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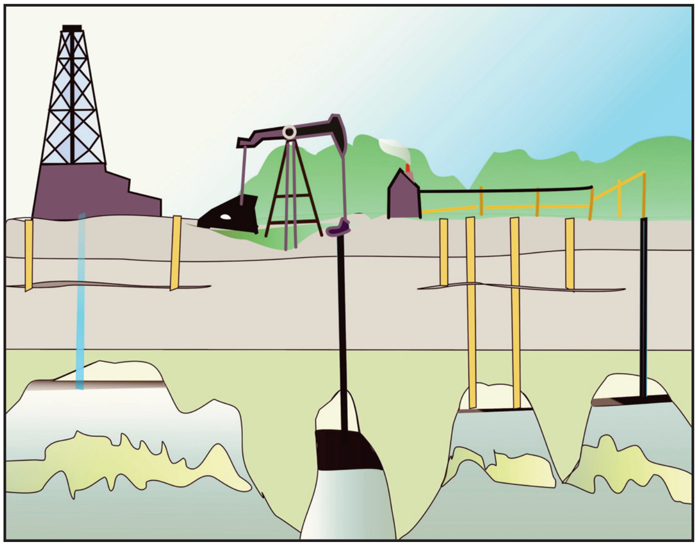

The Implications of Ontario's Historical Oil and Gas Drilling and Abandonment Practices for Abandoning Orphan and Legacy Wells

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SUMMARY
Oil and gas exploration in Ontario began in the mid-1800s, leading to the first oil well drilled in 1858 and the first commercial gas well drilled in 1889. These early discoveries kicked off a boom of exploration and development drilling activity, but well records were not mandatory until 1919 after the introduction of the Natural Gas Act R.S.O.1918, c. 12. The Ontario Bureau of Mines estimated 10,000 operating oil wells in the province at the turn of the 20th century, but there are only records for approximately 1,500 wells. By 1970 there were an estimated 50,000 wells drilled in the province though there are only records for 27,000 wells, indicating there may be tens of thousands of unrecorded or lost wells in southwestern Ontario.

Wells that are not properly plugged are a conduit for fluid movement, including brine, natural gas, oil, and hydrogen sulphide, to move from the subsurface to the surface. Historical well abandoning regulations required wells to be plugged with inferior materials including wood, clay, and rubble. Cement was not the standard plugging material until 1964. There are orphaned and legacy wells leaking natural gas and sulphur water (groundwater containing dissolved sulphate and hydrogen sulphide) creating a risk to public safety. Orphaned and legacy wells are also a risk for subsurface energy projects including geological storage of carbon dioxide, hydrogen, and compressed air energy, because the wells may provide a pathway for injected fluids to return to the surface. This study reviews well construction, legislation, and abandonment practices in Ontario beginning in 1858 and identifies five factors impacting the plugging and abandonment of orphaned and legacy wells.

Further work is required to locate unreported or lost wells and to develop new techniques to permanently plug wells to limit gas leakage, reduce greenhouse gas emissions, and improve public and environmental safety.

RÉSUMÉ
La prospection pétrolière et gazière en Ontario a commencé au milieu des années 1800, conduisant au premier puits de pétrole foré en 1858 et au premier puits de gaz commercial foré en 1889. Ces premières découvertes ont donné le coup d'envoi à un essor des activités de forage d'exploration et d'exploitation, mais l'enregistrement des puits n'est devenu obligatoire qu'en 1919, après l'adoption de la Loi sur le gaz naturel, R.S.O.1918, c. 12. Le Bureau des mines de l'Ontario estime à 10 000 le nombre de puits de pétrole en exploitation dans la province au début du XXe siècle, mais il n'existe des registres que pour environ 1 500 puits. En 1970, on estimait à 50 000 le nombre de puits forés dans la province, mais il n'existe des registres que pour 27 000 puits, ce qui indique qu'il pourrait y avoir des dizaines de milliers de puits non répertoriés ou perdus dans le sud-ouest de l'Ontario.

Les puits qui ne sont pas correctement obturés constituent un conduit pour le mouvement des fluides, y compris la saumure, le gaz naturel, le pétrole et le sulfure d'hydrogène, qui se déplacent du sous-sol vers la surface. Les anciennes réglementations relatives à l'abandon des puits exigeaient que les puits soient obturés avec des matériaux de qualité inférieure, notam-

Geoscience Canada, v. 50, https://doi.org/10.12789/geocanj.2023.50.203 pages 277–294

ment du bois, de l'argile et des gravats. Ce n'est qu'en 1964 que le ciment est devenu le matériau d'obturation normalisé. Il existe des puits orphelins et anciens qui laissent échapper du gaz naturel et de l'eau sulfureuse (eau souterraine contenant du sulfate et du sulfure d'hydrogène dissous), ce qui constitue un risque pour la sécurité publique. Les puits orphelins et les puits anciens constituent aussi un risque pour les projets énergétiques souterrains, notamment le stockage géologique du dioxyde de carbone, le stockage de l'hydrogène et le stockage de l'énergie par air comprimé, car les puits peuvent permettre aux fluides injectés de remonter à la surface. Cette étude révise les pratiques de construction, de législation et d'abandon des puits en Ontario depuis 1858 et identifie cinq facteurs ayant un impact sur les activités d'obturation et d'abandon des puits orphelins et des anciens puits.

D'autres travaux sont nécessaires pour localiser les puits non déclarés ou perdus et pour mettre au point de nouvelles techniques d'obturation permanente des puits afin de limiter les fuites de gaz, de réduire les émissions de gaz à effet de serre et d'améliorer la sécurité du public et de l'environnement.

INTRODUCTION

There have been previous studies that examine the impact of oil and gas development in Ontario. Armstrong (2019) discussed the environmental impacts of early oil and gas development, particularly in the Oil Springs and Petrolia areas of southwestern Ontario (Fig. 1). May (1998) examined early oil and gas development in Ontario, focusing on the economics, innovation, and people that played significant roles. Gray (2008) also described early oil and gas development in Ontario as well as prominent events across Canada. Skuce et al. (2015) developed a geochemical tool for identifying leaking intervals in wells in southwestern Ontario by fingerprinting water geochemistry in each bedrock formation. However, there has not been a published study of the construction and condition of early oil and gas wells drilled in Ontario, particularly from the viewpoint of abandoning leaking wells. This study reviews well construction, legislation, and abandonment practices in Ontario beginning in 1858, to identify five factors impacting abandonment of orphaned and legacy wells.

The process of permanently taking a well out of service by plugging the well according to regulations has been described as plug and abandon, plugging, legal abandonment, or wellbore abandonment (Energy Safety Canada 2023). Regulations in many jurisdictions use the term "abandon", which is the term used in this study. An abandoned well is permanently shut down, plugged, with the wellhead removed and the site cleaned up and considered safe and secure by regulators. A well that is not plugged, not producing, and does not have a responsible operator is referred to as an orphaned well. The term "legacy well" is used in this study to describe a well that was properly abandoned to the standards of the time, and for which there is no current operator. Although these are the definitions for abandoned, orphaned, and legacy wells used in this study, it is important to note that the historical use of the term abandon was inconsistent, and did not always include plugging a well, but was also used to describe an orphaned well.

Oil and gas exploration in Ontario began in the mid-1800s (Logan 1852), and the first oil well was drilled in 1858 (Ontario Bureau of Mines 1892). At the beginning of the 20th century there were more than 10,000 production wells (Ontario Bureau of Mines 1901), and an estimated 50,000 oil and gas wells were drilled by 1970 in southwestern Ontario (Hutt 1970). However, there are only records for 27,000 oil and gas wells in Ontario (Carter et al. 2021a). Few well records were kept before 1919, when record keeping became mandatory under the Ontario Natural Gas Act, and many drilled wells before 1919 were never reported or the records were lost (Caley 1946). Some well operators orphaned their wells, resulting in the knowledge of the wells' existence, location, or depth being lost (Harkness 1937, 1949, 1952). Wildcat drilling is a term referring to drilling exploratory wells outside of known oil and gas plays. Wildcat wells were more commonly unproductive, or dry, and were left without properly abandoning them (Clapp 1914).

Wells that were abandoned before 1907 were plugged with wood and rubble (Act to Prevent the Wasting of Natural Gas, S.O. 7 Edward VII c. 47). Cement, wood plugs, and lead were used to plug wells from 1907 until the 1960s, when long cement plugs, consistent with todays standards, were adopted under O. Reg. 420/68. Early well repair and plugging operations were also challenged by poor equipment (Harkness 1937) as well as limited drilling and plugging experience (Harkness 1946). However, cementing operations completed to today's standards with modern equipment may also fail due to improper cementing operations and cement degradation over time (Dusseault et al. 2000; Dusseault and Jackson 2014; Natural Resources Canada 2019). There are wells that were abandoned according to the standards of their time more than 100 years ago and the plugs have degraded due to exposure to brine and "sulphur water" (groundwater containing dissolved sulphate and hydrogen sulphide).

There are several examples of orphaned and legacy wells in Ontario that leak brine and gases at surface. Leaking wells in Elgin County were abandoned around 2010 (Carter et al. 2014). Leaking abandoned wells in Norfolk County resulted in resident evacuations (Sonnenberg 2019) and other leaking wells in Norfolk County have been studied to determine the source of methane and hydrogen sulphide emissions (Jackson et al. 2020). A leaking abandoned well supplied the fuel that produced an explosion in Wheatly Ontario in 2021, causing injuries and destroying two buildings (Ensing 2021).

