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Investigating borehole-density, sonic, and neutron logs for mapping regional porosity variation in the Silurian Lockport Group and Salina Group A-1 Carbonate Unit, Ontario

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Contents

Abstract

The Oil, Gas and Salt Resources Library (OGSRL) is a repository for data from wells licenced under the Oil, Gas and Salt Resources Act for Ontario. It has approximately 50,000 porosity and permeability drill core analyses on bedrock cores. It also has in analogue format, geophysical logs (e.g., gamma ray, gamma-gamma density, neutron, sonic) from approximately 20,000 wells. A significant challenge for geotechnical and hydrogeological studies of the region is the accessibility of digital data on porosity and permeability. Recent work completed on approximately 12,000 core analyses for the Silurian Lockport Group and Salina Group A-1 Carbonate Unit are geographically concentrated within productive oil and gas pools. An opportunity therefore exists to expand the bedrock porosity characterization for southern Ontario by using geophysical logs collected in open-hole bedrock wells that are more geographically dispersed. As part of this study, hard copy files of analog geophysical logs are converted to digital data (LAS format), followed by quality assessment and quality control (QAQC) to obtain meaningful results. From the digitized geophysical data, density, neutron, and sonic logs are selected to mathematically derive porosity values that are then compared with the corresponding measured core porosity values for the same depth interval to determine the reliability of the respective log types.

In this study, a strong positive correlation (R^2=0.589) is observed between porosity computed from a density log (density log porosity) and the corresponding core porosity. Conversely, sonic log porosity and neutron porosity show weak (R^2 = 0.1738) and very weak (R^2 = 0.0574) positive correlation with the corresponding core porosity data. This finding can be attributed to different factors (e.g., the condition of the borehole walls and fluids, the type and limitations of the technology at different points in time, knowledge of formation variability for calculations), and as such requires more investigation. The density log measures the bulk density of the formation (solid and fluid phases), and as such the derived porosity values indicate total porosity i.e., interparticle (primary) pore spaces, and vugs and fractures (secondary) pore spaces. The sonic log measures the interval transit time of a compressional soundwave travelling through the formation. High quality first arrival waveforms usually correspond to a route in the borehole wall free of fractures and vugs, which ultimately result in the derived porosity reflecting only primary porosity. As molds, vugs and fractures contribute significantly to the total porosity of the Lockport Group and Salina A-1 Carbonate strata, sonic porosity may not reflect true bulk formation porosity. The neutron porosity log measures the hydrogen index in a formation as a proxy for porosity, however, the current limitations of neutron logging tool fail to account for formation-related complexities including: the gas effect, the chloride effect and the shale effect that can lead to over- or under-estimation of formation porosity. As a result, the density log appears to be the most reliable geophysical log in the OGSRL archives for total porosity estimation in the Lockport Group and Salina A-1 Carbonate Unit. Nonetheless, sonic porosity can be combined with density porosity to determine secondary porosity, whereas a combination of density and neutron porosity logs can be used to identify gas-bearing zones.

1 Introduction

The Oil, Gas and Salt Resources Library (OGSRL) is a repository for data from wells licenced under the Oil, Gas and Salt Resources Act for Ontario. It maintains an extensive collection of (approximately 50,000) porosity and permeability drill core analyses of the intermediate to deep Paleozoic bedrock of southern Ontario. Insights into porosity and permeability variations of Paleozoic bedrock strata is of practical interest for a range of applications including petroleum exploration, production and storage, waste disposal, mapping of regional aquifers and aquitards, and alternative energy uses.

Sun et al. (2023) conducted the first regional study of porosity and permeability variations of the Silurian Lockport Group and Salina Group A-1 Carbonate Unit, using approximately 20,000 core analyses. Data for this study is geographically clustered within productive oil and gas pools in carbonate buildups (pinnacles and platform reef mounds) and consequently is not regionally or geologically representative. An opportunity therefore exists to expand the porosity characterization of Paleozoic bedrock strata of southern Ontario by using geophysical logs (e.g., gamma ray, gamma-gamma density, neutron, sonic, photoelectric effect) from boreholes that are more geographically dispersed outside of reservoirs and which are more representative of non-reservoir lithofacies. Presently the majority of the available geophysical logs in southern Ontario exist in analogue format and their conversion to digital data (LAS format) is in progress. In the interim, by utilizing currently available digitised geophysical data, this study presents a feasibility analysis of using geophysical logs, particularly density, neutron and sonic logs, to map regional porosity variability in the carbonates of the Lockport Group and A-1 Carbonate Unit.

1.1 Geological Background

The study area straddles the Michigan and Appalachian Paleozoic sedimentary basins (Figure 1). The northwestern part of the study area consists of southeastern and northcentral sections of the Michigan (intracratonic) Structural Basin, whereas the southeastern part of the study area includes the distal northwestern margin of the Alleghany sub-basin of the larger Appalachian Foreland Basin (Sanford et al. 1985; Armstrong and Carter 2010). The two basins are separated by a broad northeast to southwest trending ridge known as the Algonquin Arch (Figure 1) (Quinlan and Beaumont 1984; Ettensohn 1994, 2008).

During the deposition of the early Silurian Lockport Group, the study area was largely covered by shallow subtropical epicontinental seas (Witzke 1990; Cocks and Torsvik 2011). Both Michigan and Appalachian basins received relatively little siliciclastic sediment during this period. This resulted in the accumulation of thick carbonate dominated units and growth of small microbial mounds and larger-scale (decameter–thick) composite microbial-skeletal mounds, as well as more skeletal-rich crinoidal shoals, and vast and relatively muddy lagoonal environments in southern Ontario on the western margin of Appalachian Basin (Brunton et al. 2012; Brunton and Brintnell 2020).

