GS2024-18

Rock volatiles analysis of drill cuttings to evaluate the helium and hydrocarbon prospectivity of southwestern Manitoba (parts of NTS 62F2, K3)

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In Brief:

- Volatile analysis of legacy drill cuttings was done on three oil wells
- Results indicates zones prospective for helium and show indicators of unexplored, active hydrocarbon systems in the Devonian-age strata

Citation:
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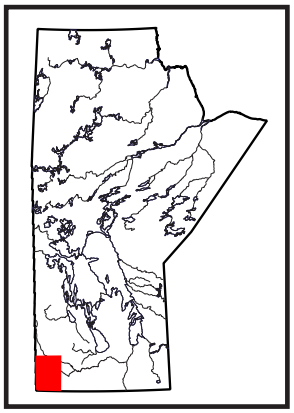
Summary

The helium and hydrocarbon 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], 16-29-12-29W1 and 1-25-4-23W1) were analyzed for a wide range of volatile compounds, including C1–C10 hydrocarbons, carbon dioxide, water and helium. Two of the wells were originally sampled in 2023, and in 2024 were sampled farther upsection, for complete profiles from the Precambrian up to the Lodgepole Formation. A new well, located farther to the east at 1-25-4-25W1, was sampled from the Precambrian to the Lodgepole Formation. All three wells show signs of potential helium accumulations and indicate a complex active helium system in the subsurface, which is affected by structural and stratigraphic controls. Hydrocarbon signatures within all three wells indicate an active oil system in Devonian strata, with evidence for migration, as well as potential for bypassed pay in the areas. Results from this study indicate a considerable untapped potential, including significant helium presence in southwestern Manitoba and indicators of unexplored, active hydrocarbon systems in formations below current oil-producing horizons.

Introduction

A review of helium occurrences in southwestern Manitoba oil and gas wells by Nicolas (2018) and Nicolas et al. (2023b) indicated the presence of a helium system in southwestern Manitoba (Figure GS2024-18-1). Traditional gas analyses conducted on samples collected downhole in oil and gas wells are the most common way to measure gases from a reservoir. The Rock Volatiles Stratigraphy (RVS) system provides a postdrilling option to measure and evaluate the residual volatile fraction trapped in drilled cuttings or core. Nicolas et al. (2023b) conducted RVS analysis on a series of drill-cutting samples from three oil and gas wells, with samples collected from the Precambrian, upsection to either the Silurian Interlake Group or the Devonian Dawson Bay Formation. The positive results reported in Nicolas et al. (2023b) led to a new suite of samples being collected for rock volatiles analysis in 2024. The Manitoba Geological Survey (MGS), again in partnership with Advanced Hydrocarbon Stratigraphy, Inc. (AHS), studied the volatile fraction of fluids in drill cuttings from three oil wells (Table GS2024-18-1) drilled in the Paleozoic. By measuring fluid, gas, hydrocarbon, rock and reservoir properties it is possible to evaluate for helium prospectivity in Manitoba, and provide insights into local hydrocarbon systems.

Nicolas et al. (2023b) described the benefits and limitations of RVS analysis and compared the results to previous studies. Subsequent core studies, such as those described in Smith et al. (2022, 2023, 2024), have reinforced the correlation between RVS helium values and those observed in gas tests.



Methodology

Drill cuttings from three historical petroleum exploration wells in southwestern Manitoba were sampled for testing by the RVS system. 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, Industry, Trade and Natural Resources, Winnipeg) in 9-6-2-26W1; 2) ASM-BTO et al Kirkella Prov. 100/16-29-012-29W1/00 (oil and gas well licence 2532) in 16-29-12-29W1; and 3) Tundra Dand 100/01-25-004-23W1/00 (oil and gas well licence 4859) in 1-25-4-23W1 (Figure GS2024-18-1). Sampling intervals were restricted to the available cuttings in storage; the sampling interval was ~6 m (20 ft.) for the well at 16-29-12-29W1 and 5 m for the wells at 9-6-2-26W1 and 1-25-4-23W1 (Table GS2024-18-1).

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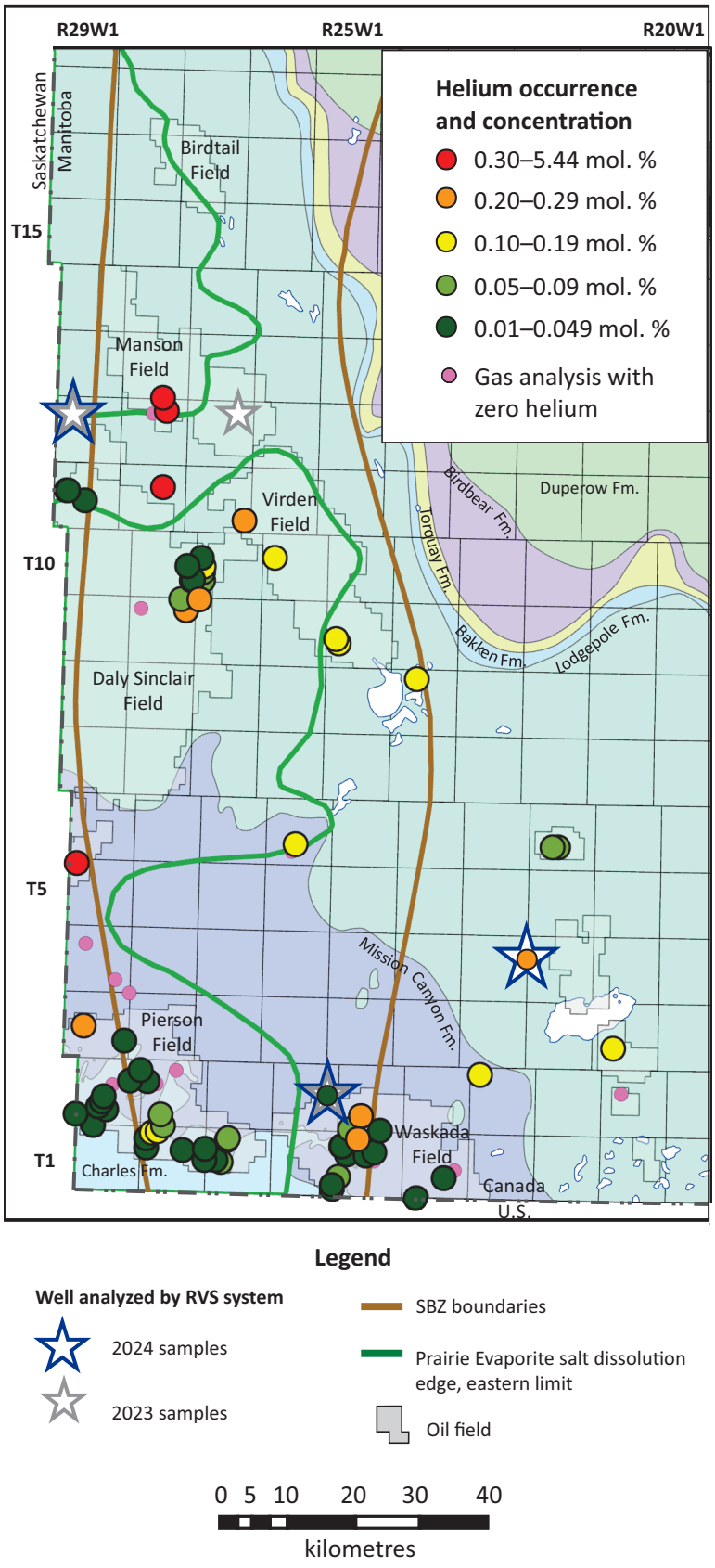