Hydrogen sulphide and natural gas are greenhouse gases, therefore leaks of these gases from orphaned or legacy wells are a source of greenhouse gas emissions. Unplugged or poorly plugged wells provide a pathway between the subsurface and atmosphere for fluid transport. This pathway may also be a risk for subsurface energy projects in Ontario that involve gas injection, including geological storage of carbon dioxide (Dessanti 2023), compressed air energy storage (Colthorpe 2021), and underground hydrogen storage (Lemieux et al. 2019).

There are industry best practices for properly abandoning wells but plugging older wells is often complicated because

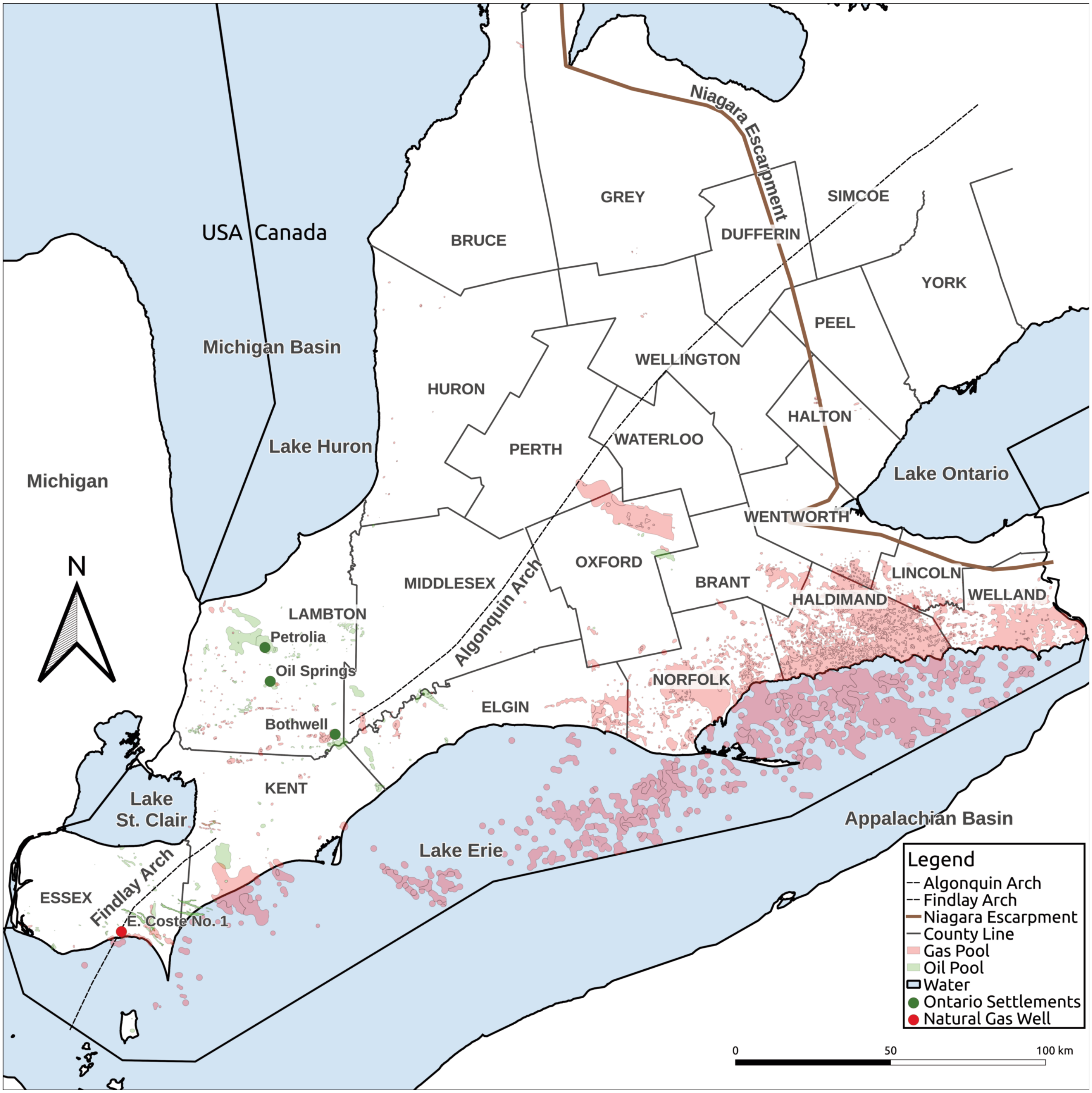

Figure 1. Study area including the first three oil field discoveries and the first commercial natural gas well.

rock can breakout from the wall of the well, or casing may be broken off in the well (Energy Safety Canada 2023). Ontario has had a program to abandon wells since 1960, originally named the Abandoned Works Fund, which was created through the Energy Act R.S.O. 1960 c. 122. The current Abandoned Works Program was refined in 2005 to abandon oil and gas wells to protect public health and drinking water resources. The challenges for the program are locating and plugging orphaned and legacy wells that have a wide range of construction methods and have plugs that have deteriorated over time.

STUDY AREA

This study focuses on southwestern Ontario, the primary oil and gas region of the province, which is bounded to the south by Lake Erie, to the west by Lake Huron and the state of Michigan, USA, and to the east by the Niagara Escarpment

(Fig. 1). The area is relatively flat with numerous lakes and rivers overlying glacial drift. The geology of the area is described in detail by Armstrong and Carter (2010) but is summarized here. The basement rocks are Precambrian crystalline metamorphic, igneous, and metasedimentary rocks referred to as the Canadian Shield. The Precambrian rocks have a southwest-plunging structural high known as the Algonquin Arch that separates the Michigan structural basin to the northwest and the Appalachian foreland basin to the southeast. In the most southwestern part of Ontario is the Findlay Arch, which is the southwestern extension of the Algonquin Arch (Carter et al. 2021b).

Sedimentation in southwestern Ontario began in the Cambrian and continued until the Devonian and potentially the Mississippian, with periods of uplift and erosion, marked by regional unconformities (Armstrong and Carter 2010). Paleozoic sedimentary strata consist of an interlayered succession of carbonates, shales, siltstones, evaporites, and sandstones. The bedrock formations dip to the southwest at 3 to 6 m/km along the Algonquin Arch into a structural low, the Chatham Sag, which is located between the Algonquin Arch and the Findlay Arch (Armstrong and Carter 2010). The bedrock dips at 3 to 12 m/km down the flanks of the arches westward into the Michigan structural basin and southward into the Appalachian foreland basin (Armstrong and Carter 2010; Carter et al. 2021b). Paleozoic strata are much thicker to the west of the Niagara Escarpment, ranging from 540 m to nearly 1400 m in the Chatham Sag, and 1600 m at the international border beneath Lake Huron (Carter et al. 2021b).

Figure 2 shows the terminology from Armstrong and Carter (2010) for the Paleozoic strata in Brant, Haldimand, Lincoln, Norfolk, Oxford, Welland, and Wentworth counties as well as eastern and central Lake Erie, which is referred to as the Eastern Counties in Figure 2. Also shown in Figure 2 are the terms used by Sir William Logan, the founding director of the Geological Survey of Canada (GSC), in the mid to late 1800's and the terms used by geologists and drillers circa 1925 (Harkness 1925). Figure 2 is intended to relate the geological terms for each unit, group or formation and not intended to illustrate unit thicknesses or duration of sedimentation. There are other rock formations for other counties listed by Harkness (1925) and Armstrong and Carter (2010) that are not shown in Figure 2 and the drillers terminology did not cover all of the labelled units in 1925 but did identify the pertinent formations.

Groundwater in Ontario becomes increasingly saline, Na-Ca-Cl-(SO_4), with distance down-dip (Carter et al. 2021b). A zone of brackish to saline water with elevated levels of sulphate and hydrogen sulphide (H_2S) is commonly found in southwestern Ontario and is referred to as sulphur water in the Ontario oil and gas community (Bailey Geological Services and Cochrane 1985; Skuce et al. 2015). Carter et al. (2021b) created a regional hydrostratigraphic framework including the sulphur water zone, which occurs from a few tens of metres to a maximum of 350 m below ground level (Carter and Sutherland 2020). The sulphur water zone occurs in all formations but is particularly prominent in the Lucas, Dundee, Bass Islands, and Guelph formations (Carter et al. 2015), and can be found beneath 22,000 km^2 of southern Ontario (Carter et al. 2021b). Below the sulphur water zone, there are several permeable units from the Silurian down to the Cambrian sandstone that contain brine with total dissolved solids concentrations between 200 and 400 g/L and are believed to be modified remnants of highly evaporated Paleozoic seawater (Dollar et al. 1991; Hobbs et al. 2011; Skuce 2014).

OVERVIEW OF EARLY DRILLING TECHNIQUES

Percussion drilling, including the spring-pole and cable tool methods, was the primary drilling method for the first six decades of the oil and gas industry (Gray 2008), but the methods were not effective for drilling through glacial drift. To get through the glacial drift, wells were dug by hand and reinforced with wood cribbing or augured with 0.1 to 0.3 m diameter auger bits (Gray 2008). Many of the wells drilled after 1863 augured a 0.25 m diameter well to 3.7 or 4.6 m below ground surface then inserted a heavy stove pipe before reducing the well diameter as they worked down lengths of progressively smaller diameter until the rock was reached, producing a well approximately 0.14 m in diameter at the top of bedrock (Harkness n.d.).

