Relation of Stratigraphy and Facies Heterogeneities to Hydrogen Sulphide Distribution in the Montney Formation of Northeastern British Columbia (Parts of NTS 093, 094)

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Introduction

The Lower Triassic Montney Formation within the Western Canada Sedimentary Basin (WCSB) is a prolific hydrocarbon reservoir hosting 12 719 billion m^3 (449 tcf) of natural gas, 2308 million m^3 (14 521 million barrels) of natural-gas liquids and 179 million m^3 (1125 million barrels) of oil (National Energy Board et al., 2013). Within Triassic reservoirs of the WCSB, the hydrogen sulphide (H_2S) content of sour gas, which is a highly corrosive and toxic gas leading to costly safety, environmental, and production measures, can range from less than 1 to up to 29% (Kirste et al., 1997; Desrocher et al., 2004). There is a range of processes that can generate H_2S, including thermochemical sulphate reduction (TSR), microbial sulphate reduction and thermal chemical alteration of organic matter in oil or kerogen (Orr, 1977; Worden and Smalley, 1996; Machel, 2001). In most sour gas reservoirs globally, sulphate-rich fluids dissolved from evaporite minerals are a key contributor to H_2S gas formation (Hutcheon et al., 1995; Machel et al., 1995; Worden and Smalley, 1996).

Within the Montney Formation, previous studies have interpreted the source of the dissolved sulphate contributing to the H_2S as evaporite beds in the overlying Charlie Lake Formation (Kirste et al., 1997; Desrocher et al., 2004; Chalmers et al., 2021). Earlier studies (Kirste et al., 1997; Desrocher et al., 2004) focused on H_2S-gas stable isotope geochemistry and did not account for the diagenetic process associated with the dissolved sulphate. Recent studies have re-evaluated Montney Formation H_2S sourcing by examining sulphate minerals associated with H_2S generation and found a mix of both Devonian and Triassic isotopic signatures (Liseroudi et al., 2020, 2021; Chalmers et al., 2021). The samples in these studies from northeastern British Columbia (BC) were selected to primarily focus investigations on the Upper Montney, with limited data from the Middle Montney or Lower Montney (Liseroudi et al., 2020, 2021; Chalmers et al., 2021). A recent study integrating stratigraphy and sulphur-isotope geochemistry highlighted the complex diagenetic history of the Montney, which is laterally discontinuous and highly variable regionally (Kingston et al., 2021). Local, detailed intramember stratigraphy or facies associated with each sample were not considered within the scope of these studies. However, local stratigraphy and the distribution of facies have been shown to influence reservoir properties (Wood, 2013; Wood and Sanei, 2016) and, likely, H_2S distribution. Previously mapped updip Montney gas-migration fairways (Wood and Sanei, 2016; Sereda and Fur, 2017; Euzen et al., 2019, 2021) may additionally impact elevated H_2S occurrences. The aim of this study is to better understand the local stratigraphic and facies context that coincides with elevated levels of H_2S distribution within the Montney Formation of northeastern BC (Figure 1) and to further build upon this by integrating and comparing the outcome with other Montney fluid-distribution studies.

Geological Background

The Lower Triassic Montney Formation unconformably overlies the Paleozoic Belloy Formation and is in turn unconformably overlain by either the Sunset Prairie Formation or Doig phosphate zone in northeastern BC (Armitage, 1962; Furlong et al., 2018a, b; Zonneveld and Moslow, 2018). The Montney Formation consists of a westward-thickening wedge of dolomitic siltstone, sandstone and bioclastic-rich intervals, which represent deposition within the lower shoreface, offshore transition and offshore marine environments (Davies et al., 1997; Davies et al.,

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2018; Zonneveld and Moslow, 2018). Regionally, there are three Montney members, the Lower Montney, Middle Montney and Upper Montney, which are well-established third-order sequences, recording an overall westward progradation of the Montney over time (Davies et al., 1997; Crombez et al., 2016; Zonneveld and Moslow, 2018). Overlying the Montney, is the Middle Triassic Sunset Prairie Formation (a mixed siliciclastic-carbonate interval), Doig phosphate zone (a phosphate-rich interval at the base of the Doig Formation), Doig Formation (clastic offshore to shoreface succession) and Halfway Formation (clastic shoreface succession; Figure 2; Armitage, 1962; Furlong et al., 2018a, b). Stratigraphically above the Middle Triassic formations lies the Upper Triassic Charlie Lake Formation, which consists of a series of evaporitic deposits (Hunt and Ratcliffe, 1959; Armitage, 1962) emplaced during a tectonically active time, as evidenced by the presence of the angular Coplin unconformity (Davies, 1997). The Triassic represents an overall regression event as the paleoshoreline moves westward through time, with the youngest Triassic sediments being eroded before deposition of the Jurassic Fernie Formation (Armitage, 1962).