Figure GS2024-18-1: *Paleozoic bedrock geology of southwestern Manitoba showing the formational subcrop edges (modified after Nicolas et al., 2010). Also shown are the 1) locations of wells sampled in 2023 and 2024 and analyzed by the Rock Volatiles Stratigraphy (RVS) system and 2) distribution of gas analyses and helium occurrences (modified from Nicolas, 2018). Select oil fields are labelled (Nicolas, 2023). Abbreviation: SBZ, Superior boundary zone.*

Table GS2024-18-1: List of wells sampled in southwestern Manitoba.

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	1485–1160	5 m	Dawson Bay Fm. to Lodgepole Fm.	Salt-gel drilling mud used in deeper section; drilled with mill-tooth drill bit
100/16-29-012-29W1/00	2532	327790.04	5546621.49	1974	1664.2	1356–765	~6 m (20 ft.)	Interlake Gp. to Lodgepole Fm.	Salt-gel drilling mud used below 589 m; drilled with mill-tooth drill bit
100/01-25-004-23W1/00	4859	394906.57	5464921.23	2000	1670.0	1655–815	5 m	Precambrian to Lodgepole Fm.	Drilled with PDC drill bit

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

The wells at 9-6-2-26W1 and 16-29-12-29W1 were sampled and analyzed in 2023 and were then sampled farther upsection (from the shallowest 2023 sample) in 2024. The well at 1-25-4-23W1 was added to the 2024 study, with samples collected from the Precambrian to the Lodgepole Formation. One of the wells sampled in 2023, the well at 13-24-12-27W1 (oil and gas well licence 10911), was not resampled in 2024. For consistency, and to allow stratigraphic comparisons, all wells were sampled through the section, from the Precambrian basement up to the lower Lodgepole Formation. Selection of the new well was based on the availability of Precambrian samples at a depth of ≥1500 m, good quality drill cuttings and sample recovery possible at ~5 m intervals continuously from the Precambrian up through to the Lodgepole Formation. The geographic location of the new well was also considered, as a location away from the effects of the sub-Phanerozoic Superior boundary zone (SBZ) and the salt dissolution of the Prairie Evaporite was preferred. The rationale to select a well located away from any major structural disturbances was to allow for comparison with those that occur in areas with known structural features.

The samples were sent to the 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. Smith et al. (2022) 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 GS2024-18-2 shows the list of compounds and rock properties analyzed from drill cuttings for this study.

Each sample consisted of 3 g of drill cuttings from each interval, starting with the vial at the maximum sample depth identified for that well. Each well was then sampled upsection, up to the lower Lodgepole Formation, ensuring a minimum of 100 samples was collected for a given well.

The same analytical methods were applied to these samples as those described in Nicolas et al. (2023b), with the exception for how the mechanical strength was measured. In 2023, the mechanical strength was measured using an automated system to measure the thickness of the sample container after a crushing force had been applied. Due to concerns about the automated system, AHS manually measured the thickness of the crushed sample containers with vernier calipers in 2024.

Table GS2024-18-2: Generalized list of compounds and rock properties analyzed by the Rock Volatiles Stratigraphy system on drill cuttings in this study. Data Repository Item DRI2024008 (Nicolas et al., 2024) 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)	

Rock Volatiles Stratigraphy results and interpretation

The entirety of the RVS data is available in Data Repository Item DRI2024008 (Nicolas et al., 2024)[2]. There is a significant amount of information that can be extracted from the RVS data. This report focuses only on the data used to evaluate helium and hydrocarbon prospectivity, but also on select data for other fluids, such as organic acids, water and CO_2, as they provide information about the overall fluid dynamics of the system. To allow more accurate comparison between the 2023 and 2024 datasets, mechanical strength was remeasured for samples from the wells at 9-6-2-26W1 and 1-25-4-23W1. The data corrections for these two wells are in Nicolas et al. (2024); the mechanical strength for 16-29-12-29W1 was not remeasured.

The drill bit used and drilling mud composition can affect the results and these factors need to be considered when interpreting RVS data (Nicolas et al., 2023b). Table GS2024-18-1 lists the drill bit used for each well analyzed in this study. 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.

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 1485 m true vertical depth (TVD), near the base of the Burr Member of the Dawson Bay Formation, up to 1160 m TVD, in the basal limestone facies of the Scallion Member of the Lodgepole Formation. The drill cuttings from this well were generated using a mill-tooth drill bit. Figure GS2024-18-2 shows the data logs for select analyses, including helium, as they relate to stratigraphy. For a comprehensive discussion of the results below 1485 m TVD, see Nicolas et al. (2023b).