Spring-pole rigs were used to drill wells in Oil Springs beginning around 1859 (Gray 2008). These rudimentary percussion drills used a 6 m cantilevered pole anchored to the ground at the butt end and levered about one-third of its length on a fulcrum. The drill bit and other downhole tools hung from the thin end of the pole, attached by rods, rope, and/or cables. Drillers jumped or rocked back and forth on the cantilevered spring pole to raise and lower the end of the spring pole. A cast-iron drill bit was attached by a line to the end of the spring pole and the percussion of the drill bit on the underlying rock chipped the rock apart. Spring-pole-drilled wells were not more than 0.1 m in diameter and were typically shallow (tens of metres), though some wells reported by the United States Geological Survey reached 90 m depth (Bowman 1911).

Edwin Drake drilled the first oil well in the United States in Titusville, Pennsylvania, in 1861 using a cable tool rig (Gray 2008). The cable tool system used an engine and a series of wheels and pulleys to raise and drop a heavy chisel on to the rock from an oil derrick erected over the well (Bowman 1911; Clapp 1914). The rock fragments created from the chisel were cleaned from the well using a bailer. Cable tool rigs could be erected in three to four days by a skilled crew (Bowman 1911) and were standard equipment in the United States by 1884 (Gray 2008).

Improvements in cable tool drilling led to the development of the Canadian Drilling System in the 1880s (Gray 2008). The Canadian System modified the derrick to incorporate sled-like runners to make it easier to move the derrick across land (Bowman 1911) and used steam engines to turn a flywheel, which moved a belt that moved the drill wheel (International Oil Drillers 2023). A camshaft mounted to the drill wheel converted the circular motion of the drill wheel into vertical motion, allowing a walking beam to pound a drill bit (Interna-

Time Scale	Logan's Terms (1850)	Niagara Area Terms (ca.1925)			Drillers' Terms (ca.1925)	Eastern Counties Terms (Armstrong and Carter 2010)	
DEVONIAN	Portage and Chemung	Port Lambton			Black shale	Port Lambton (western counties)	
		Huron				Kettle Point	
	Hamilton	Hamilton	Ipperwash		Top rock	Hamilton	Hungry Hollow
			Petrolia		Upper soap		Arkona
			Widder beds		Middle lime		
			Olentangy		Lower soap		Marcellus
	Corniferous	Delaware			Big lime	Dundee	
		Onondoga				Detroit River	Amherstburg - Onondoga
	Oriskany	Springvale				Bois Blanc/Springvale	
		Oriskany			White sand	Oriskany	
SILURIAN	Lower Helderberg Group (Onondaga)	Cayaugan	Akron		White lime	Bass Islands/Bertie	
			Bertie				
		Salina - Camillus - shale, salt and gypsum			Salt and gypsum or lime and shale	Salina Units	
	Guelph	Niagaran	Guelph		Guelph and Niagara lime	Guelph	
	Niagara		Lockport	Barton Beds			
				Gasport		Lockport	Goat Island
							Gasport
				De Cew		Clinton	Decew
				Rochester	Niagara Shale		Rochester
		Clinton	Irondequoit		Clinton dolomite		Irondequoit
	Clinton		Reynolds				Reynales
			Furnaceville		Clinton shale		Thorold
	Medina	Medina	Thorold		(not named)		
			Grimsby		Red Medina	Cataract	Grimsby
		Cataract	Cabot Head				Cabot Head
			Manitoulin		Blue shale		Manitoulin
			Whirlpool		White Medina		Whirlpool
ORDOVICIAN		Richmond	Queenston		Red shale	Queenston	
	Hudson River		Meadowvale, Streetsville, Erindale		Hudson River Shale	Georgian Bay - Blue Mountain	
		Dundas	Credit, Humber, Danforth, Rosedale				
	Utica	Utica			Utica shale		
		Collingwood				Trenton	Coburg
	Trenton	Trenton			Trenton		Sherman Fall
							Kirkfield
	Black River	Black River				Black River	Coboconk
							Gull River
							Shadow Lake
CAMBRIAN	Potsdam	Arkose			Potsdam	Little Falls	
						Theresa	
						Potsdam	

Figure 2. Stratigraphic correlation chart for the Paleozoic strata of southwestern Ontario that also includes the common drilling terms used circa 1925.

tional Oil Drillers 2023). The system used an early version of drill rods made of wood 0.05 to 0.1 m in diameter and 5.5 m in length, spliced together and reinforced at the joint by irons (Bowman 1911). Rods could be added to the string to advance the drill bit deeper. Sometimes the buckling and breaking of the rods prevented the rods from being removed from the well and the well was abandoned (Bowman 1911), presumably with rods and casing remaining downhole. The last recorded well drilled using the Canadian Drilling System was near Acton in Halton Township in 1959. The rig was decommissioned after the well was drilled, but the rig was rebuilt for display purposes in 1996 as shown in Figure 3.

Rotary drilling was introduced to the oil and gas industry in Texas around 1900 (Bowman 1911) and the technology continued to improve in the 20th century. Rotary rigs began operating in Ontario in 1955 with seven wells rotary-drilled that year, compared to 383 wells by cable tool rigs (Ontario Fuel Board 1955). By 1988 there were 135 wells drilled by rotary rigs and 64 wells drilled by cable tool rigs (Carter 1992). Rotary drilling uses a rotating drill bit at the bottom end of a string of steel drill pipe to bore into the rock. Water flushed through the string of drill rods cleans the drill cuttings from the well, which is more efficient than cable tool rigs that bailed cuttings from the well. The top of the rotary drill pipe string is connected to the swivel, which is attached to the derrick and allows the drill pipe to be raised and lowered in the well, and allows the drill pipe to be rotated. There are other advantages with rotary drilling that are outside the scope of this study. Bowman (1911) has a detailed discussion of early rotary drilling techniques.

Early practices drilled wells with a range of well diameters that were not standardized. From 1920 to 1922 North American oilfield equipment manufacturers and oil and gas producers worked together to standardize materials used in the industry to reduce the overhead cost of manufacturing equipment (Harkness 1923). The list of standardized equipment included: well casing, tubing, rig irons, threads, line pipe, weights of valves, flanges, and gas connections (Harkness 1923). Wells drilled before standard sizes were adopted may have diameters that are not consistent with current well drilling techniques, which is important to consider when plugging a well.

Cable tool and rotary drill rigs use steel casing to stabilize the well and keep glacial drift and rock fragments from entering the well. The casing also holds water out of the well and prevents drilling and production fluids from the well from entering aquifers. Modern practices use a 'surface casing' installed to depths below drinking water zones and cemented in place to limit the connection between the well and drinking water aquifers. Although the cement is relied on to prevent fluids from moving up the well in the annular space between the casing and the rock or glacial drift, poor cementing practices may allow leakage to occur (Dusseault and Jackson 2014). Once the surface casing is in place, drilling continues until the desired depth is reached. Wells are completed to prepare the well for production; this includes lowering piping or production tubing into the well, installing pumps, and configuring the top of the well (or well head) to control the fluids produced from the well and to prevent fluids from entering the well. Despite the engineering required to complete a well, a well is a pathway for fluid movement. Fluids can enter or leave the well at permeable horizons unless the horizons are isolated with cemented casing or plugged with cement or other types of plugs.

Figure 3. Canadian Drilling System rig rebuilt in 1996.

FIRST OIL AND GAS DISCOVERIES IN ONTARIO

Oil

The settlers in Enniskillen Township, Lambton County, knew of "gum oil" in the local swamps in 1830 (Clapp 1914). Sir William Logan reported "asphalt or mineral pitch" in Enniskillen Township and springs of petroleum along the Thames River in Mosa Township to the Legislative Assembly of Canada, where the discoveries were made public record (Logan 1852). James Williams from Hamilton, Ontario, went to Enniskillen in 1858 to investigate if the petroleum from the gum oil could be refined to lamp fuel and lubricating oil. Williams dug a well in the gum oil and liquid petroleum entered the well, creating North America's first oil well. Prospectors arrived the following year, 1859, creating the community of Oil Springs. Williams used the spring-pole rig to drill a productive oil well 44 m deep sometime between 1859 and 1861 (Gray 2008). Significant milestones in Ontario oil and gas exploration and development as well as key legislation regarding well abandonment are shown in Figure 4A.