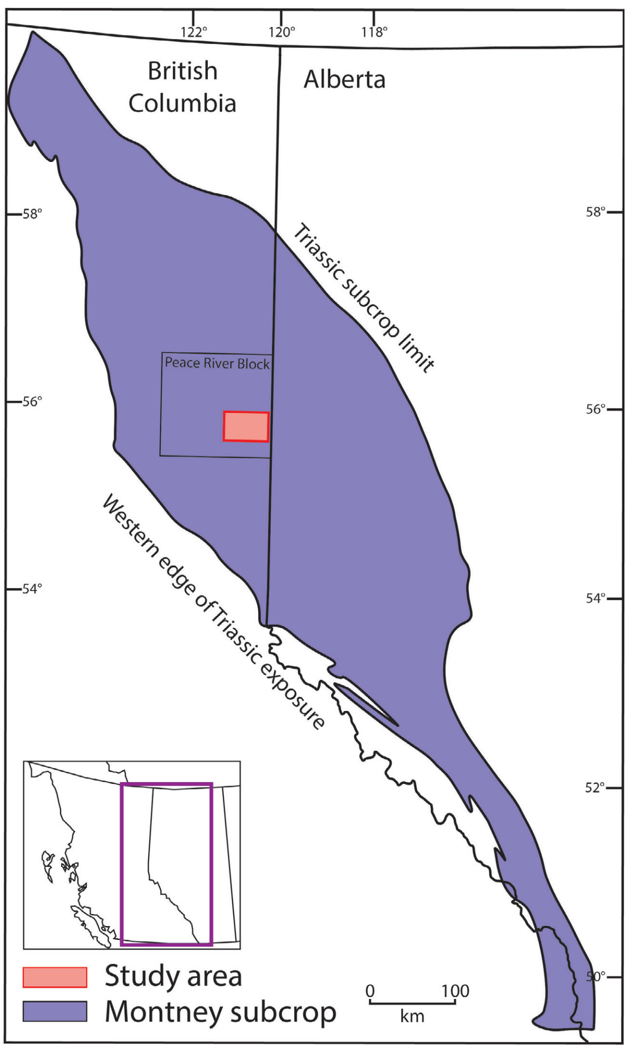

Figure 1. Location of the study area in northeastern British Columbia (modified from Wood and Sanei, 2016).

Study Area and Methodology

The area studied in this research is in northeastern BC, within the Peace River block, spanning from Twp. 79 to 81, Rge. 14 to 18 W 6th Mer. (Figure 3). This study area was selected based on the availability of a relatively dense dataset of Montney wells, a well-established structural history and the presence of varied H_2S concentrations within the different Montney members. Within this study area, the Montney Formation unconformably overlies the Paleozoic Belloy Formation and unconformably underlies the Sunset Prairie Formation (Furlong et al., 2018a, b).

Within the northeastern BC study area, 865 vertical wells penetrate the Montney Formation and 1656 lateral wells produce from the Montney Formation. Using these wells logs, a regional stratigraphic framework was established with the Lower Montney, lower Middle Montney, upper Middle Montney, and Upper Montney units by picking tops, guided by previous work by Davies et al. (2018), Euzen et al. (2018), Proverbs et al. (2018), Zonneveld and Moslow (2018) and Furlong et al. (2021). Once the regional Montney stratigraphy was established, parasequences within individual Montney units were initially selected based on coarsening-upward trends within the core, which were tied to wireline-log signatures, then correlated and extrapolated throughout the study area. Depending on

