offers good prices and boasts plenty of resources. So what happened?

According to Colquhoun, geological activity in the province was prominent in the 1980s and improved in the 1990s and into the early 2000s.

"We've got some pretty shallow plays here in Ontario. That should excite people," Colquhoun says. "There are a lot of shallow resources still available, but there is no activity – right now."

One possible reason for the decline in oil and gas production is fewer companies exploring. Colquhoun says back in the 1970s to 1990s, with more companies actively exploring there was a higher level of drilling activity.

Today, there is only one large producer, ~200,000 barrels of oil per year, the second largest company produces about 10 per cent by volume and is not an active explorer. Colquhoun says people are developing their existing assets and as a result exploration has been in decline with the last significant discovery in 2004.

Colquhoun says, "The lack of activity is an opportunity. It's a wide-open field, fertile ground for explorationists to go to work to find oil and gas."

"There are still many viable reasons to start up oil and gas activities in Ontario," he adds.

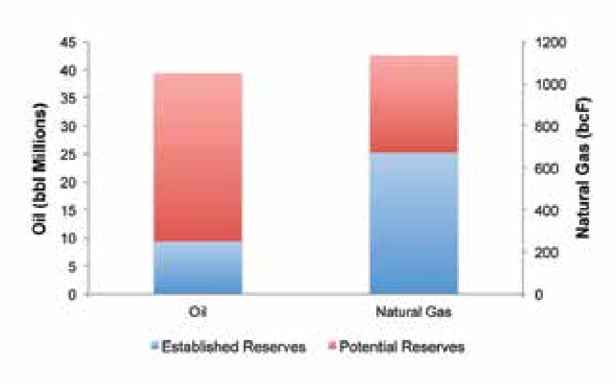
"You don't have to drill deep in Ontario. We live in a place over the Algonquin Arch that separates the Michigan and Appalachian Basins, and because of that, the oil and gas flows up towards the arch. The advantage is we have shallow resources to start with."

Colquhoun says the royalty fees in Ontario are reasonable at 12.5 per cent, exploration leases can be acquired for, on average, $10 to $15 (CAD) an acre and all leasing and royalty fees go to the landowner.

Colquhoun says to get people interested in Ontario again, they need to get the news out that Ontario is open for business.

"We have a government that is good to work with. They'll facilitate you and get your permits to drill your wells. We have the infrastructure," Colquhoun says. He adds that the industry has a good relationship with the Ontario Ministry of Natural Resources and Forestry that regulates the exploration of oil and natural gas under the province's Oil, Gas and Salt Resources Act.

Dale Holland, president of the Ontario Petroleum Institute (OPI), has similar comments.



"In the last four to five years drilling activity has declined, so now, it's open for everybody to choose where they want to explore," Holland says.

Holland says that other advantages include the availability of land, equipment and support services from companies such as his own that provide testing tools for oil and gas well services.

"Ontario has a depth of experience and expertise working in the industry," Holland says. "Ontario companies provide an educated and diverse workforce ready to tap the province's natural resource potential."

According to Jim McIntosh, consulting engineer at Jim McIntosh Petroleum Engineering Ltd., Ontario boasts the ability to build facilities for oil and gas production as it is close to market.

"You're never that far from a pipeline to hook your gas into," McIntosh says. "Once you've been successful in drilling a gas or oil well, you'll have to determine the long-term potential of whatever formation you're producing from."

Facilities are the buildings that house the equipment such as separators and tanks. Luckily, McIntosh says the weather in Ontario is mild so the equipment can also be left out in the open.

Denis Marcus, president of Harold Marcus Limited, says Ontario offers fleets of trucks to take oil to the market. "We have a termi-

nal in Sarnia called Marcus Terminals Inc., which handles most of the production in Ontario," he adds.

As well, Marcus says the price to transport oil is reasonable. "In most cases here in Ontario, the cost ranges from $1.65 to $2.75 per barrel depending on the proximity to the terminal."

Dale Norman, land manager for Elexco Land Services, says Ontario is advantageous because landowners here control their minerals, meaning they have the right to any oil and gas under their property and can see the benefits to leasing. If an exploration company finds oil, all they would require is a tank and a contract with a delivery company to take it up to Sarnia to put into the system.

"If it's natural gas, there are all kinds of pipelines running through Southern Ontario to transport the gas to market," Norman says.

Norman further stated that the decline of exploration companies working in Ontario wasn't as a result of low commodity prices but of commodity prices getting so high that it allowed these players to take their assets elsewhere to areas that were exceedingly more expensive to develop but also with an upside for the volume potential (on discovery) being huge in comparison to Ontario. The problem we have in Ontario is that these companies forgot to come back when prices tanked.

He says the availability of exploration land in Ontario is very good at the moment; there isn't a huge amount of land currently being held by lease, but believes that exploration companies are slowly trickling back.

"It's starting to pick up," Norman says.

One of the industry's most valuable assets is the Oil, Gas and Salt Resources Library (Library) often referred to as Ontario's "data warehouse". It's a not-for-profit resource centre that supports oil and natural gas development, underground storage and salt solution mining.

"Operators in Ontario automatically have a data management team working for them. Not only does the Library maintain the data that operators require but our team is available to provide the services and knowledge companies need to leverage that data," says Jordan Clark, library manager.

Clark indicates that the Library has information – data, rock cores and cuttings, geophysical logs – and the technology that enables all of the information to be readily accessible and deliverable online at www.ogsrlibrary.com.

Hugh Moran, executive director of the OPI, believes that effective, consistent communications is an important aspect of promoting oil and natural gas development.

"It's important for industry to educate, inform and engage governments, stakeholders and the public on the benefits of responsible resource development," he says. "The OPI has made a concentrated effort to establish good working relationships with all of these organizations. That, too, is another Ontario advantage." ■

EXPLORING THE OIL AND GAS PLAYS OF ONTARIO

By Ian M. Colquhoun[1], Ed Welychka[2], Jim McIntosh[3] and Jordan Clark[4]

Regional Geology Map

The position of the sedimentary basins that exist within Southwestern Ontario and within the northeastern portion of the United States illustrate how these basins are separated by the arches and Precambrian shield of northern Ontario. The northern basins are relatively unexplored.

The oil and gas deposits in Southwestern Ontario lay along the Algonquin Arch that separates the Michigan and Appalachian Basins (see stratigraphic section). Ontario sits at the up-dip position along the Algonquin Arch where oil and gas resources are observed in many different structural traps; however, stratigraphic traps, which are poorly understood or well-known, are possible. The petroleum system in Southwestern Ontario is fairly mature with over 100 million barrels of oil and more than 1.3 Tcf of gas produced, but there are very attractive remaining reserves estimates for several of the well-known trap styles in Ontario. Stratigraphic sections are provided, reflecting the geology on both the Michigan Basin and Appalachian Basin and illustrating the hydrocarbon-bearing formations within Southwestern Ontario.

Ontario Play Atlas

There are four main plays by age in Southwestern Ontario and six main play types when you include oil and gas reservoirs. Each of the four main plays have several figures that show the play fairway presented along with the geological, geophysical and economic parameters that describe each play. There are a total of seven (7) figures that display the physical nature of each play, including the play fairway, the key pools, structure contour map, magnetics, gravity and seismic images for type pool, and a geological model for each play. The remaining producible reserves for each of the geologic periods and formations are presented on the regional map as possible recoverable reserves. These figures were obtained from Bailey and Cochrane Open File Reports and the recently updated Golder and Associates economic assessment (2005) of the remaining resource potential for the Trenton-Black River HTD play (see references). The following oil and gas plays are those believed to be the most viable oil and natural gas plays to make new discoveries of economic significance for companies looking to explore within Southwestern Ontario. We examine the geology of the plays before we discuss their economic viability.

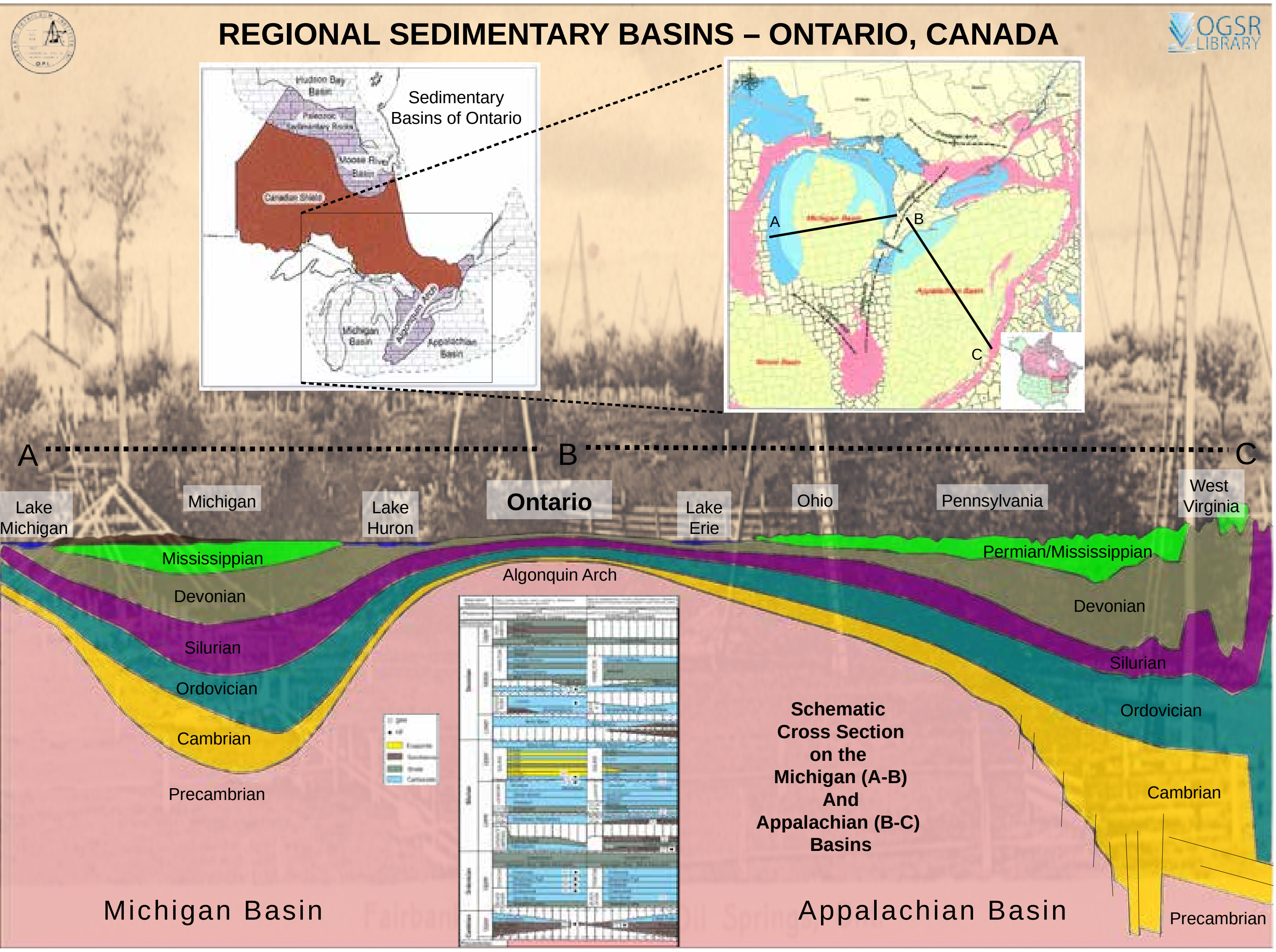
Devonian – Columbus sandy dolomites of the Dundee Formation (Anticlinal oil play)

The Devonian anticlinal oil play occurs within a very specific fairway and includes specific geological parameters important to evaluate its future exploration potential (see inset map). The anticlinal nature of the trap is tied to the dissolution of the B-Salt along prominent basement-derived faults. Dissolution of the B-salt over time resulted in the formation of the anticlinal nature of the Devonian-aged carbonates. Key characteristics of the play on seismic includes the dissolution of the B-Salt, thickening of the Hamilton Shale where the salt is completely removed and its complete absence over the productive areas of the Devonian oil pool. This is known as a geological inlier, which occurs as a result of uplift placing the older Devonian carbonates against younger shale of the Hamilton Group. The absence of the Hamilton shale may be the result of either the removal following uplift prior to deposition of the glacial cover, or non-deposition as the result of a Dundee high created by a period of uplift prior to deposition of the Hamilton shale. The trap is comprised of laterally tight shales of the Hamilton Group up against porous Columbus sands and dolomites capped by tight glacial sediments. The reservoir is comprised of porous and permeable sandy dolomites of the Columbus member of the Dundee Formation (see economics for details).

The Devonian-aged Dundee-Columbus-Lucas formations have an estimated 20 to 30 million barrels of oil recoverable left to be discovered and produced. Approximately 45 million barrels of oil has been produced to date, mainly from the Rodney, Oil Springs, Petrolia, Bothwell-Thamesville and Glencoe oil pools.

Silurian – A-1 Carbonate and Guelph (Niagaran pinnacle reef oil and gas play)

The Silurian pinnacle reef oil and gas play includes both the A-1 Carbonate and the Guelph Formation within Lambton County and the underlying Goat Island Formation in north Huron County of the Michigan Basin (see inset map). Pinnacle reefs are tall and narrow carbonate structures formed by extended periods of deposition of reef-type rocks that are easily recognized on seismic. There are examples of broad reef structures, multiple pinnacles, which appear as highs on high-resolution magnetic and gravity surveys (e.g. Dawn 156 gas pool). On seismic, individual pinnacle reefs can be observed as an apparent thinning of the overlying A-2 and A-1 carbonates over a thick section of Guelph (Niagaran), Goat Island and Gasport formation carbonates. These structures and formations appear to punch upwards into the overlying B-Salt. The trap includes a thick cap rock comprised of dense anhydrite and tight carbonate of the overlying A-2 Evaporite and laterally tight limestones of the A-2 and A-1 Carbonates. The reservoir is comprised



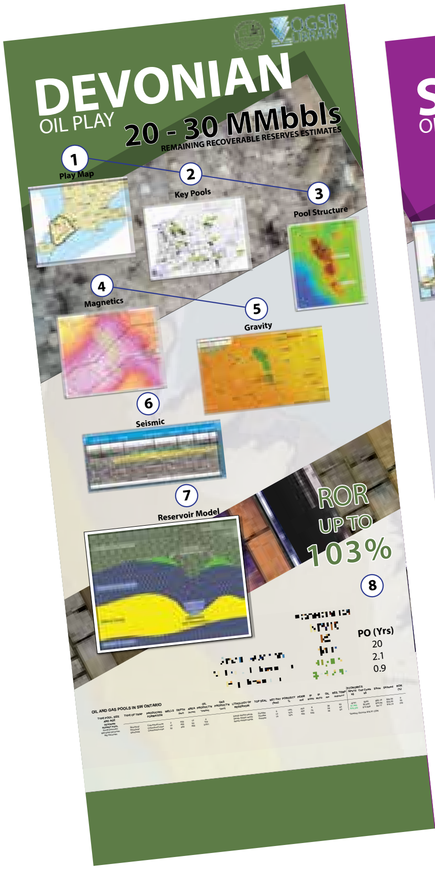
of porous and permeable limestone or dolomite within reef-type carbonates in the Guelph Formation (see economics for details).

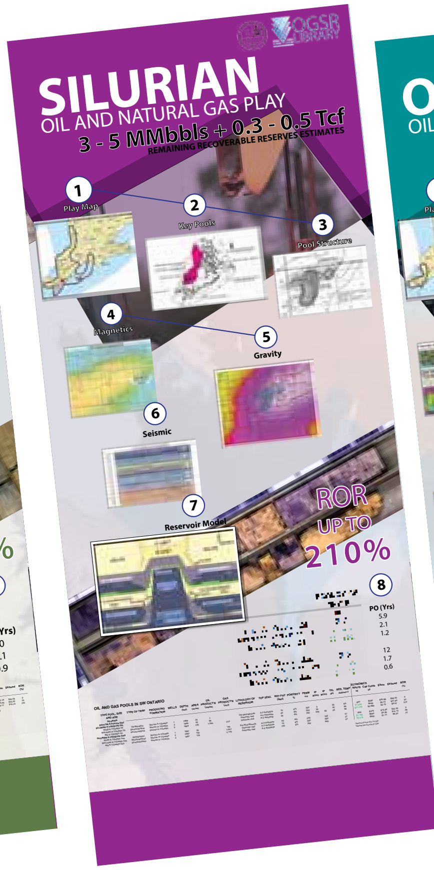
The Silurian-aged carbonates of the A-1 Carbonate and Guelph formation pinnacle reefs have an estimated three to five million barrels of oil and between 300 and 500 bcf of natural gas to be discovered and produced. Production will come from pinnacle reef complexes of onshore Ontario in the Michigan Basin and offshore Lake Erie in the Appalachian Basin. Approximately 15 million barrels of oil and 330 bcf of gas have been produced onshore Ontario for all of the carbonate plays, including the A-2 and A-1 Carbonates and Guelph pinnacle reefs of the Michigan Basin. Approximately 450 bcf of gas has been produced from the A-1 Carbonate and Guelph carbonates from offshore Lake Erie in the Appalachian Basin.

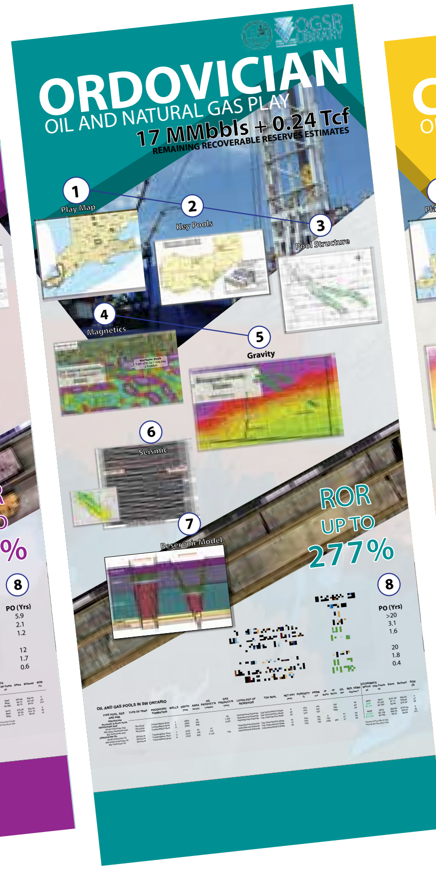
There is a relatively new play in Ontario (e.g. Aldborough 1-21-IV gas pool discovered in 2004), an over-pressured, high-porosity and permeability Grimsby sandstone gas play that occurs primarily within Aldborough and Dunwich Townships, Elgin County. These sands extend from offshore Lake Erie onshore onto the Algonquin Arch on the Appalachian Basin side in Ontario. This play is relatively new and may be significant but has very little geologic data therefore is not presented in this summary.