There was little development in the Oil Springs field until January 1862, when John Shaw dug through 14 m of glacial

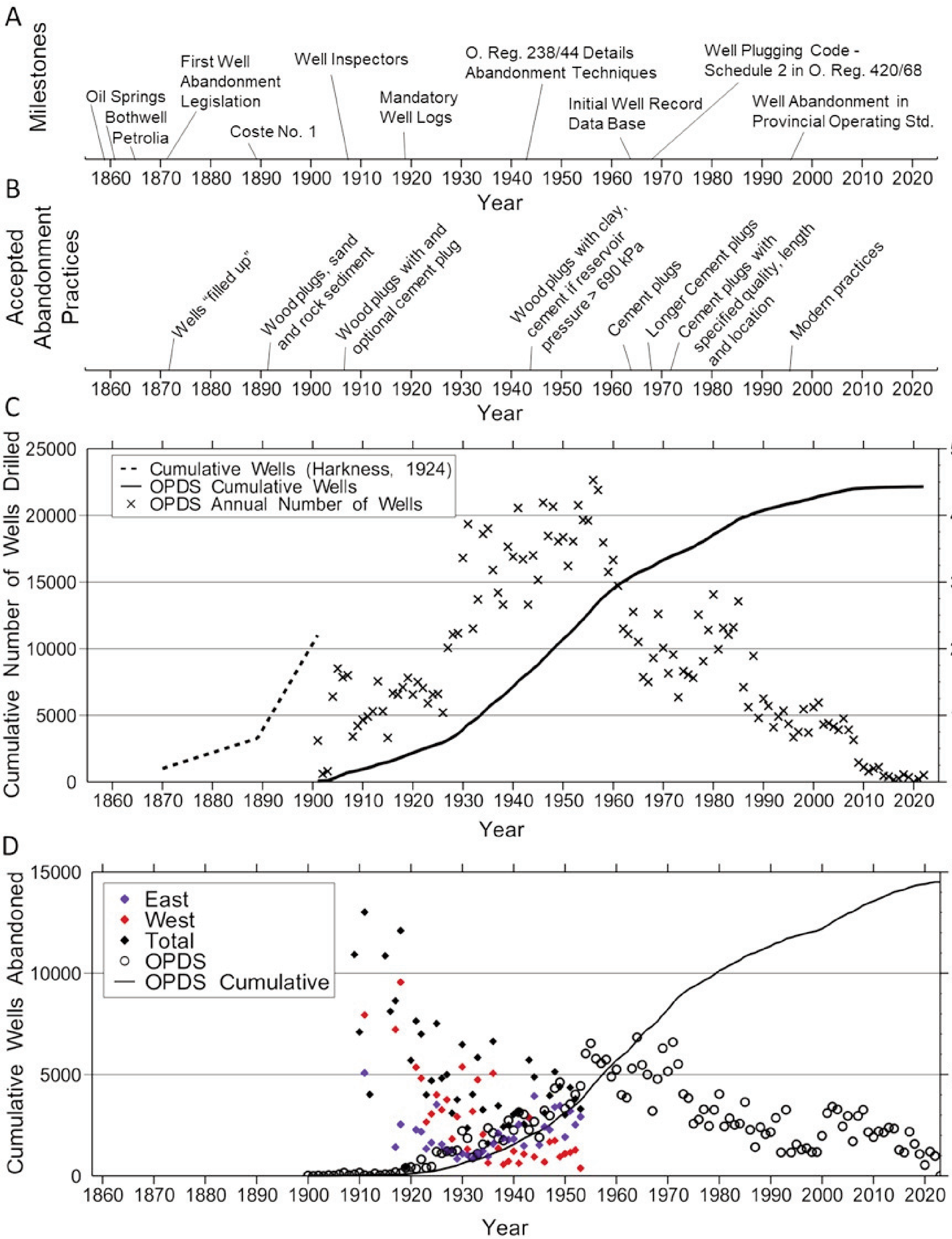

Figure 4. Timelines showing A) milestones for oil and gas development and well abandonment; B) the progression of accepted abandonment practices; C) the cumulative and annual number of wells drilled reported in the Annual Reports including Harkness (1924) and recorded in the Ontario Petroleum Data System (OPDS); D) the cumulative and annual number of abandoned wells reported in the Annual Reports and the recorded well abandonments in the OPDS.

drift then used a spring pole rig to drill through 41 m through rock to create Canada's first gushing oil well, which produced an oil exploration boom. Brumell (1892) listed 33 flowing wells in Enniskillen Township in Lambton County and by 1860 hundreds of derricks had been erected (Clapp 1914), but the location of each well was not recorded (Ontario Bureau of Mines 1892).

The next oil discovery was near Bothwell, Kent County, near the western border of Mosa Township in 1861 (Clapp 1914). Natural petroleum seeps in the Thames River led to numerous exploration wells being drilled along both sides of the river, but there were few records or descriptions of where these wells were (Harkness n.d.). John Lick began drilling the first productive well in the Bothwell field in September 1862 (Gray 2008). Other wells followed, but the lack of drilling experience and understanding of Ontario's oil and gas system led to wells drilled below the oil reservoir into an underlying aquifer, allowing saline water to enter the reservoir. The influx of saline water inhibited the production of oil (and gas) diminishing the use of the field. At the end of 1865 the 31 remaining wells in the field were pumping large volumes of water and an additional 172 wells were not in operation (Harkness n.d.; Gray 2008). By 1867 production in the field ended and remained idle until 1895 when drilling extended the field west and the oil field was revived (Ontario Bureau of Mines 1896).

Oil was discovered in Petrolea in 1865. The town name Petrolea was changed to Petrolia due to a clerical error around 1914. Exploration began in the Petrolia area because of the discovery of gum oil similar to in the Oil Springs area. Drilling techniques were similar to those used in Oil Springs and the first flowing well was drilled in Petrolia in 1865 (Caley 1946). Petrolia was the primary centre of oil development in Canada in 1867 (Armstrong 2019). Although 2500 wells were drilled in the area by 1890 (Clapp 1915), there are no reliable records for these wells (Caley 1946).

Following the discovery of oil at Oil Springs, Bothwell and Petrolia, oil exploration occurred throughout Ontario. Exploration was underway in eastern Ontario near Whitby, Bainsville, Pembroke, Caledonia Springs, North Gower, and in other townships, but there were few records for many of these wells regarding location, drilling methods, or depths (Brumell 1892). Wildcat exploration also occurred within towns, including in Toronto on Parliament St. and in Ottawa near Patterson Creek (Brumell 1892). New fields were developed in Thamesville, Dutton, Raleigh, Wheatley, Leamington, Essex, Romney, Onondoga, Belle River, Dover, and Mosa (Harkness 1924).

Natural Gas

Natural gas seeps were known throughout Canada before 1800, including Caledonia Springs in Prescott County and the Burning Spring at Niagara Falls, but the gas was not widely exploited (Selwyn 1891; Ontario Bureau of Mines 1892). A few private residential gas wells were drilled into the glacial drift in Kent County in the 1860s and used the gas for heating fuel and lighting, but none of these wells produced gas at a commercial scale (Ontario Bureau of Mines 1892). Private wells were also drilled in Welland County in 1866 (Ontario Bureau of Mines 1892) and Port Colborne in 1885 (Selwyn 1891). There were also indications of other low production gas wells (less than 1400 m^3 of gas per day) drilled in southern Ontario before 1887 but there were no records for the wells (Selwyn 1891).

Eugene Coste, a former oil and gas engineer with the GSC, used an anticline theory developed by Dr. Sterry Hunt (Hunt 1861) to explore for gas in South Gosfield Township, Essex County (Malcolm 1915). Drilling began in 1888 on the Coste No. 1 well near the Findlay Arch (Figure 1), and on January 23, 1889 (Fig. 4A), from a depth of 314 m, natural gas flowed from the well at a rate of 280,000 m^3 per day, becoming Canada's first commercial gas well (Gray 2008). A second well was drilled in the same area as the Coste No. 1 well and was used to supply the municipalities of Kingsville and Ruthven in 1890 (Ontario Bureau of Mines 1892).

Similar to the expansion of exploration after the Oil Springs and Petrolia gushers, natural gas exploration occurred in numerous townships in southern Ontario, but exploration was more concentrated in the counties surrounding the gas wells in Essex (Ontario Bureau of Mines 1892). By 1891 there were three established gas fields including Essex County, glacial drift deposits in Kent County, and the field spanning Welland and Haldimand counties. Although the natural gas supply was abundant, there was little consumption of natural gas domestically, and gas was sold via pipeline to Detroit and Buffalo in 1894 (Ontario Bureau of Mines 1895).

MILESTONES IN THE ONTARIO OIL AND GAS INDUSTRY AND WELL PLUGGING REGULATIONS

Early oil and gas discoveries encountered significant volumes of hydrocarbons and the flow of oil and gas from the wells was often difficult to control (Armstrong 2019; Ontario Bureau of Mines 1892). The lack of drilling experience and necessary equipment to control the flows resulted in significant waste of oil and gas, which was scrutinized by the public (Armstrong 2019). Some wells that were drilled through aquifers had groundwater invading oil horizons, limiting the oil production in the Bothwell field, as described above. These circumstances led to the creation of the first legislation in Ontario to plug oil wells in 1872 called an Act "to provide for the filling up of or otherwise shutting off the water flowing in to abandoned Oil Wells" S.O. 1872 c. XXXIX (Table 1). The intent of the Act was to seal off the water horizons from abandoned wells to protect the producing wells. The methods for plugging the well were not specific in the 1872 Act, indicating that "the abandoned well should be filled up, or the water flowing therein shut off in some other and what manner".

The concern for wasting oil and gas resources was a common theme in many early reports and appears to have been the primary motivation behind the legislation and practices until 1996. Significant changes to abandonment practices under the Ontario Acts and Regulations from 1872 to 2023 are listed in Table 1 and the progression of accepted abandonment practices is shown in Figure 4B. There were amendments to many of the Acts that are not listed in Table 1 because the changes

Table 1. List of Ontario Acts with significant changes to plugging and abandonment practices.