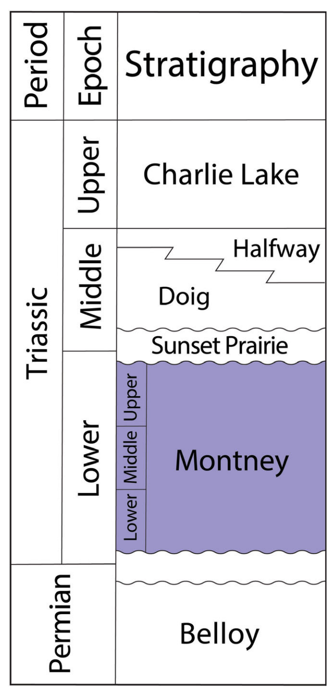

Figure 2. Stratigraphic column of the Montney Formation and surrounding formations in northeastern British Columbia (modified from Furlong et al., 2018a, b).

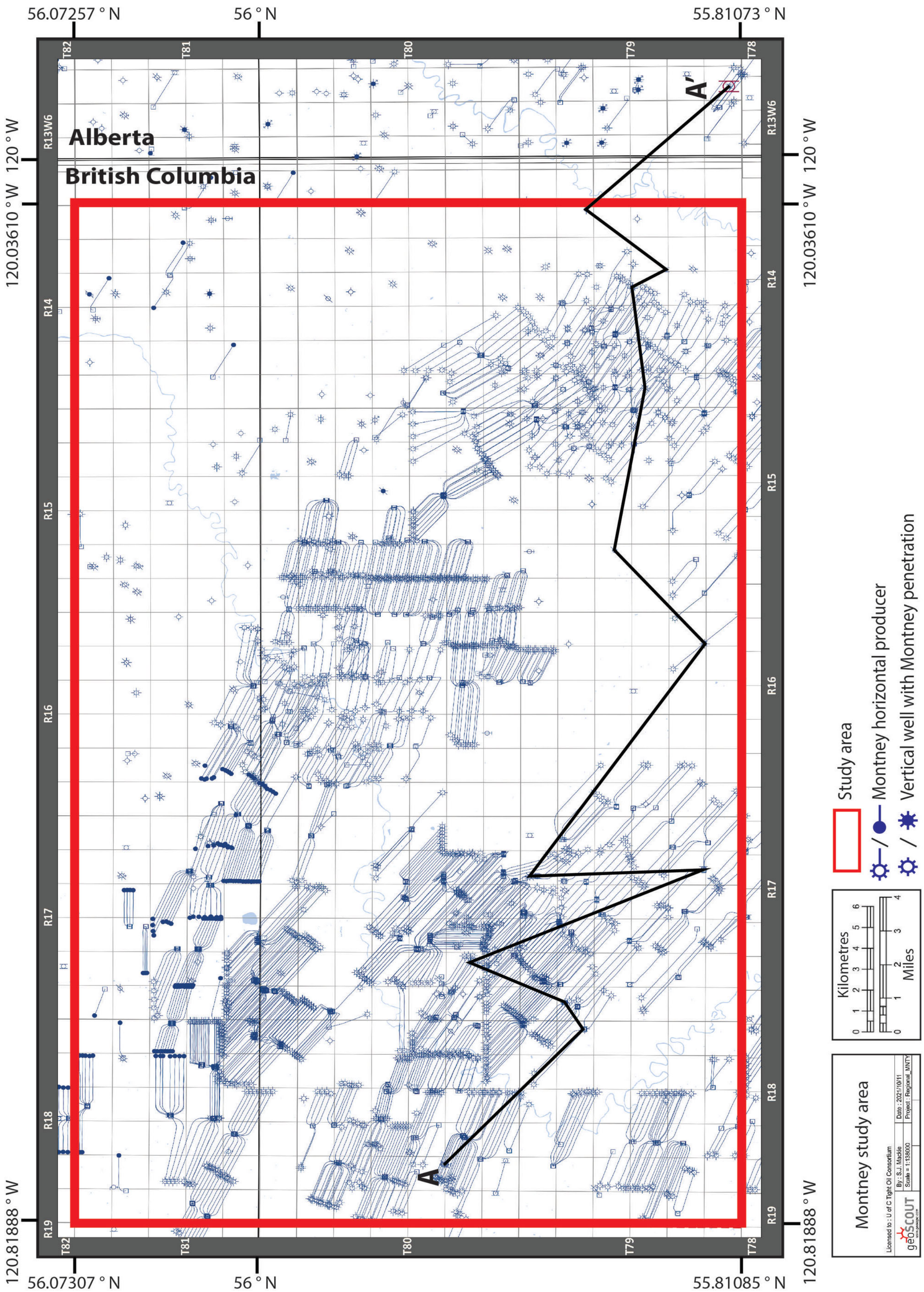

Figure 3. Study area in northeastern British Columbia, showing Montney Formation horizontal producers and vertical wells. The cross-section (A–A′) in the southern portion of the study area can be viewed in Figure 4 (geoLOGIC systems ltd., 2021).

their availability, a combination of gamma-ray, resistivity, photoelectric and neutron density/porosity logs were used in the process of correlating the logs. In general, the log patterns display an overall coarsening-upward trend (gamma decreasing and resistivity increasing upward within the log package).

Once parasequences were established throughout the study area, the facies were examined in detail. Using the Montney facies scheme established by Furlong et al. (2021), Montney facies were picked in seven cores throughout the study area. The Furlong et al. (2021) facies scheme includes detailed facies that can be binned into three categories: fine-grained silt, coarse-grained silt and carbonate-rich intervals. These binned categories allow for broad facies correlations on a larger scale. Once the facies were picked in the core, the binned facies categories were correlated to wireline-log signatures using a combination of available gamma-ray, resistivity, photoelectric and neutron density/porosity logs. After establishing the wireline-log signatures, the binned facies were correlated in the vertical wells throughout the study area; establishing the facies regionally in the study area leads to a better understanding of the vertical and lateral facies heterogeneities present. These heterogeneities were then placed in the context of the established parasequences. Using both the parasequences and facies-distribution area is key to understanding the H_2S-distribution maps.

Accessing publicly available gas-analysis data through the geoSCOUT platform developed by geoLOGIC systems ltd., the maximum recorded H_2S value for each well was obtained (geoLOGIC systems ltd., 2021). As the recorded H_2S values are highly dependent on sample-container type (e.g., natural gas cylinder, IsoTrap®), sample-point location (e.g., wellhead vs. plant) and well-production time, the maximum H_2S values were used since the research goal of this study was improved risk mitigation. Within the study area, approximately 20% of the Montney wells (334 wells) had sour gas concentrations greater than 0.01%, which was the minimum threshold recorded. The wells were categorized based on the Montney units in which they are landed