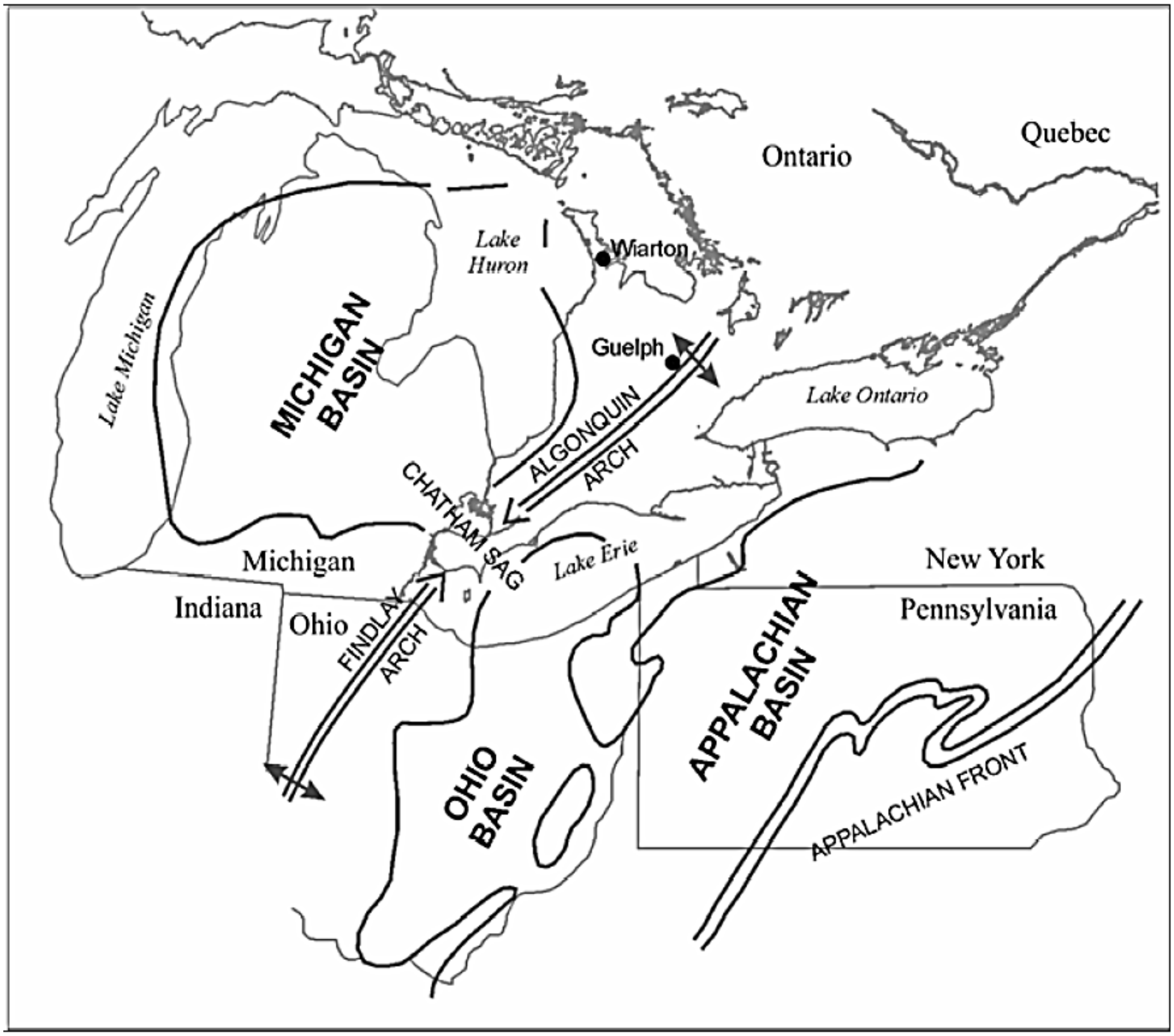


Figure 1. Silurian paleogeography relative to present-day erosional boundaries of Appalachian Foreland Basin versus Michigan Intracratonic Basin (after Brunton et al. 2012).

The Lockport Group comprises a series of shallowing-upward dolostone successions. From base to top, these successions are represented by the Gasport, Goat Island, Eramosa, and Guelph formations (Brunton 2008, 2009; Brunton et al. 2012; Brunton and Brintnell 2020). The strata of the Lockport Group disconformably overlie one of four geological formations, which include the Lions Head (a stratigraphic equivalent of the Rochester), DeCew, Rochester, and Irondequoit formations. (Figure 2) (Carter et al. 2019). The Lockport Group is disconformably overlain by the Salina Group which is made up of a succession of microbial carbonates, mixed evaporites and shales. In the subsurface of Essex, Kent, Lambton, Bruce, Oxford and Huron counties, microlaminated limestone or dolostone of A-0 Carbonate Unit overlies the highly karstic Guelph Formation, whereas in other parts of the subsurface of Ontario, the microlaminated or stromatolitic dolostones of the A-1 Carbonate Unit unconformably overlie the Guelph Formation.

The Lockport Group carbonates and the A-1 Carbonate Unit are an important source of hydrocarbons in southern Ontario and Michigan. Oil and natural gas are trapped in reefal carbonate buildups (i.e., pinnacles and platform reef mounds) with up to 128 metres of structural relief above the regional Lockport Group surface, with distinct lithofacies and enhanced porosity compared to the regional Lockport Group and A-1 Carbonate Unit (Carter et al. 2016). Most of the available core analyses are from wells drilled in these reservoirs.

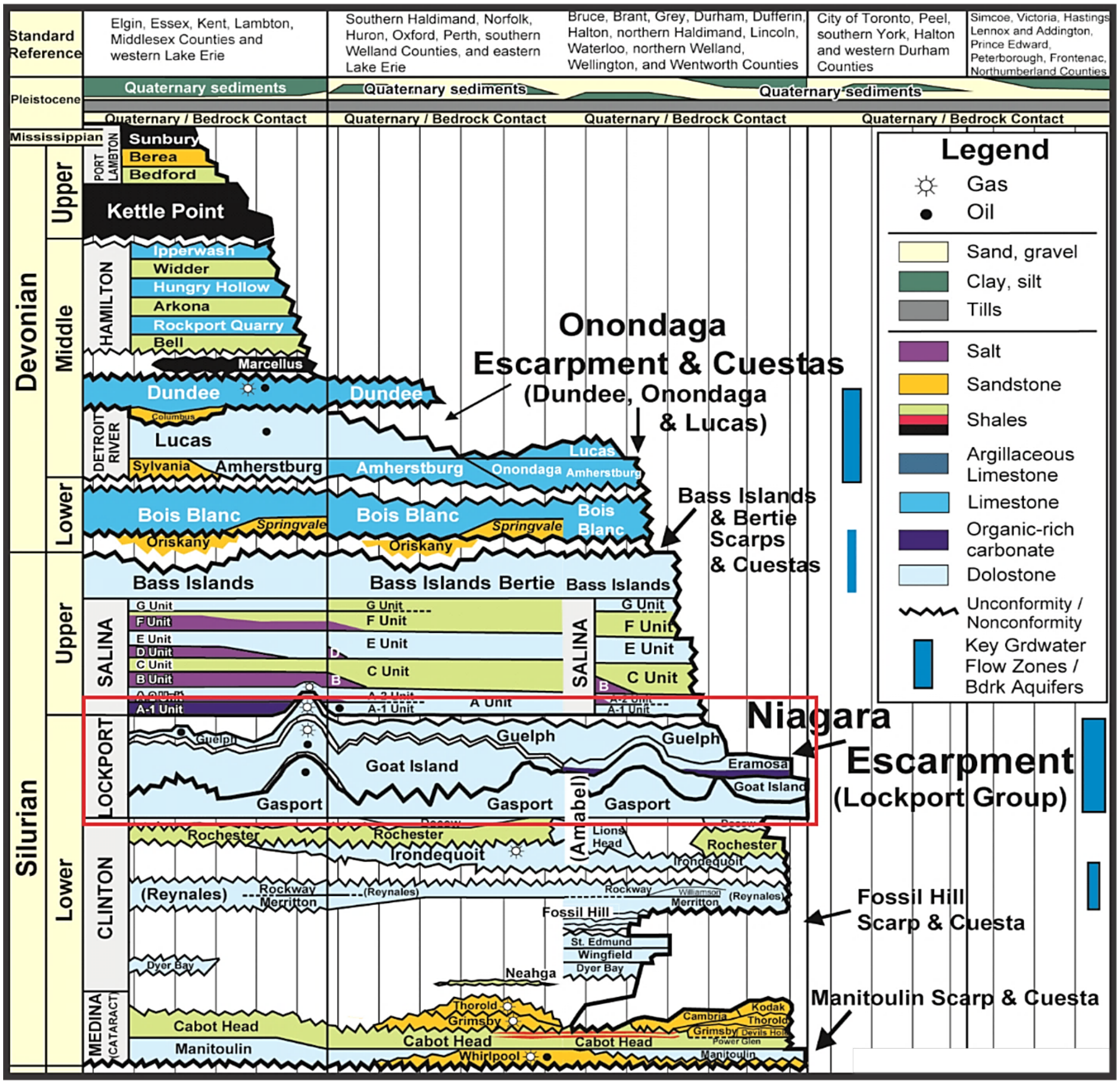


Figure 2. Stratigraphic framework of Silurian and Devonian strata in south-central and southwestern Ontario. Red rectangle indicates the stratigraphic interval of interest (after Carter et al. 2019).