Year	Act or Regulation	Notes
1872	Act to provide for the filling up of or otherwise shutting off the water flowing into abandoned Oil Wells S.O. 1872 c. XXXIX	The intent of the Act was to preserve oil reservoirs by limiting water inflow. Abandoned wells were to be filled but the methods or materials were not indicated.
1892	Act to Prevent the wasting of natural gas and to provide for the plugging of abandoned oil wells S.O. 1892, c. 56	The intent of the Act was to preserve gas reservoirs and limit the loss of leaking gas by limiting water inflow. Wells were plugged with a 1 m long wooden plug and filled with sand or rock sediment.
1907	Act to prevent the wasting of natural gas and to provide for plugging of all abandoned wells S.O. 1907 c. 47	Wells to be plugged with wooden plugs with an option to use an overlying cement plug. Wood plugs were 1 m or longer and installed across a water bearing horizon. Two appointed Inspectors oversaw plugging operations.
1918	Natural Gas Act, R.S.O. 1918, c. 12	Introduced the Natural Gas Commissioner. Act required license to drill well, well records, report plugging and abandonment methods.
1924	Well Drillers Act R.S.O. 1924, c. 75	Plugging methods are the same as the 1907 Act. Inspectors review well abandonments, and the Act requires reporting of plugging methods.
1944	Well Drillers Act O. Reg. 238/44 – Natural Gas and Oil Wells.	The Regulation required improved plugging methods as described in the text.
1954	Ontario Fuel Board Act R.S.O. 1954, c. 63	O. Reg 199/54 required the proposed plugging approach and actual methods and results to be filed with the Fuel Board. Plugging methods were consistent with O. Reg 238/44.
1960	Energy Act R.S.O. 1960, c. 122	This Act is concurrent with the Ontario Fuel Board Act governing oil and gas; requiring dry or abandoned wells to be plugged.
1960	Ontario Energy Board Act R.S.O. 1960, c. 271	Continued to use the approach under O. Reg. 199/54.
1964	Energy Act R.S.O. 1964 O. Reg 326/64 Exploration / Drilling and Production	Cement was made the standard for abandonment plugs and the proposed abandonment method must be approved by an inspector.
1968	Energy Act R.S.O. 1964 O. Reg. 420/68 Exploration / Drilling and Production	The length of plugs is increased and there are specific plugs required in abandoned wells.
1971	Petroleum Resources Act R.S.O. 1971 c. 94	The Petroleum Resources Act applies concurrently with the Energy Act 1960 and covers drilling, plugging and abandonment as well as other up-stream activities.
1972	Petroleum Resources Act R.S.O. 1971 O. Reg 45/72 Exploration, Drilling and Production	Schedule 2 – Well Plugging Code no significant changes from 420/68.
1990	Petroleum Resources Act O. Reg 915 Exploration, Drilling and Production	Schedule 2 – Well Plugging Code no significant changes from 420/68.
1996	Oil, Gas and Salt Resources Act R.S.O. 1990 c. 30 P.2	Replaced Petroleum Resources Act. Introduces Provincial Operating Standards for plugging and abandoning wells.
1997	Oil, Gas and Salt Resources Act R.S.O. 1990 O. Reg. 245/97 Exploration, Drilling and Production	Current 2023 regulation outlining requirements for upstream oil and gas activities, including plugging and abandonment.

were administrative or did not impact how a well was abandoned.

The amount of natural gas wasted in 1891 was reported to be enormous (Ontario Bureau of Mines 1892). One example was a creek-side well that was cased with a wooden pipe to 30 m depth. Gas erupted from the well projecting water, rock and stones up to 15 m in the air (Ontario Bureau of Mines 1892). Gas was allowed to escape from the well for six or seven years before the flow stopped (Ontario Bureau of Mines 1892). The first legislation to address natural gas waste was "An Act to Prevent the Wasting of Natural Gas and to Provide for the Plugging of all Abandoned Wells" S.O. 1892, c. 56 (Table 1, Fig. 4A). The intent of the Act was to plug wells within two months after production ceased, to prevent gas wasting and to preserve the reservoir. The Act required abandoned wells to be filled with sand or rock sediment from the bottom of the well to 7.6 m above the gas horizon. The well was plugged with a seasoned wood plug at least 1 m long and the same diameter as the well and installed 1.5 m below the bottom of the casing. Once the casing was removed, a second plug was installed above the first plug and the well was backfilled with 7.6 m of sand or rock sediment.

There was an estimated total of 10,000 oil wells being pumped in Ontario at the turn of the 20th century (Ontario Bureau of Mines 1901) and 11,000 wells in operation in 1901 (Harkness 1924; Fig. 4C). Oil production was primarily from the Oil Springs, Petrolia, Bothwell, Dutton (Kent County) and Thamesville (Essex County) fields. Ontario oil fields gained a reputation for having numerous wells in a field, with limited production coming from each well. Initially, the only developed oil reservoir was known as the Corniferous limestone (Ontario Bureau of Mines 1901), now referred to as the Dundee Formation (Armstrong and Carter 2010; Fig. 2). In 1902 the "Gurd Gusher" was drilled in the Raleigh field, Kent County, in the "Middle Lime" (Ontario Bureau of Mines 1902) or Hamilton Group (Fig. 2). Gas production at the turn of the century was dominantly from the Essex and Welland fields; a new discovery in Hepworth (Ontario Bureau of Mines 1901) produced gas from the Clinton and Cataract (formerly Medina) groups (Ontario Bureau of Mines 1905).

By 1901 the Ontario oil and gas fields were being depleted (Ontario Bureau of Mines 1902). Three quarters of the wells in the Essex gas field were flooded with saline groundwater, inhibiting gas production. The low production combined with natural gas exports to Detroit caused concerns that the Essex field would not be able to meet domestic demand and prompted the Ontario government to prohibit the export of natural gas from the Essex field to Detroit in 1901. By 1903 the Essex field was practically abandoned due to the limited gas production (Ontario Bureau of Mines 1904).

The failure of the Essex gas field combined with numerous reports of wasting natural gas from open wells and poorly maintained pipelines led to the 1907 Act to Prevent the Wasting of Natural Gas and to Provide for the Plugging of all Abandoned Wells S.O. 1907 c. 47 (Table 1). The Act had two primary objectives; the first was to maintain the quality of oil and gas reservoirs by preventing water from flooding oil or gas-bearing horizons. The second objective was to limit wasting gas that was leaking from wells, pipelines and other equipment. The Act required wells to be completed in a manner to prevent gas leaks two weeks after drilling. Dry wells were to be abandoned by pulling the casing and plugging the well to prevent fresh or salt water from entering the reservoir. Plugging was conducted with a wood plug or optionally a wood plug with an overlying layer of cement. Well inspections were now conducted by Provincial Inspectors who could also add specific provisions for each abandonment.

Two Inspectors were appointed to enforce proper well abandonment. One inspector was responsible for the western counties (Lambton, Kent and Essex) and the other the eastern counties (Elgin, Welland and Haldimand-Norfolk; Ontario Bureau of Mines 1909). The first inspection reports indicated many of the wells in the Enniskillen area required work to improve the condition of the well, in some cases it was difficult to identify well operators, and the number of lost or orphaned wells was unclear. Wells in other counties were in better condition likely because they were not as old as the Enniskillen wells (Ontario Bureau of Mines 1909). Oil and gas production improved by 1915 and was credited to decreased groundwater invasion of the reservoirs as a result of the well plugging and abandonment work (Ontario Bureau of Mines 1915), though there were continued reports of gas wasting. At the time of the federal election in the fall of 1908 the Tilbury East landscape was illuminated by towering torches of natural gas leading the provincial government to impose a tax on wasted gas (Lauriston 1961). The tax on natural gas wasting was two cents per thousand cubic feet in 1917, with the Inspectors responsible for enforcement (Ontario Bureau of Mines 1918).

The Tilbury gas field was discovered in 1911 and was the primary gas producer in Ontario in 1916 (Ontario Bureau of Mines 1917). Production from the field in 1917 was not able to keep up with winter demand, which led to a home fuel shortage (Ontario Bureau of Mines 1918). Gas production was diminished by water flooding the wells, inhibiting gas flow to the wells and limiting gas production. Public complaints applied pressure to the government that resulted in the Natural Gas Act R.S.O. 1918 c. 12 (Table 1, Fig. 4A), which limited the sale of natural gas to industry, focusing consumption on residences (Ontario Bureau of Mines 1918).

The Natural Gas Act was revised in 1919 to require drillers to obtain a license to drill a well and to provide proper well records and drill cutting samples (Estlin 1921). The GSC collected voluntary submissions of drill cuttings and drill core samples from wells being drilled to explore for and develop oil, gas, and salt resources in Canada, beginning in the 1800s. The samples were stored in Ottawa (Carter 2017). The first well records under the Natural Gas Act included information location, depths to the tops of rock formations, total well depth, and the estimated production. The following year the records included the name of the well logger, measured reservoir pressure, the depths of water, gas or oil encountered, and the date of completion (Harkness 1922). Reporting the method of plugging and abandoning wells was mandatory beginning in 1922 (Harkness 1923). The well operator was added to the reports in 1925 (Harkness 1926), but the drilling method (e.g. the Canadian Drilling System or rotary drilling) was not listed. Many wells prior to the Natural Gas Act R.S.O. 1918, c. 12, do not have well records, particularly dry wells and abandoned wells where the casing was pulled (Caley 1946).