and from which they produce. The wells were categorized visually by placing horizontal wells within a cross-section of vertical offsets containing the stratigraphic framework that was established based on previous work by Davies et al. (2018), Euzen et al. (2018), Proverbs et al. (2018), Zonneveld and Moslow (2018) and Furlong et al. (2021), and used to determine which landing zone was targeted based on the wireline-log signatures. These subdivisions include the Lower Montney, lower Middle Montney, upper Middle Montney and Upper Montney. Once all Montney wells were placed within a Montney unit, the maximum H_2S data was plotted and contoured logarithmically for each Montney unit due to the high fluctuation in values (0.01–1%). A compilation of major Triassic normal faults associated with pull-apart basins (Furlong et al., 2018a, b), including the southern edge of the Fort St. John graben, were then overlain onto the maps to incorporate the regional structural events.

Results

Facies Distribution and Stratigraphic Correlations

Facies, classified/identified in core based on the facies scheme from Furlong et al. (2021), highlight the geological variability within the Montney Formation. Within an individual core, coarsening-upward sequences are visible at the millimetre to centimetre scale and generally record an overall coarsening upward of the entire Montney. Correlating the core facies to the wireline-log signatures allowed for facies to be correlated across the study area, highlighting the vertical and lateral facies heterogeneities present within the Montney Formation. Within the study area, the stratigraphic framework was produced by picking parasequences within each Montney unit: four parasequences were picked within the Lower Montney, three within the lower Middle Montney, four within the upper Middle Montney and eight within the Upper Montney. Examining the correlated facies in combination with the picked parasequences makes it possible to place the facies within the stratigraphic framework (Figure 4). Generally, within individual Montney units, facies are more distal near the bottom of the unit and increase upward through the unit as they near the shoreline. Each Montney unit has the fine-grained, silt-dominated facies in the lower portion and the increased coarse-grained, silt-component facies situated stratigraphically above. However, the carbonate-rich intervals are only present within the upper portion of the Lower Montney and the upper Middle Montney in this study area. Additionally, the stratigraphic framework shows that similar facies at a similar depth are not necessarily within the same parasequence and, thus, may present slight geological differences.