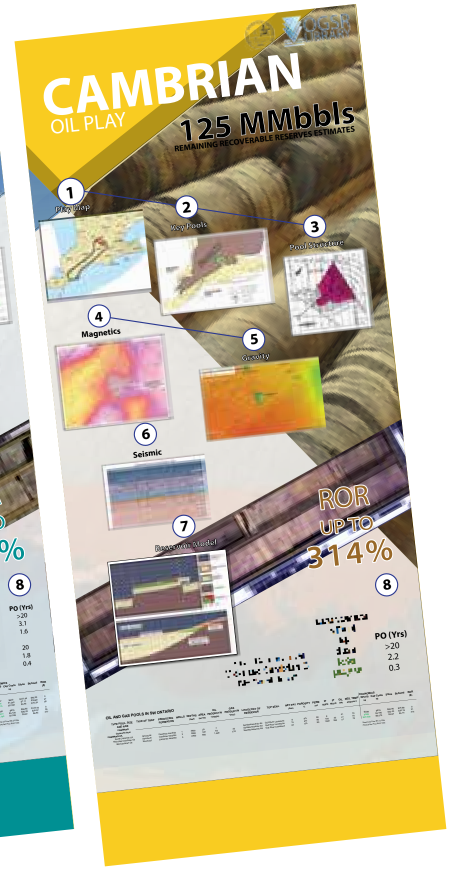
Ordovician – Trenton-Black River Group carbonates (HTD oil and gas play)

The Ordovician Trenton-Black River Group hydrothermal dolomite oil and gas play occurs mainly within Essex and Kent Counties (see inset map). Hydrothermally altered dolomites occur as the result of faulting and fracturing of the Trenton Group (Cobourg, Sherman Fall and Kirkfield formations) and Black River Group (Coboconk and Gull River formations) carbonates within extensional structures known as negative flower structures formed by left-lateral shearing. Extensional tectonics produced long, linear synclinal sag features easily recognized on seismic along with an apparent thickening of the overlying Upper Ordovician shales. The timing of faulting is critical to the formation of a trap for oil and gas. Structures with faults that continue into the Silurian and Devonian portion of the stratigraphic section result in over dolomitized or breached reservoirs. The trap includes a thick top seal of tight Ordovician shale and laterally tight limestones of the Trenton-Black









River. The reservoir is comprised of porous and permeable hydrothermally altered, porous and fractured dolomite (see economics for details).

The Ordovician-aged carbonates of the Trenton-Black River Group have an estimated 17 million barrels and 240 bcf of natural gas as possible recoverable reserves left to be discovered in Ontario (Golder 2005). Approximately 23 million barrels and 40 bcf of natural gas have been produced from the hydrothermally altered limestones of the Trenton and Black River Group carbonates.

Cambrian – Eau Claire Formation sandy carbonates (Horst Block oil play)

The Cambrian Horst Block oil play occurs within an elongated corridor along the southern edge of the Algonquin Arch of the Appalachian Basin side of Ontario (see inset map). Horst blocks formed by the intersection of faults along prominent stress directions, including an east-west fault, a north-south fault and a north-west to south-east oriented fault (i.e. Clearville Oil Pool). The horst blocks are tilted as a result of compressional forces along these prominent faults. The trap includes a cap rock and lateral seal against tight limestones of the Gull River Formation. The reservoir is comprised of porous and permeable sandy dolomites of the Eau Claire Formation (see economics for details).

The Cambrian-aged sandy carbonates and calcareous sandstones of the Eau Claire Formation have an estimated 125 million barrels of possible recoverable reserves left to be discovered and produced. Approximately five million barrels of oil has been produced, mainly from the Clearville, Willey and Gobles oil pools. More than 26 bcf of natural gas has been produced from the Innerkip gas pool, which occurs north of the Gobles oil pool. This play is the most underexplored and underdeveloped hydrocarbon play in Southwestern Ontario.

Economic parameters

The reservoir characteristics for small, medium and large reservoirs for each play type are presented along with their respective economic indicators. These are economics based on a positive result from drilling of a well into a reservoir and not a presentation of risked economics for the play types commonly used to rank prospects. The play economics were provided by Jim McIntosh and are available for distribution.

The basis for the economic analysis began with a statistical analysis of known pools sizes and their distribution within Southwestern Ontario. This provided a basis upon which to predict future pool sizes yet to be discovered within each category and play type. The play economics includes the number of wells drilled into the area expected for a pool, anticipated production of the pool, porosity, permeability, net pay, initial production flow rates, commodity type and reservoir temperature. Many of the parameters came from numerous core analyses taken from reservoirs for each play. Commodity prices used in the economic analysis reflect those that are realized within the Ontario market.

The economics incorporate the Ontario advantage: higher commodity prices as a result of Ontario's close proximity to major markets along with lower drilling and completion costs as a result of the shallower drilling depths. The lower royalties as a result of Freehold acreage and comparable operating costs mean the netbacks in Ontario are among the highest in North America. Ontario does not have heavier grades of crude oil, so superior oil prices are the norm. Natural gas prices are routinely at or above Henry Hub prices with ample gas infrastructure in place leading to lower tie-in costs and higher natural gas prices.

The small reservoir size derives a negative result in order to discourage the development of small oil and gas pools that tend to discourage companies to continue with their exploration activities. The medium and large pool sizes are conservative but demonstrate the economic viability for each individual play type. Economic parameters including NPV 10 (net present value discounted 10 per cent), capital costs and capital costs per flowing barrel of oil equivalent (BOE) and the rate of return (ROR) for each play type and size are presented. Note that the ROR gets better for deeper plays in Soouthwestern Ontario and for oil plays as a result of a superior commodity price. Years to payout is presented for each play type to allow investors and bankers a means to make decisions on which plays they want to invest their capitol or assess the economic viability of oil and gas deposits and potential reserves.

Exploring the oil and gas plays of Ontario is an industry promotional article and all the enclosed figures are available from the Ontario Petroleum Institute at opi@ontariopetroleuminstitute.com.

Author's footnotes

1 – 2289745 Ontario Ltd., geological consultant, London, Ontario.

2 – EWGGC Inc., geological and geophysical consultant, London, Ontario

3 – Jim McIntosh Petroleum Engineering Ltd., London, Ontario

4 – Oil, Gas and Salt Resources Library, London, Ontario

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THE PETROLEUM PIONEERS ARE BACK

By Jordan Clark, Library Operations; Matt Dupont, Media and Communications; Shuo Sun, Geology; Rhys Paterson, GIS and Mapping; Nicole Schoenberger, Library and Archives; Craig Irwin, Library and Archives

Ontario is home to some of the world's first petroleum pioneers. Oil explorers of the 1850s dug the famous well at Oil Springs in 1858 that is likely a commercial first for the world. These early pioneers spread across the globe and ushered in a new energy age. In Ontario, the pioneers evolved their trade with new technology and production increased up until the 1990s. Even though subsequent decades saw a decline in exploration that trend is showing signs of a reversal with 2018 exploration levels matching those not seen since 2014.

Ontario is pioneering once again with its Oil, Gas and Salt Resources Library (Library). One important thing the earlier pioneers did not have access to is a central repository of data, or any subsurface data really for that matter. Today's explorers in Ontario have the Library that compiles all available data, rock cores, rock chips, geophysical logs and production data from all industries operating under the Oil, Gas and Salt Resource Act. The Library makes this data accessible online and at the facility in London, Ont. including providing support and services to compliment all data sets.

The Library is your data management team in Ontario. We compile many useful data packages from the raw information we receive using geographic information systems (GIS) and by employing geologists in-house to perform quality assurance and review of specific geologic intervals. The organized raw information, data compilations and compiled reports published by the Library are available to all clients through the website or in person at our facility.

Media and communications highlights

The OGSR Library has been creating a lot of video content. EPEX 2018: OPI 56th Conference and Trade Show had a variety of talks that were recorded and edited together with their presentation slides with great results. If you missed the conference or would like to revisit the talks, visit our YouTube page (www.youtube.com/ogsrlibrary) and check them out. We have a lot of great video content planned for 2019 and beyond that we're excited to share: a new video about petroleum exploration in Ontario, a whole new round of EPEX talks videos, a new series geared towards students, a promo video about our recent DHCP project and more. We will also be adding virtual reality to our growing list of capabilities. Together with the 3D model of southern Ontario that's in the works (using our well data, no less), we will be offering a new immersive way to experience Ontario geology.

Geology highlights

Our OGSR geology team has been working on revising the subsurface salt front map over the past year. The scope of this project covers the whole southwestern Ontario. Overall, 2,000 wells have been selected for quality assurance (QA). Geophysical well logs, drill cuttings and cored wells have been examined to confirm/update the picks. Over 4,000 formational tops in 762 wells have been re-picked and updated in the Ontario Petroleum Data System (OPDS). Re-picking and re-mapping of these salt-bearing units are significant in improving the understanding of the salt-solution mechanics, bedrock aquifer distribution, groundwater flow pattern and energy storage location. A new salt solution boundary map has been created in ArcGIS that can be used in salt mining industry and subsurface mapping of southwestern Ontario.

GIS and mapping highlights

Geographic information systems let us visualize, analyze, inter-

pret and interpret data to reveal relationships, patters and trends. GIS can identify problems, monitor change, manage and respond to events and perform forecasting. In a way, the Library is its own geographic information system. The extensive data we hold in the Library connects industry, academics and government together into one system. The library provides data to various organizations focused on fulfilling our core mandate of improving decision-making regarding the oil, gas and salt industries.

Library and archives highlights

Starting in the summer of 2018, the OGSR Library has been working on a portal showcasing the history of Ontario's oil and gas industry. Funded by Library and Archives Canada's Documentary Heritage Communities Program (DHCP), the DHCP Brittain project was inspired by a donation of historical documents and maps to the Library by Charlie Fairbank. Roughly 10,000 document pages and more than 400 historic maps were digitized, catalogued and geo-referenced. The collection includes production figures, correspondence, reports, notes, drafts, legislation and a variety of maps, many with hand-drawn well points and details. To be launched soon, the portal will be publicly available and will provide unique insight into the history of Ontario's oil and gas industry.

The OGSR Library has prepared a database digitalizing the analysis of 492 rock cores from wells in Ontario. The database contains over 28,000 depth intervals with over 500,000 data points from rock core analysis between 1954 and 2010. The Porosity and Permeability Database reports parameters of permeability, porosity, fluid saturation and grain density for each interval analyzed. Permeability data can be used to inform flow capacity and gravity drainage potential, whereas porosity data provides an indication of the storage capacity of the rock. Fluid saturation of oil and water were analyzed and can imply the presence and quantity of these fluids within a reservoir. Finally, grain density can be used to confirm the minerology of the core. The Guelph formation, a known oil and gas producing formation, is well-represented in the database. This database can be acquired by contacting the library.

The OGSR Library is currently in the process of supplementing and updating our well licence records by using historical well cards donated by Union Gas. There were 22 donated boxes containing over 50,000 well cards from many different types of borings. The first phase of the project entails matching and adding information from approximately 9,000 well cards into our database. The library is also using this opportunity to perform quality assurance on our Ontario Petroleum Data System (OPDS) database with newly found information from these well cards. Noticeable improvements in our data include geological formation information being added to wells that were previously absent, and improved accuracy of well completion dates.

Ontario is continuing its pioneering ways with the Oil, Gas and Salt Resource Library serving the province's exploration and production, underground storage and salt solution mining industries. ■

Elexco Group of Companies:

42 YEARS OF GROWING AND SUCCEEDING

You've heard of the expression "Go West, young man"? Well, Jack Norman challenged that trend and said to himself, "Go East, young man". Forty-two years later, Norman has taken the Elexco Group of Companies through a veritable tour of the eastern part of North America. This is reflected in the company's logo, which has recently been redesigned, but still holds a strong link to the company's beginnings.

Since Elexco's inception in 1976, Norman and his employees have been providing superior quality land services to the oil and gas industry, as well as related energy and utility industries, including wind, solar and telecommunications.

This experience is demonstrated by some company statistics:

- Completed over 4,500 kilometres of easements and rights-of-way;
- Negotiated and registered oil and gas leases covering in excess of five million acres; and
- Completed over 6,500 40-year searches for easements, rights-of-way and oil and gas industry well sites

And this is just in Canada – the numbers for Elexco Land Services, Inc., the U.S. company, are equally as impressive.

Elexco's expertise stems largely from its full-time staff of management, land agents, title searchers, administrative support and GIS specialists, most of whom have been with the company for 10 to 35 years. This provides not only content specialists at the ready, but also a team who has worked together and used the same systems for many years. Efficiencies are gained from not having to recreate the wheel each time a slightly new project comes up – the collective knowledge of the team brings to bear ideas and processes that have worked well in the past, along with the insight to tweak what is needed as we move forward.

Elexco's experience and resources have allowed the company many opportunities to undertake large projects, and to service both large and small clients, while maintaining excellence in the performance of:

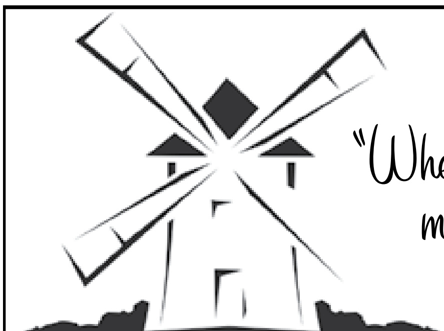
- Acquisition of oil and gas leases, gas storage lease agreements, easements and rights-of-way, surface rights, damage settlements, pooling agreements and unit operation agreements;
- Certification of title;
- 40-year title searches;
- Documentation preparation and processing;
- Administration of records and document obligations;
- GIS mapping and data solutions; and
- Project and systems management and support.

Innovation has always been a key component to Elexco's ability to creatively meet the demands of its clients' projects. For instance, Elexco's proprietary software is a critical component to its success. These systems allow in-depth continuous tracking, reporting of interests, data mapping, analysis and searchable records. Further, the company maintains property databases for Southwestern Ontario, which are accessible through its GIS mapping facility. These systems were developed well ahead of the curve, years before such systems started being offered by third parties. What is key here is that, since Elexco owns its own systems, it has the ability to tailor solutions specific to a client's needs on individual projects, and to continue to enhance systems to change with the times and an ever-evolving industry. This allows the maximum amount of flexibility compared to an "off-the-shelf" system. The energy and utility industries are cyclical and, typically, not all sectors of these industries are up or down at the same time. This flexibility has helped Elexco to remain busy with the ebbs and flows of parts of the energy sector – shifting its talents to meet the projects with the highest demand at any given point and standing the test of time for when other facets of the business make a comeback.

Innovation does not only come in the form of computer programs. Some innovation comes from thinking about the roles and tasks of a given project, and then breaking them into specific units. This allows each task to be done by an expert, greatly reducing the time for that task. Putting together different experts, each performing a different task, allows for an innovative system that saves time and money, while also improving accuracy. Although this idea is incorporated into most everything Elexco does, it is most easily demonstrated in the approach to a typical oil/gas exploration project. Land agents negotiate documents, title searchers perform the 40-year title, administrative staff prepares executable documents and reports and GIS specialists assist all the groups with mapping and data manipulation for reporting.

Elexco has been successfully dealing with one challenge facing clients in Ontario for many years: how best to evaluate potential leasing areas and quickly and easily assess same for open acreage. Clients would prefer not to spend much time or budget determining that a prospect area is already leased. As a point of interest, the information that is available to the public in Ontario, and the cost and effort to obtain same, has varied over the years and, in some ways, has become more cumbersome. In turn, Elexco's procedures and utilization of information and data, from both internal and external databases, has evolved over time to accommodate these changes. This allows clients to evaluate areas of interest without incurring the time and expense to search title for leases and compile and map the information. This methodology is another example of both innovative systems and processes coming together to provide valuable data and information to clients quickly and cost-effectively.

Elexco is, at its core, a service company. It provides a set of land-related services to the energy and utility industries. However, as you can see, Elexco is also a process company. Its services are based on established processes, many of which are grounded in innovative computer programming. And, let's not forget the final and critical ingredient to allowing those systems and processes to function well and evolve – talented, committed people with vast and diverse experience in the industry, and in providing creative solutions to our clients. This is the business model that has kept Elexco serving the Ontario market for 42 years. It is also the foundation on which the next decades will be built. ■



INDUSTRY COLLABORATION

BY HUGH MORAN,
EXECUTIVE DIRECTOR, OPI

Ontario's oil and natural gas industry explores, produces and supplies energy to the province under a regulatory regime administered by the Ministry of Natural Resources and Forestry (MNRF). The sector's ability to sustain itself in the peaks and valleys of a global energy market can be impacted by the regulatory system under which it operates.

In Ontario, a general decline in production of both oil and natural gas in recent years has threatened that sustainability. The price of natural gas at a low end for a lengthy period was compounded by the dramatic decline in price of oil in 2015 and 2016. The Ontario Petroleum Institute (OPI) and the MNRF met in March of 2016 to discuss the sector's concern. At the request of the MNRF, the OPI-MNRF Hydrocarbon Sector Working Group (Working Group) was established to obtain a greater understanding of the concerns and explore possible solutions.

The Working Group representatives from the OPI and the MNRF, including Petroleum Operations Section, met in June of 2016 to set the terms of reference and develop objectives to support and maintain a responsible and sustainable industry. Three main objectives were identified: (i) improve communication between industry and government, providing a forum for discussion of operational topics; (ii) exchange perspectives to clarify the MNRF's policy framework and its role as the industry regulator, and the role of the operator in exploration, production, and storage of hydrocarbons; and (iii) for industry members to identify concerns and provide input to government on policy proposals, updates/amendments to regulations and operating standards.

The Working Group's priority was to develop a list of industry discussion topics, and establish a framework and process to review the areas identified. Once the list of topics was identified it would be reviewed by the Working Group at large or by a subgroup formed to enable the OPI and the MNRF to engage representatives with specific experience and expertise in the topic areas to foster a collaborative review.

The list of discussion topics identified were suspended well policy, inspector protocols, historical standards, well abandonment standards, well approval process and examiner protocols. In addition, the Working Group invited the Private Natural Gas Well Association to participate in a review of challenges associated with private natural gas well rules and processes.

The Working Group undertook a review of the suspended well policy and inspector protocols with each topic reviewed by members of the OPI and the MNRF. A number of Sub-Groups, also with OPI and MNRF members, were formed to review historic standards, well approval process, well abandonment standards, and examiner protocols.

The process of review taken by the OPI-MNRF Hydrocarbon Sector Working Group is an example of what can be accomplished when industry and government working in collaboration. The work proved to be a very useful exercise in helping the industry and the regulator, the MNRF, gain an understanding of each organization's respective responsibilities.

The OPI will prepare a report in 2019 to the Deputy Minister of Natural Resources and Forestry with recommendations for each of the areas reviewed. ■

BHGE

Fullstream capability to the industry

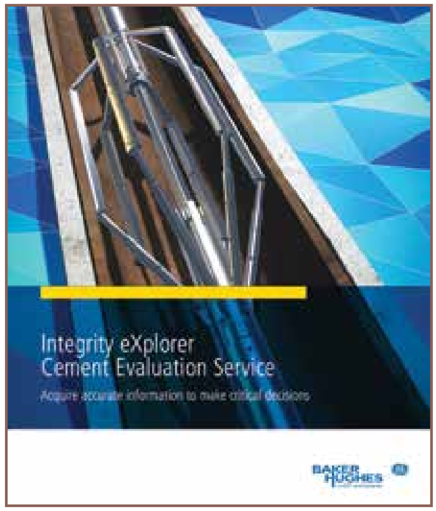
Baker Hughes, a GE company, is the world's first and only fullstream provider of integrated oilfield products, services and digital solutions. Drawing on a storied heritage of invention, BHGE harnesses the passion and experience of its people to enhance productivity across the oil and gas value chain.