The number of wells abandoned was reported annually in the Department of Mines annual reports (described below as Annual Reports) beginning in 1909 and ended in 1953, although the number of reported wells abandoned in the eastern territory was intermittent before 1919 (Fig. 4D). The total number of wells abandoned each year was calculated as the sum of the reported abandoned wells in the Annual Reports from both territories for each year from 1909 to 1953. There were 12,735 reported wells abandoned between 1909 and 1953. The relatively higher number of wells abandoned in the western counties was likely due to earlier and more drilling activity relative to the eastern counties.

The Well Drillers Act R.S.O. 1924, c. 75 (Table 1), which worked concurrently with the Natural Gas Act, set out the rules for well licensing, drilling, and inspection, as well as plugging and abandonment. Inspectors noted improved conditions in the oil and gas fields in 1927 due to the abandonment of old wells and better care of the existing wells (Harkness 1928). The Annual Reports in the following years noted successful periods of plugging and abandonment that led to improved production (e.g. Harkness 1928, 1930), but there were reports of faulty casing and ineffective well plugging that led to neglected and flooded wells (Harkness 1925, 1927).

Impacts of the World Wars and the Depression on Well Abandonment

The Fletcher oil field was discovered in 1905 and covered approximately 5,600 acres in Kent County. The field produced oil from 276 wells in the Guelph formation and Salina units with a "heavy flow" of saltwater flowing up from below the oil (Koepke and Sanford 1966). The casings were pulled from the wells in 1919 because of the high price offered for old casing during the First World War. Without the casings in the wells saline groundwater flowed up the well to surface (Williams 1920). There were several examples of properties producing as many as 200 barrels of oil per month that had casings pulled and sold (Williams 1920). The methods of well abandonment for the Fletcher field after the casings were removed were not reported.

The economic downturn of the Great Depression from 1929 through the mid 1930s had significant impacts on oil and gas wells. Abandoned wells were stripped of casing and pipe to be used in other wells, but the metal was corroded and weak (Harkness 1929). The corroded casings allowed natural gas and oil leaks to occur. This was particularly difficult to address in the spring when the fields were flooded, preventing access to the wells but allowing surface water to flood the wells (Harkness 1929). Limited capital investment through the Depression caused wells to deteriorate and well operators to orphan wells.

The war efforts during the Second World War limited capital investment into oil and gas infrastructure, necessitating equipment to be salvaged from waterlogged oil and gas fields and repurposed in operating fields (Harkness 1946, 1948a). Oil-field equipment was expensive and not readily available, which also promoted the reuse of casing and pipe even if it was corroded (Harkness 1946, 1948b). The hydrogen sulphide in the oil and groundwater water corroded equipment, gradually deteriorating the infrastructure (Harkness 1948a). Skilled labour, particularly for drilling and abandonment, was limited because nearly all experienced workers were on active war service (Harkness 1948a). The lack of skilled labour diminished the quality of well records (including accurate well locations) and well inspectors were not able to oversee many of the well plugging and abandonment operations (Harkness 1947).

The next significant regulatory change was Ontario Regulation (O. Reg.) 238/44 Natural Gas and Oil Wells (Table 1, Fig. 4A). Wooden plugs remained the primary seal but when a plug was driven to the bottom of a casing, the plug was required to seal both the open well and the casing. Wells with a pressure gradient greater than 6.9 kPa over a three-metre depth were to be backfilled with clay at least three metres above the gas producing formation, and a wooden plug placed above the clay. For wells with pressures greater than 690 kPa, two wooden plugs separated by three metres of tamped clay were required. In addition, six metres of cement was to be emplaced on top of the upper plug, then a third wooden plug installed on top of the cement. Finally, clay was tamped into the well to fill the well up to the bottom of the casing. Lead plugs could be used instead of cement plugs.

The "mud fluid method" of plugging was also acceptable under O. Reg. 238/44. The mud-fluid method was first used with cable tool rigs in California in 1909 and used a clay-water mix to create a mud with a greater density than water with the clay particles clogging the pores in rocks in the well (Collom 1922). The mud was used to inhibit the movement of gas into a well to seal off "gas sand" horizons. The drawback of the mud fluid method was that any larger grained materials in the mud, such as sand or rock fragments from the well, would not seal off the gas horizons, and allowed gas to enter the well and escape if another plug was not used (Collom 1922).

At the end of the Second World War there were 975 reported abandoned wells due to the inclusion of "idle wells" with abandoned wells (Harkness 1948a). The 975 idle wells were not operational for fifteen or twenty years, but it is not known if they were abandoned or orphaned (Harkness 1948a) and they are not shown in Figure 4D. There were no subsequent reports of these wells in the Annual Reports, making it difficult to determine if they were properly abandoned. There were also reports of thousands of wells that were abandoned with clay plugs, which was permitted under O. Reg. 238/44. There was concern about the stability of the clay if the reservoirs re-pressurized (Harkness 1948b), but there were no subsequent discussions of these wells. Significant oil and gas exploration resumed in 1949 but some companies were bankrupt, leaving operating wells in poor condition or orphaned (Harkness 1951).

Landowner complaints regarding the impact of newly drilled gas wells were notable in Welland and Haldimand counties in 1947. Sulphur water and natural gas were contaminating

https://doi.org/10.12789/geocanj.2023.50.203

domestic water wells and, in some cases, natural gas was being pumped into residences (Harkness 1949). Provincial Inspectors investigated the complaints and confirmed there were improperly cased wells allowing sulphur water to enter freshwater aquifers. However, in most cases the problem was that water wells were drilled too deep and penetrated the sulphur water aquifer (Harkness 1949), allowing natural gas and hydrogen sulphide to move up the water well into overlying aquifers. These historical water wells may continue to be a factor for hydrogen sulphide leaking from wells today.

Modernization of Plugging Practices

The Ontario Fuel Board Act R.S.O. 1954, c.63, revised and consolidated the oil and gas legislation and introduced the Fuel Board (Ontario Fuel Board 1955). The function of the Fuel Board was to control and regulate all phases of the natural gas industry. Land leases, drilling permits, and reporting requirements were modernized in a manner consistent with current practices. The detail included in the Fuel Board annual reports after 1954 was significantly less than the detailed reporting by the Department of Mines (from 1892 to 1953). Abandoned wells were not included in the Fuel Board reports but were contained in the well records and well license information. Well plugging methods in the 1950s remained consistent with O. Reg. 238/44.

The Department of Energy Resources was established by legislation in 1960, assuming oversight, regulation, and reporting responsibility for oil and gas in Ontario (Ontario Department of Energy Resources 1961). The Energy Act R.S.O. 1960, c. 122, addressed well abandonment practices, created the Abandoned Works Fund for the completion or removal of works, and prescribed the procedure for payment of money into and out of the fund. The Ontario Fuel Board was dissolved in 1960, with the administrative functions assumed by the Department of Energy Resources, and the judicial functions were taken over by the Ontario Energy Board under the Ontario Energy Board Act R.S.O. 1960, c. 271 and the Energy Act R.S.O. 1960, c. 122. The Ontario Energy Board has remained Ontario's energy sector regulator since 1960, although there have been several new Acts and amendments regarding oil and gas in the province. The introduction of O. Reg. 326/64 (Table 1) disallowed the use of clay for well plugging, prescribing cement plugs as the standard for abandonment. O. Reg. 326/64 also required an application for a permit to bore, drill or deepen a well (Form 103) as well as a scaled plan showing the well co-ordinates, certified by an Ontario Land Surveyor or Professional Engineer. Previous descriptions and maps of well locations were relative to cultural or natural landmarks such as buildings, intersections and water bodies, but the scaled plan significantly improved the accuracy of well locations.

Standard well abandonment methods improved with the introduction of O. Reg. 420/68, that listed Schedule 2, the Well Plugging Code. Additives to cement were permitted for faster curing, or viscosity reduction etc., but the cement had to have a minimum weight of 1737 kg/m^3. Bridge plugs could be made of wood, stone, gravel, or lead, but could not include a non-drillable material. The intervals between plugs were to be filled with water or drilling mud, adding another barrier to fluid flow. Cement plugs were to be set above and below each water interval as well as across each oil and gas horizon and were now longer, with a minimum length of 7.6 m above and 7.6 m below fluid zones. In addition to plugging the porous oil and gas horizons in a well, 7.6 m plugs were to be set in the top of the Cambrian, Trenton, Queenston, Clinton-Cataract, Guelph, Salina, Dundee, and bedrock formations to prevent fluid flow into or out of these oil and gas-bearing formations. Separate rules were also introduced regarding well casings in the abandonment process. If surface casing was left in a well, the well had to either have a cap welded to the casing or be plugged with 3 m of cement prior to cutting the casing off one m below surface. When the surface casing was removed from the well, the well was filled to surface with clay or sand or cuttings as the surface casing was withdrawn and a final cement plug was set between one and two metres from surface.

The Petroleum Resources Act R.S.O. 1971, c. 94 (Fig. 4A) took responsibility for oil and gas exploration, drilling and production. The enabling regulation (O. Reg. 45/72) contained Schedule 2, the Well Plugging Code that identified all of the essential elements from O. Reg. 420/68. The Petroleum Resources Act was amended and renamed the Oil, Gas and Salt Resources Act R.S.O. 1990, c. 30 P.2. The enabling regulation was written in 1997 O. Reg. 245/97 and created five different classes of examiners, including the Class I examiner who was responsible for examining wells with respect to used casing, cement quality, isolation of porous zones, cement tops, well control equipment, and well abandonment. Abandonment requirements were no longer listed in the regulation; they were moved to a Provincial Operating Standard that could be updated without legislative approval, streamlining the process to update abandonment practices.