Trends in H_2S

The H_2S data were split according to the Montney Formation unit to which they belonged, and maps were constructed to logarithmically contour the data (Figure 5). The Lower Montney had the smallest dataset with only nine wells, of which eight, or 88%, have H_2S (≥0.01%); the H_2S concentration spanned from 0.01 to 1.00%. The Lower Montney wells are landed in the eastern portion of the study area and represent a limited dataset; there are too few wells landed in the Lower Montney near the normal faults to confidently correlate structural trends to H_2S distribution.

The lower Middle Montney had 241 wells, of which 123, or 51%, had H_2S (≥0.01%). The data from the lower Middle Montney exhibited an arc trend across the study area that

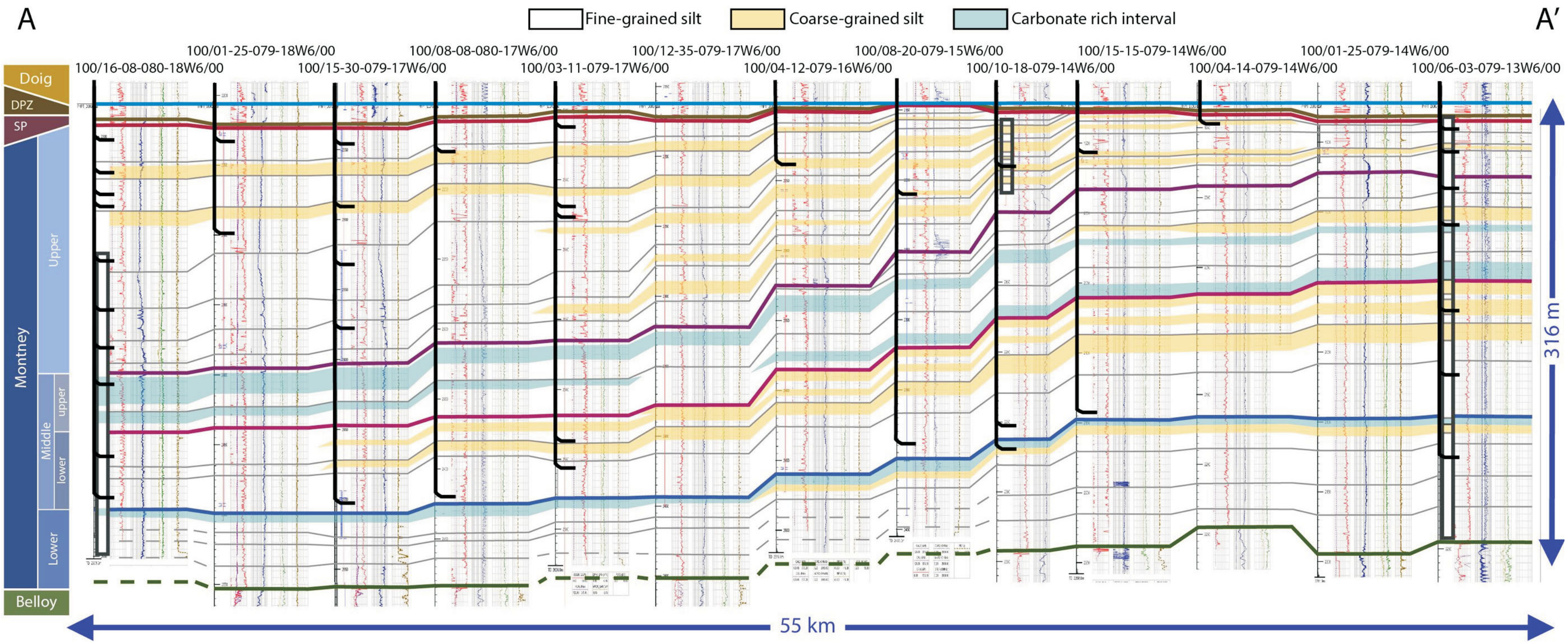

Figure 4. Stratigraphic cross-section highlighting the Montney Formation units and the parasequences within individual Montney units in northeastern British Columbia. The Montney facies, based on a scheme developed by Furlong et al., (2021) were mapped across the study area and constrained laterally within individual parasequences. The variability in vertical and lateral facies heterogeneities highlights the complexity of the Montney Formation. Montney lateral facies are schematically projected onto cross-section A–A′ (location shown in Figure 3), highlighting various operational target zones. Well logs are accessed through the geoSCOUT program (geoLOGIC systems ltd., 2021). Abbreviations: DPZ, Doig phosphate zone; SP, Sunset Prairie.

