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Hydrocarbon Self-Sourcing and Migration in the Montney Formation: A Mass Balance Organic Geochemistry Approach at the WCSB Scale

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Summary

Quantifying hydrocarbon generation in unconventional oil and gas plays is critical to understanding the degree of self-sourcing and charge by migration, both of which are important to characterizing regional petroleum systems. The three main sequences of the Triassic Montney Formation in the Western Canadian Sedimentary Basin are relatively lean with respect to present-day TOC. As a result, the prolific hydrocarbon charge has been variously attributed to some combination of overlying and underlying TOC-rich source rocks, as well as distal Montney facies in the deep basin. A mass-balance organic geochemistry approach is presented here to spatially quantify Montney hydrocarbon generation as a function of original TOC, generative potential, and thermal transformation. The totals across the basin are separated into phase windows and compared to today's estimated resource in place. Results highlight regions with excess and deficit hydrocarbon generation in relation to resource in place, with further respect to depth, erosional surfaces, and subcrop edges. Calculations show that the Montney has generated more than twice the hydrocarbons in place today, far more than is sufficient to charge the entire system. Where maximum generation has taken place, most of the hydrocarbons have necessarily left the local system (migrated out vertically and/or horizontally). Where reservoired volumes exceed generation, migration to the local system is required (from down-dip Montney and overlying Doig and Nordegg source rocks) to fill the hydrocarbon generation shortfall. The above observations are consistent with available oil family data. This evaluation provides a first-order delineation of where hydrocarbon charge of Montney Formation requires migration, and it underscores the importance of regionally characterizing the lateral variability in source rock hydrocarbon generation in unconventional systems.

Introduction

The Lower-Middle Triassic Montney Formation in the Western Canadian Sedimentary Basin (WCSB) comprises interbedded, fine-grained dolomitic to siliciclasitic sandstones, siltstones, and shales. Three main sequences (lower, middle, and upper) can be defined by regional unconformities and sequence boundaries (Figure 1). Each Montney sequence consists of three main facies (proximal, distal, and deep basin) associated with prodeltas sourced from the east. Deep basin shelf facies have higher TOC compared to the distal and proximal prodelta facies (Proverb et al., 2018). Subcrop edges of the Montney sequences differ in their eastward extent (Figure 2), and their relation to the overlying Doig and Nordegg source rocks play a key role in the overall petroleum system (Figure 3).

The Doig Phosphate Zone (PZ) ranges up to 13 wt% TOC, and the "Nordegg member" of the Fernie Formation ranges up to 28 wt% TOC (e.g., Riediger et al., 1990; Crombez et al., 2017). Present-day TOC (TOC_{pd}) in the Montney, in contrast, is low (typically <2.0 wt%). As a result, the

prolific hydrocarbon charge of the Montney was historically assumed to be dominantly sourced from the overlying TOC-rich source rocks and possibly underlying Devonian source rocks, with proposed contribution from distal Montney facies in the deep basin (e.g., Euzen et al., 2021). More recently, Montney condensate and oils produced from Montney reservoirs have been documented (Feng, 2022; Wurz et al., 2022; Rudra et al., 2024; Zumberge et al., 2025). The capability of the Montney alone to generate sufficient hydrocarbons (HCs) to charge the entire system has been questioned in the past (e.g., Wood et al., 2022), but the recent identification of discrete oil families in Montney reservoirs is key to delineating variable HC charge. This study presents a mass balance organic geochemistry approach to quantifying HC generation by the Montney across the entire WCSB. Comparison to estimated resource in place reveals wide variability in migration character across the basin.