2 Dataset and Methodology

2.1 Dataset

For this study, two sets of data are used — 67 LAS files converted from hardcopy analogue geophysical logs of 33 petroleum wells, of which 27 had core data (see Figure 3 for well locations, and Table 1 for details). Importantly, in this study, several challenges associated with the dataset are recognized which include:

a) unavailability of one or more of the four key geophysical logs for the select individual wells;
b) caliper logs were not used to assess the borehole wall conditions due to lack of availability;
c) several neutron logs were only available in counts per second (CPS) not neutron porosity (NPHI) Future work could develop a relationship based on available data;
d) limited stratigraphic extent of the core data (see Table 1).
e) Information on instrument types is available from the OGSRL.
f) Information on whether a well was open wall or cased is available from the OGSRL.

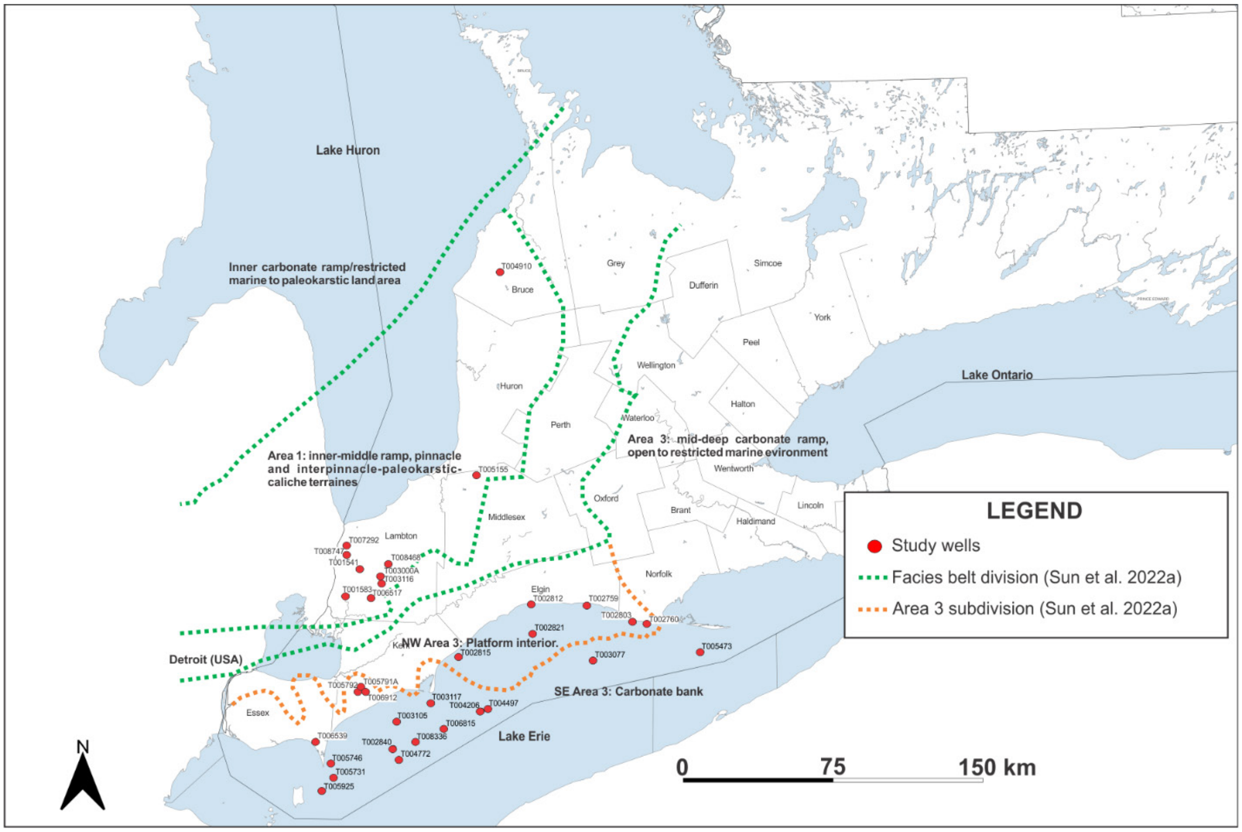


Figure 3. Map of southern Ontario showing the locations of petroleum industry wells (red circles) used in this study, and inferred paleogeographic boundaries (dotted lines) of the Lockport Group (see Sun et al. (2023) for details). Area 1 covers the inner ramp; Area 2 the inner-middle ramp; and Area 3 the middle-outer ramp of the Lockport Group.

Table 1. Summary of the petroleum well data used in this study. Depth in LAS file is recorded in metres (m) or feet (ft). Gamma Ray (GR) is measured in American Petroleum Institute (API) unit, or counts per second (CPS). Neutron (N) is measured in counts per second (CPS), or in neutron porosity hydrogen index (NPHI %). Bulk density (BD) is recorded in grams per cubic centimeter (g/cc). Sonic (S) travel time is measured in microseconds per meter (µsec/m), or microseconds per foot (µsec/ft). "x" indicates unavailable data. Data collection were referenced to API standard by the data collector/reporter.

