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Volatiles analysis of drill cuttings to evaluate the helium prospectivity of southwestern Manitoba (parts of NTS 62F2, K3)

by M.P.B. Nicolas, C.M. Smith[1] and M.P. Smith[1]

In Brief:

- Volatiles analysis of legacy drill cuttings was done on three oil wells
- High helium values indicate potential economic concentrations in the Red River and Deadwood formations
- Hydrocarbon indicators show hydrocarbon systems in the Dawson Bay and Red River formations

Citation:
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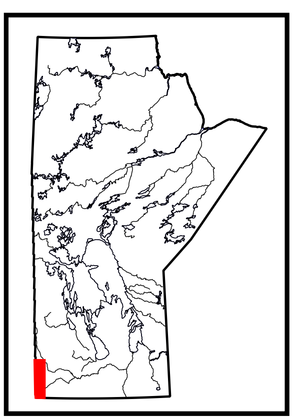

Summary

The helium prospectivity of southwestern Manitoba was evaluated using the Rock Volatiles Stratigraphy (RVS) system. Drill cuttings from three legacy oil wells (L.S. 9, Sec. 6, Twp. 2, Rge. 26, W 1st Mer. [abbreviated 9-6-2-26W1], 13-24-12-27W1 and 16-29-12-29W1) were analyzed for a wide range of volatile compounds, including C1–C10 hydrocarbons, carbon dioxide, water and helium. The deepest portions of each well were sampled, from the Precambrian basement to the Dawson Bay Formation, at intervals defined by the drill cuttings recovered. All three wells show signs of helium accumulation with economic potential. Of particular note is the well at 9-6-2-26W1, it had the highest helium values ever measured by the RVS system to date in any legacy sample for which self-sourcing of the helium—formed by radioactive decay of in situ uranium- and thorium-bearing basement rocks or shale—was not possible. These values are higher than those measured in samples from Saskatchewan's producing helium plays. These high values indicate an active prolific helium system in southwestern Manitoba. Additionally, analysis of the RVS data indicates bypassed deep hydrocarbon system opportunities in Manitoba.

Introduction

A review of helium occurrences in southwestern Manitoba oil and gas wells by Nicolas (2018) indicated that 80% of oil and gas wells tested in Manitoba have helium gas occurrences, including six wells with economic helium concentrations, between 0.30 and 2.00 mol. % helium (Figure GS2023-11-1). This work points to deeper lower Paleozoic formations, particularly the Ordovician Winnipeg and Cambrian Deadwood formations, as the most prospective for helium. Since hydrocarbon accumulations have not been identified in these horizons yet in Manitoba, helium accumulations and production would be classified as green helium because of the low greenhouse gas emissions associated with production. This is in contrast to brown helium, where helium production is a byproduct of oil and gas operations with its associated greenhouse gas emissions.

In Manitoba, Williston Basin strata occur at relatively shallow depths, the maximum depth to the Precambrian basement is 2.7 km in the extreme southwestern corner of the province. This means Manitoba is a low-cost location to explore for hydrocarbons and helium, however, despite this shallow depth, deep exploration in Manitoba has been limited to historical hydrocarbon exploratory holes. Modern oil and gas exploration and production is currently focused in late Devonian, Mississippian and Jurassic strata, leaving a large portion of Manitoba's stratigraphic column, over a large geographic region, underexplored for pore-space resources. By studying and analyzing drill cuttings recovered from deep exploratory archival wells drilled over the last 70 years or more, a new appreciation for once hidden economic treasures may come to light using innovative analytical techniques.

The geochemical analysis of core and drill cuttings is an important tool in understanding the mineralogy, diagenesis, depositional environment and fluid history of a unit. Common analysis methods include traditional core analyses (rock properties and water/oil saturations), X-ray diffraction (XRD), X-ray fluorescence (XRF), isotopic geochemistry and Rock-Eval pyrolysis. Detailed analysis of the geochemical signature of the residual volatile fraction of the fluids trapped within sample pore spaces using the Rock Volatiles Stratigraphy (RVS) system is an innovative new approach that provides valuable information and insights into the fluid history of a stratigraphic unit and its surrounding area. The RVS system directly measures the residual volatile fraction trapped in drill cuttings and core samples, including C1–C10 hydrocarbons, helium, water and other volatile compounds, as well as the mechanical rock strength. These data can then be used to provide proxy data for rock and reservoir properties, such as permeability, wettability, hydrocarbon and helium pay zones and gas and oil migration routes, and to determine the proximity to the oil-water contact. The advantage of this analytical method is

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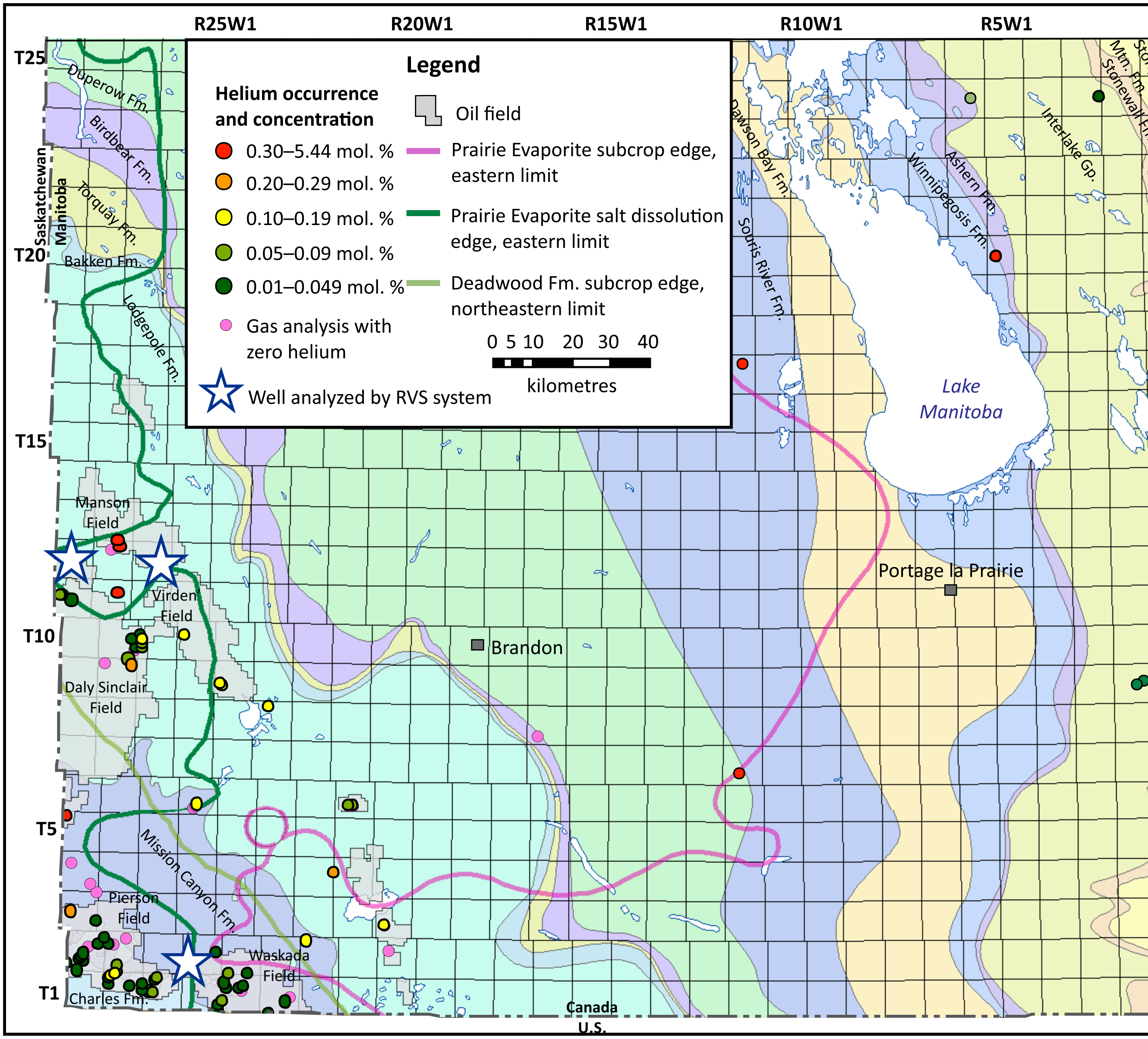