Helium

Smith et al. (2022) stated that a reading above 0.7 nanomol (nmol) helium on a RVS log indicates a potential economic accumulation of helium. The comparison of drill cuttings between wells drilled with different drill bits (i.e., mill-tooth bits versus PDC bits) in Nicolas et al. (2023b) indicated that this threshold is better applied to wells with drill cuttings the size of coarse-grained sand to pebbles. A lower threshold is needed for wells with drill cuttings the size of medium to coarse sand. The well at 9-6-2-26W1 has large enough drill cuttings to use the 0.7 nmol helium threshold.

Above 1485 m TVD, helium values show a positive response in the Dawson Bay Formation (1490 m TVD) with a peak at the top of the Burr Member before decreasing to the middle of the Harris Member of the Souris River Formation (1400 m TVD). The helium values drop upsection, indicating a break in the helium system (i.e., no further upward migration of helium), until the top of the Torquay Formation is reached, where the values peak at 0.92 nmol; the Upper Member of the overlying Bakken Formation may be acting as a seal to the helium system below. In this well, the highly organic shales of the Upper Member of the Bakken Formation might even be contributing helium to the system (Nicolas et al., 2023b), further increasing the helium accumulation at this stratigraphic level. Overall, the helium distribution throughout the section in this well is variable but consistently present. This indicates an active helium migration system, which, despite being constrained by tight rock units in places, has sufficient migration pathways that transect many stratigraphic boundaries. This suggests a structural control on fluid movement, such as an efficient fracture network or nearby faults.

Hydrocarbons

Above 1400 m TVD, the helium values decrease to near background levels and there is a noticeable increase in CO_2 and hydrocarbon gas volume levels upsection. This depth also coincides with a sudden increase in formic acid levels and the beginning of a decline in hydrocarbon liquid volumes. This break may indicate an oil–gas transition zone.

Also of note is a marked occurrence of high CO_2, near zero to low helium values, and distinct high formic acid and sulphate values constrained within the Souris River Formation to lower Duperow Formation. This, together with a variable interbedded lithology typical of these formations, suggests a complex stratigraphic and depositional environment influencing the fluids.

An observation from the 2023 results (below 1485 m TVD; Figure GS2024-18-2; Nicolas et al., 2023b), which has not been previously reported, is the correlation of the responses from two drillstem tests (DST) with the responses on the profiles. Drillstem test 1 was at 1535–1520 m TVD, at the top of the Winnipegosis Formation, and DST 3 was at 1602–1596 m TVD, at the top of the Interlake Group. The results of DST 1 in the Winnipegosis Formation indicate a fair to good initial blow followed by a steady flow throughout the test, and results of DST 3 in the Interlake Group indicate a strong steady air blow throughout the test (oil and gas well licence 2610). Correlation of the DST 1 depths with the RVS log shows the helium values are moderately low, but the hydrocarbon response is high. The total water is capped at this depth giving it a high total water content, which coincides with moderately high hydrocarbon liquid volumes, and a sudden spike in acetic acid. These responses may coincide with the oil-water

[2] MGS Data Repository Item DRI2024008, 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.