BHGE helps its customers acquire, transport and refine hydrocarbons more efficiently, productively and safely, with a smaller environmental footprint and at lower cost per barrel. Backed by the digital industrial strength of GE, the company deploys minds, machines and the cloud to break down silos and reduce waste and risk, applying breakthroughs from other industries to advance its own. With operations in over 120 countries, the company's global scale, local know-how and commitment to service infuse over a century of experience with the spirit of a startup – inventing smarter ways to bring energy to the world.

BHGE has been in operation locally supporting the Ontario oil and gas industry for over 30 years, providing a wide range of services supporting both the upstream and downstream sectors of the Ontario industry. See below for a brief summary of some of the services in BHGE portfolio currently active in the Ontario industry.

The BHGE wireline services group provides a complete suite of downhole electric wireline logging services for every well environment, including cased-hole advanced formation evaluation, production and reservoir engineering and petrophysical and geophysical data-acquisition services. BHGE is the major provider of casing inspection services for the vast bulk of underground storage wells present in Ontario with continuous enhancement in service delivery over the years.

The recent development of the Integrity eXplorer cement evaluation tool for gas-filled boreholes is an example of the continued partnership with the underground storage market to develop services to improve



the operational efficiency.

The BHGE Downstream Chemicals group has focused on the supply and management of specialty chemical treatment programs to maximize the value of the downstream assets. Service lines such as process chemicals, finished fuel additives, water treatment and contaminate removal has been provided for the Refineries and Terminals.

The BHGE Process and Pipeline Service group has historically provided complimentary services at all phases of our customer's asset life cycle: Engineering Services, Pre-Commissioning, Maintenance, Inspection and De-Commissioning and Pipeline services.

BHGE's groundbreaking Bently Nevada technology encompasses rack-based and distributed machinery condition monitoring software and hardware solutions, vibration monitoring equipment and sensors that enable greater asset reliability and enhanced efficiency for your operations, backed by an expert global support system.

Unexpected machinery failure is expensive. It results in unplanned downtime and can cause secondary failures to other machine components, which can create HSE (health, safety and environment) risk. Bently Nevada is leading the charge to minimize machine failure and keep your projects moving forward.

From market-leading gas turbines and steam turbines to a suite of axial, centrifugal and reciprocating compressors and gearboxes, BHGE has been the premier supplier of turbomachinery solutions and services for oil and gas, power generation and other industrial applications. Our turbomachinery solutions are proven to help customers optimize production, efficiency and safety for a complete range of semi-submersible platforms and floating production units.

The merger of Baker Hughes and General Electric has created BHGE, a company with the fullstream capability, the portfolio, the technology, and the people to radically transform the oil and gas industry and deliver unparalleled improvement in industrial yield to our customers. From reservoir to refinery, from the depths of the sea to the cloud. We are fullstream. ■

GAS STORAGE AND A MERGER ON THE WAY

Enbridge Gas is serious about gas storage in Ontario.

Servicing over two million residential and commercial customers in the Toronto, Niagara and Ottawa areas, Enbridge has 11 natural gas storage reservoirs located in Southern Ontario. Ten of those reservoirs are located in the Lambton and Kent counties, at an average depth of 2,000 feet, and the remaining reservoir is located in the Niagara region, 700 feet underground. The Lambton and Kent reservoirs are in ancient carbonate reefs and the Niagara reservoir is contained in sandstone. The reservoirs range in size from 0.3 billion cubic feet to 26.1 billion cubic feet.

Gas is injected into the reservoirs – or reefs – during the warmer months when the customer demand for gas is on the lower side. The gas is then withdrawn and delivered to customers. This process manages the supply of natural gas delivered by pipeline into Ontario by maintaining the gas flow at or near contracted pipeline capacity year-round, even though the gas consumed by customers varies by season.

Kathy McConnell, manager of reservoir development at Enbridge, says, "We are one of the few companies in Ontario that drill horizontal wells, as opposed to vertical ones."

"In our experience, the deliverability from one horizontal well is equivalent to the deliverability of 3.5 vertical wells."

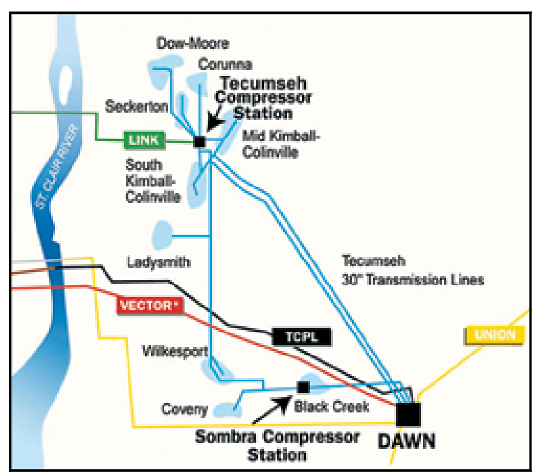
Drilling horizontal wells is quite expensive; however, it works well in the storage application. McConnell says some other production companies in Ontario drill horizontally, but the economics do not support the expense.

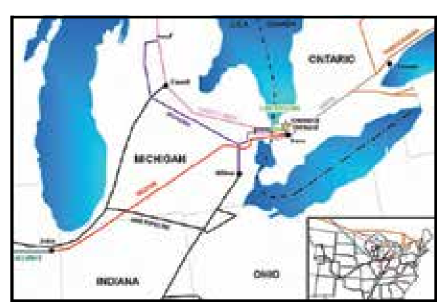
"For us, it's a good method, because it reduces our footprint and we can position wells to a certain degree, so we can utilize our own property and not bother other landowners. To date, we've drilled 11 horizontal wells, and they've been quite successful," she says.

In the future, Enbridge plans on drilling two horizontal injection/withdrawal wells and two vertical observation wells in the Dow-Moore DSA. In the meantime, the company continues to maintain their wells by casing corrosion logging, repairing wells and testing and acidizing wells.

McConnell adds, "Union Gas and Enbridge Gas are two great companies with strong histories and will amalgamate to one company on Jan. 1, 2019. We're not only combining the storage entities but the distribution entities too."

On its own, Enbridge has 115 billion cubic feet of storage, while Union Gas has 155 billion cubic feet of storage. When combined, they will have a shared storage capacity of 270 billion cubic feet. For more information, visit enbridgegas.com. ■





ONTARIO HYDROCARBON STORAGE IN SALT CAVERNS

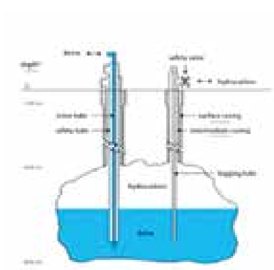
By Jug Manocha, P. Eng., Operations Engineer, Ontario Ministry of Natural Resources and Forestry

The underground storage of petrochemicals and liquefied petroleum products in geological formations is a significant industry in the province of Ontario. It provides economic and environmental benefits for the companies and consumers. There are 71 active hydrocarbon storage caverns with a combined storage capacity of 3.5 million square metres (22 million barrels). All these caverns are in bedded salt formations and primarily within B Unit salt strata. In Southwest Ontario, the B Unit as per the inset map extends from Goderich through Sarnia to Windsor.

The hydrocarbon storage in salt storage caverns in Ontario began in the early 1950s. These caverns were developed by a solution mining process that involves drilling a well to the Salina formation, installing the casings, and injecting water to dissolve the salt and recover brine at the surface. This controlled solution mining process is continued until the cavern shape and size have been developed and the cavity is full of brine. For most storage operations, a brine displacement method is used for hydrocarbon storage. This involves injecting hydrocarbon product into the cavern and displacing brine to a storage pond. Similarly, when the product is required, the brine is pumped into the cavern and the hydrocarbon is recovered as seen in Figure 2. Control and instrumentation systems are implemented to ensure operations are conducted safely.

Hydrocarbon feedstocks, intermediate products and finished petrochemical products are stored in the Sarnia and Windsor areas. These hydrocarbons include natural gas liquids (NGL), liquified petroleum gases(LPG's), ethane, ethylene, propylene, butane and other similar products. Currently natural gas is not stored in these caverns.

The readily available salt formations for storage at Sarnia the refineries and petrochemical plants and at the Windsor storage terminal, provide for large volume storage caverns. The advantage of the subsurface storage in salt caverns include lower capital costs, lower operating costs and lesser safety and environmental concerns, and require considerably less surface space. The following outlines some of the geological parameters for suitable hydrocarbon/petrochemical storage in these areas.



Depth: ***300-720 metres***

Thickness: *Up to 90 metres in `B' salt. Additional salt layers above and below*

Caprock: *Above the salt formations to minimize potential for leaks*

Temperature: *16-200 C at depth*

Storage Capacity: *50,000 square metres (315,000 barrels). Range from 9,500 m 3 to 250, 000 square metres.*

Pressure gradient: *Storage typically below 15.9 kPa/m (.7 psi/ft).*

Product pressure: *Average 3535-4100 kPa (500-600 psig), to a maximum of 7550 kPa(1100 psig)*

The Oil, Gas and Salt Resources Act (OGSRA) and the associated Ontario Provincial Operating standards outline the requirements for underground hydrocarbon storage caverns in Ontario. These provincial standards require compliance with The Canadian Standards Association Standard Z341.2 Salt Cavern – Storage of Hydrocarbons in Underground Formations, which provides the requirements. This standard outlines a life cycle approach and includes the requirements for the well design, construction, operations and maintenance, emergency planning and response, and decommissioning and abandonment. These requirements are to provide safety protection and to ensure long-term integrity of the cavern system.

In 2018, Ontario amended the OGSRA to allow for Compressed Air Energy Storage (CAES) projects in salt caverns. A project for CAES in salt cavern is under development at Goderich. CAES is being stored in a cavern system that was initially developed for salt solution mining operations.

For 60 years, the salt solution mined hydrocarbon storage caverns have been successfully used for storage of hydrocarbons. The bedded salts in Ontario, with the lateral extent and depths, provide potential for further developing solution mined caverns for storage of hydrocarbons and for other energy products. ■

WORKING TOGETHER:
EXPERIENCE, EXPERTISE AND INNOVATION
SAFEGUARDS FOR GAS STORAGE APPLICATIONS

By Hugh Flesher, Product Manager, Surface Safety Systems, Stream-Flo Industries Ltd.

Established in 1962, Stream-Flo Industries Ltd. is a worldwide manufacturer and supplier of wellhead and Christmas tree equipment, gate valves, actuators and check valves. Through our sister company, Master Flo Valve Inc., we have also become a leading manufacturer and supplier of surface and subsea chokes and control valves to the global energy market.

Stream-Flo, a family-owned Canadian company, has been working with the underground gas storage stakeholders in the Ontario region for over 10 years, developing long-term partnerships and providing automated valve systems that ensure fail-safe operation of wellhead shut-in equipment. The collective experience and expertise of the Stream-Flo Surface Safety System team, working closely with the various disciplines at the end user's local site, fosters a high level of cooperation and collaboration, resulting in engineered solutions that are fit for purpose and meet expectations.

The Stream-Flo Surface Safety System self-contained hydraulic linear actuator was developed to monitor and react to certain wellhead and flow line events that, if left unattended, could cause major damage to assets and disruptions to normal operations as well as a negative impact on the environment. The Stream-Flo Emergency Shutdown System (ESD) is designed to hold the line valve in the open position by using an integrated fluid power source. Upon detecting a fault such as excessive heat or abnormal flow line pressure fluctuations the ESD system ensures that the shutoff valve moves to the fully closed (safe) position. A local manual override mode is also included in the system should it be necessary to force the valve closed at the wellsite.

The Stream-Flo self-contained hydraulic ESD offers absolute reliability in a simplified user-friendly package, with performance that effectively eliminates spurious trips and false closures, allowing dependable operation and uninterrupted flow while maintaining the integrity of the equipment and, in particular, the environmental safeguards. The mainstay of the ESD system is the Stream-Flo reverse-acting gate valve, designed to be self-closing, and unlike any other type of shutoff valve used in the energy industry. The calculated geometric ratio of the valve stem dynamic thrust to the gate drag friction drives the valve to the fully closed position under line pressure. The integral hydraulic pump system and associated controls serve to open the gate valve using manual force and revert to the auto mode once the flowline is operating in a steady state.

Working in common with a highly educated, widely diverse and skillfully experienced workforce within the Canadian gas storage industry has encouraged Stream-Flo to further develop innovative and high performing safety systems for wellhead and flowline equipment that delivery security and an assurance of reliability mandated by this industry. The acceptance of our ESD systems by those that know the exacting requirements inspires improvements and advancements in the technologies.

Stream-Flo is heavily involved in bringing innovative technologies to the gas storage market. Working with a sister company, Dycor Technologies Inc., we are developing state of the art ESD systems that through data analytics offer performance and diagnostic information such as out of range alarms, equipment health and predictive maintenance alerts. This type of dedicated monitoring system serves to lower lease operating costs with fewer site visits while extending well flow uptime through enhanced cycle life and provides an extra degree of environmental protection. Optimization of our customer's operations with remote supervision and control of the ESD safety system is one innovation that Stream-Flo is bringing to the gas storage market.

We are committed to continue providing engineered solutions and local support to meet the unique challenges of the gas storage industry. ■

ONTARIO PETROLEUM INSTITUTE

AN INDUSTRY ASSOCIATION

The Ontario Petroleum Institute (OPI) has evolved during its 55 years of involvement as a not-for-profit industry association representing explorationists, producers, contractors, geologists, petroleum engineers and other professionals, individuals directly related to the oil and gas, hydrocarbon storage and solution-mining industries of Ontario.

The OPI's fundamental objectives are as relevant and important today as they were at its inception to encourage responsible exploration, maintain a relationship with government, keep members informed and educate the general public.

The exploration and production of oil and natural gas has made a valuable contribution to the province supplying energy, jobs and supporting the economic prosperity of communities throughout Ontario. For decades, this value-added industry has safely and sustainably produced millions of barrels of oil and billions of cubic feet of natural gas for Ontarians.

Presently, there are 130 companies producing and storing oil and natural gas, and two salt/solution mining companies operating throughout Southwestern Ontario. The production and storage includes the historic oil wells of Lambton County and the Dawn Hub one of the largest natural gas storage facilities in North America. The Government of Ontario through the Oil, Gas and Salt Resources Act oversees these industries. The Ministry of Natural Resources and Forestry has administrative responsibility for regulatory implications of the Act, Regulation 245/97 and the Provincial Operating Standards.

Ontario's oil and natural gas industry provides an estimated $77 million in direct oil and natural gas product revenues, approximately 700 full-time jobs, several millions in annual royalties and significant yearly corporate taxes in contributing to the Ontario's economy.

The OPI also manages the Ontario Oil, Gas and Salt Resources Trust which includes the Oil, Gas and Salt Resources Library an important resource centre offering its members and the public the most current geological information for the exploration and development of crude oil, natural gas, hydrocarbon storage and salt solution mining.

As an industry association the OPI has two significant challenges in 2019 – developing new exploration opportunities and fitting into the climate change environments. To a degree, these two issues interconnect as the ability to develop and explore natural resources will be impacted by the measures implemented to manage climate change. The Ontario industry with its experience, expertise and ability to innovate will meet these challenges.

The OPI is pleased to have the opportunity to bring readers the 2019 Ontario Oil & Natural Gas magazine to provide readers with the most current information on one of the province's historic industries. It affords us with a window to view how the oil wells of 1858 and natural gas wells soon after continue to contribute along with the innovation and technology that has been developed and applied in the ensuing 160 years. Thank you to the content contributors and sponsors for your participation in the magazine.

The OPI is committed, as a not-for-profit industry association on behalf of members, stakeholders and partners, to its continuing role of advocating for oil and natural gas exploration and production, hydrocarbon storage and salt solution mining. ■

Hugh Moran, Executive Director
Ontario Petroleum Institute

ONTARIO OIL AND GAS PLAYS

1. Exploration, Production and Geology

By Carter, T.R.1; Clark, J.2; Colquhoun, I.1; Dorland, M.3; and Phillips, A.4

1. Geological consultant, London, ON
2. Ontario Oil, Gas and Salt Resources Library
3. Geological consultant, Woodstock, ON
4. Clinton-Medina Cataract Group Inc., Calgary, AB

This paper is the first of a four-part series. Part 2 and 3 will describe conventional oil and gas plays in the Paleozoic bedrock of southern Ontario. Part 4 will provide a review of the unconventional resource potential of Ontario.

Petroleum exploration, production and storage

In 1858, James Miller Williams dug a well at the site of an oil seep in the swamps of Enniskillen Township in southern Ontario. This discovery, now known as Oil Springs, became North America's first commercial oil well. The larger Petrolia oil field was discovered nearby in 1862. Thousands of wells were drilled in the surrounding area in the resulting rush of fortune-seekers. These early explorationists pioneered many of the exploration and production methods used in the industry today, exporting the technology, techniques, drillers and skills to countries around the world (Gray, 2008a, 2008b, Kemp and Caplinger, 2007, Lauriston, 1961, McGee, 2004, Miller, 1986, Morritt, 1993). Discoveries of natural gas were made as early as 1870 in the Niagara Peninsula but were not commercially developed (Lauriston, 1961).

In 1889, the first commercial gas wells were completed by Eugene Coste in Essex County near Leamington and, later in the same year, another discovery was made 10 kilometres east of Port Colborne in the Niagara Peninsula. These two fields, Kingsville and Welland, one at each end of southern Ontario, were quickly developed, and gas was soon being marketed in Ontario and exported to Detroit, Toledo and Buffalo.

Portions of the first producing oil and gas fields such as Oil Springs, Petrolia and Welland still continue to operate, with over 700 active wells. However, most of the current oil and gas production is from pools discovered in the last 25 years. Well records are available for nearly 27,000 wells, most of which were drilled in southern Ontario. Currently there are approximately 1,200 wells producing oil and 1,200 producing gas in commercial quantities. There are also 550 "private gas wells" utilized to produce natural gas for private non-commercial use on rural properties in parts of southern Ontario.

In conjunction with the historic production, several Canadian oil and gas industry "firsts" were recorded in Ontario: the first natural gas syndicates/utilities marketing gas to industry and for home use; the first commercial underground storage of natural gas in geological formations in 1942 following experimental test injections in 1915; the first pipeline export of natural gas to the United States in 1890 to Buffalo and in 1895 to Detroit; the first import of natural gas from the United States in 1947 through a pipeline under the Detroit River (Lauriston, 1961); the first offshore gas well, drilled in Lake Erie in 1913 (Lauriston, 1961, Gray, 2008a); and the first storage of hydrocarbons in a solution-mined salt cavern in 1952.

Presently, predominantly small, Ontario-based operators dominate exploration and production. Historically, several small local companies have grown into large national and international corporations with long-term economic impact, including Imperial Oil, Union Gas, former McColl-Frontenac (Texaco Canada), British-American Oil Co. (Gulf Canada) and White Rose (purchased by Shell Canada).