Figure GS2023-11-1: Location map of sampled sites in southwestern Manitoba (modified from Nicolas, 2018). Abbreviation: RVS, Rock Volatiles Stratigraphy.

that it does not require freshly drilled or wellsite-sealed samples for reliable and useful results—this method works equally well on old legacy samples collected more than 60 years ago (Smith and Smith, 2020). Additionally, the RVS system uses a small sample size (0.4 cm^3) making it suitable for the analysis of drill cuttings. Unlike short interval cores, the benefits of using drill cuttings are their regular sampling interval throughout the drilling of a well and the number of wells with drill cuttings. This allows for higher density sampling across multiple formations and vertical depths.

The Manitoba Geological Survey (MGS) in partnership with Advanced Hydrocarbon Stratigraphy, Inc. (AHS) studied the volatile fraction of fluids in drill cuttings from three oil wells (Table GS2023-11-1) drilled in the lower Paleozoic by measuring fluid, gas, hydrocarbon, rock and reservoir properties to evaluate for helium prospectivity in Manitoba, and provide additional insights into local hydrocarbon systems.

Rock Volatiles Stratigraphy

Applications of the RVS system and previous studies

Rock Volatiles Stratigraphy analyses have been conducted on legacy drill cuttings and core from various international locations to evaluate the potential for subsurface pore-space resources, as well as to conduct post-mortem analysis on underperforming wells. Resources evaluated using the RVS system include helium,

Table GS2023-11-1: List of wells sampled.

Unique well identifier (UWI)	Licence number	Easting (Zone 14, NAD83)	Northing (Zone 14, NAD83)	Year drilled	Total depth (m TVD)	Sample depth range (m TVD)	Sample interval	Stratigraphy	Comments
100/09-06-002-26W1/00	2610	358365.58	5440090.64	1979	1986.0	1485–1985	5 m	Dawson Bay Fm. to Precambrian	Salt-gel drilling mud used in deeper section; drilled with mill-tooth drill bit
100/13-24-012-27W1/00	10911	352879.84	5544135.85	2018	1496.0	1005–1496	5 m	Dawson Bay Fm. to Precambrian	Salt-saturated drilling mud used below 1039 m; drilled with PDC drill bit
100/16-29-012-29W1/00	2532	327790.04	5546621.49	1974	1664.2	1362–1664	~3 m (10 ft.)	Interlake Gp. to Precambrian	Salt-gel drilling mud used below 589 m; drilled with mill-tooth drill bit

Abbreviations: PDC, polycrystalline diamond compact; TVD, true vertical depth.

hydrocarbon, hydrogen and geothermal. It can also evaluate the potential of the rock for carbon storage.

Prior work in Saskatchewan included using the RVS system to analyze three cores where helium was confirmed in drillstem tests (DSTs; Smith et al., 2022a, 2023c). This work began in 2022 with the examination of the British American Saskatchewan Landing core from the Wilhelm area and is reported in Smith et al. (2022a). The Wilhelm helium play area was developed in the 1960s starting with the discovery well B.A. Wilhelm 101/03-10-017-14W3/00 (petroleum and gas well licence 62H013, Saskatchewan Ministry of Energy and Resources, Regina). The DST results of 1.8 to 2.0% helium were achieved from the Cambrian Deadwood Formation (Yurkowski, 2016; Smith et al., 2022a) and this well produced 3.036 x 10^6 m^3 (107,250 million standard cubic feet) of helium from 1963 to 1977 as 1.3% of the total produced gas volume. Data from the RVS study showed strong relationships with historical DST, core and wireline data providing confidence that zones with higher relative helium—identified as a median value of 0.7 and mean value of 1.1 ±0.85 nanomoles (nmol) of helium measured in the historical pay zone interval—could be identified in the core, as well as the identification of features relevant to the subsurface helium system (Smith et al., 2022a). Of particular note, using the RVS system, tight zones (low porosity and permeability) were found to contain more helium than high porosity and permeability zones. In addition, mathematical techniques that are weighted more toward determining a baseline value, like using a median or the centre of a Gaussian fit to a data histogram to identify an apparent baseline mode across the section, were found to produce helium values that were more representative than a mean value. An expansion of this study in 2023 included the analysis of two additional cores from Shell Prud'homme 6-36-38-28W2 (Shell Prud'homme; petroleum and gas well licence 67E067 Saskatchewan Ministry of Energy and Resources, Regina; Winnipegosis test) and CPEC Forget 11-16-007-07W2 (CPEC Foget; petroleum and gas well licence 97E213, Saskatchewan Ministry of Energy and Resources, Regina; Red River-Yeoman test). Both sections had reported concentrations of 0.44% helium by DST. Using the RVS system, core samples covering the Shell Prud'homme DST interval had a median of 0.218 and mean of 0.221 ±0.019 nmol of helium, and the similar CPEC Forget DST interval had a median of 0.203 and mean of 0.218 ±0.035 nmol of helium (Smith et al., 2023c). This RVS analysis demonstrated that both the mean and median of the measured nanomoles of helium from the tested core provided similar ratios of helium to the DST values, showing that RVS results can provide meaningful semiquantitative information from core that can be related back to subsurface helium content (Smith et al., 2022a, 2023a, c). The RVS technology has been used to evaluate other helium plays, such as those in the Four Corners region and Oklahoma panhandle in the United States (Smith et al., 2022b, 2023c).