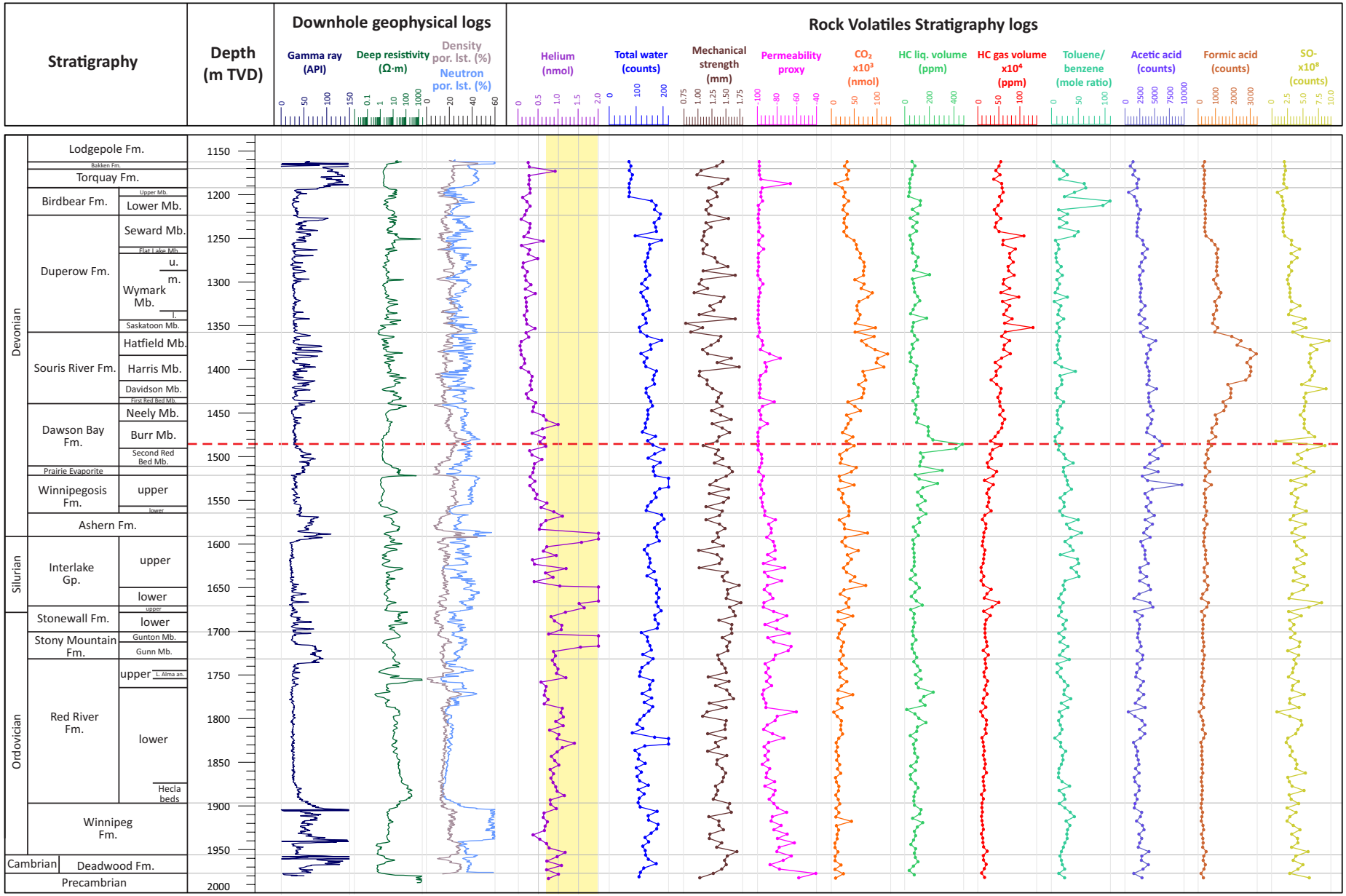

Figure GS2024-18-2: *Stratigraphy and Rock Volatiles Stratigraphy data logs for the oil and gas well at L.S. 9, Sec. 6, Twp. 2, Rge. 26, W 1st Mer. (9-6-2-26W1, southwestern Manitoba), including select downhole geophysical logs. Samples were collected at 5 m intervals. The red dashed line indicates the break between the 2023 data reported in Nicolas et al. (2023a, b) and the new 2024 data (above the red dashed line). 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; l., lower; liq., liquid; por. lst., porosity of limestone; m., middle; TVD, true vertical depth; u., upper.*

contact for the hydrocarbon system occurring within the Dawson Bay Formation. Therefore, the DST may have been done too low in the section to show positive oil results. For DST 3, the corresponding depths coincide with very high helium values, a CO_2 peak and a good permeability index reading, but with unremarkable hydrocarbon liquid and gas volumes. This indicates that the strong steady air flow from this test was likely due to the helium and CO_2 accumulated at this depth.

In the Burr Member of the Dawson Bay Formation, the hydrocarbon liquid volume on the RVS logs shows a dramatic increase with a corresponding increase in hydrocarbon gas volumes, indicating the presence of hydrocarbons (Figure GS2024-18-2). The low toluene/benzene ratio indicates that there has been limited migration of hydrocarbons out the system, which suggests an oil trap nearby. This could be a potential oil exploration interval in this area.

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 1360 m TVD, in the lower Interlake Group, up to 765 m TVD, in the basal limestone facies of the Scallion Member of the Lodgepole Formation. The drill cuttings from this well were generated using a mill-tooth drill bit. Figure GS2024-18-3 shows the data logs for select analyses, including helium, as they relate to stratigraphy. For a comprehensive discussion of the results below 1360 m TDV, see Nicolas et al. (2023b).

Helium

The helium system in this well shows a break at 1365 m TVD, just below the 2023–2024 sample boundary, where the values drop to near zero. Two isolated helium-rich zones occur upsection from this break. The first occurs in the Winnipegosis Formation as a thin helium show, where the thick salt of the Prairie Evaporite above acts as a barrier to the helium migrating upward from the lower Paleozoic section. The second occurs from 1025 to 985 m TVD and extends from the Hatfield Member of the Souris River Formation to the lower Wymark Member of the Duperow Formation. The helium system in this well is constrained to the lower Paleozoic formations.

Hydrocarbons

The 1025–985 m TVD interval coincides with a high hydrocarbon liquid volume and corresponding low water content within the Hatfield Member of the Souris River Formation to the middle Wymark Member of the Duperow Formation. The base of this section, at 1025 m TVD, also coincides with a marked change in acetic acid and formic acid values and a sharp increase in sulphate values. The change likely corresponds to an oil-water contact that is partly controlled by stratigraphic and lithological variations.

There were DSTs conducted on this well at 771–763 m TVD and 781–774 m TVD, coinciding with the Bakken Formation. These intervals returned poor results with no oil or gas shows. The RVS results for hydrocarbon indicators support these findings, indicating no active oil system in these tested formations (Figure GS2024-18-3). However, farther down the section, in the interval from the middle Dawson Bay to upper Souris River formations, there are high liquid hydrocarbon volumes in combination with the anomalously high toluene/benzene values, and a slight drop in water content. This indicates that there is likely an active oil system through this section with some ongoing migration that is worth exploring within this well or at nearby locations.

Oil and gas well at 1-25-4-23W1 (licence 4859)

Drill cuttings collected from the well at 1-25-4-23W1 were sampled from 1655 m TVD, in the Precambrian, up to 815 m TVD, in the Scallion Member of the Lodgepole Formation. Figure GS2024-18-4 shows the data logs for select analyses, including helium, as they relate to stratigraphy.

Helium

The drill cuttings from this well were generated using a PDC drill bit. These finer grained drill cuttings will still yield valuable results in volatile analysis, but the results will be significantly attenuated due to the loss of macropores during drilling. Comparing the volatile analysis profile to those of the wells at 9-6-2-26W1 and 16-29-12-29W1 will be difficult, therefore it is recommended that only general trends of volatile results be compared when necessary. Additionally, the threshold of 0.7 nmol helium as the lower economic limit cannot be applied to this well, however, values occurring above the threshold do indicate very high helium values.

The helium system in this well is consistently distributed throughout the section, with several distinctive high peaks. However, there is a clear break where helium values drop to zero above the Bakken–Lodgepole formation contact. This indicates that, despite the high permeability of the Lodgepole Formation, the shale of the Upper Member of the Bakken Formation is a very effective seal for helium.

Aside from the isolated peaks, the section from the Red River Formation to the middle Stonewall Formation shows elevated helium values, consistent with the profiles in the other wells analyzed. Within this section, the highest helium values occur between the Stony Mountain Formation and the Stonewall Formation, where the system is capped by the tight t-marker unit. This suggests an active helium system may extend farther east, away from structural disturbances. After the helium peak in the Stonewall Formation, the helium values decrease gradually in the lower Interlake Group. This gradual decrease in helium values upsection in the lower Interlake Group is also observed in the well at 16-29-12-29W1 (Figure GS2024-18-3), which is in contrast to the wells at 9-6-2-26W1 (Figure GS2024-18-2) and 13-24-12-27W1 (Nicolas et al., 2023b).