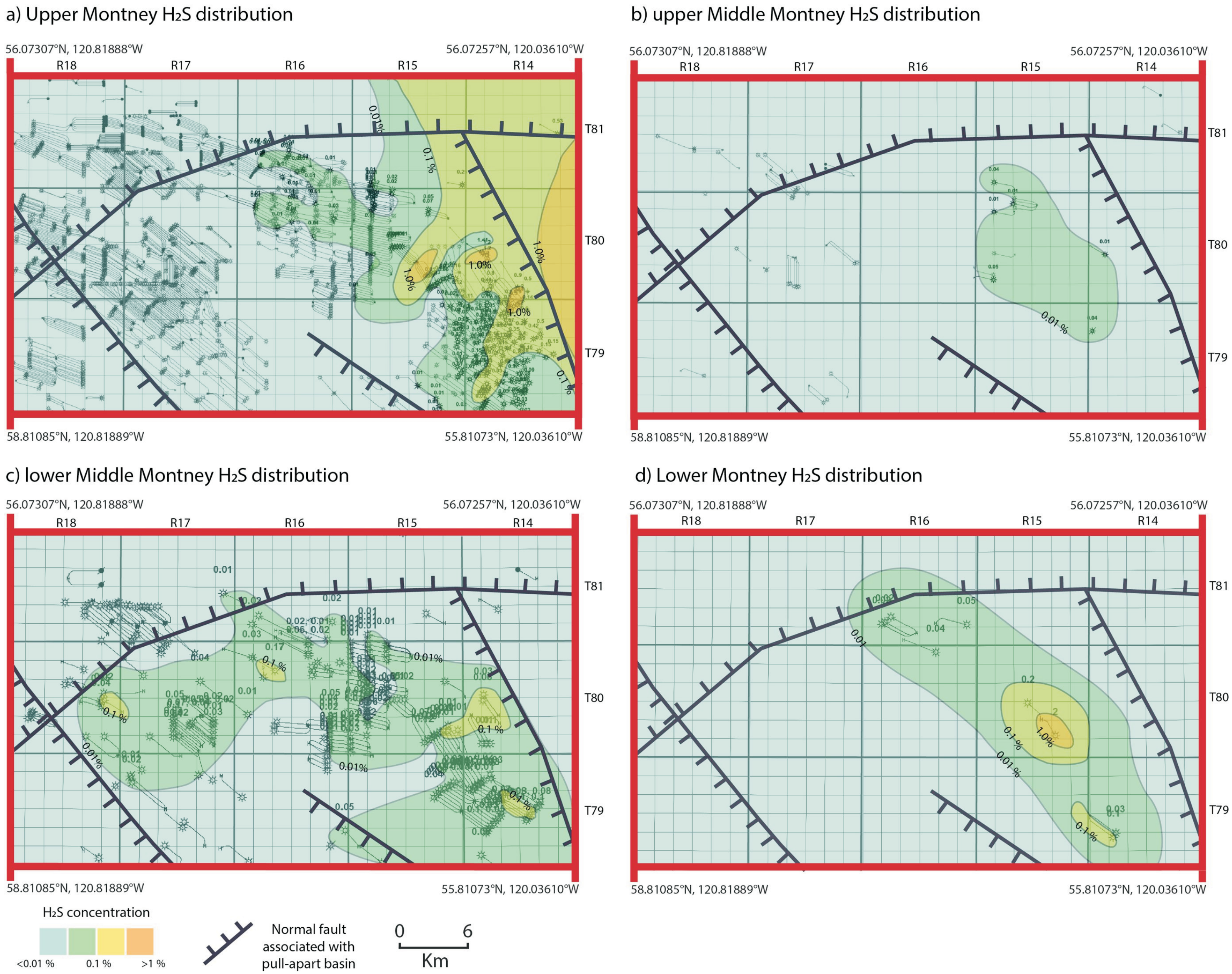

Figure 5. Montney Formation H_2S distribution within the study area, northeastern British Columbia, split according to individual Montney units and contoured logarithmically with an overlay of major normal faults compiled from Furlong et al. (2018a, b): **a)** Upper Montney H_2S map, showing a drastic increase in H_2S content toward the east of the study area; **b)** upper Middle Montney H_2S map, showing a small dataset primarily with H_2S in the eastern portion of the study area; **c)** lower Middle Montney H_2S map, displaying an arc shape across the study area, which may change as more wells are drilled in the northern portion; and **d)** Lower Montney H_2S map, using a very limited dataset that shows high enrichment of H_2S in the eastern portion of the study area.

marginally aligns with the pattern of faulting. However, the trend may become more linear and may fill in toward the north and south as more wells are drilled and the gas is tested over time. The H_2S concentration spread varies from 0.01 to 0.1%.

The upper Middle Montney consists of a sparse dataset with a total of 41 wells, of which 6, or 15%, are enriched in H_2S (≥0.01%). The H_2S concentration ranges from 0.01% to just under 0.1%. The wells containing H_2S are concentrated in the eastern portion of the study area. There are too few wells landed in the upper Middle Montney near the normal faults to confidently correlate structural trends with H_2S distribution.

The Upper Montney has the largest dataset with 1365 wells landed, of which 197, or 14%, are enriched in H_2S (≥0.01%). The Upper Montney wells with H_2S are concentrated in the eastern portion of the study area and rapidly increase in concentration from 0.01% to 1%. Generally, although there are faults in the eastern portion of the study area enriched in H_2S, the fact there are insufficient Upper Montney wells directly near the eastern fault means this trend cannot be fully correlated and the matter requires further investigation.

Discussion

Examining the H_2S-production distribution maps for each Montney unit alongside the regional cross-section allows to better visualize the trends from the datasets. In the Upper Montney, the elevated H_2S is primarily in the eastern portion of the study area. Upper Montney wells that reveal the same binned, coarse-grained silt facies within a single parasequence can have absent, low or high H_2S content, highlighting