Cumulative production to the end of 2014 totals 1.33 tcf of natural gas and 90.4 million barrels of oil (Oil, Gas and Salt Resources Library, 2015) from approximately 340 pools (Figure 1). All production is from conventional reservoirs in Paleozoic rocks in southern Ontario. In 2015, annual production totalled 5.7 bcf of natural gas and 400,000 bbls of crude oil. Approximately 65 per cent of Ontario's annual production

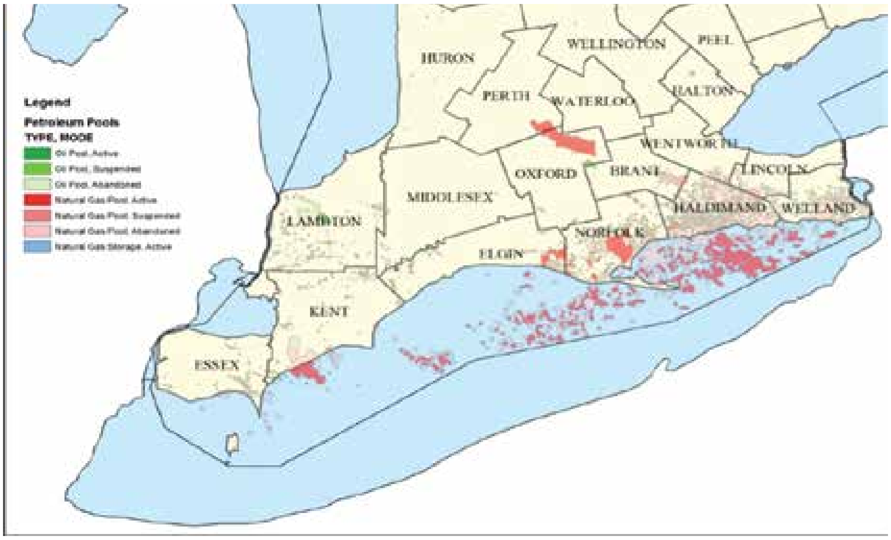


Figure 1. Oil, gas and natural gas storage pools in southern Ontario. More detail is available in the Pools and Pipelines Map published by the Ontario Oil, Gas and Salt Resources Library (2015).

of natural gas is derived from Crown lands beneath Lake Erie.

Underground storage of natural gas and liquefied hydrocarbons are important industries in Ontario. There are 35 natural gas storage pools in operation in southern Ontario, utilizing depleted natural gas reservoirs, with storage capacity for 6.9 billion cubic metres (245 billion cubic feet) of gas. These pools are serviced by 284 injection/withdrawal wells and 96 observation wells. A total of 71 solution-mined caverns in salt beds are utilized for underground storage of liquefied hydrocarbons and petrochemicals at the refineries and petrochemical plants at Windsor and in the Sarnia area. There is storage capacity for 22 million barrels of product. The caverns are serviced by 105 wells and provide safe, large-capacity and economical subsurface storage at depths of 400 to 700 metres (Carter and Manocha, 1996).

Statutes and regulations

Ontario statutes (Oil, Gas and Salt Resources Act) and regulations (O.Regulation245/97) can be viewed or downloaded from www.ontario.ca/laws. The Provincial Standards, Applications to Drill or Operate a Well and specified forms for filing of reports can be viewed or downloaded from www.ogsrlibrary.com.

Exploration for, and production of, oil from wells located in the waters of the Great Lakes is prohibited by regulation and provincial policy. Oil can be produced from land-based deviated or horizontal wells drilled beneath the lakes.

Geology

Southern Ontario is underlain by Paleozoic sedimentary rocks ranging in age from Cambrian to Mississippian (Johnson et al, 1992, Armstrong and Carter, 2010) (Figures 2, 3, 4). These strata attain a maximum thickness of 1,425 metres in southern Ontario, thickening to 4,800 metres and 7,000 metres respectively in the centres of the Michigan and Appalachian basins (Armstrong and Carter, 2010).

A sinuous northeast-southwest basement ridge, the Algonquin Arch, is the dominant bedrock structural feature of southern Ontario, formed by differential crustal movements in response to regional tectonic events (Figure 2). Crustal subsidence formed the Michigan and Appalachian Basin depocentres to the northwest and southeast respectively. Paleozoic strata have very shallow dips, ranging from three to six metres/kilometres southwestwards along the crest of the Algonquin Arch into the Chatham Sag, and 3.5 to 12 metres/kilometres down the flanks of the Algonquin Arch into the basins.

The Paleozoic succession is cut by a number of relatively minor faults, exhibiting both normal and strike-slip senses of movement. Maximum measured displacement is 100 metres. Despite the relatively minor structural deformation of these strata, faults are an important control on the formation of oil and gas traps in the Paleozoic strata of southern Ontario, in particular in Ordovician and Cambrian strata.

The Paleozoic strata overlie a Precambrian basement complex of deformed crystalline metamorphic rocks of the Grenville Province that are over one billion years old. Local relief on the Precambrian surface is only a few tens of metres after nearly 500 million years of erosion predating deposition of Paleozoic sediments. All bedrock in southern Ontario is overlain by unconsolidated sediments of largely Pleistocene age, averaging a few tens of metres and ranging up to 200 metres in thickness.

Oil and gas plays

All of Ontario's oil and gas discoveries and production to date are found in southern Ontario in Paleozoic rocks that are similar to, and extensions of, Michigan and Appalachian basin play types (Figure 5). From 1860 to 1989 cumulative production from Appalachian Basin oil and gas reservoirs totaled more than 2.5 billion barrels of oil and 30 tcf of natural gas from the drilling of more than 500,000 wells (Ruppert and Ryder, 2014). This does not include production from the prolific Marcellus and Utica plays with current production rates of 18 bcf/day and 3.7 bcf/day respectively (EIA, 2016). Cumulative production of oil and gas in the state of Michigan, which encompasses most of the Michigan Basin, from 1925 to the end of 2015, totals 1.34 billion barrels oil

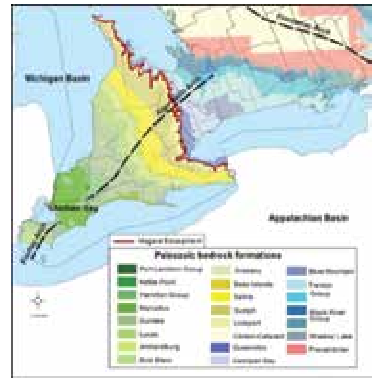


Figure 2. Bedrock geology of southern Ontario, showing Paleozoic sedimentary rock formations and regional structures. The Niagara Escarpment is a prominent physiographic feature on the bedrock surface.

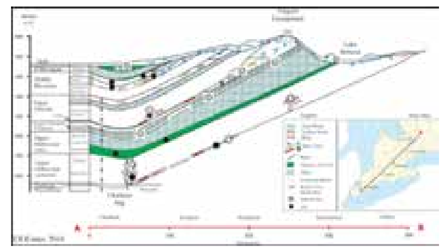


Figure 3. Geologic cross-section of southern Ontario showing oil and gas-bearing intervals, organic-rich shales, and regional water-bearing intervals coded by water type. Modified from Carter et al (2014).

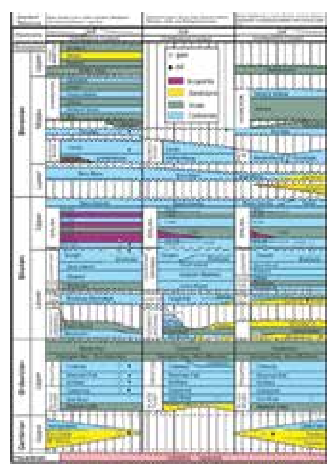


Figure 4. Paleozoic bedrock stratigraphy of southern Ontario showing principal oil and gas producing intervals. Modified from Armstrong and Carter (2010).

and eight tcf of natural gas, from the drilling of over 56,000 wells (Harrison, 2016).

Commercial quantities of oil and gas in conventional reservoirs have been discovered at several stratigraphic intervals and comprise five principal plays: CAM – structural and stratigraphic traps in Cambrian sandstones and sandy dolomites; ORD – hydrothermal dolomite reservoirs in middle Ordovician limestones; CLI – stratigraphic traps in lower Silurian sandstones and associated carbonates; SAL – reefs and

Interval	***Cumulative Production through 2014***			
	OIL (m3)	OIL (bbls)	GAS (x1000 m3)	bcf
DEV	7,175,000	45,129,000	0	0
SAL	2,401,000	15,102,000	21,168,000	747.5
CLI	6,900	47,300	14,357,000	507.0
ORD	3,951,000	24,851,000	1,225,000	43.3
CAM	839,000	5,277,000	906,000	32.0
Total	***14,373,000***	***90,406,000***	***37,657,700***	***1,329.8***

Table 1. Cumulative Oil and Gas Production in Ontario, summarized from Oil, Gas and Salt Resources Library (2015).

structural traps in middle Silurian carbonates; and DEV – structural traps in Devonian fractured, dolomitized carbonates and sandstones (Lazorek and Carter, 2008). Cumulative production by play is summarized in Table 1.

Potential resources

There have been four quantitative assessments of conventional oil and gas potential in Ontario: Bailey Geological Services Ltd. and Cochrane, R.O. (1984a, 1984b, 1985, 1986, 1990;), Osadetz et al (1996), Golder Associates (2005) and the Canadian Gas Potential Committee (1997, 2001, 2006). Based on these assessments, remaining oil to be produced or still undiscovered at the end of 2014 is estimated to be 190 mmbo (81 per cent beneath the Great Lakes), and 1.45 tcf of natural gas (62 per cent beneath the Great Lakes).

Provisional quantitative estimates of potential oil and gas resources in Ontario were included in regional studies of resources in all of Canada by Hutt et al (1973) and Proctor et al (1983). No rigorous analysis of individual pools or plays was attempted. There have been no commercial discoveries of oil or natural gas in the Hudson Bay/James Bay region of Ontario. Hydrocarbon systems in Hudson Bay are documented by Lavoie et al (2013) and Hamblin (2008).

The Craigleith Shale Oil Works near Collingwood, Ont. was the site of North America's first unconventional oil production in 1859. Since that time, there has been no discovery of commercial quantities of oil or gas in the shales of Ontario and no high-volume hydro-fracture treatments have been completed in either shales or conventional reservoirs. No quantitative resource estimate has been completed for unconventional resources in the organic-rich shales of Ontario. Collection of new technical data relevant to assessment of the resource potential of both the Kettle Point (Antrim-equivalent) and Blue Mountain (Utica-equivalent) shales has been completed by the Ontario Geological Survey (Béland-Otis, 2015a, 2015b; Béland-Otis, 2012a, 2012b).

Ontario Oil, Gas and Salt Resources Library

Well records and related subsurface geological data collected by the Ontario government from petroleum industry operations are accessible at the Ontario Oil, Gas and Salt Resources Library (www.ogsrlibrary.com). The Library is a unique and very successful not-for-profit public resource centre and data warehouse of information on the subsurface geology and oil, gas, salt and hydrocarbon storage resources of Ontario, and the occurrence and types of deep groundwater in the bedrock of southern Ontario.

The Library and its data resources are owned by the Ministry of Natural Resources and Forestry (MNRF). It has been operated by the Ontario Oil, Gas and Salt Resources Corporation (OOGSRC) since 1998 as the trustee of the Oil, Gas and Salt Resources Trust (OGSR Trust). The OGSR Trust was formed by the MNRF pursuant to the requirements of S.16 of the Oil, Gas and Salt Resources Act enacted in 1997. The OOGSRC is a wholly owned subsidiary of the Ontario Petroleum Institute.

Summary

Exploration for conventional resources has reached a mature stage of development in Ontario, but there still remain many opportunities, including: new pool discoveries in several well-defined plays; large unexplored areas in Ordovician and Cambrian strata; large remaining volumes of oil in discovered pools that could be recovered by technological improvements in secondary/tertiary recovery methods; conversion of additional depleted natural gas pools to natural gas storage; development of new hydrocarbon storage caverns; natural gas reservoirs in areas presently underserviced by pipelines; and new play concepts. There has not yet been any production of oil or gas from unconventional reservoirs in the subsurface of Ontario, despite the presence of organic-rich shales in the Kettle Point (Antrim), Blue Mountain (Utica) and Marcellus formations.

Exploration has declined to historic lows in the last few years due to low commodity prices, a problem that is not unique to Ontario. Previous downturns have traditionally been utilized as an opportunity for reassessment of exploration and development opportunities. Advantages of exploration in Ontario include: market access; extensive road, power and pipeline infrastructure, low lease and royalty costs, mainly freehold land with low lease costs, long-life reservoirs with low decline rates, local oilfield services, stable regulatory environment, and low drilling, transportation and service costs.

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Bailey Geological Services Ltd. and Cochrane, R.O., 1984a. Evaluation of the conventional and potential oil and gas reserves of the Cambrian of Ontario; Ontario Geological Survey, Open File

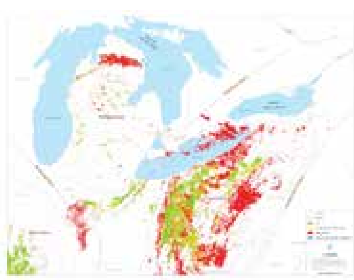

Figure 5. Oil and gas fields of the northeastern United States and Canada (Ontario Oil, Gas & Salt Resources Library, 2014). Ontario plays are extensions of plays in the neighbouring Michigan and Appalachian basins.

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ONTARIO OIL AND GAS PLAYS

2. Cambrian and Ordovician Conventional Plays

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Figure 1. Regional geological relationships, showing Paleozoic basins and the Algonquin Arch.

Introduction

This paper is the second of a four-part series. Part 1 summarized the exploration, production and geology of Ontario. This paper describes conventional oil and gas plays in the Cambrian and Ordovician strata of southern Ontario. Part 3 will describe conventional oil and gas plays in the Silurian and Devonian strata. Part 4 will provide a review of the unconventional resource potential of Ontario. The regional Paleozoic geology of southern Ontario was described in Part 1 of this series.

The Paleozoic sedimentary strata of southern Ontario straddle a regional arch, dipping down its flanks into the Michigan and Appalachian basins (Figure 1), forming a natural regional trap. Stratigraphic relationships of Cambrian and Ordovician strata, which are the subject of this paper, are described in Figure 2.

Ontario's Cambrian and Ordovician strata have produced over 28 million bbls of oil and 73 bcf of natural gas from reservoirs at depths of less than 1,200 metres. They are located in the heart of Canada's most populous and industrialized province, with well-developed infrastructure and a big appetite for hydrocarbons. Oil and gas development opportunities still remain, especially in these strata, the oldest, thickest and least explored of Ontario's Paleozoic sedimentary rocks.

The Cambrian Play: Geology of Cambrian Strata

Upper Cambrian siliciclastic and carbonate rocks are the oldest preserved Paleozoic strata in southern Ontario and lie directly on the Precambrian basement. They underlie approximately 48,000 square kilometres (Bailey and Cochrane, 1984), an area slightly less than 50 per cent of that underlain by younger Paleozoic strata. Thickness of the Cambrian section ranges from approximately 175 metres in the centre of Lake Erie to zero metres at the pinch-out edge (Figure 3).

During Upper Cambrian time, sediments were deposited throughout southern Ontario, onlapping and extending over the Algonquin Arch as early Paleozoic seas transgressed the Precambrian surface (Johnson et al., 1992). Subsequent exposure and erosion during development of the regional pre-Upper Ordovician Knox Unconformity resulted in the removal of Lower Ordovician and much of the Cambrian strata from southern Ontario (Johnson et al., 1992). In the central part of southern Ontario the Cambrian sediments were completely removed by erosion over the crest of the Algonquin Arch. The distribution of Cambrian strata around the edges of the Algonquin Arch with successively younger units overlapping one another to lie directly on the Precambrian basement indicates that the arch had a configuration very similar to the present during Upper Cambrian time (Sanford and Quillian, 1959; Bailey, 2005).

West of about longitude 81 degrees, or the approximate location of London, Ont., the basal sedimentary rocks consist of mainly quartz sandstone (Mount Simon Formation); overlain by sandstone, sandy and shaley dolomite (Eau Claire Formation); and then buff to grey-buff dolomite (Trempealeau Formation). East of about longitude 81 degrees, the basal sedimentary rocks consist of arkose and quartz sandstone (Potsdam Formation); overlain by dolomite, sandy dolomite, and sandstone (Theresa Formation); and then light buff, crystalline dolomite (Little Falls Formation). As the Cambrian strata approaches its pinch-out edge on the Algonquin Arch these units become less distinct and the formation terminology becomes less appropriate (Bailey and Cochrane, 1984), with formation top picks recorded as unsubdivided Cambrian in the Ontario petroleum well database.

Geology of the Upper Ordovician Shadow Lake Formation

In the Early Ordovician, tropical seas withdrew from southern Ontario and a prolonged period of exposure and erosion of the underlying Cambrian strata down to the Precambrian basement occurred. This

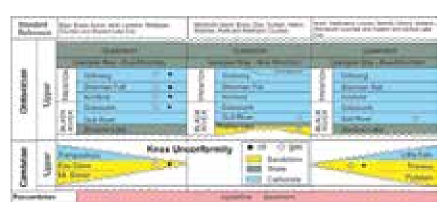

Figure 2. Stratigraphic relations of Ordovician and Cambrian strata of southern Ontario showing oil and gas-bearing intervals. Column headings indicate county names for geographic reference, from west (Michigan Basin) to east (Appalachian Basin) across southern Ontario. Modified from Armstrong and Carter (2010).

Figure 3. Subcrop limits of Cambrian strata in the subsurface of southern Ontario and largest discovered pools. Modified from Trevail (1990), Lazorek and Carter (2008), and Ontario Oil, Gas and Salt Resources Library (2015).

is referred to as the "Knox Unconformity" (Bailey and Cochrane, 1984; Coniglio et al., 1990). The Shadow Lake Formation is the basal unit of the Upper Ordovician Black River Group (Figure 2). It represents the onset of sedimentation following the Knox Unconformity as the Upper Ordovician sea transgressed over the Precambrian/Cambrian erosional surface and washed the weathered detritus into paleotopographic depressions (Coniglio et al., 1990).

Lithology and thickness of the Shadow Lake Formation is variable due to local variations in sediment source, and paleotopographic relief of the underlying Precambrian/Cambrian erosional surface (Sanford 1961; Trevail 1990). The depositional environment was nearshore marine, with facies including a mixture of regolith, aeolian, alluvial and shoreline deposits reworked by the transgression (Coniglio et al., 1990). Sediment was primarily derived from eroded Cambrian and Precambrian rocks. The Shadow Lake Formation is two to three metres thick throughout most of southern Ontario, locally reaching a maximum of 15 metres (Armstrong and Carter, 2010).

In the crestal portions of the Algonquin Arch where the Cambrian sandstone has been removed by erosion, the Shadow Lake Formation rests directly on the Precambrian basement (Figure 3). The Shadow Lake Formation generally consists of a lower coarse sandstone grading up into interbedded silty or dolomitic or calcareous sandstone overlain by sandy and silty shale and shale with minor thin limestone or dolostone interbeds. The sandstones are highly variable in grain size, sorting, and cementation and may be locally porous and permeable. The overlying shales are often bright green with floating quartz sand grains and thin interbeds of greenish and grey thin limestone and dolostone (Caley and Liberty, 1950; Burgess, 1962; Liberty, 1955; Williams and Telford, 1986; Trevail, 1990; Coniglio et al, 1990; Armstrong and Carter, 2010).

Cambrian Reservoir Trap and Seal

Reservoir rocks are porous sandstone and sandy dolostone of Cambrian or Shadow Lake Formations. Traps are fault-bounded structures as in the Clearville Pool, stratigraphic pinch-out as in the Gobles and Innerkip pools, or a combination of structural faulting and stratigraphic pinch-out as in the Willey Pool (Figure 4). Gross pay thickness is up to nine metres with average porosity of nine to 12 per cent and permeability ranging from one to 300 mD. Reservoir depths range from 700 to 1,200 metres (Bailey and Cochrane, 1984). Hydrocarbon migration into the traps occurred regionally through the Cambrian sandstone and a porous alteration zone in the uppermost Precambrian (Sanford et al., 1985; Harper et al., 1995).