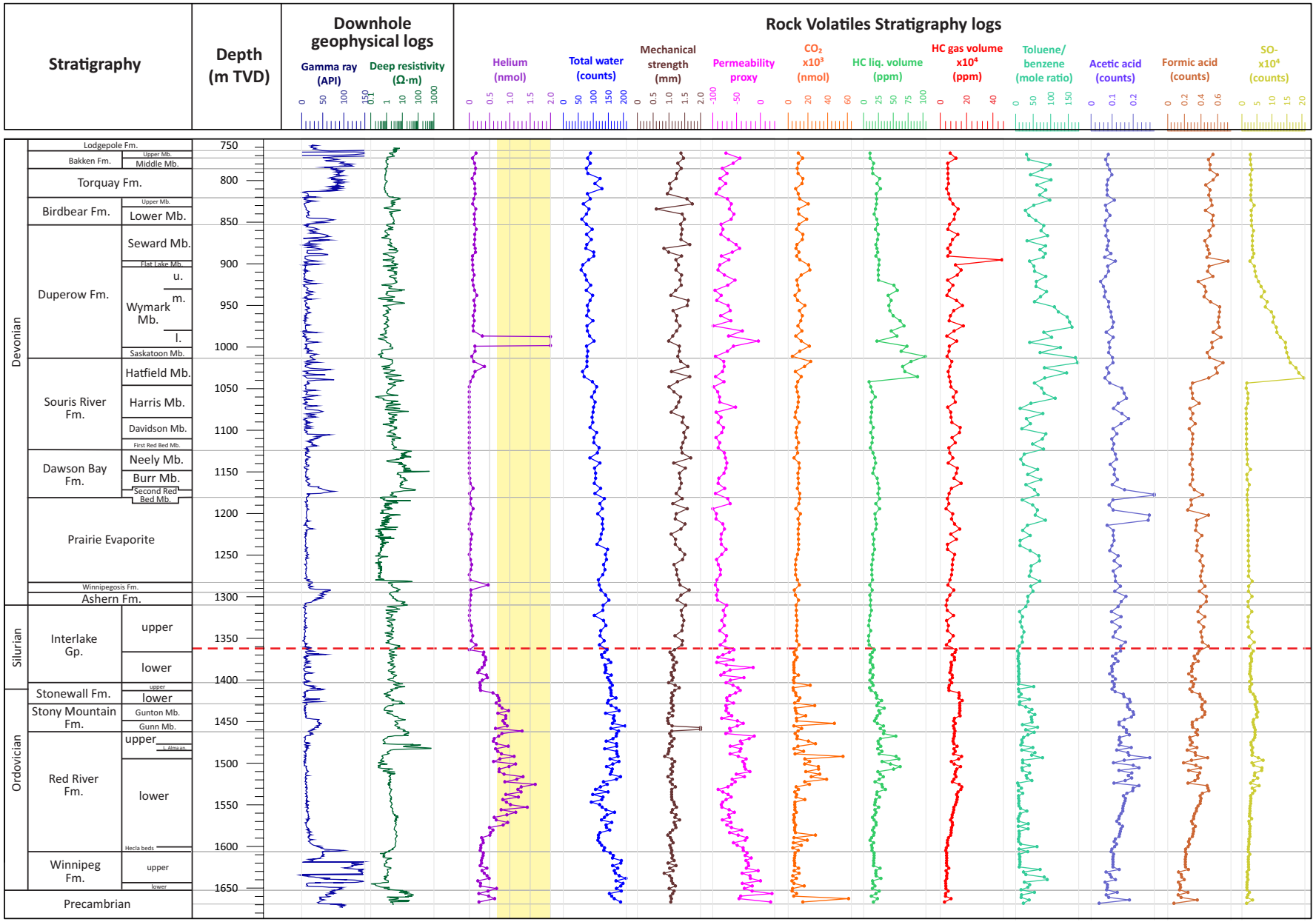

Figure GS2024-18-3: *Stratigraphy and Rock Volatiles Stratigraphy (RVS) data logs for the well at L.S. 16, Sec. 29, Twp. 12, Rge. 29, W 1st Mer. (16-29-12-29W1, southwestern Manitoba), including select downhole geophysical logs. Samples above 1360 m TVD were collected at ~6 m (20 ft.) intervals; samples below 1360 m TVD were collected at ~3 m (10 ft.) intervals. The red dashed line indicates the break between the 2023 data reported in Nicolas et al. (2023a, b) and the new 2024 data (above the red dashed line). 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., lower; L. Alma an., Lake Alma anhydrite; liq., liquid; m., middle; TVD, true vertical depth; u., upper.*