Licence	Well Location	Log Type (Unit)	Top Log Interval (m)	Btm. Log Interval (m)	Depth (LAS)	Cored Intervals	Year of Logging	Borehole Fluid Type	Fluid Level (m)
T001541	Area 1	GR (API & CPS), N (CPS)	0.0	722.4	m	A 1 Carbonate Unit	1964	Brine	Full
T001583	Area 1	GR (API), N (CPS)	0.0	690.1	m	A 1 Carbonate Unit	1965	Brine	33.5
T003000A	Area 1	GR (API)	0.0	666.9	m	A 1 Carbonate Unit, Guelph Fm, Goat Island Fm, Gasport Fm, Rochester Fm	1970	Mud	Full
T003000A	Area 1	S (µs/ft)	341.7	666.0	m	A 1 Carbonate Unit, Guelph Fm, Goat Island Fm, Gasport Fm, Rochester Fm	1970	Mud	x
T003116	Area 1	BD (g/cc)	487.7	644.3	m	A 1 Carbonate Unit, Guelph Fm, Goat Island Fm	1970	Mud	Full
T003116	Area 1	GR (API), N (CPS & NPHI%)	0.0	644.3	m	A 1 Carbonate Unit, Guelph Fm, Goat Island Fm	1970	Mud	Full
T006517	Area 1	GR (API), N (NPHI%), BD(g/cc)	22.0	536.1	m	A 1 Carbonate Unit, Guelph Fm, Goat Island Fm, Gasport Fm	1984	Salt Brine	x
T007292	Area 1	GR (API), N (NPHI%), BD (g/cc)	20.0	772.7	m	A 1 Carbonate Unit, Guelph Fm, Goat Island Fm	1988	Air/ Water	735.0
T008468	Area 1	GR (API) - Sonic (µs/m)	521.0	681.0	m	A 1 Carbonate Unit, Guelph Fm, Gasport Fm	1997	Brine	x
T008747	Area 1 (Inter-Pinnacle)	GR (API), N (CPS)	559.0	783.3	m	A 0 Carbonate Unit, Guelph Fm, Goat Island Fm	1959	Mud	Full
T004910	Area 1 (Pinnacle)	GR (API) , N (CPS)	157.0	907.0	m	Guelph Fm	1979	Macogel	x
T004910	Area 1 (Pinnacle)	S (µs/m)	157.0	908.0	m	Guelph Fm	1979	Mud-Gel	x
T005155	Area 1 (Pinnacle)	GR (API), N (NPHI%)	261.0	570.0	m	Guelph Fm	1979	KCL-Gel	x
T005155	Area 1 (Pinnacle)	S (µs/m)	262.0	568.0	m	Guelph Fm	1979	KCL-Gel	x
T002759	NW Area 3	GR (API), N (CPS)	0.0	462.1	ft	Guelph Fm, Goat Island Fm, Gasport Fm,	1969	Mud	Full

Licence	Well Location	Log Type (Unit)	Top Log Interval (m)	Btm. Log Interval (m)	Depth (LAS)	Cored Intervals	Year of Logging	Borehole Fluid Type	Fluid Level (m)
						DeCew Fm, Rochester Fm.			
T002760	NW Area 3	GR (API), N (CPS)	0.0	474.0	ft	Guelph Fm, Goat Island Fm, Gasport Fm, Rochester Fm	1969	Water	Full
T002803	NW Area 3	GR (API), N (CPS)	0.0	473.7	ft	Guelph Fm, Goat Island Fm, Gasport Fm	1969	Water (Salt)	Full
T002812	NW Area 3	GR (API), N (CPS)	0.0	495.3	ft	Guelph Fm, Goat Island Fm, DeCew Fm	1969	Water (Salt)	Full
T002815	NW Area 3	BD (g/cc)	0.0	686.7	ft	Guelph Fm	1969	Mud	Full
T002815	NW Area 3	GR (API), N (CPS)	0.0	687.3	ft	Guelph Fm	1969	Mud	Full
T002821	NW Area 3	BD (g/cc)	411.5	555.7	ft	A 1 Carbonate Unit, Guelph Fm	1969	Mud	Full
T002821	NW Area 3	GR (API), N (CPS)	0.0	555.7	ft	A 1 Carbonate Unit, Guelph Fm	1969	Mud	Full
T002840	SE Area 3	BD (g/cc)	286.5	591.6	m	Guelph Fm	1969	Mud	Full
T002840	SE Area 3	GR (API), N (CPS)	0.0	591.6	m	Guelph Fm	1969	Mud	Full
T003077	SE Area 3	BD (g/cc)	381.0	565.1	ft	A 1 Carbonate Fm, Guelph Fm	1970	Mud	Full
T003077	SE Area 3	GR (API), N (CPS)	0.0	565.1	ft	A 1 Carbonate Fm, Guelph Fm	1970	Mud	Full
T003105	SE Area 3	BD (g/cc)	76.2	568.5	m	Guelph Fm	1970	Water	8.8
T003105	SE Area 3	GR (API), N (CPS)	0.0	568.5	m	Guelph Fm	1970	Water	8.8
T003117	SE Area 3	BD (g/cc)	91.4	624.5	m	A 1 Carbonate Unit, Guelph Fm	1970	Mud	Full
T003117	SE Area 3	GR (API), N (CPS)	0.0	624.5	m	A 1 Carbonate Unit, Guelph Fm	1970	Mud	Full
T004206	SE Area 3	GR (API), N (NPHI%), BD (g/cc)	0.0	812.3	ft	A 1 Carbonate Unit, Guelph Fm	1976	Polybrine	x
T004497	SE Area 3	GR (API), N (NPHI%), BD (g/cc)	27.4	691.6	m	x	1977	Polybrine	x
T004497	SE Area 3	GR (API), N (NPHI%), BD (g/cc)	705.9	1435.6	m	x	1977	Gel Cem	x
T004772	SE Area 3	GR (API), N (NPHI%), BD (g/cc)	29.3	1328.9	m	x	1978	Gel Chem/ Polybrine	x
T004772	SE Area 3	S (µs/ft)	286.5	1328.9	m	x	1978	Gel Chem/ Polybrine	x
T005473	SE Area 3	GR (API), N (NPHI%), BD (g/cc)	50.0	1426.0	m	x	1980	Gel Chem	x
T005473	SE Area 3	S (µs/ft)	165.0	1426.0	m	x	1980	Gel Chem	x

Licence	Well Location	Log Type (Unit)	Top Log Interval (m)	Btm. Log Interval (m)	Depth (LAS)	Cored Intervals	Year of Logging	Borehole Fluid Type	Fluid Level (m)
T005731	SE Area 3	GR (API), N (NPHI%)	19.0	484.7	m	A 1 Carbonate Unit, Guelph Fm, Goat Island Fm	1981	Polybrine	x
T005731	SE Area 3	S (µs/m)	27.0	484.5	m	A 1 Carbonate Unit, Guelph Fm, Goat Island Fm	1981	Polybrine/ FreshWater	x
T005746	SE Area 3	GR (API), N (NPHI%)	48.0	200.1	m	A 1 Carbonate Unit, Guelph Fm	1981	Gel Chem	x
T005746	SE Area 3	S (µs/m)	14.5	197.8	m	A 1 Carbonate Unit, Guelph Fm	1981	Gel Chem	x
T005746	SE Area 3	S (µs/m)	197.0	490.4	m	A 1 Carbonate Unit, Guelph Fm	1981	Gel Chem	x
T005791A	SE Area 3	GR (API), N (CPS & NPHI %)	10.0	461.0	m	A 1 Carbonate Unit, Guelph Fm	1982	Fresh Water	x
T005792	SE Area 3	GR (API), N (NPHI %)	134.0	542.0	m	A 1 Carbonate Unit, Guelph Fm, Goat Island Fm	1982	Gel Water	x
T005925	SE Area 3	GR (API) - S (µs/m)	25.2	455.6	m	A 1 Carbonate Unit, Guelph Fm	1982	Polybrine/ Gel Chem/ Water	x
T006539	SE Area 3	GR (API), N (NPHI%), BD (g/cc)	59.0	1060.0	m	x	1984	Brine	x
T006539	SE Area 3	S (µs/ft)	59.0	1060.0	m	x	1984	Brine	x
T006815	SE Area 3	GR (API), N (NPHI%), BD (g/cc)	315.0	1423.7	m	x	1985	Polybrine	x
T006815	SE Area 3	S (µs/ft)	315.0	1433.1	m	x	1985	Polybrine	x
T006912	SE Area 3	GR (API), N (NPHI%), BD (g/cc)	90.0	1153.0	m	x	1985	Salt brine	x
T006912	SE Area 3	S (µs/ft)	0.0	1153.0	m	x	1985	Salt brine	x
T008336	SE Area 3	GR (API), N (NPHI%)	20.0	636.5	m	A 1 Carbonate Unit, Guelph Fm	1995	Gel Chem	x
T008336	SE Area 3	S (µs/m)	5.0	644.7	m	A 1 Carbonate Unit, Guelph Fm	1995	FreshWater/ Gel Chem	x