Vertical displacement along normal faults has created structural traps by juxtaposition of porous Cambrian and Shadow Lake Formation strata against non-permeable lithologies (see Figure 4). At the Clearville Pool, the reservoir is formed by porous sandstone and sandy dolostone in the crest of a tilted horst block sealed by overlying shales of the Shadow Lake Formation and laterally by non-porous Gull River Formation limestones. The Willey Field contains several uplifted structural fault blocks trapping oil in the Cambrian similar to the Clearville Pool, but with some stratigraphic influence as it is positioned near the Cambrian pinch-out edge. Some of the overlying Shadow Lake Formation sediments are also porous sandstones and form part of the reservoir. Shale of the upper Shadow Lake Formation provides the top seal.

The Arthur Pool located 65 kilometres north of the Innerkip Pool has produced 1.3 bcf of gas from porous strata at the Precambrian-Paleozoic unconformity. The reservoir geology is poorly understood due to a lack of records, but is believed to be comprised of porous Shadow Lake and Cambrian sandstones, which are overlain by Shadow Lake Formation shale or Gull River Formation limestone.

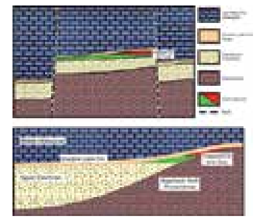

Figure 4. Cambrian play conceptual model. Top, structural trap associated with faulting as at the Clearville and Willey pools. Bottom, pinch-out style trap along Algonquin Arch as at Innerkip and Gobles pools. Modified from Bailey Geological Services Ltd., Cochrane, (1984) and Lazorek and Carter (2008).

Stratigraphic traps occur along the updip pinch-out edge of porous Cambrian and/or Shadow Lake Formation strata against the flanks of the Algonquin Arch (Figures 3, 4). All commercial oil and gas pools discovered to date are on the Appalachian Basin side of the arch.

The stratigraphic trap containing the Gobles and Innerkip pools is formed by porous sandstones preserved within a subtle basement low that extends 40 kilometres north of the regional Cambrian pinch-out edge on the southern flank of the arch and averages eight kilometres in width. Carter et al (1996) attribute the basement low to the effects of fault displacements on the Precambrian surface. Shales and sandy

Figure 5. Gobles Pool with oil leg in green and the type well location shown. Modified from Bailey and Cochrane (1984).

shales of the Shadow Lake Formation provide the top seal and create conditions favorable for stratigraphic entrapment of hydrocarbons. The reservoir sandstone ranges from only a few metres to over nine metres in thickness. Bailey (2003) has proposed that a significant portion of the gas-producing sandstones in the Innerkip Pool are not Cambrian but should be assigned to the Shadow Lake Formation, which is a major revelation impacting future exploration of Innerkip-style reservoirs.

The Gobles Pool was discovered in February 1960 by the Paris Petroleum No. 1 well (Figure 5). The discovery well was cable tool drilled to 2,917 feet and encountered four bbls/day of oil and associated gas in the Cambrian at 2,882 to 2,899 feet. In July 1960, the Robert McMaster & Sons Gobles No. 2 well drilled to the southwest (down-dip) found 12 bbls/day oil with some gas. Figures 6, 7, and 8 show a log, core description and thin section photomicrographs for type well Kewanee Gobles No. 37 in the Gobles Pool.

Cambrian Reservoir characteristics

Core analyses show average porosity of 9.2 to 11.8 per cent to a maximum of 20 per cent and average permeability of one to 67 mD and locally up to 300 mD for the major pools (Bailey and Cochrane, 1984). Within the known reservoirs, the Cambrian units are generally porous and permeable throughout but mixed lithologies cause large fluctuations in porosity and permeability values. The presence of mixed grain sizes, filling of pores by clays and cementation has resulted in reduction of primary inter-particle porosity and permeability in the siliciclastic units. In the Innerkip pool primary porosity has been substantially reduced by authigenic and diagenetic illite and chlorite clays and extensive quartz and K-feldspar overgrowths, and calcite, dolomite and anhydrite cements (Dorland, 2001). Formation of secondary intercrystalline porosity and permeability by dolomitization has occurred in the carbonate units, which also has been reduced by clays and cements.

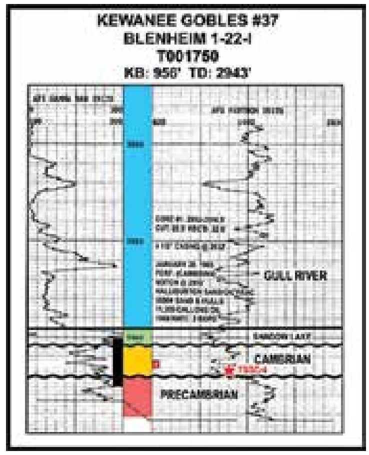

Figure 6. Interpreted gamma-ray neutron log for type well Kewanee Gobles #37. Core location is shown in black. TSGC-4 shows the location of the thin section photomicrographs. Modified from Phillips (2013)

Cambrian exploration and production history

Exploration targeting the Cambrian and/or Shadow Lake Formation in southern Ontario has resulted in 20 discoveries. The first Cambrian gas reservoir, the Electric pool, was discovered in 1948, followed by the Innerkip Pool in 1961. The Innerkip Pool is the largest gas pool in the play, with production starting in 1966. After 22 years of production, only six wells were producing with cumulative gas production of 3.4 bcf to the end of 1988. An additional 98 wells were drilled from 1989 to 2004 after discovery of the main sand channel to the north and northeast of the initial producing area. Over 89 per cent of the Cambrian gas production in Ontario has been derived from the Innerkip gas pool, with cumulative production of 27.6 bcf to the end of 2015.

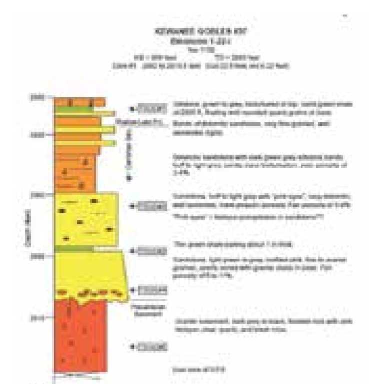

Figure 7. Core description/log for type well Kewanee Gobles #37. Core #1 cut 22.5' from 2892-2914.5' and recovered 22'. Modified from Phillips (2013).

Oil was first discovered in the Cambrian in 1923 but did not result in any commercial production. Discovery of the Gobles Pool (1.6 mmbo and 1.1 bcf gas) in 1960 stimulated exploration for Cambrian oil reservoirs, and was quickly followed by discovery of the Clearville Pool (1.5 mmbo) in 1962 and the Willey Pool (2.1 mmbo) in 1965. Over 93 per cent of the Cambrian oil production has been derived from these three pools, with cumulative production of over 5 million bbls to the end of 2015. Initial potential per well for Cambrian oil production is difficult to determine with certainty due to lack of records, but Bailey and Cochrane (1984) report individual wells producing up to 166 bbls/day from the Willey Pool.

Cambrian exploration potential

The Cambrian play is largely underdeveloped with considerable potential for additional discoveries. Prospective areas could be any place where porous clastics are present at the Precambrian/Paleozoic unconformity since the unconformity acted as a major fluid conduit throughout its history (Sanford et al., 1985; Harper et al., 1995). Only 1,150 wells have tested Cambrian targets in southern Ontario. Potential resources for the Cambrian play were estimated by Bailey and Cochrane (1984) at 131.3 million bbls oil and 222 bcf of natural gas.

The relatively new concept that the Innerkip Pool produces gas from Shadow Lake Formation strata in addition to Cambrian is significant for future exploration of this type of reservoir. Now, exploration for another Innerkip or Gobles type reservoir is not confined to areas where the Cambrian pinches out against the Precambrian basement. There are large prospective areas beyond the Cambrian subcrop pinch-out edge where the Shadow Lake Formation is present and where there has been limited exploration.

The Arthur gas pool is located on top of the Algonquin Arch, 65 kilometres north of the Innerkip pool. Well records are incom-

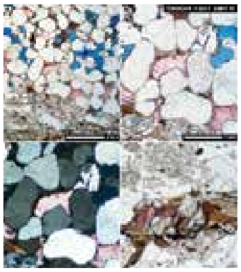

Figure 8. Thin section photos for core sample TSGC #4. (A) Large round quartz grains cemented by calcite (red) overlying granite/gneiss lithoclast. PPL. (B) Enlarged view from panel A showing calcite cement between quartz grains. PPL. (C) Same view as panel B but with cross polarized light. (D) General view of granite/gneiss lithoclast(?) from lower part of thin section. Modified from Phillips (2013).

plete but production appears to be derived principally from the Shadow Lake Formation. This is an example of a reservoir at the unconformity far removed from Cambrian strata. The area north of the Innerkip Gas Pool has very few wells, but an intriguing number of gas shows in the Shadow Lake Formation. The untested areas could easily fit another Innerkip gas or Gobles pool. It is surprising that no known recent exploration effort has been directed at this play. Also, it is important to note that there is no water leg associated with the Innerkip, Gobles or Arthur pools so it should be easier to find economic reserves in this play.

Middle Ordovician Trenton-Black River Oil and Gas Play

At the time of deposition of the regional limestones of the Black River and Trenton Groups, there was no discernible expression of the Algonquin Arch in southern Ontario. The Black River Group was deposited on a carbonate ramp, shallowing gradationally from southwest to northeast with corresponding thinning of the group from a maximum of nearly 150 metres near Windsor, to zero at the erosional edge in eastern Ontario (Figure 9). The overlying Trenton Group is more complex, averaging 150 metres in thickness in most of the subsurface of southern Ontario (Figure 10). Where not dolomitized, these rocks have some of the lowest measured hydraulic conductivities of all the Paleozoic strata in southern Ontario. These strata occur 850 metres or more in the subsurface in the Windsor area, and subcrop east of Toronto.

The Trenton-Black River Group carbonates were deposited on a storm-dominated, shallow crinoidal ramp (Kobluk and Brookfield 1982). The depositional sequences represent deepening-upwards cycles of shallow marine sedimentation (Aigner, 1985). They are overlain by thick shales of the Blue Mountain, Georgian Bay and Queenston Formations, and locally by shaley carbonates of the Collingwood Member of the Cobourg Formation (Figure 2), forming a regional seal for hydrocarbon migration and a barrier for water movement. Beneath Lake Erie, the combined thickness of these formations exceeds 500 metres, thinning from south to north and averaging 200 to 300 metres in most of southern Ontario. Both the Georgian Bay Formation and Queenston Formation contain interbeds of limestone.

The lowermost 10 to 50 metres of the Blue Mountain Formation, immediately overlying the Trenton Group, is dark grey to black and contains elevated levels of organic matter. Together with the underlying Collingwood, this Utica-equivalent interval is a potential unconventional source of oil and natural gas, to be discussed in the last paper of this series.

Geology of the Black River Group

The Shadow Lake Formation, already described above, is the basal unit of the Black River Group, and represents the initiation of deposition of Middle Ordovician sediments in southern Ontario following a prolonged period of exposure and erosion represented by the Knox Unconformity. It is conformably and gradationally overlain by very fine-grained lime mudstones of the Gull River Formation in most of southern Ontario (Figure 2). There is commonly a thin, regionally occurring bed of coarse dolomite in the Gull River, which may contain oil or natural gas, sometimes in commercial quantities. The Gull River coarsens upwards into the Coboconk Formation, which consists of fine to medium grained, bioturbated, fossiliferous limestones – mostly peloidal wackestones, packstones and grainstones.

Geology of the Trenton Group

The bioclastic limestones of the Coboconk are sharply overlain by the shalier limestones of the Kirkfield Formation, which grade upwards into fossiliferous bioclastic limestones comprised of wackestones, packstones and grainstones. The overlying Sherman Fall Formation consists of a basal facies of shaley lime mudstone to wackestones grading upwards into bioclastic lime grainstones. This upper unit is commonly termed the Sherman Fall "fragmental" by petroleum geologists. The uppermost unit of the Trenton Group is the Cobourg Formation, comprised of fossiliferous and argillaceous nodular limestone, with organic-rich partings. In the deep subsurface the uppermost few metres of the Cobourg Formation is dolomitized and is informally referred to as the "cap dolomite" (Armstrong and Carter, 2010).

Trenton-Black River Reservoirs

These structurally controlled oil fields are interpreted to have formed within a regional fault and fracture network that provided conduits for fluids that dolomitized the regional limestone and created the reservoirs. They are commonly referred to as hydrothermal dolomite (HTD) reservoirs (Hurley and Budros, 1990, Davies and Smith, 2006). A later pulse of hydrothermal fluid assisted with hydrocarbon maturation, migration and emplacement. The resulting linear fields have dimensions that range from 300 to 1,000 metres wide and up to 15 kilometres long in Ontario, and 0.5 to two kilometres wide and 60 kilometres long in the Albion-Scipio, Stoney Point and Napoleon oil fields within central and southeast Michigan. Similar reservoirs have been discovered in New York, Ohio, Pennsylvania and West Virginia in the Appalachian Basin.

These narrow reservoirs are expressed on seismic sections as a sag or structural low, which coincides with those areas of the reservoir that are well-fractured, dolomitized and contain reservoir quality rock (Figures 12, 13). These structures have been interpreted as graben-like features created by bounding faults; however, an alternative explanation includes regional fault and fracture patterns with accompanying shears created by wrench-faulting during several phases of extensional tectonics in the Taconic and Alleghanian orogenies. The dominant northwest-southeast trends are attributed to wrench-faulting associated with the Pennsylvanian Appalachian orogeny, overprinting the earlier fault and fracture patterns within southeastern Michigan and southern Ontario.

Reservoir development within the Trenton-Black River carbonates is usually within dolomitized grainstones that contain high matrix porosities, surrounded by fractured and dolomitized mudstones, wackestones and packstones (Figure 11). The reservoirs are laterally extensive vertical "chimneys" of dolomite created by pervasive dolomitization with laterally extensive secondary porosity, along a linear trend of dolomite chimneys. Dolomite chimneys were created by hydrothermal dolomitization within negative flower structures and localized by en-echelon shearing along a main fault trace (Figure 12;). Less intense fracturing and dolomitization within relatively bioclastic-poor sediments created isolated dolomite chimneys or pod-like reservoir development.

For a regional comparison, in southern Ontario, reservoir facies are best developed within the bioclastic grainstones of the Sherman Fall Formation and within the Coboconk Formation, whereas fractured mudstones and wackestones with accompanying vugular porosity characterizes reservoir development of Albion-Scipio, Stoney Point and Napoleon fields in central and southeastern Michigan.

Trapped hydrocarbons may have been sourced from the overlying Upper Ordovician shales and migrated at depth along fractures into the Cobourg and Sherman Fall Formations (Sanford 1961). Alternatively, the hydrocarbons originated from the Ordovician carbonate rocks themselves. The Cobourg Formation contains up to three per cent organic carbon content and has been exposed to high enough temperatures to generate hydrocarbons (Colquhoun 1991, Obermajer et al, 1996, 1999). Trapping mechanisms include the overlying Upper Ordovician shales (200 to 300 metres thick), a thin cap dolostone atop the Cobourg (one to five metres thick) and tight regional limestones along the lateral edges of the reservoirs. Hydrothermal dolomite textures may also provide local permeability barriers between shear planes within individual dolomite chimneys.

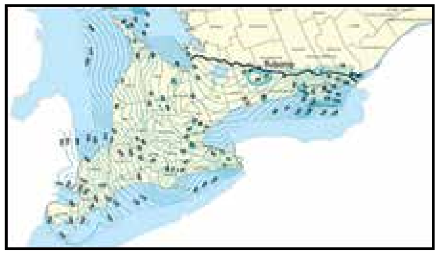

Figure 9. Isopach map (metres) of the Black River Group. Data from Ontario Geological Survey (2011).

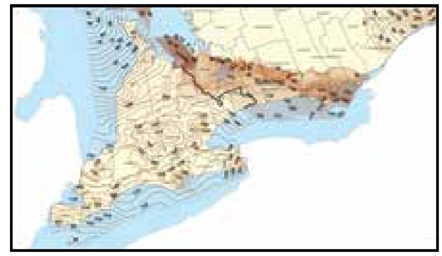

Figure 10. Isopach (metres) of the Trenton Group. Data from Ontario Geological Survey (2011).

Reservoir characteristics

There are a total of 71 Trenton-Black River oil and gas pools in southern Ontario with recorded production. Most pools are oil reservoirs that contain solution gas, but there are several gas pools as well. The top 14 oil pools (upper 20 per cent) produced between 700,000 bbls and 6.2 million bbls of oil. Initial production rates as high as 500 bbls per day have been were reported. The top 19 gas pools (upper 25 per cent), including solution gas production and gas producing fields, range between 370 mmcf and 14.1 bcf gas.

Core analyses demonstrate wide ranges in matrix porosity from three to 15 per cent with accompanying vugular and fracture porosity, which can range from 18 per cent to more than 45 per cent for large open fractures. Permeability estimates range between tens and several hundred millidarcies within specific portions of the reservoir and as high as 10 darcies when large open fractures are encountered, which greatly enhance initial productivity rates. Homogeneous reservoir quality grainstones exhibit average porosities of eight per cent with an average permeability of 150 millidarcies. Well productivity is variable depending upon the number of open fractures encountered by the well bore, which increases local permeability.

Oil is sweet, 40 degrees API and accompanied by solution gas. Typical water saturation within normal hydrodynamic regimes for Trenton-Black River reservoirs vary between 15 and 40 per cent, irreducible water saturation commonly ranges between 15 and 25 per cent. These reservoirs may contain prolific water production located much higher within the stratigraphic column, sometimes accompanied by small to large quantities of oil depending on location of the well within the structure. Typical initial decline rates for a producing well are estimated at 15 to 25 per cent per year (Figure 14).

Dolomitization, hydrothermal alteration and emplacement of hydrocarbons

The controlling structures of the dolomite chimneys are interpreted to be wrench faults from extensional tectonics. Within southwestern Ontario extensional faulting occurred as early as upper Ordovician and was active up to middle Devonian time, during both the Taconic and Appalachian orogenies.

The first stage of reservoir development included dolomitization of the host limestone and creation of secondary porosity and permeability, or at least a major part of it, by warm basinal fluids. These warm fluids migrated through the Cambrian sandstones by hydrostatic pressures influenced by basin-wide circulation of brines, up along faults and fractures into the overlying carbonates and progressively dolomitized the limestone. Dolomitization also occurred along preferred pathways within porous bioclastic-rich carbonates. Timing on the dolomitization event is likely prior to maximum subsidence of the basin (more than 300 Ma), following initial development of the pull-apart structures during upper Ordovician time ~440 Ma, and predating hydrocarbon migration (Colquhoun, 1991).

Subsequent to dolomitization, further alteration by hydrothermal fluids resulted in stacked reservoirs in some places and segregated reservoirs in others. The timing of this event was estimated using Lopatin basin modeling techniques to be ~250 Ma or during late Permian (Colquhoun 1991). Several tectonic events occurred over a short time frame including a structural overprinting event during Pennsylvanian time.