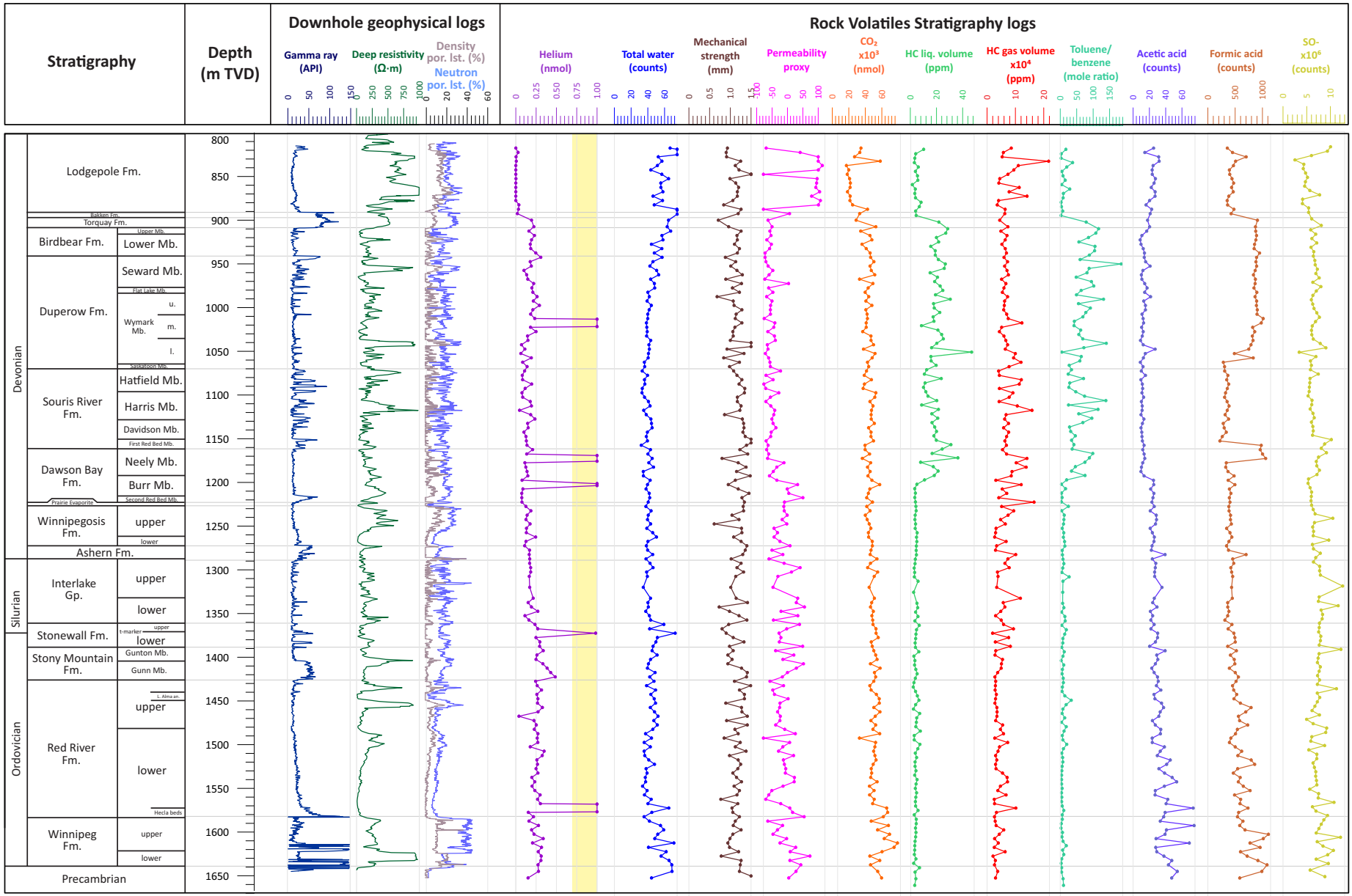

Figure GS2024-18-4: *Stratigraphy and Rock Volatiles Stratigraphy (RVS) data logs for the oil and gas well at L.S. 1, Sec. 25, Twp. 4, Rge. 23, W 1st Mer. (1-25-4-23W1, southwestern Manitoba), including select downhole geophysical logs. Samples were collected at 5 m intervals. Yellow highlighted area 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; l., lower; liq., liquid; por. lst., porosity of limestone; m., middle; TVD, true vertical depth; u., upper.*

Four other peaks were noted in the section, at the base of the Red River Formation, at the top of two of the members of the Dawson Bay Formation, and at the top of the middle Wymark Member of the Duperow Formation. Each of these are coincident with known occurrences of tighter lithologies, commonly, but not exclusively, anhydrite may be acting as a seal, contributing to the trapping and accumulation of helium in these stratigraphic horizons (Smith et al., 2023).

Hydrocarbons

In the section from the Neely Member of the Dawson Bay Formation (~1195 m TVD), continuously up to the base of the Bakken Formation (~900 m TVD), the hydrocarbon liquid volumes are significantly higher than anywhere else in the section. Overall, this section also has high toluene/benzene ratios, lower permeability and low acetic acid values. Within this section, the formic acid shows two blocky signatures, a small one at the bottom of this zone and one starting at 1060 m TVD depth. The latter also coincides with a further increase in hydrocarbon liquid volumes and toluene/benzene values. This indicates two separate hydrocarbon-bearing intervals, a thin one at 1195–1155 m TVD, and a much thicker one at 1060–900 m TVD. The bottom interval coincides with a helium peak, as well as slightly elevated hydrocarbon gas volumes, and the top of the lowest interval coincides with the First Red Bed Member of the Souris River Formation. This member is likely forming a localized cap for this hydrocarbon system, preventing or limiting the upward migration of fluids. The lack of a clear break of RVS values between the two intervals suggests the two intervals may be connected to some degree and the interval between them (1155–1060 m TVD) is acting as a pinch point, slowing down the fluids' migration upward. The higher interval (1060–900 m TVD) is quite thick and indicates hydrocarbons have migrated through this Devonian strata. The increase in water content upsection and no coinciding acetic acid and formic acid response to indicate an oil-water contact, suggests this interval may be waterlogged. Therefore, searching for oil updip from this location may prove to be a good exploration strategy.

The helium peak at 1015 m TVD also coincides with a small increase in hydrocarbon gas volumes and low hydrocarbon liquid volumes, as well as very low permeability. This low permeability may provide insight into the pore space size and the ability for the rock to hold onto the water and helium more tightly in small pore spaces. This becomes an interesting observation when considering the small size of the drill cuttings for this well. It is possible that the fine-grained cuttings from this well show a trend normally masked by the stronger signature of the coarse-grained drill cuttings. Consequently, nanoporosity may have a larger role in the system than previously thought.

This well produced oil from the Lodgepole Formation for a short time but was quickly deemed uneconomic and abandoned (oil and gas well licence 4859). The RVS results indicate little hydrocarbon liquids in the Lodgepole Formation and a high water content. The low toluene/benzene ratios do not support upward migration of oil to supply this small oil accumulation, suggesting oil migration in the Lodgepole Formation of this area is driven by lateral fluid flow along porous Mississippian strata. This supports the model of local stratigraphic trapping of hydrocarbons (Klassen, 1996). The high hydrocarbon gas volumes are unexpected and may be an artifact of the smaller drill cuttings and preservation of nanoporosity.