2.2 Methodology

Hard copy analogue geophysical logs were initially converted to LAS format using NeuraLog© software at the OGSRL. This was followed by quality assessment of these LAS files to ensure data consistency, which was done using a mechanism built into NeuraLog that provides statistics and highlighting on non-overlapping areas of tracing. Finally, the LAS files were combined with the core analysis data and transferred to a Microsoft Excel spreadsheet for data analysis. The density-derived, sonic-derived, and neutron porosity values were then compared with corresponding measured core porosity values for the same depth intervals. Furthermore, combined analyses of logs, particularly neutron and density porosity logs, and sonic and density porosity logs were carried out to gain insights on the utility of integrating multiple geophysical logs for porosity analysis.

3 Results

3.1 Density Log

The formation density log measures the bulk density (RHOB) of the formation using a gamma source on the tool to generate gamma rays. RHOB is recorded in g/cc and the log can be used to derive total porosity of a formation. A cross plot of the core porosity versus RHOB values shows a strong negative correlation ($R^2 = 0.5857$) (Figure 4A). Density porosity (DPHI) values were derived using the formula: $\phi_D = (\rho_{ma} - \rho_b)/(\rho_{ma} - \rho_{fl})$ (Asquith et al. 2004), where ϕ_D is density derived porosity, ρ_{ma} the matrix density (limestone = 2.71 g/cc, dolomite = 2.876 g/cc, anhydrite = 2.977 g/cc), ρ_b the formation bulk density (from the log), ρ_{fl} the fluid density (1.2 g/cc), show equally strong but positive correlation ($R^2 = 0.589$) with the corresponding core porosity values (Figure 4B).

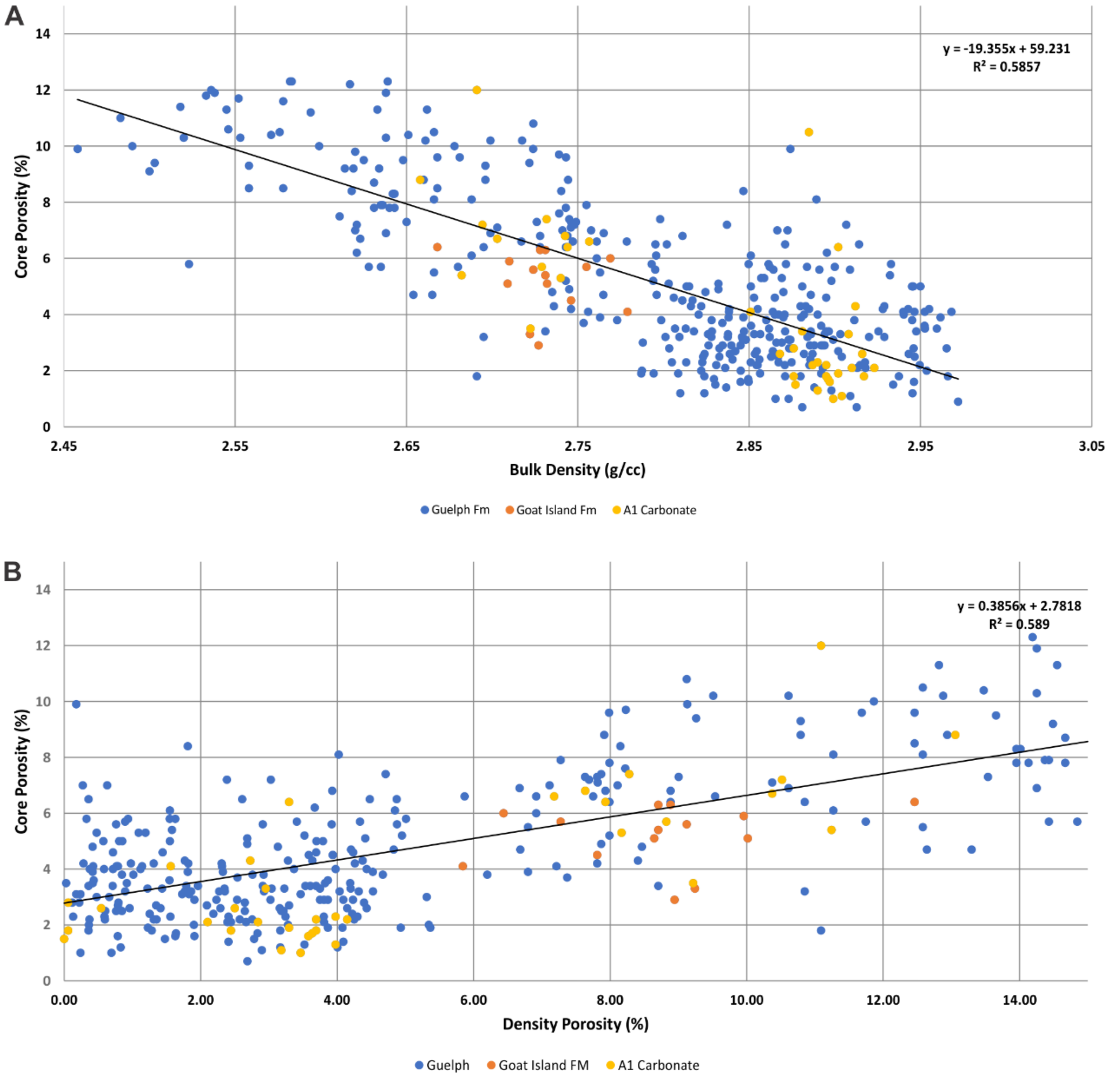
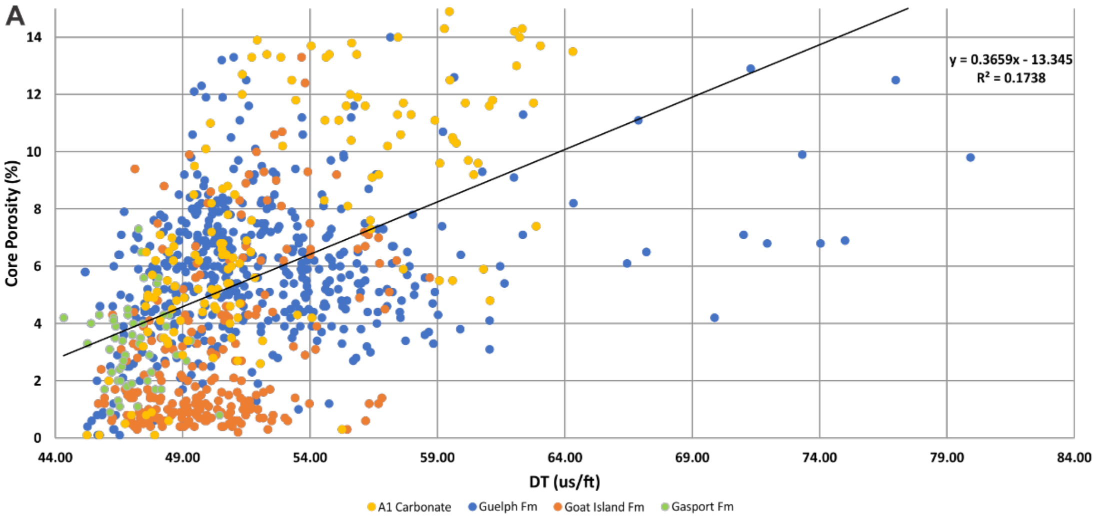