Sample considerations and comparisons

The availability of samples, whether drill cuttings or core, that can be recovered from any given well will vary, as will the volatile data that can be extracted. The benefit of core samples is they allow for representative sampling of small stratigraphic intervals, as demonstrated by Smith et al. (2023a). Therefore core is the superior sample type due to the ability to select features, control sample intervals, better preserve the absolute quantities of volatiles and extract unique water data. However, core is limiting as it is more rarely collected and covers short specific (biased) intervals compared to drill cuttings.

Drill cuttings have the benefit of covering a wider stratigraphic section and of being collected from a higher density of wells. However, they do not afford detailed geological interpretation/description or core analyses, and they are small, have a predetermined sampling interval and may have been washed and dried at the wellsite prior to storage. Some tests have shown that unwashed but dried drill cuttings provide good quality RVS results, likely due to the drilling mud encapsulating the grains. For drill cuttings, the drill bit used and drilling mud composition can also affect the results, and these factors need to be considered during interpretation. For example, polycrystalline diamond compact (PDC) drill bits, commonly used to drill modern wells, shear and grind the rock to a much finer grain size, destroying much of the macro- and microporosity, compared to mill-tooth bits, such as tricone/rock/cable tool diamond-drill bits, typical of older technologies. For RVS analysis, larger drill cuttings are preferred as rock morphology has not been overly compromised and sample handling has been minimal thus the escape of volatiles from pore spaces has been minimized.

The sample type will directly affect the range of compounds that can be analyzed. For example, core samples will allow for the measurement of a wider range of volatile compounds and can allow for unique water data collection, permeability measurements, and more accurate mechanical strength data collection. In comparison, cuttings may not retain volatiles as effectively as core given the higher degree of trauma and disaggregation of the rock samples.

When comparing between core and drill cuttings data, the data can only be used semiquantitatively. Broadly, the data from cuttings and core can only be compared at the microcrystalline level and care should be taken in comparing data from different sample types. However, learning from multiple datasets over the years, AHS has developed standards to carefully compare RVS results between wells and sample types, thus allowing a careful comparison of the data reported here with other RVS study results (Smith et al., 2022a, 2023a, c).

Using the RVS system for helium studies

The work by Smith et al. (2022a) in Saskatchewan prompted this study of drill cuttings to provide insights into the helium prospectivity of the stratigraphy of Manitoba. Smith et al. (2022a) described core samples in relation to existing well data to assist in understanding the RVS results, as they can be applied to helium-prospectivity and systems analysis.

Smith et al. (2022a) found that more than 40 volatile compounds can be measured from core samples, but that less compounds could be reliably analyzed from drill cuttings. Table GS2023-11-2 shows the list of compounds analyzed for this study. Despite the data compromise that comes from drill cuttings, the ability to measure a wider stratigraphic section and to have more well selection options was found to be beneficial for RVS analysis for helium-prospectivity mapping. Using drill cuttings is an effective way to evaluate a large area with limited data, as is found in Manitoba. It should also be noted that the data gathered also provide valuable insight into hydrocarbon- and water-rich zones, CO_2-rich intervals, oil-water contacts, depositional environments and mechanical rock strength.

Methodology

Drill cuttings from three historical petroleum exploration wells in southwestern Manitoba were sampled for testing by the RVS system (Figure GS2023-11-1). The three wells sampled for this study are 1) Corex Coulter Prov. 100/09-06-002-26W1/00 (oil and gas well licence 2610, Manitoba Economic Development, Investment, Trade and Natural Resources, Winnipeg) in L.S. 9, Sec. 6, Twp. 2, Rge. 26, W 1st Mer. (abbreviated 9-6-2-26W1); 2) Surge North Hargrave COM SWD 100/13-24-012-27W1/00 (oil and gas well licence 10911) in 13-24-12-27W1; and 3) ASM-BTO et al Kirkella Prov. 100/16-29-012-29W1/00 (oil and gas well licence 2532) in 16-29-12-29W1. Sampling intervals were restricted to the cuttings vials in storage; the sampling interval was either ~3 m (10 ft.) or 5 m (Table GS2023-11-1).

Well selection was based on several criteria, including availability of Precambrian samples at depths of ≥1500 m, recovered samples of the Deadwood and/or Winnipeg formations, drill cuttings quality and quantity and regularity of the sampling interval. Geographic location was also considered, locations with known or suspected structural disturbances nearby, such as salt collapse or faulting, were selected. The rationale for this was that the areas with more disturbances may provide more opportunities for potential migration of helium and other volatile substances through the section. The wells at 9-6-2-26W1 and 16-29-12-29W1 have had the entire Prairie Evaporite salts section dissolved, whereas the well at 13-24-12-27W1 has the thick Prairie Evaporite section preserved but is in close proximity to known structural disturbances and possible faulting, which formed the southern extent of the Manson oil field.

Table GS2023-11-2: Generalized list of compounds and rock properties analyzed by the Rock Volatiles Stratigraphy system on drill cuttings in this study. Data Repository Item DRI2023014 (Nicolas et al., 2023) provides details on compounds, properties, proxies and calculations.

Compounds	Rock properties
Methane	Mechanical strength
Ethane	Permeability proxy
Propane	Hydrocarbon liquid volume
Butanes	Hydrocarbon gas volume
Pentanes	Total water
Benzene	Equivalent oil production
C6 naphthenes	Equivalent gas production
Hexanes	Gas-oil ratio (GOR)
Toluene	
C7 naphthenes	
Heptanes	
C8 aromatics	
C8 naphthenes	
Octanes	
C9 naphthenes	
Nonanes	
C10 naphthenes	
Decanes	
CO_2	
Helium	
Nitrogen	
Formic acid	
Acetic acid	
SO- (sulphate proxy)	