During these later stages of tectonic adjustment, the diagenetic seal became partially breached and rejuvenated and/or newly formed faults and fractures developed lower within the structures allowing formation waters and hydrocarbons to migrate into higher stratigraphic positions. In several trends the interior of the reservoir became tight from over-dolomitization and the hydrocarbons migrated to a higher stratigraphic position. The timing of this last stage is currently unknown but occurred during unloading and cooling of the basin.

History of the Trenton-Black River Play

Trenton and Black River Group carbonates of the Michigan and Appalachian basins have been prolific oil and gas producers since the late 1800s with the discovery of gas in the Trenton Group carbonates east of Findlay, Ohio and oil outside of Lima, Ohio in 1894 and 1895, respectively. The giant Lima-Indiana field that was developed following these discoveries produced more than 500,000 bbls of oil and approximately one Tcf of gas during the late 1800s and into the early 1900s (Keith and Wickstrom, 1992, Caprarotta et al. 1988) and was the first giant oil and gas field discovered in North America. Approximately 100,000 wells have been drilled in this field. The reservoir is a stratigraphic trap in regional dolomites on the crest of the Cincinnati and Findlay arches.

Discovery of the first oil and gas reservoir demonstrably linked to faulting and dolomitization did not occur until 1917 with completion of the first gas well in the Dover oil and gas pool in southern Ontario. The next big discovery did not occur until 1936, when the first well was drilled in the Deerfield oil pool located in Monroe County in Michigan. Deerfield is located along the Lucas-Monroe monocline that is an extension of the Bowling Green fault zone.

The Albion-Scipio field, the best-known pool of the Trenton-Black River HTD play type, was discovered in 1957, largely by serendipity. The pool has been developed by 734 oil wells with cumulative production of approximately 150 million bbls of oil (American Oil & Gas Historical Society, 2016). The first wells in the field were completed as flowing wells with initial potential of hundreds to thousands of bbls per day.

During the 1950s and 1960s a number of relatively minor discoveries were made in Ontario. The modern phase of exploration and development occurred in 1983 to 2004 with 39 new pool discoveries containing 93 per cent of the oil reserves and 62 per cent of the natural gas. The largest of the Ontario Trenton-Black River pools found in this time was the Goldsmith-Lakeshore field (Figure 15) with cumulative production of 6.2 million bbls oil. The field is 15 kilometres long and 300 to 1,000 metres in width, extending beneath Lake Erie where it has been accessed by horizontal wells drilled from onshore locations. In 2009, the Napoleon pool was discovered in Michigan, and to date is the last significant discovery.

Exploration methods and success rates

Traditional exploration methods include 2D seismic used to identify a structural low or sag feature atop the Trenton. Over the years, operators began using more robust seismic methods such as Mega Bin 3D seismic surveys or 2D swaths, which simulates a 3D survey but for less cost. The 3D seismic survey allows the operator to more easily identify the dolomite chimney characteristics within the hydrothermal dolomite play.

Much of southern Ontario between London and Niagara Falls has not been evaluated for potential structures using seismic or drilling of deep wells. It is recommended to begin exploration using high-resolution magnetic surveys (HRAM) and lineament analysis to identify major fault trends, followed with several 2D seismic lines to confirm faults and define a linear trend. A conventional exploratory well should be drilled to confirm the location of productive intervals. Successful exploratory drilling should be followed up with a 3D seismic survey over the entire linear trend to guide development drilling.

Drilling in the Ordovician play by Consumers' Gas, Pembina Exploration, Ram Petroleum and Paragon Petroleum Corporation (and its predecessors) during the 1980s and 1990s claimed a 67 per cent success rate for exploration wells and over 80 per cent for development wells. Their successor, Talisman Energy, posted

Figure 11. Typical dolomite fabric in a Trenton-Black River reservoir.

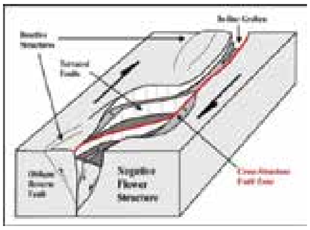

Figure 12. Isometric representation of a pull-apart basin (modified from Dooley and McClay, 1997) showing sag or "graben" structure.

development success numbers above 90 per cent. Dundee Energy LLP acquired Talisman's Ontario assets in 2010 and is the current operator of the majority of the Trenton-Black River oil and gas pools in southern Ontario.

Trenton-Black River Exploration Potential

The Ordovician play area occupies approximately 120,000 square kilometres. Potential recoverable resources are estimated to be 40 million bbls of oil, of which 23 million bbls has been produced. Potential gas resources are estimated to 281 bcf, with only 41 bcf recovered (Golder Associates 2005). Total number of wells drilled for Ordovician oil and gas targets in Southwest Ontario are estimated at ~1,700. There has been no recent exploration activity in this play in Ontario.

Trenton-Black River oil and gas pools are prolific producers. Very large parts of southern Ontario have never been explored for this type of reservoir. The regional occurrence of small gas pools and shows of natural gas indicate significant undiscovered potential.

Summary

Like most plays in Ontario the Cambrian and Ordovician plays have a long history of successful exploitation and have made significant contributions to Ontario's production of oil and natural gas. Estimates of potential remaining resources suggest there are still significant discoveries to be made, especially when oil and gas prices have recovered. The size and quality of the discovered pools and the large unexplored area should provide sufficient incentive for additional exploration, and the excellent data resources available at the Ontario Oil, Gas and Salt Resources Library should reduce the risk.

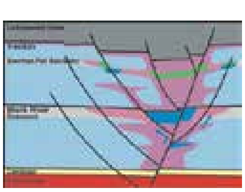

Figure 13. Conceptual model of a Trenton-Black River reservoir. Modified from Colquhoun (2012).

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Figure 14. Production profile for a typical Trenton-Black River oil well.

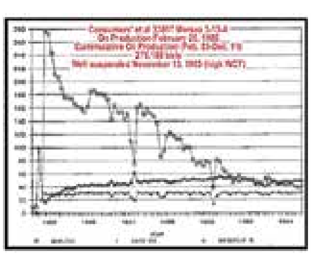

Figure 14. Production profile for a typical Trenton-Black River oil well.

ONTARIO OIL AND GAS PLAYS

3. Silurian and Devonian Conventional Plays

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Introduction

This paper is the third of a four-part series. Part 1 summarized the exploration, production and geology of Ontario. Part 2 summarized the conventional oil and gas plays of the Cambrian and Ordovician strata of Ontario. This paper describes conventional oil and gas plays in the Silurian and Devonian strata of southern Ontario. Part 4 will provide a review of the unconventional resource potential of Ontario.

The Paleozoic sedimentary strata of southern Ontario straddle a regional arch, dipping down its flanks into the Michigan and Appalachian basins (Fig.1), forming a natural regional trap. Stratigraphic relationships of Silurian and Devonian strata which are the subject of this paper are depicted in Figure 2.

Ontario's Silurian and Devonian strata have produced over 60 million bbls of oil and over 1.2 tcf of natural gas from reservoirs at depths of less than 700 metres. In addition, a total of 258 bcf of natural gas working storage volume has been developed in depleted Silurian natural gas reservoirs in southern Ontario, and 22 million barrels of storage capacity for liquefied petroleum products in solution-mined caverns in Silurian salt formations. Ontario is Canada's most populous and industrialized province, with well-developed infrastructure and a big appetite for hydrocarbons. Oil and gas development opportunities still remain for new pool discoveries, secondary recovery and storage development.

Figure 1. Regional geological relationships, showing Paleozoic basins and the Algonquin Arch.

The Lower Silurian Sandstone Play

Sandstones of the Lower Silurian Thorold, Grimsby and Whirlpool formations underlie an extensive area beneath the Niagara Peninsula and eastern and central Lake Erie (Figure 3). They are part of an extensive blanket of Silurian sands in the Appalachian Basin extending south through Pennsylvania, Ohio and New York, and into northern Kentucky that have produced over 11 tcf of natural gas (McCormac et al., 1996).

During early Silurian time, large amounts of sand, silt and clay were eroded from Taconic highlands to the south and were deposited into the Appalachian Basin. Sand deposition was restricted to the Appalachian side of the Algonquin Arch. The Whirlpool Formation is the lowermost of these clastic strata in Ontario. It rests unconformably on red shales of the Ordovician Queenston Formation and consists of white orthoquartzitic sandstone initially deposited in a braided fluvial environment, grading upwards into a shallow nearshore marine environment. It is gradationally overlain by and laterally transitional into Manitoulin Formation dolostone northwest of the Whirlpool depositional edge, and overlain by the Cabot Head Formation in the east.

The Cabot Head Formation is comprised predominantly of grey-green non-calcareous shales with subordinate sandstone and carbonate beds. It occurs regionally in southern Ontario, ranging from 40 metres in thickness beneath Lake Erie to only 12 metres over the Algonquin Arch, thickening again to the northwest. It is gradationally overlain by interbedded red shales and sandstones of the Grimsby Formation, up to a maximum of 24 metres in thickness beneath Lake Erie. The Grimsby is disconformably overlain by clean white sandstone and grey-green silty shales of the Thorold Formation ranging up to 6.5 metres in thickness (Armstrong and Carter, 2010).

Within this wedge of clastic sediments, porosity is best developed in sands of the Whirlpool, Grimsby and Thorold formations, and to a lesser extent in the Cabot Head Formation. They occur as extensive regional blankets and in channels and bars. In onshore parts of southern Ontario, porosity and permeability is generally best developed and most consistent in the Thorold Formation. Beneath Lake Erie the most productive intervals are developed in the Grimsby and Whirlpool formations. Marine shales of the Rochester Formation form a regional seal for the Thorold/Grimsby sands.

Natural gas occurs wherever there is suffi-

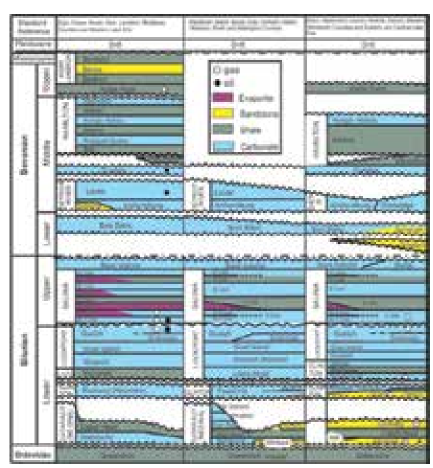

Figure 2: Stratigraphic relations of Silurian and Devonian strata of southern Ontario showing oil and gas-bearing intervals. Column headings indicate county names for geographic reference, from west (Michigan Basin) to east (Appalachian Basin) across southern Ontario. Modified from Armstrong and Carter (2010).

Figure 3. Silurian sandstone subcrop edges in Ontario. Modified from Bailey Geological Services and Cochrane (1986), and Lazorek and Carter (2008).

cient porosity development, making this a classic continuous-distribution style of play. The sands are part of an immense basin-centred stratigraphic trap extending south of Lake Erie into the states of Pennsylvania, Ohio and New York. Most wells drilled into the Thorold, Grimsby and Whirlpool in this area encounter natural gas, but commercial production depends on the relative percentage of sand versus clay and silt and degree of cementation. Predicting the location of these 'sweet spots' can be a challenge, with drilling success rates dropping to less than 50 per cent for offshore Lake Erie gas development as the play has matured.

The continuous nature of the reservoir, commingled production, the long drilling history, poor production records and lack of pressure measurements make it impractical to define pool boundaries and size with any confidence. In Lake Erie, production is largely commingled into only a few pipelines before measurement, and production volumes are reported by administrative production units rather than geological pools. In addition, the generally low reservoir permeability makes it difficult to prove pressure communication between wells (Bailey and Cochrane, 1986). Recent infill wells into some of the more mature pools in Lake Erie have seen evidence of communication and depletion of some of these sandstone reservoirs.

Average depth of the reservoirs ranges from as little as 60 metres up to 625 metres. Gross pay thickness varies from a few metres to 10 metres or more in several pay zones, with some production occurring locally from the immediately overlying carbonates of the Irondequoit Formation (Figure 4). Net pay thickness is usually less than two to five metres (Figure 5). Porosity ranges from three per cent to 25 per cent, with a nine per cent cutoff commonly used for wells on Lake Erie. With better porosity, horizontal permeability can range from one to 500 millidarcies. Water content is generally low and oil is usually absent in the up dip portion of this play (MacDougall, 1973, Molgat and Davies, 2004). Average annual decline rate is 10.92 per cent and median value is 8.3 per cent (Bailey and Cochrane, 1986).

In the onshore portion of the play, in Norfolk County, initial reservoir pressures range from 400 to upwards of 700 psi. Initial natural production rates on successful wells average 50 to 100 mcfd but this is greatly improved by fracture treatment. Most onshore wells are drilled with cable tool rigs to minimize formation damage. Offshore Lake Erie initial production rates range from gas shows to over three mmcf/d and cumulative production per well ranges from 0.05 to three bcf (Molgat and Davies, 2004).

Exploration and production history

The Silurian sandstones are a mature exploration play and have been an important and reliable source of gas production since 1889. Gas production is recorded from 25 named pools, fields and Lake Erie production units. All of the large on-shore pools were discovered before 1910 and on Lake Erie between 1959 and 1970. Most of the development drilling on Lake Erie has occurred since 1968, with approximately 1,600 wells drilled to test Silurian sandstone targets in an area of approximately 7,400 square kilometres. Approximately 6,000 wells have been drilled in the onshore portion of the play in an area of 4,500 square kilometres. On-shore wells are drilled on 25 to 100-acre spacing in developed areas. On Lake Erie, wells are drilled on 630-acre spacing. Down spacing to 315-acre spacing has been attempted with limited success in mature pools.

By the end of 2014, approximately 245 bcf of gas had been produced on-shore and 235 bcf had been produced from beneath Lake Erie (Ontario Oil, Gas and Salt Resources Library, 2015, Bailey and Cochrane, 1986), with all of the Lake Erie production occurring since the early 1960s. With only minor exceptions, all production from Silurian sandstones is natural gas. Total oil production from Silurian sandstones amounts to only 43,700 bbls of oil, the vast majority from the Onondaga pool south of the city of Brantford.

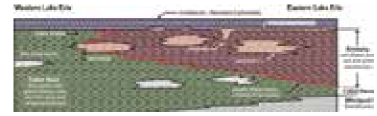

Figure 4. Conceptual cross-section through the Cabot Head-Grimsby clastics of eastern Lake Erie showing lateral facies changes. Modified from Bailey Geological Services and Cochrane, 1986, and Lazorek and Carter (2008)

Resource potential

Bailey and Cochrane (1986) calculated total "potential reserves" (discovered and undiscovered) of approximately 1.24 tcf for the Silurian sandstone play using a volumetric method with a model area approach. They estimated recovery factors as low as 15 per cent on Lake Erie. This is due to the low permeability, heterogeneous distribution of porosity and permeability, and the average 630-acre spacing of the wells. The Canadian Gas Potential Committee assumed a 65 per cent recovery factor and estimated original gas-in-place in discovered pools at 877.5 bcf. In both cases, large volumes of natural gas remain to be produced.

There is no significant oil production from the on-shore portion of this play with the exception of the Onondaga pool. Several wells drilled on Lake Erie encountered shows of oil, and two wells; Consumers' 13022 Lake Erie 155-Y, and Consumers' Pan American 13056 Lake Erie 100-J, tested significant flows of crude oil. Although there are likely to be potential oil resources in these sandstones beneath the lake, offshore oil production is not permitted by government regulation at this time, and wells with oil shows are required to be plugged. These sandstone reservoirs produce both oil and

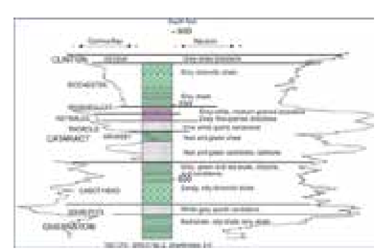

Figure 5. Type log of Lower Silurian clastics in southern Ontario.

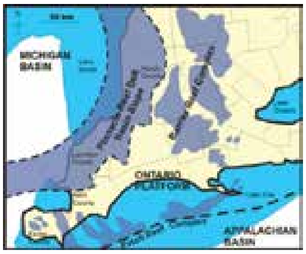

Figure 6. Reef belts in Ontario. Modified from Coniglio et al., 2003.

gas down dip along the south shore of Lake Erie in Pennsylvania and Ohio.

The Silurian "Niagaran" Carbonate Play

The Silurian carbonate play includes all reservoirs in the Lockport Group and those in the overlying Salina Group (Figure 2). Four types of traps have been recognized: pinnacle reefs, platform reefs, incipient reefs and structural traps related to faulting (Bailey and Cochrane, 1990, Carter et al., 1994, Canadian Gas Potential Committee, 2005, Lazorek and Carter, 2008).

During deposition of the Lockport Group, southern Ontario and Michigan were located at about 20 to 25 degrees south of the equator and North America was rotated about 30 degrees clockwise from its present orientation (Rine, 2015). Most of southern Ontario was a shallow carbonate platform lying between the slightly deeper water of the slowly subsiding Michigan Basin to the west and the Appalachian Basin to the southeast. These conditions were ideal for the formation of barrier and patch reef complexes in the warm shallow waters of the Ontario Platform, and for the formation of isolated pinnacle and incipient reefs in the relatively deeper waters sloping into the Michigan Basin (Figure 6). In Michigan, these strata are known as the Niagaran, generally correlative to the Lockport Group.

Pinnacle reefs are reef buildups greater than 50 metres in height (Bailey and Cochrane, 1990), ranging up to 128 metres above the regional inter-pinnacle surface (McMurray, 1985), with basal areas ranging from 23 hectares to a maximum of 368 hectares where closely-spaced reefs form a reef complex with reservoir communication (Bailey and Cochrane, 1990). Incipient reefs are usually less than 30 metres in height. Both reef types occur in a belt or trend approximately 50 kilometres wide running through Lambton, Huron and Bruce counties, and extend completely around the Michigan Basin (Figure 6). Pinnacle reefs are the most-studied of the reefs due to their importance as oil and gas reservoirs.

Reef development in Ontario began as crinoidal shoals in the Gasport and Goat Island formations with most biohermal development in the Guelph Formation. In Ontario, stages of reef development include a basal mud mound, organic reef, skeletal wackestones, and stromatolites, in vertical succession (Smith et al., 1993, Carter et al., 1994, Charbonneau, 1990) (Figure 7). These are very similar to stages and facies documented by Huh et al. (1977) and others in Michigan. Several episodes of subaerial exposure have been documented in pinnacle reefs, creating erosional discontinuities and extensive paleokarst horizons, leading Brintnell (2012) to describe pinnacles as karst towers. Post-depositional subaerial exposure in southern Ontario has reduced the inter-reef Guelph Formation in southern Ontario to a paleosol karst rubble two to six metres thick (Carter et al, 1994).

Most reefs in southern Ontario have been intensively dolomitized, resulting in destruction of almost all primary depositional fabric, with intensity of dolomitization increasing toward the platform (Coniglio et al, 2003). Infiltration of hypersaline seawater during deposition of salt beds in the overlying Salina Group has created issues with salt plugging in some Ontario pinnacles.

In Ontario, the net result is a complex, stratified reservoir with widely varying porosity and permeability, both vertically and laterally. Recent work in Michigan has identified distinct differences in windward and leeward reef margins (Grammer et al., 2010, Rine, 2015). The reefs were buried by carbonates, evaporites and minor shales of the Upper Silurian Salina Group and are sheathed with a layer of anhydrite (Figure 7) that forms the seal for these reservoirs.