Figure 4. Scatter plots showing (A) bulk density (g/cc) versus corresponding core porosity (%), and (B) density-derived porosity (%) versus corresponding core porosity (%). Number of data points = 385.

3.2 Sonic Log

The acoustic or sonic log measures the interval travel time (DT) of a compressional soundwave travelling along the borehole wall between one or more transmitters to one or more receivers in the probe. The DT logs are provided in µsec/ft or µsec/m, and can be used to derive porosity of a formation. DT values, when compared with the corresponding measured core porosity values show a weak positive correlation ($R^2 = 0.1738$) (Figure 5A). Sonic porosity (SPHI) values were derived using the formula: $\phi_S = (\Delta t_{log} - \Delta t_{ma})/(\Delta t_{fl} - \Delta t_{ma})$ (Asquith et al. 2004), where ϕ_S is sonic-derived porosity, Δt_{ma} the interval transit time in the matrix (limestone = 47.6 µsec/ft, dolomite = 43.5 µsec/ft, anhydrite = 50 µsec/ft) Δt_{log} the interval transit time in the formation (from the log), Δt_{fl} the interval transit time in the fluid in the formation (freshwater mud = 189 µsec/ft, saltwater mud = 185 µsec/ft) also show a weak positive correlation with the corresponding core porosity values ($R^2 = 0.1738$) (Figure 5B).



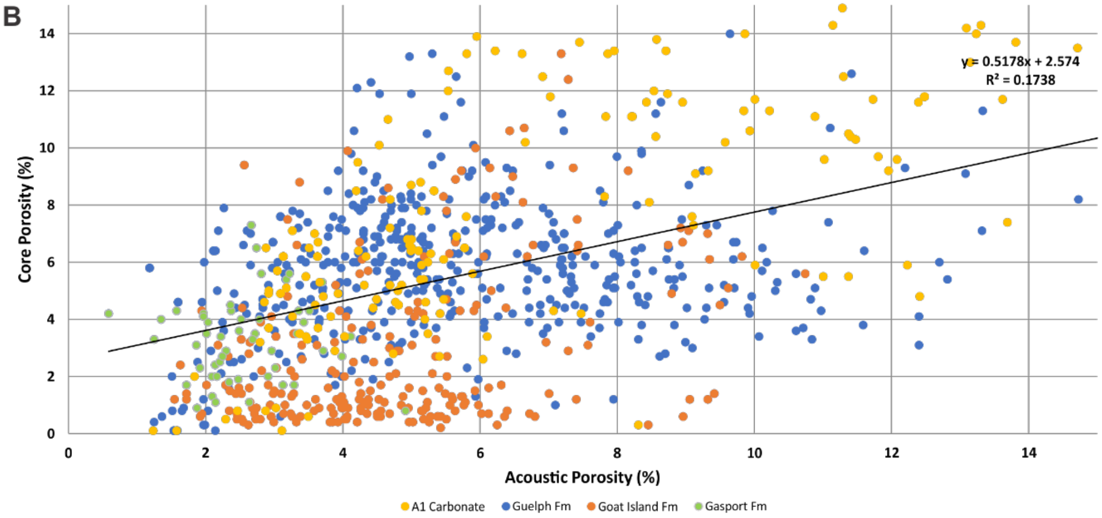


Figure 5. Scatter plots showing (A) interval transit time (µs/ft) versus corresponding core porosity (%), and (B) sonic-derived porosity (%) versus corresponding core porosity (%). Number of data points = 944.

3.3 Neutron Log

The neutron log measures the amount of hydrogen concentration in a formation as a proxy for porosity. It is typically used to measure liquid (water or oil) filled porosity (NPHI) in clean (i.e., shale-free) formations. NPHI values, when compared with the corresponding measured core porosity values show the weakest positive correlation ($R^2 = 0.0574$) (Figure 6).

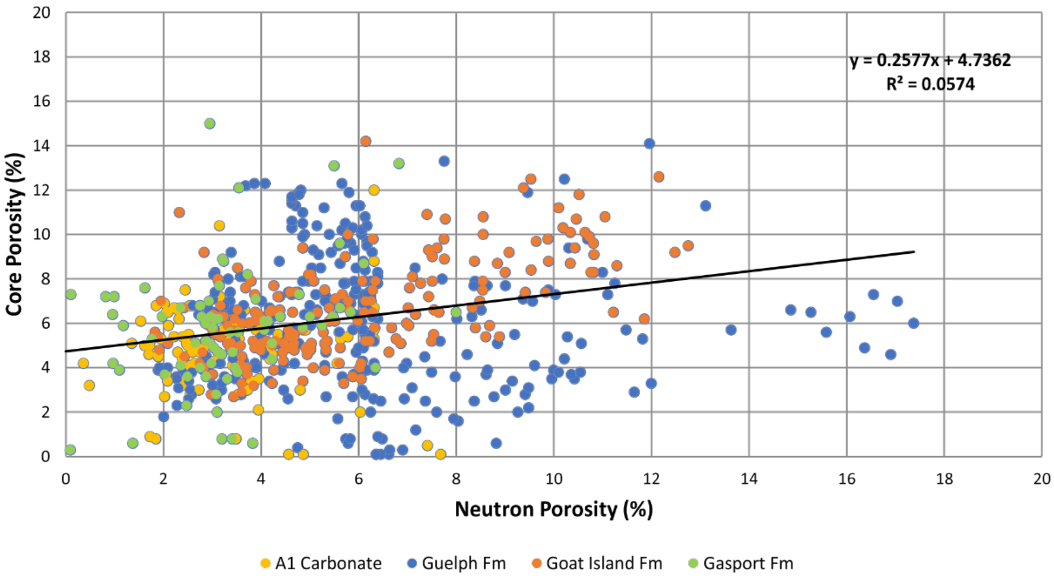


Figure 6. Scatter plots showing (A) neutron porosity (%) versus corresponding core porosity (%). Number of data points = 656.