The samples were sent to the Advance Hydrocarbon Stratigraphy, Inc. (AHS) laboratory in Tulsa, Oklahoma, for analysis by their proprietary cryotrap mass spectrometer (CT-MS) system specially designed to analyze for C1–C10 hydrocarbons, helium, formation water, CO_2, sulphur gases, organic acids and mechanical strength (Table GS2023-11-2). Each sample consisted of 3 g of drill cuttings from each vial, starting with the deepest cuttings vial, then sampling upsection for a total of 100 samples per well. Approximately 0.4 cm^3 of rock sample was crushed with a 1.8 tonne (2 ton) force applied by a piston press over a 6.35 mm (¼ in.) square area, while inside a plugged hollow brass cylinder. The cylinder was interfaced to the CT-MS system through a syringe inserted into a nitrile septum at the top of the brass cylinder; the crushing force was applied radially. After crushing, the volatiles were gently vacuum extracted and analyzed in two aliquots using the same rock sample. The first aliquot was analyzed at 20 mbar pressure (1/50th of an atmosphere pressure), and the second aliquot was analyzed 2 mbar pressure (1/500th of an atmosphere pressure). The benefit of analyzing the same suite of volatiles from the same rock sample, but under increasing vacuum extraction conditions, provides insights into where the volatiles resided in the fabric of the rock and how readily they were released from the rock sample. These measurements can be related to rock properties, such as permeability. Following the vacuum extraction, the volatiles were condensed in a liquid nitrogen cooled cryotrap—after extraction and condensation of a given aliquot was completed the cryotrap was slowly warmed and volatiles sublimated off sequentially providing a separation stage before they were passed to the mass spectrometer. Some volatiles, like helium and methane, do not condense under liquid nitrogen conditions, these are analyzed by effectively capturing headspace samples from the cryotrap, which are passed directly to the mass spectrometer. Under this workflow, helium was only measured for the 20 mbar vacuum extraction. Mechanical strength of the rock sample was measured as a byproduct of the crushing process. This was accomplished by measuring the thickness of the sample following the crushing process and is directly related to the competency of the rock. In the case of cuttings, this has been observed to potentially relate more to grain strength than unconfined compressive strength, due to the disaggregated nature of the cuttings. More details of the methods used and how they can be interpreted are described in Smith and Smith (2020) and Smith et al. (2021).

Rock Volatiles Stratigraphy results and interpretations

The entirety of the RVS data is available in Data Repository Item DRI202314 (Nicolas et al., 2023)[2]. There is a significant amount of interpretation that can be extracted from the RVS data. This report will focus on the data used to evaluate helium prospectivity, but also on select data on other fluids, such as hydrocarbons, water and CO_2, as they provide information about the overall fluid dynamics of the system.

Oil and gas well at 9-6-2-26W1 (licence 2610)

Drill cuttings collected from the well at 9-6-2-26W1 were sampled from 1985 m true vertical depth (TVD), in Precambrian rocks, to 1485 m TVD, in the lower Burr Member of the Dawson Bay Formation. Figure GS2023-11-2 shows the data logs for select analyses, including helium, as they relate to stratigraphy.

When comparing to similar work done in Saskatchewan (Smith et al., 2022a), a helium reading above 0.7 nmol helium on an RVS log indicates a potential economic accumulation of helium, however, correlation and interpretation with other RVS data must be done to narrow down the true potential pay zone. The helium data show three discrete very high helium intervals: 1585–1600 m TVD (lower Ashern Formation to upper Interlake Group), 1645–1675 m TVD (lower Interlake Group to upper Stonewall Formation), 1705–1725 m TVD (Stony Mountain Formation), however, most of the interval from 1645 to 1980 m TVD (lower Interlake Group to Precambrian) has nearly constant ≥0.7 nmol helium readings, with only a few short intervals with lower values. Helium and other gas volumes are expected to be underrepresented in the data due to degassing over time during storage, therefore, these values will serve as a minimum of the expected true amounts in the subsurface. In Figure GS2023-11-2, the ≥0.7 nmol helium concentrations are highlighted in yellow.

The interval of particular interest in this well is in the Red River Formation and uppermost bed of the Winnipeg Formation, where between 1785 and 1902 m TVD the logs have a distinctive blocky response. The gamma-ray log indicates a moderately clean carbonate—likely dolostone—with an increasing silty-sand content through the Hecla beds into the uppermost Winnipeg Formation sandstone, as is typical for this interval. When comparing the deep resistivity and total water logs, the results complement each other since the resistivity is consistently high on average, whereas the total water is on average the lowest in the section. This suggests this interval could contain either hydrocarbon fluids and/or other gases. To get a better reading on what fluids may be dominating the section, other logs provide valuable information. The CO_2 and hydrocarbon liquid and gas indicator logs all show no anomalous readings, and actually have slightly lower readings on average compared to many other parts of the section. In contrast, helium values are on average consistently high—above the 0.7 nmol cutoff—suggesting this may be a helium-prospective zone.

Within the Red River Formation, a spike in total water centred at 1825 m TVD is associated with a moderate increase in

[2] MGS Data Repository Item DRI2023014, containing the data or other information sources used to compile this report, is available online to download free of charge at https://manitoba.ca/iem/info/library/downloads/index.html, or on request from minesinfo@gov.mb.ca, or by contacting the Resource Centre, Manitoba Economic Development, Investment, Trade and Natural Resources, 360-1395 Ellice Avenue, Winnipeg, Manitoba R3G 3P2, Canada.