Ontario Petroleum Data System

The 'Ontario Well Data System' was developed in 1964 through a partnership between the University of Western Ontario and the Ontario Department of Energy and Resources Management (Hutt 1970). The information from all the available petroleum well records was transcribed into the new system, producing a database of 10,000 well records in southern Ontario (Hutt 1970).

The Ontario government established the Petroleum Resources Laboratory in London, Ontario, in 1971, under the Petroleum Resources Act (Table 1). The existing Ontario rock sample collection was shipped from the GSC in Ottawa to the Petroleum Resources Laboratory, and Ontario began to consolidate the geological information derived from oil and gas exploration and development (Oil, Gas, and Salt Resources Library 2023).

The Petroleum Resources Laboratory was renamed the Oil, Gas and Salt Resources Library (OGSRL) in 1997 (Carter 2017) with the enactment of the Oil, Gas and Salt Resources Act R.S.O. 1990, c. 30 P.2. The library is operated by the Oil, Gas and Salt Resources Corporation under the terms of a Trust Agreement with the Ontario government. The Corporation is a subsidiary of the Ontario Petroleum Institute (OPI), which is a non-profit industry association that represents explorationists, producers, contractors, geologists, petroleum engineers and other professionals, individuals, or companies directly related to the oil and gas, hydrocarbon storage, and solution-mining industries of Ontario. The library collection includes well drilling and completion records, rock chip samples from 13,000 wells, rock core samples from 1000 unique wells, and over 20,000 geophysical logs (Clark et al. 2020).

The Ontario Well Data System was updated to an Oracle platform database that is maintained by the Ontario Ministry Natural Resources and Forestry and the Ontario Oil Salt and Gas Resources Library and was renamed the Ontario Petroleum Data System, or OPDS (Carter and Castillo 2006). The database has records for approximately 27,000 wells with location co-ordinates and a well location accuracy code indicating the accuracy of the geographic co-ordinates for the wells, with the accuracies ranging from 1 metre to over 1000 metres (Clark et al. 2020). Over 95% of the wells have coordinates with accuracies within 200 metres (Clark et al. 2020). There have been several quality assurance reviews of the petroleum well records, with a focus on well locations and geological formation tops, most recently during the completion of 3-D models of the bedrock geology of southern Ontario by the Geological Survey of Canada (Carter et al. 2021a).

There is a discrepancy between the 10,000 wells reported by the Ontario Bureau of Mines (1901) and the 1518 well records in the OPDS drilled before 1900 (Fig. 4C). The discrepancy highlights how many wells do not have records and how many wells have been lost. The cumulative number of wells in Ontario provided by Harkness (1924) is shown separately from the number of well records in the OPDS shown in Figure 4C because there were no well records. If the values are combined, the total number of wells in southwestern Ontario would exceed 32,000 wells. The wells in the OPDS were mapped as the number of wells per km^2 and show multiple areas that have more than 125 recorded wells per km^2 (Fig. 5A). The high oil well densities around Petrolia, Oil Springs, and Bothwell stand out in Figure 5A, as well as the high density in Middlesex County that is currently named the Glencoe oil field but was historically known as the Mosa field. The other high-density oil well area is the Tilbury pool in Kent County. The high-density of gas wells is associated with the gas pool in Norfolk, Haldimand, and Welland counties. For comparison, the areas of lower well density, such as in Perth County, are as low as one well per km^2, although there may be localized areas with higher well densities.

The OPDS has records for abandoned wells that include the plugging date and some information regarding the plugging contractor, number of depth intervals plugged, length of each interval, amount of cement used in each interval, the type of cement used as well as a section of plugging notes for more complicated plugging operations. The total number of wells abandoned listed in the OPDS (Fig. 4D) is fewer than the number of abandoned wells reported in the Annual Reports until 1937. This is likely due to limited record keeping although well plugging and abandonment records were required under the Natural Gas Act R.S.O. 1918 (Table 1). After 1937, the number of abandoned wells in the Annual Reports and in the OPDS are similar except for during the Second World War, when the lack of reporting and drilling expertise was noted (Harkness 1947, 1948a). There are a total of 14,500 abandoned wells in the OPDS for southwestern Ontario and the distribution of abandoned wells is similar to the distribution of drilled wells, only there are fewer recorded abandoned wells (Fig. 5). There are records for approximately 7,000 wells abandoned before 1964 (Fig. 4D) that would have been abandoned with rock sediment, wood plugs, clay, and potentially a cement plug depending on the year the well was plugged and the reservoir pressure (Fig. 4B). Cement plugs became the standard method for plugging wells in 1964 (O. Reg. 326/64, Table 1, Fig. 4B). There may be thousands of wells in Ontario that were not abandoned using cement plugs.

The wells shown in Figure 5 represent the known well locations. Clapp (1914) identified wildcat drillers as potential sources of unplugged wells because wildcat drillers worked rapidly, abandoning dry wells without casing off the water or properly abandoning the wells. The locations of some wildcat wells are unknown and are unlikely to have been abandoned and would not be captured in Figure 4 or Figure 5.

OTHER FACTORS AFFECTING THE CONDITION OF WELLS FOR ABANDONMENT

Well Maintenance and Enhanced Oil Recovery

Well maintenance and early Enhanced Oil Recovery techniques also had an impact on the condition of wells. The Roberts Torpedo was an iron container with dynamite or nitroglycerine that was lowered down a well then exploded, which was referred to as 'shooting a well' (May 1998). Shooting a well was the earliest reported technique for enhancing oil and gas recovery in Ontario (Selwyn 1891) but wells were also shot to clean out accumulated sediment, paraffin, salt, and other matter (Harkness 1933). The first reported well that was shot was in 1872 in Lambton County and the technique was used without regulation for 19 years (May 1998). Wells in other fields were also shot, including in Welland (Selwyn 1891), Dawn (Ontario Bureau of Mines 1892), Tilbury (Hume 1932; Harkness 1923), and Dover West (Hume 1932). There were limited notes and reports of wells being shot, though according to May (1998) it was a regular practice. The last reported well shooting was Pinetree et al. Dover 8-10-V in December 1979, which was shot with 230 kg of nitroglycerine.

Chemical treatments by the Dowell Company of Michigan improved recovery in ten wells in the Petrolia field and four wells in the Oil Springs field, but the results were not economical and there were limited details on their use (Harkness 1933). Acid treatments were introduced in Ontario in 1932 (Harkness 1933), but the challenge with the Ontario wells was the "home made" casing packers that were designed with one packer that could isolate an interval between the packer and the bottom of the well. The problem was the rock was permeable and the acid moved from the well into the formation (Harkness 1937). The packer system was not able to isolate low permeability

https://doi.org/10.12789/geocanj.2023.50.203

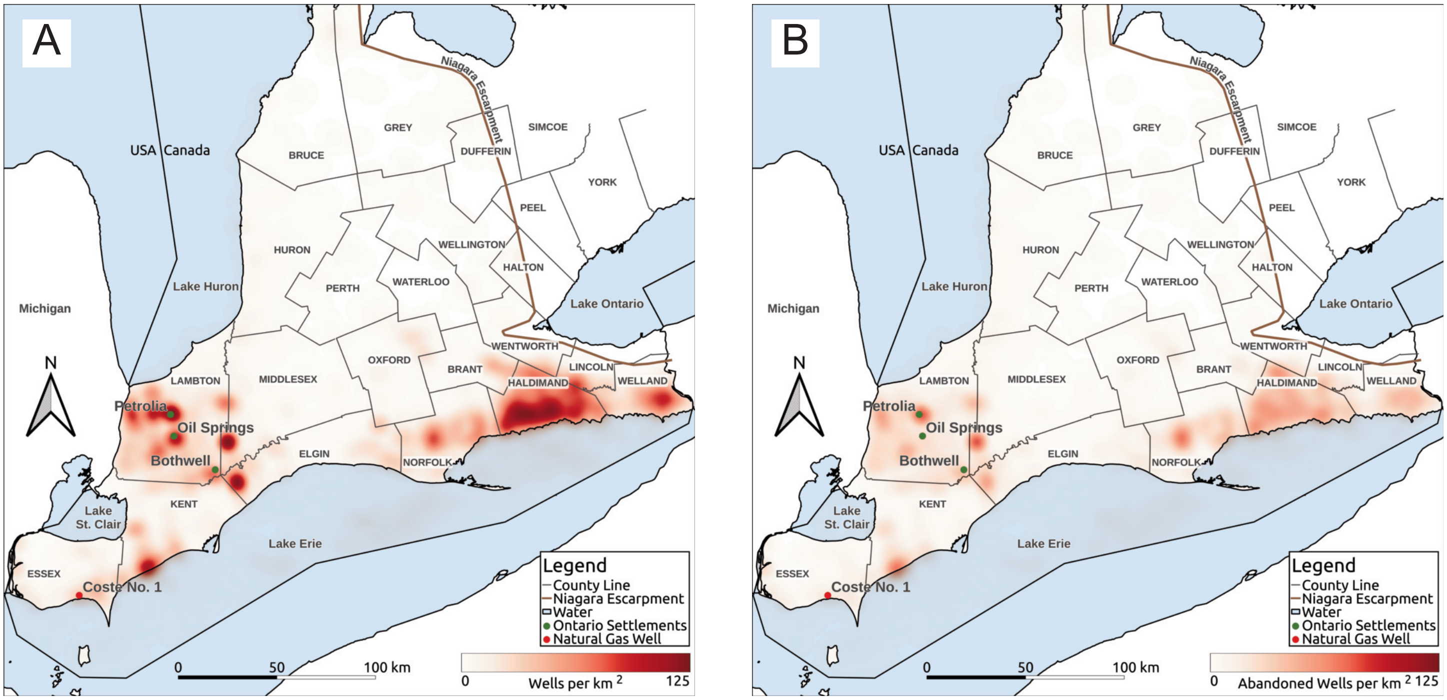

Figure 5. Well density maps for A) drilled wells in the Ontario Petroleum Data System (OPDS) (n = 22,156); and B) abandoned wells in the OPDS (n = 14,507).

zones in a well where the acid treatment could increase the permeability. Although the acid treatments did not have the desired effect, there were small production increases in wells due to the thorough cleaning of the limestone walls of the well, removing the accumulated paraffin, scale, and other sediment (Harkness 1937).