4 Discussion

When compared with the corresponding core porosity, density-derived porosity values show the strongest positive correlation ($R^2 = 0.589$, whereas sonic-derived porosity and neutron porosity values show a weak ($R^2 = 0.1738$) and very weak ($R^2 = 0.0574$) positive correlation, respectively (Figures 4, 5, 6). This result can be attributed to multiple factors (the condition of the borehole walls and fluids, the type and era of the technology, status of tool calibration, knowledge of formation variability for calculations, quality of the core porosity measurements, different scales of investigation between core and log measurements, depth errors) and requires further investigation to refine the dataset. Density logs use gamma rays to measure the bulk density. Porosity derived from density logs reflects all the pore spaces (primary and secondary pore spaces) in a formation, and thus can provide an approximation of the true porosity in optimal logging conditions (Tiab and Donaldson 2015).

Sonic logs measure the shortest time required for a compressional soundwave (P wave) to travel through 30.48 cm (one foot) of a formation which corresponds to a route in the borehole wall free of fractures and vugs (i.e., secondary pore spaces) (Tiab and Donaldson 2015). Therefore, porosity derived from sonic log only displays primary pore spaces (i.e., intercrystalline and interparticle pore spaces). Secondary pore spaces (molds, vugs and fractures) comprise a significant portion of the total porosity of the dolostones of the Lockport Group and Salina Group A-1 Carbonate (see Sun unpublished), consequently the sonic log is suggested to be a less accurate tool for total porosity estimation. Nonetheless, sonic log can be used in secondary porosity estimation of these dolostones, which is calculated using the formula: $\mathrm{SPI} = \mathrm{DPHI} - \mathrm{SPHI}$, where SPI is the secondary porosity index of a formation, DPHI the density-derived porosity, SPHI the sonic porosity (e.g., Figure 7E).

The neutron tool measures the hydrogen index in a formation as a proxy for porosity with the assumption that all the hydrogen in the formation is in the form of pore-filling liquid (i.e., water or oil). In practice, this measurement is complicated by several factors including: a) when pores are filled with gas instead of oil or water, the neutron porosity reads less than the actual formation porosity due to lower concentration of hydrogen in gas than in oil or water. This lower concentration is not accounted for by the processing software of the neutron log (Asquith et al. 2004); b) aside from hydrogen, when chlorine is present in the formation, it can contribute significantly to neutron absorption. If the drilling mud, mud filtrate or formation fluids contain a significant amount of dissolved chloride ions, which often is the case, the tool will measure a lower flux of neutrons, thereby overestimating the porosity. This is called chloride effect, and is associated with wells drilled or logged in the presence of drilling muds containing dissolved chlorine, or in formations containing particularly salty formation waters (Glover 2000); and c) when clays are present in the formation matrix, the neutron log yields porosity values higher than the actual formation porosity and d) lacking information about the calibration of the tool(s). This porosity increase is called shale effect, and it occurs because additional hydrogen atoms present within the clay's structure and clay bound water gets misinterpreted as part of the porosity by the processing software of the neutron log (Asquith et al. 2004). Accordingly, the disparity between neutron porosity and the actual formation porosity (i.e., core porosity) is suggested to be caused by these formation-related complexities and current limitations of the neutron logging tool.

Although, the density-derived porosity (DPHI) produced the highest correlation with the core porosity values among the logs selected for this study, the results should be considered in the following contexts. For carbonate strata such as the Lockport Group and A-1 Carbonate Unit, in stratigraphic intervals containing either water or liquid hydrocarbons, DPHI reads approximately the correct porosity, as do neutron logs (NPHI). Both DPHI and NPHI track each other with DPHI on the right and NPHI on the left (e.g., Figure 7B). On the contrary, for stratigraphic intervals containing gas, DPHI yields values that are greater than the true porosity, whereas NPHI returns values lower than the true porosity (e.g., Figure 8B), resulting in a crossover effect on the log display. As mentioned above, this log pattern is attributed to presence of gas in the formation with density and hydrogen index lower than oil or water (Asquith et al. 2004; Tiab and Donaldson 2015). Importantly, porosity values in these gas-bearing zones can be determined by combining the two logs using the formula: $\phi_{\mathrm{NDgas}} = \sqrt{((\phi_{\mathrm{N}}^2 + \phi_{\mathrm{D}}^2)/2)}$ (Asquith and Krygowski 2004), where ϕ_{NDgas} is the porosity of the gas-bearing zone, ϕ_{N} the neutron porosity, ϕ_{D} the density porosity (e.g., Figure 8C).