Patch or platform reefs generally exhibit less than 50 metres of buildup but underlie very large geographic areas on the platform east of the pinnacle reef belt. Most of these reefs have been dolomitized. Discovered pool sizes range up to a maximum of 280

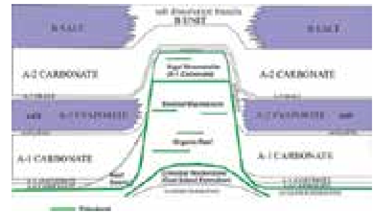

Figure 7. Pinnacle reef conceptual model, based on Carter et al (1994), Rine (2015), Huh et al (1977), Bailey (2000), Charbonneau (1990), Smith et al (1993).

bcf of natural gas in the Tilbury platform reef. Many of these reefs contain dissolved H2S, up to two per cent concentration.

Individual pinnacle reefs may contain up to 42 bcf of natural gas and 1.6 million barrels of oil. Depths to top range from 300 to 700 metres. Gas pay thicknesses range up to 95 metres, with initial open flow in discovery wells commonly exceeding 10 mmcf/d with a maximum reported of 65 mmcf/d (Bailey and Cochrane, 1990), and initial shut-in pressures up to 1000 psig. Porosity varies considerably within individual reefs due to the complex, heterogeneous internal stratification, reef versus non-reef facies, karst, salt-plugging and post-depositional and post-burial diagenesis. Average measured porosity reported in 29 different drill core analyses from 18 different pinnacle reefs which have now been converted to natural gas storage is 7.7 per cent, with some thin intervals exceeding 30 per cent porosity and maximum horizontal permeability of 1,000 to 10,000 millidarcies (Carter et al., 1996).

Hydrocarbons also occur in dolomitized zones of the Salina A-1 and A-2 Carbonate units. Traps most commonly occur where dolomitized carbonates of the Salina A-1 and A-2 are upthrown along with Guelph dolostones along regional faults as well as in structural drapes of A-1 and A-2 over the Guelph reef buildups.

Figure 8. Natural gas storage pools (red) in southern Ontario. The one storage pool in Welland County is in Whirlpool Formation sandstone, the rest are in Guelph reefs.

Exploration and production history

Niagaran reefs have been a major exploration target and source of hydrocarbons in Ontario and Michigan for several decades. Over 900 discrete pinnacle reef reservoirs have been discovered in the Michigan Basin (Armstrong and Goodman, 1990, Armstrong et al., 2002). These pools have produced over 490 million barrels of oil and 2.9 tcf of natural gas (Grammer et al., 2010).

In southern Ontario, approximately 5,000 wells have been drilled to test targets in Silurian carbonate rocks. In 1889, the first commercial gas well in Ontario was completed by Eugene Coste in Essex County in the Kingsville-Leamington-Mersea Field. Production was from the Guelph Formation and the Salina A-1 Carbonate with an initial gas flow reported at more than 10 mmcf/d at a depth of 1,030 feet and a pressure of 420 psi (Lauriston, 1961). This marked the beginning of the natural gas industry in Ontario. Initial followup drilling to this discovery focused on oil-producing reservoirs, most with associated natural gas. In late 1905, the Tilbury field was discovered with the drilling of the Kerr No. 1 well in Tilbury East Township. At the time it was produced as an oil well, occurring as it did at the transition between the oil and gas legs of the field. The oil accumulation is now known as the Fletcher Oil Pool. The natural gas was flared, as there was no viable market for it. Subsequent drilling eventually resulted in the realization that a very large gas field had been discovered and it had considerable value for energy and lighting. The Tilbury Gas Field is by far the largest natural gas reservoir in Ontario, with cumulative production of at least 280 bcf of natural gas, and 1.2 million barrels of oil from the associated Fletcher Oil Pool. Actual production may have been much higher due to initial poor record-keeping and wasteful gas-flaring practices after discovery. The oil pool was prematurely abandoned as the scrap metal value for the casing during the First World War was more valuable for the war effort. This oil and gas reservoir consists of a platform reef in the Guelph Formation and associated porosity in the overlying, draping A-1 and A-2 Carbonate units.

Figure 9. Devonian pool fairway (Lazorek and Carter, 2008).

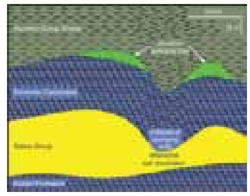

Figure 10. Conceptual model of Devonian structural traps formed by differential salt dissolution in the underlying Salina Group (after Lazorek and Carter, 2008).

Production from the Tilbury field provided a reliable supply of natural gas that resulted in the creation of a large number of competing gas syndicates to deliver and market the gas. It was the initial mainstay of natural gas production for the Union Gas Company. Union Gas Limited, now a division of Spectra Energy, became Ontario's largest natural gas utility through competition and a process of acquisition and merger, supplying natural gas to domestic and industrial users across large parts of southern Ontario. Enbridge, Union's main competitor in southern Ontario, recently announced plans to merge with Spectra.

In total, 182 reservoirs have been discovered in the Niagaran play in southern Ontario – 57 in incipient reefs, 61 in pinnacle reefs, 29 in platform reefs and 35 in structural traps. Pool production records at the Ministry of Natural Resources and Forestry and the Oil, Gas and Salt Resources Library indicate that the first pinnacle reef reservoirs were discovered in 1930 and 1931, and the next not until 1941. Between 1949 and 1958, there was a string of successes with discovery of 19 additional pinnacle reef reservoirs. Gravity prospecting techniques were used with some success at this time. With improvements in seismic acquisition and processing (Mantek, 1976) an additional 32 productive pinnacles were drilled between 1965 and 1992. Only eight have been drilled subsequently as a result of declining exploration activity. Drilling success for incipient reefs follows a similar trend. Reservoirs in structural traps were discovered intermittently beginning in 1902, with the most active period occurring from 1948 to 1959 when 14 of the 35 known pools were discovered.

By the end of 2014, approximately 15.1 million bbls of oil had been produced from the Silurian carbonates in southern Ontario. Gas production has totaled approximately 331 bcf from onshore reservoirs with an additional 443 bcf from beneath Lake Erie.

Natural gas storage

Ontario imports 99 per cent of the approximate one tcf of natural gas it consumes each year, largely from western Canada but with increasing quantities from the northeastern United States. Pipeline capacity is not large enough to supply peak demand in the winter, so natural gas is injected underground into depleted natural gas reservoirs in the summer for temporary storage. In the winter, the gas is withdrawn from storage to satisfy increased demand. Thirty-two pinnacle reefs and two incipient reefs have been converted to natural gas storage, with total working volume of 269 bcf of natural gas and combined peak withdrawal capacity of over 5 bcf/d. All pools are delta-pressured above discovery pressure to increase working capacity, which varies from 1.7 to 34 bcf. The pools are serviced by 309 injection/withdrawal wells and 78 observation wells. Most of these reservoirs are located in Lambton County, with one in Kent County and two in Huron County. One small storage pool located in Welland County is developed in porous sandstone of the Whirlpool Formation (Figure 8). The development of gas storage is regulated by the Ontario Energy Board.

Experimental injections were performed in southern Ontario as early as 1915 to test the feasibility of storing natural gas in depleted natural gas reservoirs. The first commercial underground storage of natural gas in geological formations in Canada began in 1942 in the Dawn 47-49 pinnacle reef, north of Sarnia. Dawn 47-49 was also the first pinnacle reef gas reservoir discovered in Ontario in 1930. With completion of gas pipelines from western Canada to Ontario in 1957, there was an increase in natural gas supply, which then spurred development of additional storage capacity (Wolnik, 2007).

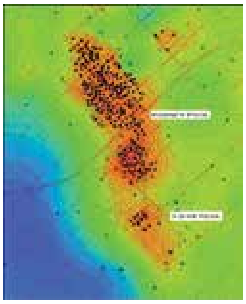

Figure 11. Structure on top of the Dundee Formation Rodney and 7-D-VII pools.

Most of the conversions of depleted reservoirs into storage reservoirs occurred between 1960 and 2000.

Potential resources

This is a mature play, but still with opportunities for further discoveries both on and offshore. There is potential for discovery of isolated reservoirs within previously delineated reefs, which have been only partially affected by salt-plugging, as well as opportunities for enhanced recovery from developed reservoirs. The concept of Rine (2015) regarding leeward debris aprons around pinnacle reefs has not been applied to reservoir development in Ontario. The karst tower concept of Brintnell (2012) may also be useful. There is potential for conversion of additional reefs for use as natural gas storage reservoirs. While early exploration methods focused on gravity anomalies to locate pinnacle reefs, 2D seismic is now far more important in combination with careful study of drill cuttings samples to identify reef proximity indicators. Detailed mapping of dolomitization patterns and thickness variation of the Salina A-1 Carbonate Unit may also provide a useful guide to undiscovered pinnacle reefs. 3D seismic has been acquired over most reefs that are utilized for natural gas storage in order to accurately define closure for establishment of regulatory boundaries and to optimize infill-drilling locations for storage development.

Incipient reefs are a largely overlooked target in this play because of the difficulty in reliably targeting these elusive traps. Most of the incipient reefs discovered to date were found while exploring for pinnacle reefs. An exploration program directed at incipient reefs could be rewarding if a consistently successful exploration method were devised. The smaller size of these reservoirs requires a high drilling success rate.

The structural play is poorly understood and the importance of dolomitization related to faulting has not been widely recognized. Further study may create opportunities for new pool discoveries.

Estimates by Bailey and Cochrane (2016) indicate total "potential reserves" (discovered and undiscovered) of approximately 1.0 tcf of natural gas and 18.1 mmbo. Cumulative production to the end of 2014 totals 15.1 mmbo and 774 bcf of natural gas.

The Devonian Play

The Middle Devonian play includes reservoirs in the Lucas Formation and the overlying Dundee Formation (Figure 2).

During early Middle Devonian time, the seas in northeastern North America were restricted to two large epicontinental basins: the Michigan and Appalachian basins. The basins were separated by a northeast-southwest tending basement high known as the Algonquin Arch, with the Michigan Basin located to the northwest and the Appalachian Basin to the southeast of the arch (Figure 1). Throughout much of the early Middle Devonian the basins were largely independent, with some communication likely in the Chatham Sag area and also through an inlet northeast of London (Fagerstrom, 1983). The Michigan Basin periodically experienced conditions of hypersalinity whereas the Appalachian basin sediments were deposited under open marine conditions throughout this time interval. The seas then transgressed over the Algonquin Arch and merged into an open marine environment of normal salinity. The marine incursion resulted in erosion of the upper Detroit River Group and a disconformity separates the Lucas Formation from the overlying Dundee Formation. The presence of numerous hardground surfaces and thickly bedded bioclastic limestones in the Dundee Formation attest to relatively shallow water, subtidal conditions. A major disconformity separates the Dundee Formation from the overlying Hamilton Group (Uyeno et al., 1982).

The Detroit River Group unconformably overlies the Bois Blanc Formation and is composed of, in ascending order, the Sylvania Sandstone, Amherstburg Formation and the Lucas Formation. Several lithofacies comprise the Lucas Formation including laminated lime mudstones, peloidal-intraclastic packstones to grainstones, stromatoporoid floatstones, dolomicrites to finely crystalline dolostones, calcareous sandstones and minor evaporates. These lithofacies indicate a peritidal environment subjected to periodic exposure.

The Dundee Formation is characterized by rocks and fossils typical of a shallow marine, subtidal environment which contrasts with the generally peritidal carbonates of the Lucas Formation. Four lithofacies are recognized in the Dundee Formation: packstone to grainstone, wackestone to packstone, mudstone to wackestone and mudstone.

The Lucas Formation hosts two distinct reservoir types: a microcrystalline dolomite unit and a calcareous sandstone. The dolomite unit is the primary reservoir in the Oil Springs Pool and has porosity in the range of 12 to 30 per cent, with permeability of five to 430 md. The sandstone unit is the producing reservoir in the Glencoe Pool where porosity ranges from 10 to 21 per cent and permeability generally varies from 50 to 200 md.

Reservoirs in the Dundee Formation reservoir are characterized by a significant unit known as the "Columbus zone", with additional production from fracture porosity as well as from a microporous matrix within fractured limestones. The Columbus zone is a siliciclastic-rich dolomitized limestone with porosity commonly in the 12 to 30 per cent range and permeability varying between 50 and 2,500 md and is the producing reservoir in the Rodney Pool.

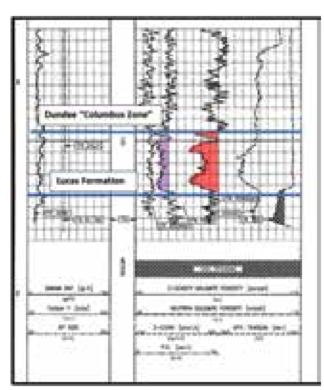

Figure 12. Log section of a productive well in Rodney. GGOL #13, Aldborough D-VII. Initial flow 5 bopd with a shut-in pressure of 175 psig.

All of the middle Devonian pools (Figure 9) are located on structural domes which are the result of differential dissolution of salt beds in the underlying Salina Group (Figure 10). Brigham (1972) suggested that there were two major periods of salt dissolution which affected Middle Devonian sedimentation and structure.

POOL NAME	DISCOVERY YEAR	CUMMULATIVE PRODUCTION (barrels)	ACTIVE
Oil Springs	1858	10,437,000	Yes
Petrolia	1862	18,798,000	Yes
Bothwell-Thamesville	1862	3,354,000	Yes
Wallacetown	1898	253,000	No
Glencoe	1917	1,139,000	No
Watford-Kerwood	1938	132,000	No
Rodney	1949	10,845,000	Yes

Table 1. Cumulative production of major Middle Devonian oil pools by discovery year to 2015, rounded to nearest 1,000.

History of the Play and Production

The Middle Devonian Lucas and Dundee formations of Ontario have produced approximately 45.1 million barrels of oil (mmbo), which equates to approximately 50 per cent of Ontario's oil production to date. The first commercial oil production in North America was from these shallow Middle Devonian carbonates in 1858 at Oil Springs, Ontario. Three of the largest oil fields in Ontario are Middle Devonian in age and include Petrolia (18.8 mmbo), Rodney (10.8 mmbo), and Oil Springs (10.4 mmbo). Bothwell-Thamesville (3.3 mmbo) and Glencoe (1.1 mmbo) were also significant discoveries (Table 1). Since 1858, a total of 27 Middle Devonian pools have been put on production. One hundred and fifty-eight years later, four of these early discoveries are still producing.

With the exception of the Rodney Pool, which was discovered in 1949, the major discoveries, due to their vintage, have very limited documentation or data (Bailey and Cochrane, 1985). The lack of data includes accuracy of well locations, detailed production information, reservoir pressures and rock samples. Fortunately, historical information was recorded within reports and unpublished manuscripts prepared by Colonel R.B. Harkness, a former Ontario oil and natural gas commissioner, between 1915 and 1951. Harkness documented an Oil Springs well that had an initial flow of 7,500 bopd and numerous wells in Petrolia with initial flows exceeding 400 bopd. A number of the Harkness notations reference enormous volumes of oil spilled on the surface and into adjacent creeks due to the inability of operators to control the high flow rates, as well as insufficient tank storage capacity. In one documented occasion, an uncontrolled well flowed enough oil to cover Lake St. Clair with an oil slick several inches thick.

Early exploration methods were limited to drilling surface oil seeps and tar beds and the practice of drilling surface test holes to define the top of the bedrock for structural mapping. Since the Rodney discovery in

1949, there have been no significant Middle Devonian discoveries. This may be in large part due to an industry change in exploration focus.

Middle Devonian Rodney Pool

The Rodney Pool was discovered in 1949 by using shallow test wells to define structure on the top of the Dundee Formation. Initial production rates varied per well from two to 118 bopd, with an average of 20 bopd (Malcolm, 1962). By 1956, production from the pool had peaked at 1,120 bopd with the completion of 193 wells drilled on an average of 6.25-acre spacing (Malcolm, 1962). In 1961, the operator, Canada Cities Service commenced water-flooding the pool and the company reported that production from wells enhanced by water-flood ranged from two to 81 bopd with an average of 12 bopd (Malcolm, 1967). Oil recovery per well at that time ranged from 2,000 to 45,000 barrels with an average of 13,000 barrels. At peak performance, the water-flood resulted in a 232 per cent increase in daily production volumes and an estimated 55 per cent recovery of the original oil-in-place. After 67 years of production, the Rodney Oil Pool is still producing approximately 66 bopd with a relatively low decline rate.

The Rodney Pool is a good example to illustrate a Middle Devonian pool in Ontario due to the relatively recent timing of development and availability of accurate geological and engineering data. The Rodney and 7-D-VII pools (Figure 11) are situated to the east of a large northeast-southwest trending fault structure. The fault was instrumental in providing the mechanism for the dissolution of up to 60 meters of salt in the underlying Salina Group to the west of the fault in post-Middle Devonian time. Approximately 50 to 55 meters of Salina salt is preserved underlying the Rodney pools to the east of the fault. The salt remnant provided the basis for structural traps within the overlying Middle Devonian section with 10 to 15 meters of closure.

A type log from a productive well in Rodney is illustrated in Figure 12.

Exploration potential

Over the past 35 to 40 years, there has been very little exploration effort directed towards the Middle Devonian reservoirs. In part, this may be due to the success of exploration for Silurian and Ordovician reservoirs. Within the Middle Devonian pool fairway (Figure 9) there are numerous areas with a relatively low-drilling density that have the potential for localized Silurian Salina salt remnants and the development of coincident shallow Devonian structures. In addition, a significant amount of 2D seismic data has been acquired in those areas in search of Silurian pinnacle reefs that is possibly available for purchase and reprocessing. The Ontario Geological Survey acquired and released a high-resolution magnetics survey in 2010 that covers a portion of the Middle Devonian fairway. This may assist in defining the location of deep-seated faults and salt dissolution patterns.

From an economic perspective, the Middle Devonian reservoirs continue to be an attractive geological target, due to their shallow depth (120 to 150 metres), high-gravity oil (38 degrees API), relatively high yields (30,000 to 60,000 barrels per well) and long productive life-span. Prospective areas within the Devonian pool fairway (Figure 9) have been only lightly explored, and the potential exists for new discoveries.

Summary

Like most plays in Ontario, the Silurian and Devonian plays have a long history of successful exploitation and have made significant contributions to Ontario's production of oil and natural gas. Estimates of potential remaining resources suggest there are still significant discoveries to be made, in addition to opportunities for secondary recovery and for natural gas storage. Positive factors to consider are the size and quality of the discovered pools, the presence of highly developed infrastructure, and the excellent data resources available at the Ontario Oil, Gas and Salt Resources Library.

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ONTARIO OIL AND GAS PLAYS

4. Unconventional Resource Potential of Ontario

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Introduction

This paper is the fourth of a four-part series. Part 1 summarized the exploration, production and geology of southern Ontario. Part 2 summarized the conventional oil and gas plays of the Cambrian and Ordovician strata of southern Ontario. Part 3 described the conventional oil and gas plays in the Silurian and Devonian strata of southern Ontario. This paper will provide a review of the unconventional resource potential of Ontario.