Discussion

Helium

A comparison of all the volatile profiles indicates that the well at 9-6-2-26W1 has the most prospective helium profile, with helium values never going below a baseline or falling below detection and consistently being high, particularly from the Deadwood to Winnipegosis formations. This may indicate that helium can migrate through the entire studied section. The 1-25-4-23W1 well is the only well with a sample from the Lodgepole Formation, providing insight farther upsection. The results suggest that there is helium throughout the system below the Lodgepole Formation, but the helium values drop to below detection above the Bakken Formation. This may indicate that the Bakken Formation serves as break in the regional helium cap, and that any helium present above is driven by a different helium system. Analysis results reported in Nicolas (2018) also indicate very low to no helium in the Lodgepole Formation, but they also showed the helium system returns higher in the section in the Mission Canyon and Amaranth formations. Testing farther upsection, throughout the Mississippian strata and beyond, could help better understand the relationship—if any exists—between the lower Paleozoic strata and the Mississippian and above strata.

The presence of helium throughout the sampled sections in all the wells is interesting, as several sealing units are present, and the volume of helium required to infiltrate a section several hundred metres thick over a vast area is substantial. This points to a complex helium system affected by both horizontal and vertical migration. The consistent occurrence of helium in the Red River and Winnipeg formations, as seen in RVS logs and gas analyses, suggests local generation of helium from a deeper widespread source, such as the Precambrian basement. Radioactive decay within the granitic basement results in the upward diffusion of gases into the porous Winnipeg and Red River formations and they are sealed locally by tight mudstone and anhydrite in the upper parts of the section. All the profiles for the Winnipeg Formation show a high water content, which may be related to the porous and permeable nature of the interbedded sand units within the formation. This would therefore affect the ability of the helium to accumulate within the lower Winnipeg Formation; the helium would be forced to diffuse out and upsection to the Red River Formation, which supports the presence of overall higher helium values in this formation.

In comparison, the seemingly random nature of the high helium occurrences and peaks above the Red River Formation suggests a more complex system, with influences from a combination of stratigraphic factors, porosity variations, structural elements and fracture networks (and faults?). These seemingly random accumulations occur most often in the Dawson Bay to Duperow formations—this corresponds to an approximately 300 m thick interval with helium prospectivity in the Devonian section.

Thick evaporitic units are considered the best seals for helium, and the only well in this study with a thick section of salt preserved is at 16-29-12-29W1. Interestingly, this is also the only well to have a strong helium system break, just below the Prairie Evaporite. The presence of the Prairie Evaporite may therefore play an important role in the helium system, not only from a sealing perspective, but also from a structural perspective. When the Prairie Evaporite is absent, there is evidence for multistage dissolution upsection, and extensive fracture networks both above and below, which are responsible for the enhanced water flow needed to dissolve the thick halite package. It is no coincidence that the preferential dissolution of the Prairie Evaporite follows the SBZ; this Precambrian crustal suture has caused Phanerozoic-aged faulting, fracturing and stratal disturbances, both syn- and postdeposition (e.g., McCabe, 1959; Dietrich and Bezys, 1998; Nicolas, 2012; Nicolas and Yang, 2022).

Nicolas (2018) indicated that the Bakken Formation may be both a source (upper shale member) and reservoir (middle sandstone member) for helium. The Upper Member of the Bakken Formation is a highly organic shale often with a high gamma-ray signature on geophysical logs. There is variability in the gamma-ray readings on logs, from being high (>250 API) to low (<100 API), that has been shown to be related to the geographic location within the basin (Nicolas, 2012). In this study, the well at 9-6-2-26W1 has a very high gamma-ray response (>350 API) with a corresponding high helium value (0.27 nmol), the well at 16-29-12-29W1 has a high gamma-ray response (~300 API) with a moderate helium value (0.18 nmol), and the well at 1-25-4-23W1 has a lower gamma-ray response (~100 API) and low helium value (~0.01 nmol). It is uncertain whether there is a predictive correlation between the gamma-ray signature of the Bakken Formation and the helium values. With the limited data from this study, this is more of an observation, but is worth tracking to see if the helium self-sourcing ability of the Bakken Formation is related to its gamma-ray signature, which indicates the radioactive decay of the shale and subsequent contribution of helium to the system.

Since 2023, core studies at AHS have further reinforced the theory that rock properties exert a strong control on the helium retained in the rock sample. This study supports this theory as seen in the volatile profiles, where trends in helium-rich zones are similar in all of the wells. Smith et al. (2023, 2024) show further evidence that the residual helium in the rock samples can be quantitatively related to the helium that would be observed in a gas test. Although most RVS studies were conducted on core samples, using this information to extrapolate to drill cuttings and calibrate the RVS results to compensate for the size of the drill cuttings would be a useful tool when evaluating newer wells. Helium is present in the 1-25-4-23W1 drill cuttings, despite absolute abundances being significantly less than those observed in the other two wells, and the well being drilled with newer technology drill bits. The data support that this is likely an artefact of sample type and not the true helium concentrations in the subsurface.

Hydrocarbons

The hydrocarbon story for these wells is also interesting. The well at 1-25-4-23W1 produced oil from the Lodgepole Formation, whereas DSTs at the other wells showed no oil. However, the liquid hydrocarbon volumes on the profiles indicate that

- the 9-6-2-26W1 well has a strong signature in the Burr Member of the Dawson Bay Formation;
- the 16-29-12-29W1 well has a strong signature from the Hatfield Member of the Souris River Formation to the middle Wymark Member of the Duperow Formation; and
- the 1-25-4-23W1 well has a strong signature in the upper Dawson Bay Formation to the base of the Bakken Formation.

All these zones, which are located in stratigraphic intervals below the current oil-producing horizons in Manitoba, may represent unexplored hydrocarbon reservoirs that have not been adequately tested. The petroleum technical well file for 1-25-4-23W1 indicates a live oil show within the Dawson Bay Formation (oil and gas well licence 4859). Although the presence of economic accumulations of oil may or may not be present, at a minimum, the toluene/benzene profiles indicate oil migrating through the system in all these wells. Notably, the 16-29-12-29W1 well has the highest liquid hydrocarbon volumes in combination with anomalously high toluene/benzene values, when compared to the same section in the other wells, indicating an active hydrocarbon system through the Souris River and Duperow formations in this area.