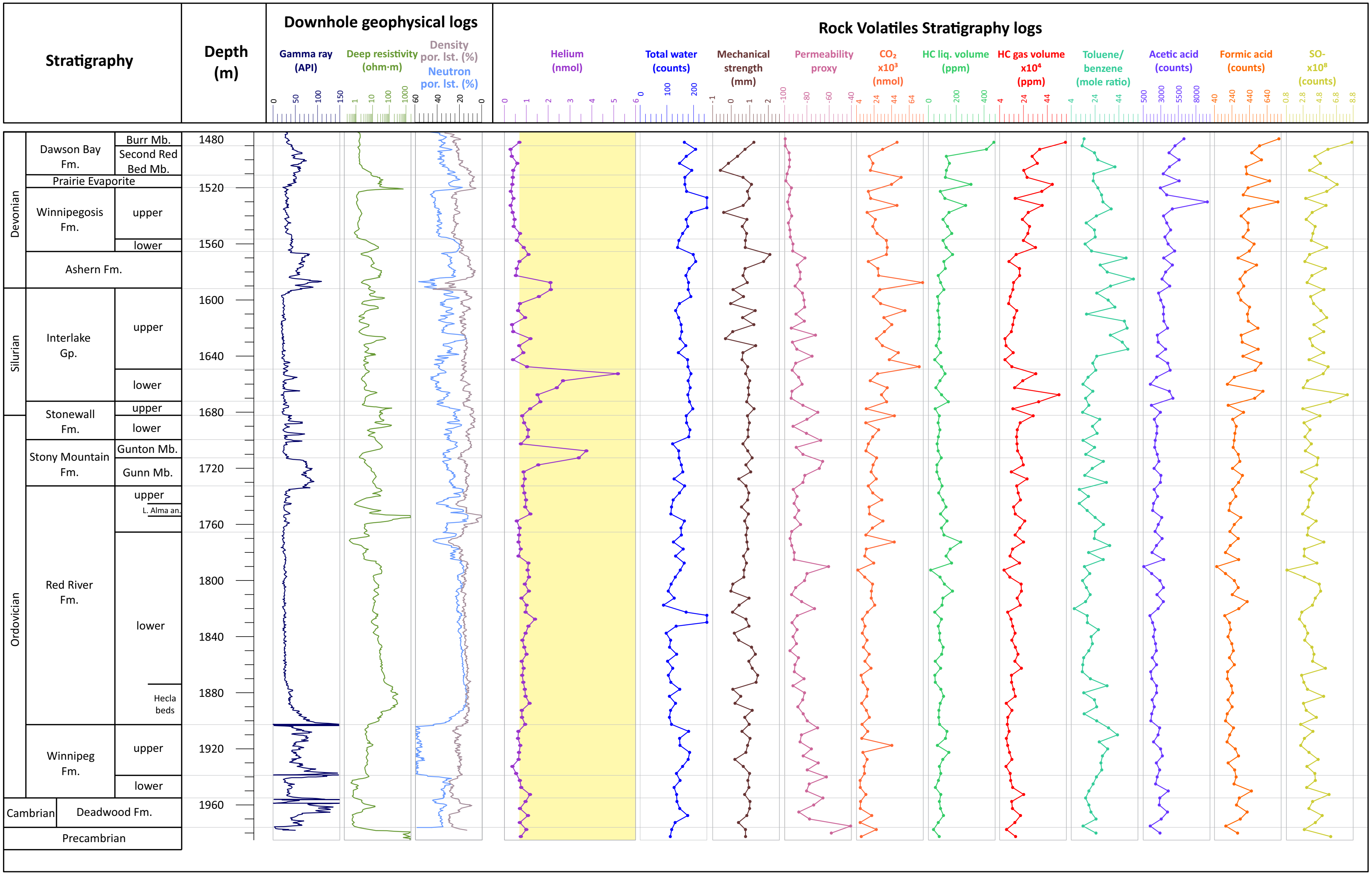

Figure GS2023-11-2: *Stratigraphy and Rock Volatiles Stratigraphy (RVS) data logs for the oil and gas well at L.S. 9, Sec. 6, Twp. 2, Rge. 26, W 1st Mer. (9-6-2-26W1), including select downhole geophysical logs; RVS sample intervals are every 5 m. Yellow highlighted area on the helium track shows values ≥0.7 nanomoles (nmol). Mechanical strength of the sample increases from left to right on the mechanical strength log; the permeability proxy log indicates increased permeability from left to right. Abbreviations: HC, hydrocarbon; L. Alma an., Lake Alma anhydrite; liq., liquid; por. lst., porosity of limestone.*

helium. On the mechanical strength log, the total water spike occurs in the middle of a zone of lower mechanical strength, between 1800 and 1845 m TVD. This decreased mechanical strength supports a potential zone of natural fractures within the Red River Formation, as has been identified in other deep wells at this same stratigraphic interval. Additionally, immediately above this water spike, the CO_2, hydrocarbon liquid and gas values increase, but still within the zone of high helium. This suggests that the composition of any fluid resource in this formation may be different above the spike than that below it.

The basal sand of the lower Winnipeg Formation and the upper half of the Deadwood Formation interval also have similar log responses to the Red River Formation, suggesting another thin helium-prospective zone, with the upper Winnipeg Formation middle shale unit acting as a partial barrier separating the upper zone from the lower zone, and with the Precambrian basement granite underlying these units as the source of helium.

Going upsection, in the interval that includes the Stony Mountain Formation, the higher helium values are concentrated in the Gunton Member, where the neutron log indicates a higher porosity. Additionally, the resistivity changes from low to high, forming a distinct 'shoulder' in the log response, with corresponding decreases in the total water, CO_2 and mechanical strength, all corresponding to the increase in helium. This combination of changes suggests the helium is diffusing upward abutting against a top seal (lower Stonewall Formation) in a zone of lower porosity, this interpretation would be consistent with core analysis done in Saskatchewan using the RVS system (Smith et al., 2022a). Given that the diameter of a helium atom is so small, it is able to diffuse into smaller pore spaces than larger molecules of water and CO_2, making the effective porosity for helium lower and the helium more mobile in seemingly tight spaces. This top seal did not prevent the helium from being present and/or migrating upward, but did act as a very strong sealing feature to other compounds or a baffle for the helium, requiring volatiles to move laterally to infiltrate past the feature. The gamma-ray log does not suggest a local in situ radioactive decay source in the sedimentary rock, and the high values are more likely the result of helium migration through a complex fracture network.

Further upsection, there are two helium anomalies within the Interlake Group. The upper Interlake Group anomaly shows higher than average CO_2 and total water values, and lower mechanical strength. This suggests that this interval, which is high in helium, is also high in other gases and is likely water-wet. Increased porosity and a decrease in mechanical strength in the upper Interlake Group anomaly interval may be related to the major erosional unconformity between the Silurian Interlake Group and Devonian Ashern Formation, which would have compromised these rock units through erosion, weathering, leaching and surface fractures. In the lower Interlake Group anomaly, the total water values and hydrocarbon gas volume responses are high, the CO_2 response is high immediately above the highest helium response, and the neutron log suggests possibly more porosity immediately below the high helium response. This may be due to a molecular sorting process whereby the relatively mobile hydrocarbon gases, which are better preserved in legacy samples, got trapped in porous rocks and were unable to move into the very tight rocks, which trapped and preserved the helium being observed here.

At the top of the sampled section, in the Dawson Bay Formation, immediately above the Second Red Bed Member, the hydrocarbon liquid and gas logs show a positive excursion. The logs indicate the presence of residual oil and gas within porous beds, although the low resistivity and higher total water values indicate that the beds may be water-wet. The acetic acid and formic acid responses increase as well, indicating the proximity to an oil-water contact. These oil and gas indicators mimic those shown in the well at 13-24-12-27W1 (licence 10911), discussed later in this report. Of interest, leading up to the Dawson Bay Formation, the Winnipegosis Formation shows marked increases in hydrocarbon gas and liquid volumes across the entire formation section.