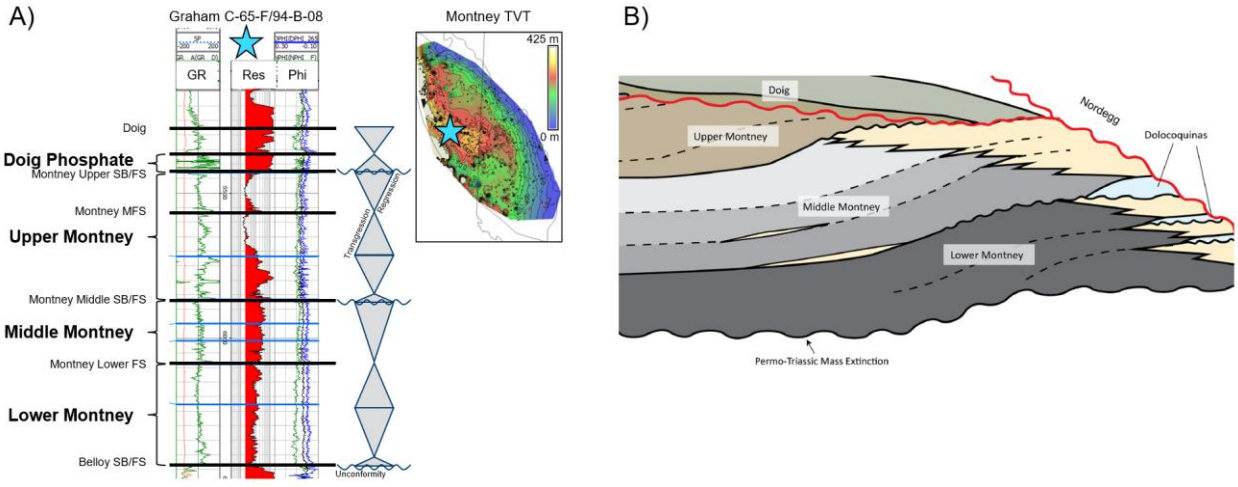


Figure 1. A) Type log, tops, and sequence stratigraphic interpretation used in this study (location shown on Montney gross thickness map). B) Schematic cross-section from SW to NE through the Montney Formation in the WCSB, showing a basic overview of the relative juxtaposition of stratigraphic units and associated facies trends (modified after Watt et al., 2022). SB – sequence boundary, FS – flooding surface, MFS – maximum flooding surface, TVT – true vertical thickness.

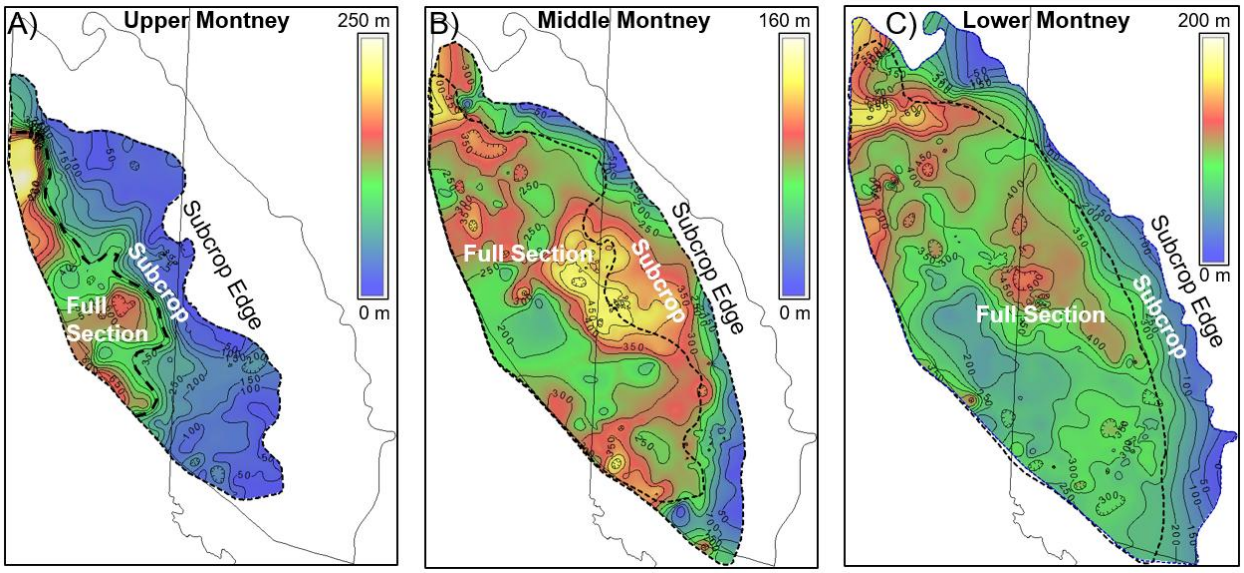


Figure 2. TVT and extents of A) upper Montney, B) middle Montney, and C) lower Montney (contours in feet). Dashed lines show erosional subcrop surfaces and subcrop edges.