the lateral variability. The H_2S content increases eastward and may be linked to the overlying thinning of the Doig–Halfway formations to the east (Edwards et al., 1994), allowing for sulphate-rich fluids sourced from anhydrite beds in the Charlie Lake Formation to diffuse downward into the Montney Formation (Desrocher et al., 2004). Between the 100 08 20 079 15 W6 00 well and the 100 04 14 079 14 W6 00 well (BC Oil and Gas Commission, 2021), the Doig and Halfway formations thin by approximately 12%, from about 118 to around 103 m. In addition to the thinning overlying units, there are structures in the east that may additionally be linked to the elevated H_2S content; further work needs to be done to fully understand this relationship. Within the Charlie Lake Formation, tectonic activity is evident, as indicated by the presence of the angular Coplin unconformity (Davies, 1997), and may have provided conduits for early sulphate-rich fluid migration. This is consistent with recent sulphur-isotope fingerprinting analysis that shows that Upper Montney samples in northeastern BC have a Triassic signature (Chalmers et al., 2021), but contrasts with previous studies in west-central Alberta, which have shown a Devonian signature on sulphur-isotope data that has been interpreted as upward fluid migration through faults acting as conduits (Liseroudi et al., 2020), thus highlighting the regional diagenetic variability within the Montney Formation (Kingston et al., 2021).

A recent study by Liseroudi et al. (2021), based on the relationship between the $\delta^{34}S$ values of the present-day produced-gas H_2S and other sulphur-bearing species from the Montney and neighbouring formations, proposed a dual in situ and migrated TSR-derived origin for the H_2S gas, with substantial contributions of in situ H_2S in the Montney Formation. Within a single Upper Montney parasequence in a similar binned facies over a distance of under 10 km, the increasing H_2S content eastward suggests that in situ H_2S-generating mechanisms increase eastward. These in situ mechanisms may be increased due to early dissolution from the Charlie Lake anhydrite associated with a combination of the overlying thinning Halfway–Doig formations, bringing the Charlie Lake Formation closer to the Montney (Edwards et al., 1994), and faults acting as fluid conduits. However, further research needs to be completed to better understand this relationship.