When comparing data from the well at 9-6-2-26W1 to the data from the other two wells, the well at 9-6-2-26W1 has significantly higher values for helium, hydrocarbon oil and gas and CO_2. This points to a more active fluid system in the deeper parts of the basin in Manitoba, specifically in the Waskada and Pierson oil fields area (Twp. 1 to 3, Rge. 24 to 29W1). Reinforced by the core analyses done in Saskatchewan (Smith et al., 2022a, 2023b), the high helium responses in Manitoba require a significant helium source to be present and helium in sufficient quantities for it to accumulate to that degree. In the history of AHS doing these RVS tests and studies on legacy samples, this well returned the highest helium values measured to date using RVS analysis on samples for which uranium- and thorium-rich basement rocks or sedimentary rocks were not directly present to self-source the helium. These results are indicative of a high level of prospectivity and a significant amount of helium migrating through the system, with particular focus on the lower Red River Formation section.

Oil and gas well at 13-24-12-27W1 (licence 10911)

Drill cuttings collected from the well at 13-24-12-27W1 were sampled from 1496 m TVD, in the Precambrian rocks, up to 1005 m TVD, in the lower Burr Member of the Dawson Bay Formation. Figure GS2023-11-3 shows the data logs for select analyses, including helium, as they relate to stratigraphy.

The helium values for this well are considerably low, with all data points but one plotting below 0.7 nmol helium, with the sample at 1255 m TVD having a reading of 0.75 nmol. This one sample also has corresponding small peaks in hydrocarbon liquid and gas values. With a thickness of less than 10 m, this zone is too small for consideration as a helium target.

The lower Red River Formation section and Winnipeg Formation (from 1365 to 1480 m TVD) shows a consistently higher

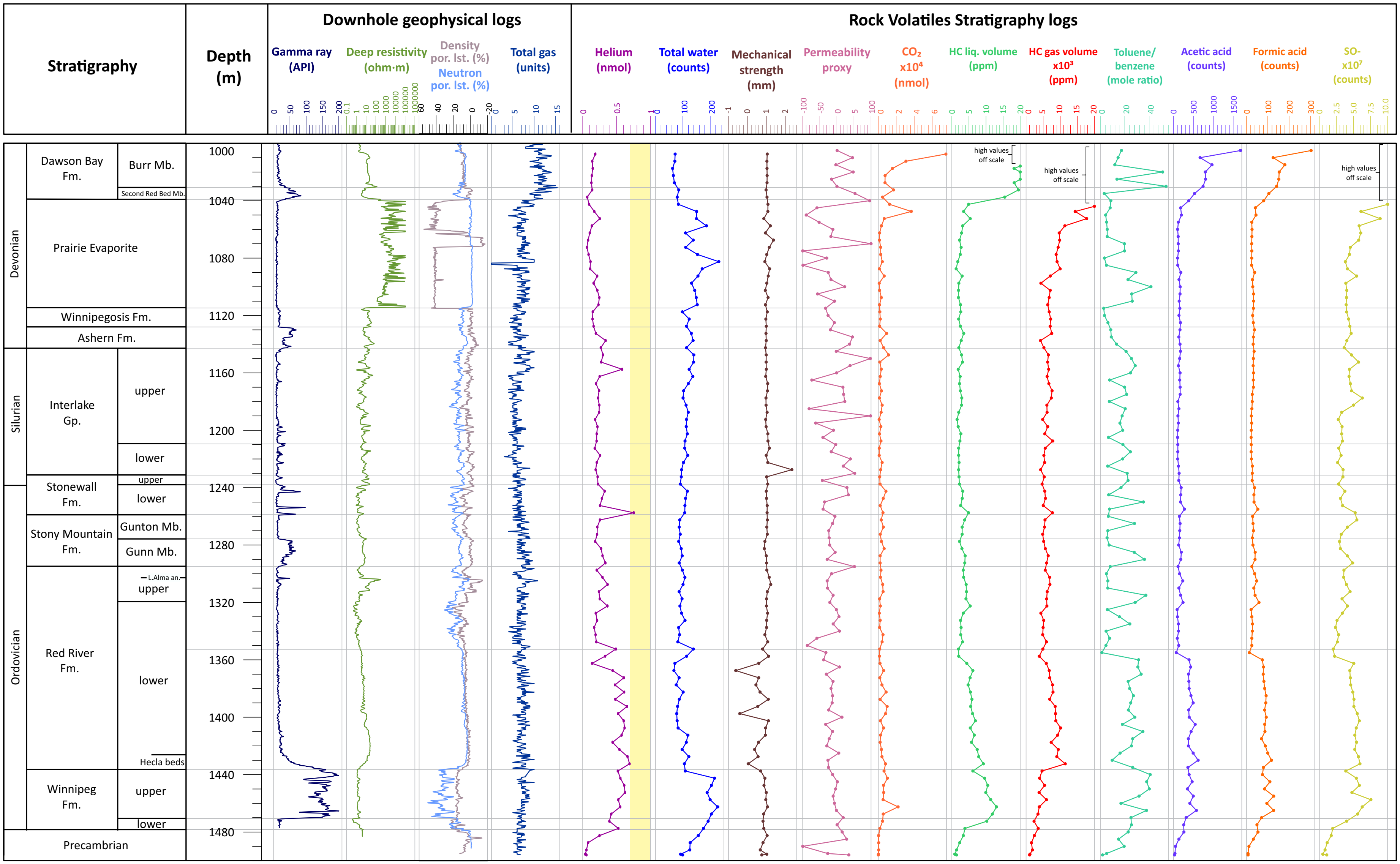

Figure GS2023-11-3: Stratigraphy and Rock Volatiles Stratigraphy (RVS) data logs for the well at L.S. 13, Sec. 24, Twp. 12, Rge. 27, W 1st Mer. (13-24-12-27W1), including select downhole geophysical logs; RVS sample intervals are every 5 m. Yellow highlighted area on the helium track shows values ≥0.7 nanomoles (nmol). Mechanical strength of the sample increases from left to right on the mechanical strength log; the permeability proxy log indicates increased permeability from left to right. Abbreviations: HC, hydrocarbon; L. Alma an., Lake Alma anhydrite; liq., liquid; por. lst., porosity of limestone.

helium content than the strata above, but still falls just below the 0.7 nmol helium cutoff. The lower Red River Formation section is marked by a decrease in porosity, as seen by the neutron log and low mechanical strength responses. The gamma-ray and resistivity logs do not show any significant changes, suggesting a subtle change in lithology, perhaps more diagenetic, has occurred between 1365 and 1480 m TVD. Changes in the SO- (sulphate proxy) data support this, as this measures the presence of sulphate compounds as they breakdown in the system, which can be tied to depositional environment and diagenesis. Sample descriptions in the technical well file (Fire Sky Energy Inc., 2018) indicate a change between 1350 and 1355 m TVD from dolostone above to limestone below. The decrease in mechanical strength may reflect this porosity increase, but may also be related to fracturing within this interval. A potential zone of natural fractures is also seen within this same stratigraphic interval on the logs for the well at 9-6-2-26W1 (Figure GS2023-11-2).