Gas injection used in the Oil Springs area in 1951 improved short-term oil recovery (Harkness 1953). Gas and water injection was also proposed for the Rodney field (Harkness 1954), and was promoted as a technique to improve recovery for several years (Oakley 1963). Finally, water floods were carried out in the Petrolia and Oil Springs fields, but few details were reported (Ontario Fuel Board 1955; Oakley 1963).

The use of well maintenance and enhanced oil recovery (EOR) techniques may have significant implications for subsequent well abandonment. Shot wells will likely have debris and casing in the well and the rock walls may be fractured to an unknown distance into the rock. The explosions will have impacted the condition of the wells, and the wells may be difficult to plug due to debris in the well, the larger diameter of the well, or additional pathways created in the fractured rock for fluids to travel through. Similarly, wells treated with acid may have additional pathways created for fluid flow and the well diameter may be larger at the treated horizon.

Impacts of Hydrogen Sulphide

The issues of poor well construction and poor abandonment practices are compounded by the presence of hydrogen sulphide in the oil, gas, and groundwater. Some Ontario crude oils, principally from the Devonian oil pools, have a high hydrogen sulphide content that readily corrodes equipment, requiring frequent replacement of equipment including pumps, sucker rods, tubing, cables, jerker rods, and pump jacks (Harkness 1948a). There are notes regarding sulphur gas and sulphur water dating back to a gas well drilled in Humberstone Township, Welland County in 1866 (Ontario Bureau of Mines 1892). Gas fields along the shore of Lake Erie also contain hydrogen sulphide, including the Eden gas field south of Tillsonburg which produced natural gas with 0.7 % volume hydrogen sulphide (Harkness 1936), the Tilbury field (up to 0.6 % volume; Harkness 1923), and the Declute field (0.7 % by volume; Caley 1946). The corrosive effects of the hydrogen sulphide on steel well casings, production piping, and tubing is known in the Ontario petroleum industry. For example, Figure 6 shows the corrosion of on a section of ten-year-old 7.3 cm diameter tubing from the Morpeth gas field.

The impact of sulphur water on groundwater resources was discussed above and identified by landowner complaints in 1947 (Harkness 1949). Inspectors identified the problem as water wells and gas wells that were drilled into the sulphur water zone that created a pathway for the sulphur water to move into overlying aquifers. Artesian flow of sulphur water from oil and gas wells occurs in topographic lows near the Lake Erie shoreline, such as Big Otter Creek (Elgin County) and Big Creek (Norfolk County), where it constitutes a drilling hazard (Carter et al. 2021b). Static water level maps for the Lucas-Dundee Aquifer from a 3-D hydrostratigraphic model, which is readily accessible using free viewer software (Carter et al. 2022), can be used to predict where artesian flow of sulphur water may occur in Ontario.

IMPLICATIONS FOR WELL ABANDONMENT

A review of the history of oil and gas exploration and development in Ontario identified five factors to consider when abandoning wells.

Figure 6. Production tubing (7.3 cm diameter) from the Morpeth gas field showing corrosion due to hydrogen sulphide.

1. Well Location. The first challenge to properly abandon an orphaned or legacy well is to locate it. There were an estimated 50,000 wells drilled by 1970 (Hutt 1970) but there are only 27,000 wells in the database (Clark et al. 2020), suggesting there are numerous wells that are not accounted for. Few well records were kept before the implementation of the Natural Gas Act R.S.O. 1918, and many drilled wells were not reported or were lost (Caley 1946). There were also periods when record keeping was poor or wells were lost, such as during the Great Depression (Harkness 1929). Much of the skilled drilling and oilfield experience was lost during the Second World War, lowering the accuracy of well locations and quality of well plugging operations (Harkness 1947). The accuracy of reported well locations improved under the Energy Act in 1964. Though not discussed in the text above, changes to the landscape have also made it more challenging to locate wells. Wells drilled near the shoreline of Lake Erie or at the edge of a ravine may no longer be evident or easily accessible due to erosion changing the landscape. Land development has also encroached on areas of oil and gas development, impacting the ability to locate and access orphaned or legacy wells.
2. Well Construction. Drilling techniques and the equipment available to drillers changed remarkably from 1858 to the modern era, which had significant implications for well construction. Early casings were made of wood or steel in a range of diameters. Some wells were cased without cement, allowing for the casing to be removed once drilling was completed. The majority of wells in Ontario were drilled using a cable tool method. The standardization of equipment in 1922 resulted in cost reductions and efficiencies for operating drill rigs. This also produced wells with predictable diameters, which is important for plugging operations. Methods for plugging legacy wells must be adaptable for a range of well sizes and for cased or uncased wells.
3. Well Condition. Wells abandoned more than a century ago have corroded cement and casing that may make it challenging to access the rest of the well beneath. Shooting a well was designed to fracture the rock but may have also damaged the casing and cement. Acid treatments were also designed to increase the permeability of the rock surrounding the well but may have also degraded casing and cement. Shot and acid-treated wells may also be irregularly shaped with pockets of exploded or acidized rock, and plugging operations must be able to adapt to a range of well diameters within the same well.
4. Legacy Wells. Previous well plugging efforts may have pulled or partially pulled the casing, resulting in a poor well condition that will need to be addressed prior to plugging. Wells abandoned before 1964 were plugged with sediment, wood, rubble, clay, and some cement, and have a higher probability of leaking because of the deterioration of these poor plugging materials. It was not until 1964 that cement was used as the primary material for plugging wells, followed by long cement plugs in 1968. Even with modern techniques and equipment, poor cement operations make it possible for any well plug, new or old, to fail and leak. Well plugging operations should account for wood, steel, clay, drilling mud, wax, and other related hydrocarbons in the well that could inhibit plugging operations, in addition to other debris in the well that may impede access to the well. In addition, the steel surface casing may have been recovered in plugged wells, making it impossible to use magnetic methods to help locate the well.
5. Hydrogen sulphide. Hydrogen sulphide in oil, natural gas, and groundwater is known to corrode equipment, casings, and cement, impacting well conditions, and is a consideration for plugging a well. Hydrogen sulphide dissolved in groundwater continues to leak from legacy wells in Ontario and must be considered when planning abandonment operations. In particular, the potential impact to casing and cement corrosion, and the risk to workers, should be addressed before plugging operations begin. Water wells and oil and gas wells drilled into aquifers that contain sulphur water may also be a conduit for natural gas and hydrogen sulphide to move into overlying aquifers. Geological formations known to contain sulphur water are documented by Carter et al. (2021b) and the geographic and stratigraphic distribution is modelled and mapped in a 3D hydrostratigraphic model.

Further work is required to locate unreported or lost wells and to develop new techniques to find these wells. Current plugging operations rely on cement to plug the wells, but cement shrinkage, channeling, and fracturing create pathways through cement, impacting the long-term performance of cement plugs (Dusseault et al. 2000). New plugging techniques are required to permanently plug wells. Permanently plugging these wells will limit hydrocarbon and brine leakage from these wells, improving public safety and reducing greenhouse gas emissions. It should be noted that plugging standards for water wells in Ontario, O.Reg.903 Ontario Water Resources Act R.R.O 1990 permit the use of clay (bentonite) for plugging (Ontario Government 2023).

The detailed reporting in the Department of Mines annual reports was essential to understanding activities, successes, and failures in the Ontario oil and gas industry and provided context for understanding abandonment activities from 1891 to 1953. The annual reports from the Fuel Board and subsequent regulatory agencies did not have the same detail, limiting our understanding of activities from 1954 until now. It is important, particularly for well drilling and well plugging, to have detailed notes so the methods and results can be reviewed to improve future drilling and plugging performance.

ACKNOWLEDGEMENTS

This research was funded by the Program for Energy Research and Development from Natural Resources Canada, Government of Canada. The authors thank Terry Carter, Cath Ryan, and an anonymous reviewer for their thorough review and recommendations that greatly improved the manuscript. The authors also thank the Oil, Gas and Salt Resources Library for their GIS expertise creating the maps. Finally, thank you to the journal editors Andrew Kerr and Cindy Murphy for their input and Janice Allen for thorough copy editing.

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Received August 2023
Accepted as revised November 2023