In the lower Middle Montney and Lower Montney, H_2S content increases with proximity to the contact between the lower Middle Montney and Lower Montney, and the contact with the underlying Paleozoic Belloy Formation. Additionally, the carbonate-rich facies present along the boundary between the lower Middle Montney and Lower Montney may act as an in situ sulphate source. Wells landed stratigraphically higher within the lower Middle Montney do not have high H_2S concentrations. In comparison, wells landed closer to the base of the lower Middle Montney and in the Lower Montney produced relatively higher concentrations of H_2S gas. Another potential sulphate source is the underlying Belloy Formation, which is known to contain anhydrite (Naqvi, 1972). Previously mapped isopachs of Lower Montney in this study area thin westward by approximately 100 m (BC Oil and Gas Commission, 2012). However, due to the limited number of Lower Montney produ-cers in this study and marginal variations in the lower Middle Montney H_2S concentrations (0.01–0.1%), there is no distinct trend between Lower Montney thickness and H_2S content. Further work is required to properly understand the Montney H_2S-Belloy Formation relationship. Within the lower Middle and Lower Montney, two examples were found in which H_2S concentrations increased temporally during production (Table 1). The increase in H_2S content may be due to diffusion upward through time as the wells are produced or may be derived from faults acting as fluid conduits, similar to the situation that has been established in Alberta (Liseroudi et al., 2020).

Table 1. Examples from two wells in northeastern British Columbia show Lower Montney and lower Middle Montney H_2S production varying with time. Publicly available gas-analysis data accessed through the geoSCOUT program (geoLOGIC systems ltd., 2021). Abbreviation: UWI, unique well identifier.

UWI	Unit	Test date	H2S (%)
100 03 17 079 14 W6 00	lower Middle Montney	12-Sep-2019	0
100 03 17 079 14 W6 00	lower Middle Montney	17-Sep-2020	0.02
102 12 08 079 14 W6 00	Lower Montney	01-Sep-2019	Trace
102 12 08 079 14 W6 00	Lower Montney	20-Sep-2020	0.1

Conclusions and Future Work

Within the northeastern BC study area, H_2S concentrations in the Upper Montney increase toward the east as the Halfway and Doig formations thin, bringing the overlying anhydrite beds of the Charlie Lake Formation nearer to the Montney Formation. The Upper Montney of northeastern BC has been shown to contain sulphate minerals with a Triassic signature, supporting in situ H_2S that is TSR derived (Liseroudi et al., 2021) and not solely sourced from fluids that migrated up from underlying strata. Within the study area, H_2S in the Lower Montney and lower Middle Montney Formation increases downward, approaching the carbonate facies at both the lower Middle Montney–Lower Montney boundary and the underlying Paleozoic Belloy Formation, which is another anhydrite-rich carbonate unit. Although the dataset from the Lower Montney is limited, the H_2S concentration of produced gases is shown to increase over time in a few isolated examples, potentially implying that fluids drawn to the wellbore include H_2S diffusing or migrating through faults upward, which is consistent with previous regional findings (Liseroudi et al., 2020, 2021). Further work is required to better understand this process and sulphur-isotope fingerprinting of wells landed in the lower Middle Montney and Lower Montney formations is recommended for future studies. Understanding from where the stratigraphically lower H_2S is sourced may help better understand H_2S distribution in northeastern BC. In addition, further delineating of structures in the Lower Montney may provide insight into whether the fluids are migrating through faults acting as conduits or if they are diffusing sporadically from the underlying Belloy Formation. Comparing previously published mapped updip gas-migration fairways (Wood and Sanei, 2016; Sereda and Fur, 2017; Euzen et al., 2019, 2021) with the H_2S distribution mapped in this study may also provide insight on fluid-migration pathways. Improved understanding of the facies and stratigraphic controls on H_2S distribution within northeastern BC is key to enhancing prediction and mitigation of this highly toxic gas, improving environmental and worker safety, as well as improving the economic perspective for operators in this area.

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