The section from 1365 to 1480 m TVD overall has high total water values, particularly in the Winnipeg Formation section, with an increase in hydrocarbon liquid values, and a corresponding increase in toluene/benzene ratio and acetic and formic acid counts. The Winnipeg Formation section has distinctly lower hydrocarbon gas values than the overlying section. This combination of trends suggests that significant volumes of hydrocarbons have likely migrated through the Winnipeg Formation to Red River Formation interval, and the Winnipeg Formation interval is now water-wet as most hydrocarbon liquids and gases have been flushed out. The Winnipeg Formation flushed zone corresponds to the Winnipeg Formation sandstone aquifer.

The Burr Member of the Dawson Bay Formation section, immediately above the Second Red Bed Member, also shows the presence of a good hydrocarbon system, with the hydrocarbon liquid and gas logs both showing very high (off the scale) values, and low total water values, which suggest the system is not fully flushed. The acetic and formic acids logs show positive inflections indicating the proximity to or location of an oil-water contact. Positive inflections in the toluene/benzene ratio indicate the migration of hydrocarbons through the strata (Smith, 1968). In support of the findings of the RVS data, a gas log collected while drilling shows an increase in total gas within the same Dawson Bay Formation interval, and sample descriptions in the technical well file indicate oil shows in the cuttings (Fire Sky Energy Inc., 2018).

Overall, the well at 13-24-12-27W1 has the lowest RVS values of all three wells. This is likely a function of the drill cuttings themselves, which were much finer grained than those from the other two wells, which is a direct reflection of the PDC drill bit used at this wellsite. The drill cuttings from this well were the size of coarse- to medium-grained sand, which is common in modern drilling, in comparison to the other wells that were more coarse-grained sand to pebble-sized cuttings. It is suspected that the size of the cuttings themselves impact the RVS results, with the coarser grained cuttings providing more reliable results since they have not been subjected to as much surface area exposure through grinding and 'washing' during standard sample preparation at the wellsite. The coarser grained cuttings would also maintain a more accurate representation of original macro- and microporosity and rock properties and would retain more pore-space fluids and volatiles. This reinforces the work of AHS, which suggests that the RVS values from finer grained cuttings, although still valuable, have more attenuated responses, which need to be considered when evaluating the fluid systems in these wells and when comparing them to other datasets.

Oil and gas well at 16-29-12-29W1 (licence 2532)

Drill cuttings collected from the well at 16-29-12-29W1 were sampled from 1664.2 m TVD, in the Precambrian rocks, up to 1362.5 m TVD, in the Interlake Group. Figure GS2023-11-4 shows the data logs for select analyses, including helium, as they relate to stratigraphy.

The helium values for this well show good results, above 0.7 nmol consistently between 1420.4 and 1572.8 m TVD, correlating to the lower Stonewall Formation to lower Red River Formation interval, but with particularly high values in the lower portion of the lower Red River Formation section (1511.8–1572.8 m TVD). Within this latter section, between 1536.2 and 1572.8 m TVD, the total water, CO_2 and hydrocarbon liquid values are lower than those above. These indicators suggest that the interval between 1536.2 and 1572.8 m TVD may be the best helium-prospective interval. Immediately above 1536.2 m TVD, which still has high helium values, the hydrocarbon liquid and gas and total water values all increase, suggesting that even though there is good helium accumulation here, hydrocarbons and water may dilute the helium. In addition, the interval between 1472.2 and 1536.2 m TVD shows more variable resistivity readings in the zone with higher helium values, with minor variations in the gamma-ray log and large responses in the SO- data, which may suggest a changing rock type. According to the sample descriptions in the technical well file (Asamara Oil Corporation Limited, 1975) for this well, this interval corresponds to a change from dolostone above ~1493 m TVD to limestone below. In addition to the lithology change, the SO- data may give insight into the brine composition of the formation waters, which ultimately affected the resistivity response. The depositional environment of the Red River Formation gradually changed from open marine to a more restricted environment upsection, resulting in the deposition of the Lake Alma anhydrite. The sulphate proxy (SO-) may be an indication of this change, as the SO- values drop off immediately after the deposition of the anhydrite bed.

The hydrocarbon liquid and gas logs between 1414.3 and 1533.1 m TVD suggest that this well is close to a hydrocarbon system. Similar to the situation with the Dawson Bay Formation section in the 13-24-12-27W1 well, the toluene/benzene ratios indicate the migration of hydrocarbon liquids (Smith, 1968). The positive inflection of acetic and formic acids at 1533.1 m TVD