Future work and recommendations

Future work with this project will include sampling neighbouring wells that have been drilled with different technologies to make a series of direct comparisons on RVS signatures. This will also allow for the potential tracking of shallower sealing features.

Although not currently part of the immediate scope, recommended work includes sampling through the Mississippian up to the lower Jurassic to further understand the helium system above the Bakken Formation. Sampling wells within active oil fields, as well as far away from the oil field system (east of Rge. 20W1 and north of Twp. 17), would provide a broader context for the regional helium migration patterns and their relationship to structural controls.

Economic considerations

The RVS data from three Manitoba wells indicate a considerable untapped potential, including significant helium presence in the deeper subsurface of southwestern Manitoba. Since these helium shows are not associated with large producing oil and gas pools, helium produced from these zones would be classified as green helium, making it a highly attractive target for investment and exploration, particularly in the growing market for environmentally sustainable resources. The RVS data also show indicators of active hydrocarbon systems in unexplored horizons that are deeper than the current oil-producing horizons in Manitoba, offering an additional upside, thus positioning the region for resource development.

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References

Dietrich, J.R. and Bezys, R.K. 1998: Basement-sedimentary cover relationships along the Churchill-Superior Boundary Zone, southwestern Manitoba; *in* Eighth International Williston Basin Symposium, J.E. Christopher, D.F. Gilboy, D.F. Paterson and S.L. Bend (ed.), Saskatchewan Geological Survey, Special Publication 13, p. 175.

Klassen, H.J. 1996: An overview of the regional geology and petroleum potential, Lodgepole Formation, southwestern Manitoba; Manitoba Energy and Mines, Petroleum and Energy Branch, Petroleum Open File POF 15-96, 42 p.

McCabe, H.R. 1959: Mississippian Stratigraphy of Manitoba; Manitoba Department of Mines and Natural Resources, Mines Branch, Winnipeg, Publication 58-1, 99 p.

Nicolas, M.P.B. 2012: Stratigraphy and regional geology of the Late Devonian-Early Mississippian Three Forks Group, southwestern Manitoba (NTS 62F, part of 62G, K); Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, Geoscientific Report GR2012-3, 92 p.

Nicolas, M.P.B. 2018: Summary of helium occurrences in southwestern Manitoba; *in* Report of Activities 2018, Manitoba Growth, Enterprise and Trade, Manitoba Geological Survey, p. 110–118.

Nicolas, M.P.B. 2023: Manitoba's designated oil fields and pools 2023; Manitoba Economic Development, Investment and Trade, Manitoba Geological Survey, URL <https://manitoba.ca/iem/petroleum/f_p_codes/poolbook_2023.pdf> [October 2024].

Nicolas, M.P.B. and Yang, C. 2022: Stratigraphy and distribution of the potash-bearing members of the Devonian Prairie Evaporite, southwestern Manitoba (parts of NTS 62F, K); *in* Report of Activities 2022, Manitoba Natural Resources and Resource Development, Manitoba Geological Survey, p. 87–95.

Nicolas, M.P.B., Matile, G.L.D., Keller, G.R. and Bamburak, J.D. 2010: Phanerozoic geology of southern Manitoba; Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map SM2010-1, 2 sheets, scale 1:600 000.

Nicolas, M.P.B., Smith, C.M. and Smith, M.P. 2023a: Rock Volatiles Stratigraphy data from drill cuttings from three oil wells in southwestern Manitoba (parts of NTS 62F2, K3); Manitoba Economic Development, Investment, Trade and Natural Resources, Manitoba Geological Survey, Data Repository Item DRI2023014, Microsoft® Excel® file.

Nicolas, M.P.B., Smith, C.M. and Smith, M.P. 2023b: Volatiles analysis of drill cuttings to evaluate the helium prospectivity of southwestern Manitoba (parts of NTS 62F2, K3); *in* Report of Activities 2023, Manitoba Economic Development, Investment, Trade and Natural Resources, Manitoba Geological Survey, p. 93–104.

Nicolas, M.P.B., Smith, C.M. and Smith, M.P. 2024: Rock Volatiles Stratigraphy data from drill cuttings from four oil wells in southwestern Manitoba (parts of NTS 62F2, K3); Manitoba Economic Development, Investment, Trade and Natural Resources, Manitoba Geological Survey, Data Repository Item DRI2024008, Microsoft® Excel® file.

Smith, C.M., Gordon, P.S., Smith, T.M. and Smith, M.P. 2024: Advanced novel analysis of helium in legacy cores from nine wells having known helium contents: an attempt to develop a helium exploration and production tool; Canadian Energy Geoscience Association–Canadian Society of Exploration Geophysicists, Annual Convention (GeoConvention 2024), June 17–19, 2024, Calgary, Alberta, abstract, URL <https://geoconvention.com/wp-content/uploads/abstracts/2024/107588-advanced-novel-analyses-of-helium-in-legacy-cores.pdf> [September 2024].

Smith, C., Smith, M.P., Gordon, P.S., Smith, T.M., Flynn, J., Kohlruss, D. and Yurkowski, M.M. 2023: Understanding the subsurface helium system of Saskatchewan with a focus on traps/seals via volatiles analysis of helium and other compounds in legacy cores; *in* The Rocky Mountain Association of Geologists, North American Helium Conference, Program Book, March 22–23, 2023, Westminster, Colorado, p. 50–51.

Smith, C.M., Smith, M., Gordon, P., Smith, T., Flynn, J., Priddell, T. and Yurkowski, M. 2022: Rock volatiles analyses of the B.A. Saskatchewan Landing Core — detailed fluid, reservoir, and cap rock insights from the C1-C10 hydrocarbons, organic acids, CO_2, formation water, helium, various sulfur gases, and mechanical strength: implications for helium system analysis; *in* Twenty-Ninth Williston Basin Petroleum Conference, Dr. Don Kent Core Workshop Volume, Saskatchewan Geological Society, Special Publication No. 27, p. 1–9.