Ontario, or more correctly, Canada West prior to Confederation, was an unconventional oil producer as early as 1859. The Craigleith Oil Shale Works began production in a quarry outside Collingwood and would produce up to 1,000 gallons a day of lamp and lubricating oils from 30 to 35 tons of black Ordovician shale in cast-iron retorts (Dabbs, 2007). The discovery and development of conventional oil production from the Oil Springs and Petrolia Oil Pools in Lambton County, 200 miles to the southwest, proved cheaper and the oil shale operation closed down in 1863.

On the south shore of Lake Erie in Fredonia, New York, natural gas was being produced from shale 38 years earlier in 1821 (Curtis, 2002). William Hart dug a 27-foot well into the Devonian shales along Canadaway Creek and, by 1825, the natural gas was supplying light for two shops, two stores and a grist mill (Harper and Kostelnik, 2007). These two early discoveries proved the existence of unconventional oil and gas production in the area. By the 1860s, cheaper conventional oil and gas production became the dominant product and it would be over 100 years before unconventional resources would come back into the picture.

Figure 1. Ontario Heritage Foundation roadside marker near the gate of Craigleith Provincial Park.

In late 1982, the Ontario Geological Survey (OGS) initiated the Oil Shale Assessment Project to evaluate the resource potential of Ontario's Paleozoic black shales. The multiphase project saw the drilling of core holes in the province through the 1980s with additional drilling and testing continuing to the current decade. The Geological Survey of Canada (GSC) has also published a preliminary inventory of Shale Gas possibilities in Canada, which included seven organic-rich units in Ontario (Hamblin, 2006). These efforts, in combination with recent shale oil and gas discoveries in surrounding jurisdictions (Pennsylvania , Quebec, Ohio and Michigan) in the Appalachian and Michigan Basins has re-focused attention to Ontario's unconventional potential. Three of those units in southern Ontario will be examined herein; the organic-rich black shales and mudstones of the Ordovician Collingwood-Blue Mountain (Utica), the Devonian Marcellus, and the Devonian Kettle Point formations (Figure 2).

Ordovician Collingwood-Blue Mountain "Utica"

The black, organic-rich upper Ordovician shales and mudstones that overly the Trenton-Black River carbonates in southwestern Ontario have a complicated nomenclatural history (Armstrong and Carter 2010). The widespread dark grey to black shales seen

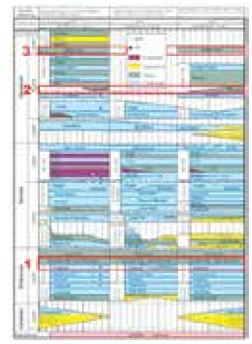

Figure 2: Stratigraphic columns of southern Ontario with highlighted organic-rich black shale intervals. Modified from Armstrong and Carter (2010).

in oil and gas wells in the subsurface traditionally was called the Collingwood Shale (Sanford, 1961). Those working the outcrop belt and shallow subsurface consider only the transitional shaley limestone section at the top of the Trenton-Black River carbonates to be the Collingwood Member of the Lindsay Formation (Russell and Telford, 1983). The Lindsay Formation is the outcrop equivalent of the Cobourg Formation (Armstrong and Carter, 2010). The thick dark-coloured organic shales above would be the lower part of the Blue Mountain Formation. Recent work by the Ontario Geological Survey (Russell and Telford, 1983; Béland-Otis, 2012) and Sweeney (2014) place these shales into the Rouge River Member of the Blue Mountain Formation. Regardless of which name is used these shales all form part of the distal portion of the larger "Utica Black Shale Magnafacies" (Lehmann et al, 1995; Hamblin, 2006). These organic-rich strata were deposited under anoxic conditions prior to and during initial deposition of the upper Ordovician siliciclastics in the Appalachian Basin.

The Rouge River organic-rich shales are the lowermost documented facies of the Blue Mountain Formation, which, in turn, is

Figure 3: Ordovician black shale distribution (blue) in Southern Ontario. (NRCAN website).

conformably overlain by the Georgian Bay Formation. The two formations are grouped together in the Ontario petroleum well database due to the difficulty of making a consistent formation top pick for the Blue Mountain. The Blue Mountain Formation is dominantly composed of soft, laminated, non-calcareous grey to dark grey shale with only minor interbeds of limestone and siltstone. The proportion of limestone and siltstone beds increases gradually upwards into and within the Georgian Bay Formation. The Georgian Bay-Blue Mountain clastics form a wedge that thickens gradually from northwest to southeast into the Appalachian Basin (Figure 4). Organic-rich facies of the Rouge River Member comprise only the lowermost two to 50 metres, also thickening to the southeast. Depth to the top of the Rouge River ranges from outcrop in the northwest to over 900 metres beneath parts of Lake Erie.

The drilling and testing program conducted by the Ontario Geological Survey to evaluate the resource potential of these black shales has yielded some critical geochemical data (Barker, 1985, Obermajer et al, 1999, Béland-Otis, 2015). These data indicate that some of these black to dark grey mudstones are good to excellent Type II organic-rich source rocks which are thermally mature over a large area in the subsurface of southwestern Ontario (Figure 5). Moving deeper in the basin these organic-rich units thicken.

Figure 6 displays an overlay of the sonic and resistivity log of a well drilled in west central Lake Erie in 1978. This Delta Log R technique (Passey et al, 1990) identifies shales with source rock potential. The green highlighted separation between the sonic and resistivity curves is an indicator of good source rock potential. The presence of low velocity kerogen will lower the Rt values on the sonic curve and the higher Rt values on the resistivity curve indicate the presence of generated hydrocarbons in mature source rocks. The well-site geologist reported oil shows and staining in the shale samples through this interval. The shaded crossover on the Delta Log R plot indicates over 160 feet (48.8 metres) of source potential in the lowermost Blue Mountain interval. Unfortunately, very few wells in southwestern Ontario have associated resistivity logs. Historic wells in Ontario traditionally did not include wireline logs or only included a GR-Neutron log suite at best, with many wells predating this technology entirely. This makes identification and correlation of these organic-rich units more challenging. Elsewhere in the "Utica" play operators have landed their horizontal wells in the more brittle transitional facies of the upper Trenton Group and steered the horizontal leg up towards the overlying shale contact. In Ohio, the Point Pleasant zone is the target. In Encana's discovery well in Michigan, Petoskey State Pioneer 1-3-HD1, the Collingwood Member at the top of the Trenton was the horizontal landing point and the 5304' horizontal leg was steered up to the Utica Shale contact (Phillips, 2016).

Resource potential

In the northeastern United States, the Utica Formation is the subject of intensive exploration and evaluation as an unconventional source of natural gas and crude oil. The United States Geological Survey (USGS) has assessed the unconventional oil and natural gas resource potential of the Utica Formation (Kirschbaum et al., 2012) in an area covering parts of Maryland, Ohio, New York, Pennsylvania, Virginia and West Virginia. They estimate a mean resource volume of 940 million barrels of "technically recoverable" oil and 939 billion cubic feet of associated natural gas within the Utica Shale Oil Assessment Unit (AU) at the 50 per cent probability level, with a range from 590 to 1,386 million barrels at the 95 per cent and five per cent probability levels respectively. An additional resource of 37 trillion cubic feet of natural gas and 200 million barrels of natural gas liquids is estimated to occur within the Shale Gas Assessment Unit.

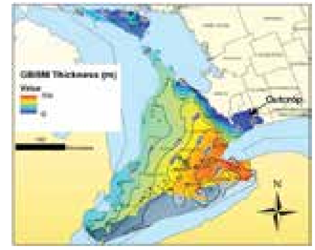

Figure 4. Isopach of the combined Georgian Bay and Blue Mountain (GBBM) formations, showing thickening from northwest to southeast into the Appalachian Basin. Organic-rich facies of the Rouge River Member comprise only the lowermost 2 to 50 metres, also thickening to the southeast.

Development of the Utica shale in the United States did not begin until approximately 2010 (Geology.com, 2014). Since that time, 1,807 horizontal wells have been drilled into the Utica in Ohio alone (http://oilandgas.ohiodnr.gov/shale#SHALE, accessed on Oct. 11, 2016). Daily production as of Sept. 12, 2016 totals 3.6 billion cubic feet/day of natural gas and 69,000 barrels/day of crude oil (Energy Information Administration, 2016).

Total organic carbon content in the Utica Shale Oil AU ranges from one to three per cent. In Ontario, Obermajer (1999) measured values from 0.74 per cent to 2.69 per cent in the Blue Mountain Formation and up to 7.5 per cent in the Collingwood. In both areas, organic geochemical indicators show the presence of oil-prone Type II organic matter with a thermal maturity in the oil window.

A quantitative resource potential estimate for the Ordovician shales of southern Ontario has not been completed.

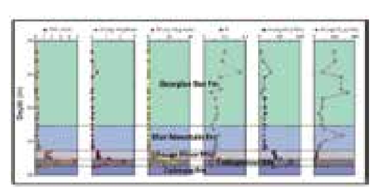

Figure 5: OGS SG11-02, Arthur 4-6-V (T012100) Strat Test. Rock-Eval®6 pyrolysis logs (TOC, S1, S2, PI, HI, OI) from core samples (Béland-Otis, 2015). White-filled dots represent questionable data due to low TOC, S1 and/or S2.

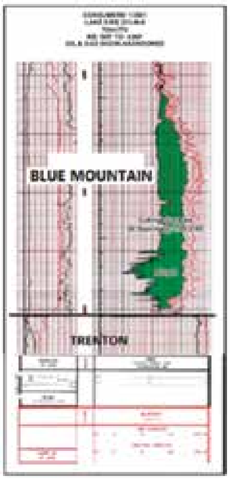

Figure 6: Consumers' 13501 Lake Erie 313-N-4 (T004772) △ Log R Plot, sonic-resistivity overlay through the lowermost 200 feet of organic-rich shales overlying the Trenton Group. (Phillips, 2014).

Devonian Marcellus

The thick Upper Devonian shale sequence of the Appalachian Basin has seen a lot of interest in recent years. The Marcellus shale gas play is the largest in the United Sates with proved reserves (to end of 2014) of 84.5 tcf. The Marcellus also had the most reserves (22.1 tcf) added in 2014 (EIA, 2015). The distal edge of the Marcellus Shale in the Appalachian Basin extends up into southwestern Ontario (Figure 7).

The Ontario Geological Survey included the Marcellus Shale in their resource potential evaluation in the 1980s (Johnson et al, 1989). Initial mapping indicated that the sub-crop edge ran very close to the north shore of Lake Erie and most of the potential would therefore be under the lake. This was confirmed with the drilling of five shallow core holes along the north shore of Lake Erie. Only three of the five shallow wells intersected Marcellus Shale. Geochemical analyses were performed on these three shallow cores, core from an industry well at Port Stanley and cuttings samples from several Lake Erie wells targeting deeper Silurian strata. The report concluded that the Marcellus contains a significant thickness of organic-rich Type II/III shale that is marginally mature to mature (Johnson et al, 1989, Hamblin, 2006).

The Devonian black shales have a long history of gas production along the south shore of Lake Erie in New York, Pennsylvania and Ohio. The USGS has grouped them into the Northwestern Ohio Shale and Marcellus Shale Assessment Unit (Milici and Swezey, 2006). The area to the north under Lake Erie is a natural extension to this play. With over 2,000 wells drilled in the Canadian waters of Lake Erie, a large number have recorded gas shows while drilling through the Devonian shale section. Figure 8 displays the open-hole logs from the Consumers' 13184 Lake Erie 154-M-4 well drilled in 1972. While drilling at a depth of 584' (178.0 metres) the well kicked gas at a rate estimated at 1 mmcf/d (28,320 m3/d). The well was killed with heavier drilling fluid and tested after reaching total depth. The gas rate on the test was reported as 50 mcf/d (1,416 m3/d) with a shut-in pressure of 235 psig. The caliper log shows washout around the depth where gas was encountered. It is of interest to note the fractured shale unit that produced the gas show is not the lower Marcellus Shale but a more brittle overlying shale unit in the Hamilton Group. Range Resources noted that in their early Marcellus horizontal wells in Washington County, Pennsylvania, those landed in the lower Marcellus section had modest initial production rates averaging only 478 mcfe/d. Subsequent drilling in the same area during which the horizontal legs were landed higher in the shale section saw significantly higher initial production rates averaging 3,527 mcfe/d (Zagorski, 2015).

The Marcellus section has yielded a number of gas shows while drilling deeper Silurian gas wells in the central portion of Lake Erie and along the sub-crop edge near the north shore of Lake Erie. In a small sampling of 89 wells drilled on Lake Erie around the well shown in Figure 8, 26 wells (29 per cent) had gas shows in the shallow Devonian section as reported by the driller (Phillips, 2014).

Resource potential

The Marcellus shale gas play is the largest gas field in the United States with 84.5 tcf in proved reserves at the end of 2014 (U.S Energy Information Administration, 2015) and a mean undiscovered natural gas liquids resource of 3.4 billion barrels (Coleman et al., 2011). Annual production in 2014 totalled 4.9 tcf of natural gas. The Marcellus play underlies an area of over 72,000 square miles, occurring in a continuous accumulation encompassing most of Pennsylvania, West Virginia, Ohio and New York, as well as parts of Maryland and Virginia. Depths to the Marcellus vary from outcrop to nearly 11,000 feet (3,350 metres), with most production occurring where the formation is 2,000 to 6,000 feet below sea level (http://www.eia.gov/todayinenergy/detail.php?id=20612). Thickness varies from less than 50 feet to 300 feet (15 to 90 metres) in most of the productive area, reaching even greater thicknesses feet in New York. Production is derived almost exclusively from horizontal wells completed

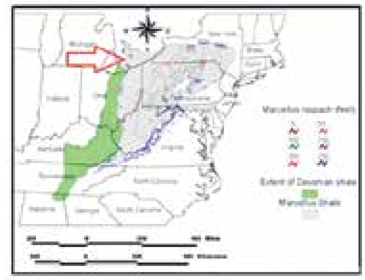

Figure 7: Marcellus Shale Isopach Map (Milici, 2005). The red arrow indicates the extension of the shales into southern Ontario.

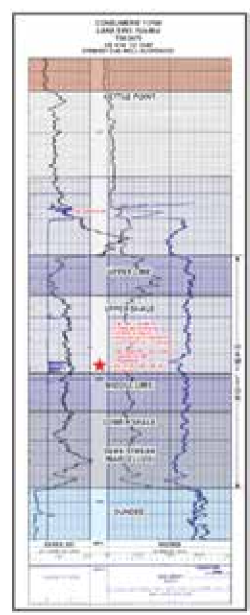

Figure 8: Open-hole logs Consumers' 13184, Lake Erie 154-M-4, showing the Devonian shale section from Kettle Point at 367 feet to top of Dundee Formation limestone at 689 feet. Driller terminology has been used to describe the formations of the Hamilton Group.

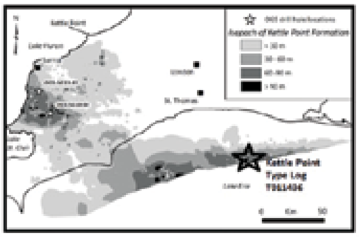

Figure 9. Isopach map of the Kettle Point Formation (Béland Otis, 2013). Well T003476 in Fig.8 is located 20 km east of well T011436.

with multi-stage, high-volume hydrofracture treatments. Hydraulic fracturing has been banned in New York state.

There have been no horizontal wells drilled in the Marcellus in Ontario and there is no production from this formation. No quantitative resource assessment has been completed.

Devonian Kettle Point

The Upper Devonian Kettle Point formation overlies the Hamilton Group (which includes the Marcellus Shale) and is preserved through the central portion of southwestern Ontario in the Chatham Sag (Figure 9), underlying an area of over 4,000 square kilometres.

Typically, the Kettle Point formation is overlain by Quaternary sediments, except for a small area south of Sarnia where Port Lambton Group shales and siltstones overlie the Kettle Point Formation. It is equivalent to the productive Antrim shale in Michigan and the Ohio shales in Ohio, Pennsylvania and New York (Russell, 1985). The Kettle Point succession of black organic-rich shales and grey-green organic-lean shales can exceed 100 metres thickness, but the preserved thickness is generally much less, averaging about 30 metres. The black shales within the sequence exhibit the highest organic content up to 15.1 wt. per cent, with thermal maturity data indicating these shales to be immature to marginally mature (Barker, 1985, Obermajer et al, 1997).

Drilled in the summer of 2006, 11 wireline recoverable cores (105.50 to 164.65 metres) were cut in the Kettle Point Shale and three wireline recoverable cores (186.50 to 209.00 metres) were cut in the Marcellus Shale interval. Total organic carbon values in the Kettle Point were measured at 6.08 and 12.87 wt. per cent (Phillips, 2014). These values fall in line with those obtained from the Ontario Geological Survey onshore Ontario wells (Béland-Otis, 2013).

Early reports from the Geological Survey of Canada refer to the common seepage of natural gas from the thick sand and gravel deposits that overlie the Kettle Point Formation. Water well records commonly record the occurrence of natural gas in the groundwater in the same area (Singer et al., 1997, 2003) and petroleum well records document gas shows in the upper few metres of the Kettle Point (Carter et al., 2008). Many domestic water wells in areas underlain by the Kettle Point black shales must be vented outdoors to prevent methane from entering residences and farm buildings.

The Ontario Geological Survey drilled and cored two boreholes through the full thickness of the Kettle Point formation to collect core and gas samples (Béland-Otis, 2013). Drill core samples from the boreholes were analysed for gas content, gas composition, isotopic composition of methane, total organic carbon, oil, gas and water saturation, permeability, porosity, mineralogy, adsorption isotherms and rock mechanics. Both thermogenic and biogenic gas were identified. The stratigraphically equivalent Antrim Shale Play to the west in central Michigan also includes a significant component of biogenic gas (Martini et al., 2003).

The open hole logs from the Talisman Central Lake Erie 157-V-4d (T011436) in Figure 10 illustrate the Devonian Kettle Point and Marcellus Shale section.

Resource potential

The Antrim Shale in Michigan has been developed by over 9,000 wells, with cumulative production of 2.5 trillion cubic feet of natural gas to the end of 2006 (Goodman and Maness, 2008), and exceeding three tcf of natural gas to date. Annual production at the end of 2006 totalled 140 billion cubic feet, which declined to 95 billion cubic feet by 2014. Well depths range from 150 to 600 metres. Many wells have been on production for more than 30 years.

A significant proportion of the natural gas in the Antrim has been produced by in situ microbial methanogenesis (Martini et al., 2003) of organic carbon. The identification of biogenic gas in the Kettle Point formation suggests that the same play type may occur in southern Ontario.

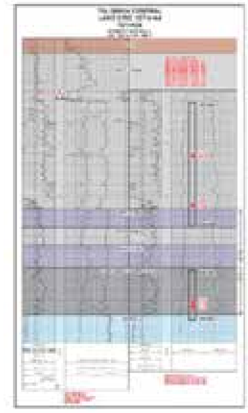

Figure 10. Kettle Point type well (Phillips, 2014), showing Kettle Point Formation from 82.5 metres to 156.2 metres. Driller terminology has been used to describe the formations of the underlying Hamilton Group.

No quantitative resource assessment of the Kettle Point Formation in southern Ontario has been completed.

Summary

To date, only a handful of vertical wells have cored and tested the Ordovician and Devonian shales and mudstones in Ontario. Most of these data have confirmed hydrocarbon potential within these units. No horizontal wells have been attempted to test the resource potential of shales in Ontario. The shallow depths and proximity to large urban centres may present some unique challenges for future development, as well as opportunities.

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