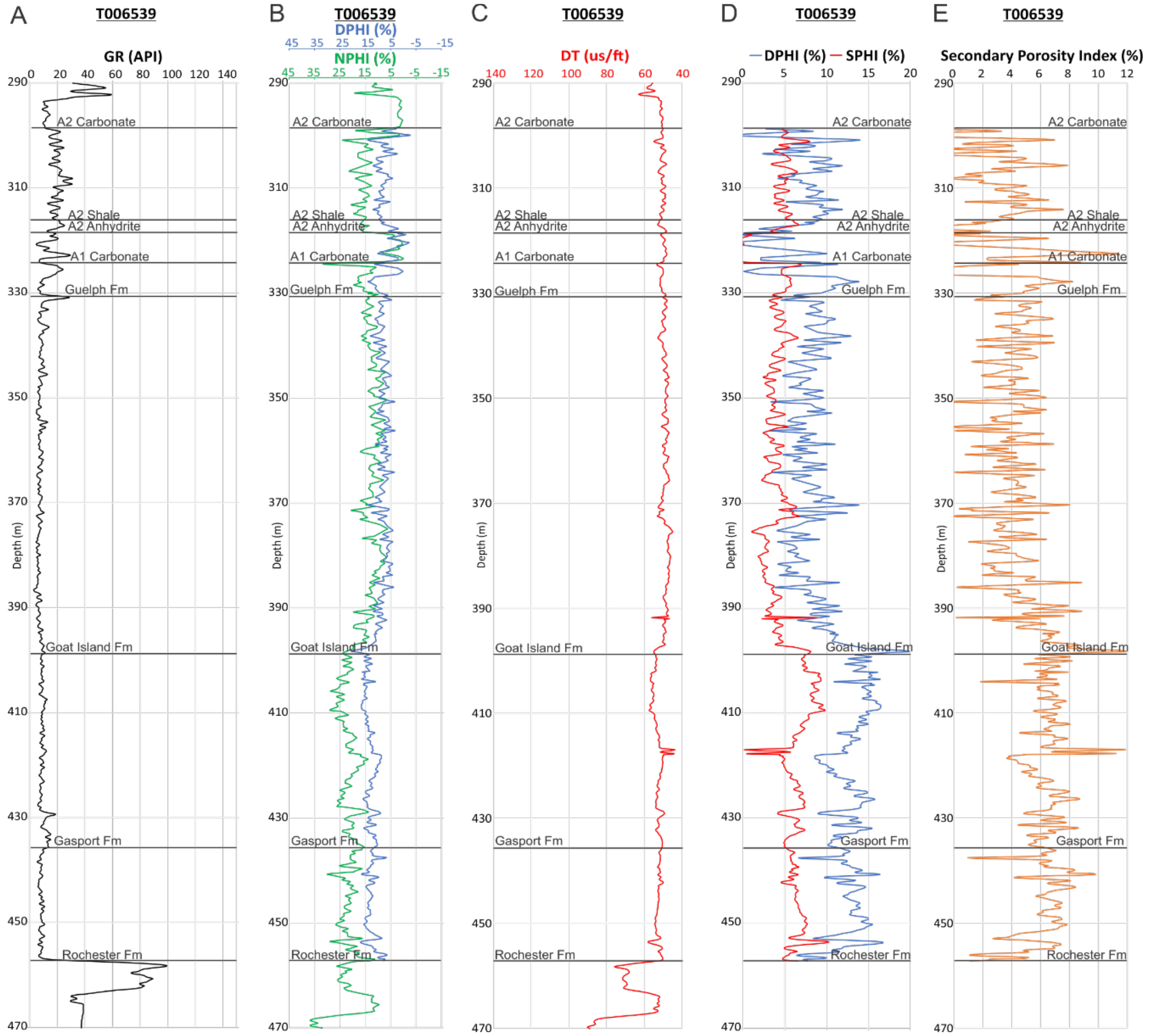


Figure 7. Geophysical logs (left to right) for Well Licence: T006539. A) GR log presented in API unit. B) Combined neutron porosity (NPHI) and density porosity (DPHI) logs displayed in percentage. C) Sonic log shown in µs/ft. D) Combined sonic porosity (SPHI) and density porosity (DPHI) logs presented in percentage. E) Secondary Porosity Index determined by subtracting SPHI from DPHI shown in percentage. In (B), note that DPHI and NPHI track each other at constant separation with DPHI on the right and NPHI on the left indicating liquid-filled porosity. In (D), note the difference between sonic-derived porosity (SPHI) and density-derived porosity (DPHI). DPHI values are higher and as such lies on the right side of the plot. Caliper log and core data were not available for this hole.

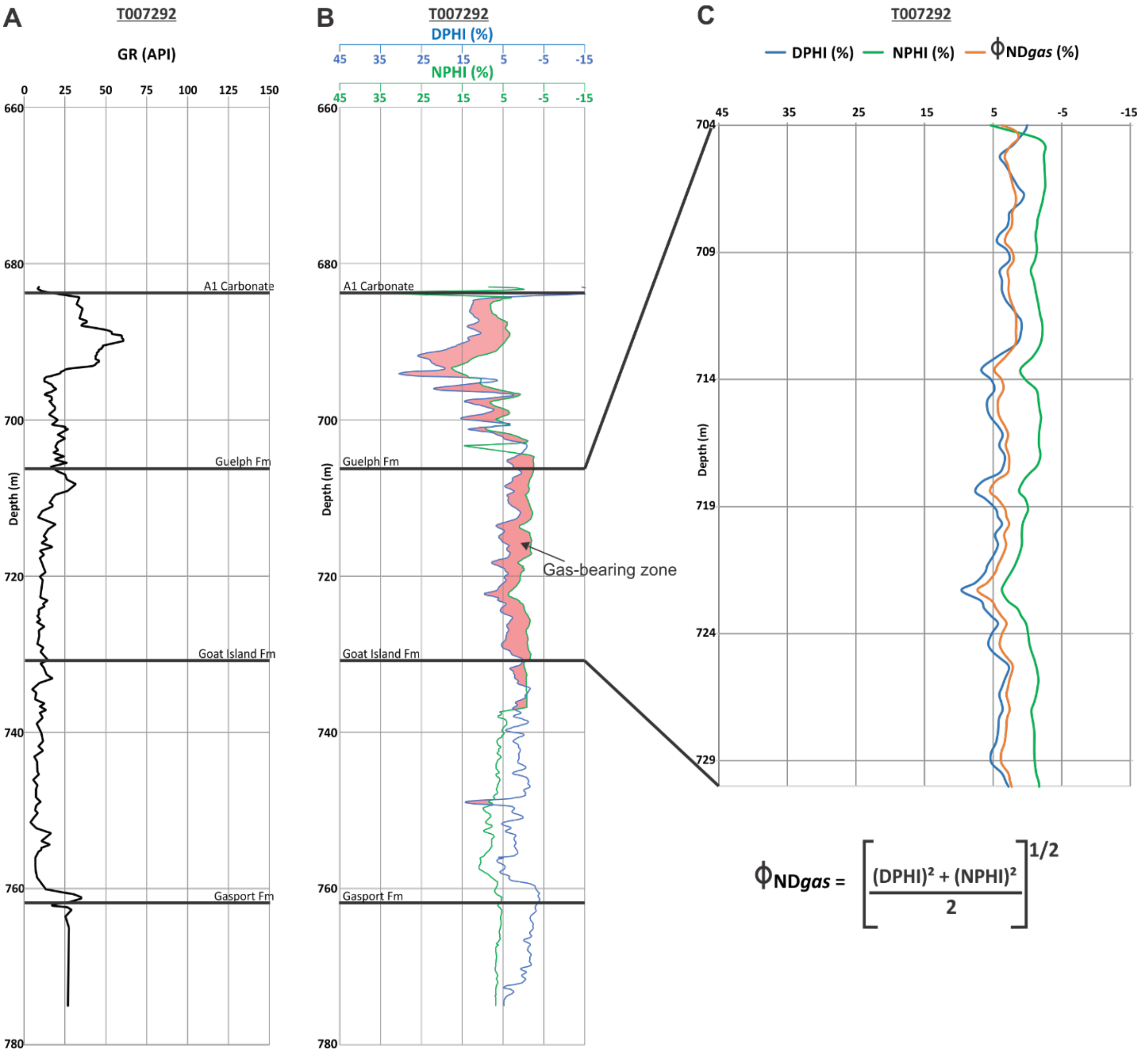


Figure 8. Geophysical logs (left to right) for Well Licence T007292. A) GR log presented in API unit. B) Combined neutron porosity (NPHI) and density porosity (DPHI) logs displayed in percentage. C) Combined logs comprising DPHI, NPHI and Φ_{NDgas} (i.e., porosity corrected for the gas-bearing zone) shown in percentage. In (B), note the gas-bearing stratigraphic intervals highlighted in red yield NPHI values lower than DPHI (i.e., NPHI lies on the right, and DPHI on the left side). In (C), note the Φ_{NDgas} values are close to average of DPHI and NPHI log readings.

5 Conclusions

This study investigates the feasibility of using borehole density, sonic and neutron logs for mapping regional porosity variation in the Silurian Lockport Group and Salina Group A-1 Carbonate Unit. Out of the three geophysical log types investigated, density-derived porosity shows the strongest positive correlation (R^2 =0.589) with the corresponding measured core porosity of the formations. Sonic-derived porosity and neutron porosity show weak (R^2 = 0.1738) and very weak ($R^2 = 0.0574$) positive correlation, respectively, with the corresponding measured core porosity of the formation. Accordingly, borehole density (RHOB) is postulated to be the most reliable geophysical log for total porosity estimation in the Lockport Group and Salina Group A-1 Carbonate Unit strata. Nonetheless, to determine porosity of a formation with highest accuracy, all three logs should be used together because: a) combination of sonic-derived porosity (SPHI) and density-derived porosity (DPHI) can provide a good secondary porosity estimation in carbonate rocks; and b) combination of DPHI and neutron porosity (NPHI) can be used to identify and determine more accurate porosity values for gas-bearing zones.

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