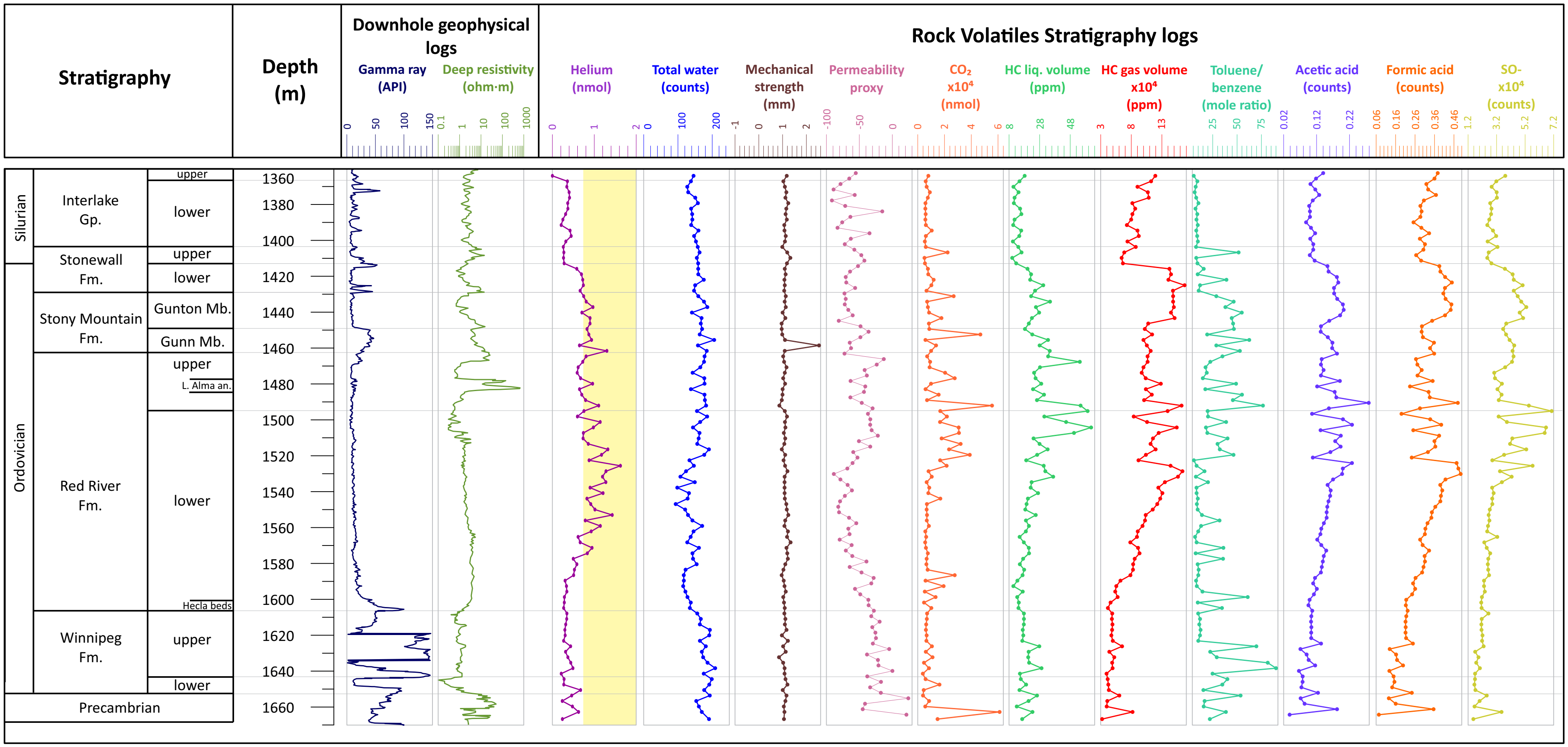

Figure GS2023-11-4: *Stratigraphy and Rock Volatiles Stratigraphy (RVS) data logs for the well at L.S. 16, Sec. 29, Twp. 12, Rge. 29, W 1st Mer. (16-29-12-29W1), including select downhole geophysical logs; RVS sample intervals are every ~3 m (10 ft.). Yellow highlighted area on the helium track shows values ≥0.7 nanomoles (nmol). Mechanical strength of the sample increases from left to right on the mechanical strength log; the permeability proxy log indicates increased permeability from left to right. Abbreviations: HC, hydrocarbon; L. Alma an., Lake Alma anhydrite; liq., liquid.*

indicate an oil-water contact nearby, with oil and water interactions occurring throughout the 1414.3–1533.1 m TVD section. Sample descriptions in the technical well file make note of oil staining and oil cut between 1493 and 1500 m TVD (Asamara Oil Corporation Limited, 1975).

Interestingly, the mechanical strength range for this well is fairly low, with only one large spike at 1457.0 m TVD, which correlates to a stratigraphic break suggesting possible diagenetic changes in the rocks in this area. This suggests the strata in this area have a fairly uniform rock strength competency, with no fracture zones.

Deeper down in the section, within the Winnipeg Formation, there are some indicators of a hydrocarbon system moving through, with slight increases in the values for hydrocarbon liquid and gas and high toluene/benzene ratio values. The total water values here are higher, suggesting a water-wet interval.

Tectonic effects, fracturing and basement features

As mentioned previously, the three wells selected for RVS analysis were chosen based on certain criteria. A focus on areas with known structural disturbance was key, in order to maximize the opportunity for fluid migration throughout the section and to verify sealing and trapping mechanisms, as well as potentially provide insight into helium sources. Multistage dissolution of the Prairie Evaporite and structural collapse of overlying strata has been well documented in Manitoba (e.g., Nicolas 2012; Nicolas and Yang, 2022); the dissolution front is shown in Figure GS2023-11-1 as a north-trending, westward-moving front, with a path of accelerated dissolution around Twp. 12. The dissolution of this thick salt section has been linked to fluid flow from deep Precambrian-derived fractures formed by movement related to the sub-Phanerozoic Superior boundary zone that underlies southwestern Manitoba. These structures and processes all play an important part in helium sourcing, migration and trapping. Additionally, the Precambrian paleotopography and composition and the presence of the Deadwood Formation, which is productive for helium in Saskatchewan (Yurkowski, 2016, 2021), all play an important role in deciphering the helium story.

The magnitude of the helium values and the wide stratigraphic distribution of those values seen in this dataset was unexpected, and suggests a more complex system of fractures and helium sources at play in Manitoba. There is a need for more detailed data collection and analysis from more wells, perhaps in areas with less obvious structural affects, including detailed lithological and mineralogical study and evaluation of seismic cross-sections in the vicinity of the three wells studied here.

Conclusions

All three wells in this study show signs of helium accumulation of varying degrees. The well at 9-6-2-26W1 has returned the highest helium values measured by the RVS system to date in legacy samples for which self-sourcing of the helium from in situ uranium- and thorium-bearing basement rocks or shale was not possible. This indicates an active prolific helium system and bypassed deep hydrocarbon system opportunities in Manitoba. Helium target zones in this well include the Red River Formation and the Winnipeg–Deadwood formations intervals. The well at 16-29-12-29W1 also shows good indications of potential helium target zones within the Red River Formation. At first glance, the data from the well at 13-24-12-27W1 suggests that there is no helium target zone, since most helium values fall below 0.7 nmol, however, if the affect of drill cutting size on the RVS analysis is taken into consideration, there is an expectation of an attenuation of results, thus the Red River Formation could be a zone of interest. Further testing for helium is recommended. Additionally, if the helium data from RVS analysis are considered as minimum values, all three wells have helium target zones in the Red River Formation. In the deeper basin, an additional target zone would be the porous strata of the Deadwood Formation immediately overlying the Precambrian basement.

Despite the lack of hydrocarbon production in Manitoba from below the Devonian Torquay Formation, the hydrocarbon indicators in the RVS data clearly show that significant amounts of hydrocarbons have migrated through these deep strata. No economical deep hydrocarbon accumulations have yet been discovered in Manitoba, and little exploration in these deeper horizons has occurred in more than three decades. Modern evaluation of these deep strata using modern economic analysis, combined with advanced drilling techniques and downhole geophysical logs, is required to accurately and meaningfully evaluate these horizons to unlock the pore-space resources, including helium and hydrocarbons, contained within them.

Economic considerations

The global demand for helium has resulted in a dramatic increase in helium exploration projects, with many of them located in Canada. With concerns about climate change, extracting helium from nonhydrocarbon reservoirs—known as green helium–is of particular interest. The RVS data from three Manitoba wells indicate a robust helium presence in the deeper parts of the southwestern subsurface of Manitoba. Since these helium shows are not associated with large producing oil and gas pools, this would classify most, if not all of Manitoba’s helium, as green helium, automatically making it an attractive investment and exploration opportunity waiting to be unlocked.

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