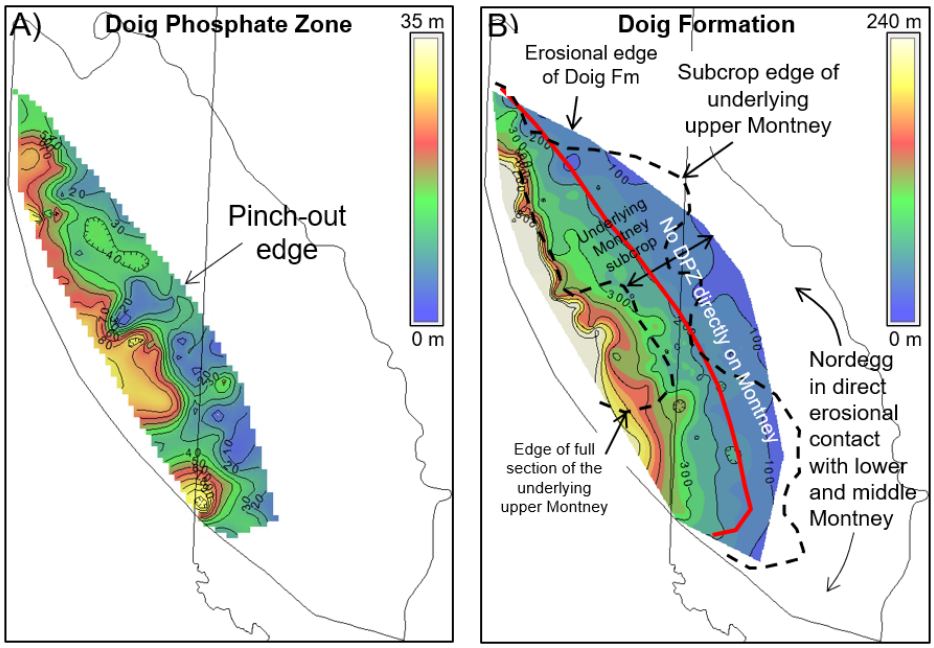


Figure 3. TVT and extents of A) the Doig Phosphate Zone (DPZ), and B) the Doig Formation with the pinch-out edge of the Doig PZ (red line) (contours in feet). Dashed lines in B) show erosional subcrop edges of underlying upper and middle Montney. Note extent of the DPZ in relation to the upper Montney subcrop surface, and where the Nordegg is in direct erosional contact with lower and middle Montney subcrop surfaces.

Methods

The mass balance organic geochemistry approach presented here aims to spatially quantify Montney HC generation as a function of original TOC (TOC_o), generative potential, and thermal transformation. Mapped TOC_{pd} in an area with highly variable thermal maturity, such as a large basin, can be considered the present-day residual from the differential stresses of catagenesis, and therefore such maps obscure the original depositional conditions with respect to organic carbon preservation. Conversion from TOC_{pd} to TOC_o rewinds the thermal stress of maturation and is a foundation to the mass balance analysis. Deriving the best possible TOC_{pd} and thermal maturity maps is critical, because they are key elements in a series of mass balance organic geochemistry equations expressed here in map form to best capture known geologic complexity (Figure 4).

A regional thermal maturity map was created using core data from several public and academic sources. Quality-screened pyrolysis data were favored over vitrinite reflectance in lower maturity areas, but only vitrinite reflectance data are valid and used in the higher maturity gas window. Two depth-maturity gradients were derived from two broad regions of the basin and were applied to evenly scattered well points for areas with little to no core data (Figure 5).

The transformation ratio (TR) map was derived as a function of thermal maturity using an analog Type II kinetics curve from Waples and Marzi (1998) (Figure 5). Note maximum transformation along the deep basin and minimal generation along the shallow eastern basin.

Due to low TOC and the lack of discrete, isolatable source rock shale intervals, a log-based bulk density-TOC relationship is not reliable for the Montney Formation. A favorable GR-TOC relationship (Feng, 2022) is instead used here to create a TOC_{pd} map for the gross Montney section (Figure 6). TOC_o is calculated as a function of thermal maturity, TR, HI_o, and convertible carbon (Cc), where HI_o=442 (from thermally immature core samples) and %Cc=0.376 (from Daly and Edman, 1987) (Figure 6).

Full generative potential of the gross Montney section is a function of HI_o, TOC_o, and thickness and can be scaled and expressed as hydrocarbon pore volume (HCPV) in MMRBO/Sec (initially without a formation volume factor (FVF)) (Figure 7). Note that the conversion from mg HC/g rock uses the constant 20.082 (bbl-g)/(ac-ft-mg HC), which assumes a rock bulk density (source rock shale) to oil density ratio of (2.2 g/cc)/(0.85 g/cc). A final map of HCs generated is revealed by applying the TR map to the full generative potential map (Figure 7). The map is separated into thermal maturity phase windows, generalized FVFs are applied, and stock tank volumes are calculated (Figure 8). Volumes are converted to gas equivalent, when applicable, for comparison to today's estimated resource in place (Figure 8).

Equations		Required Elements
Transformation ratio (TR), function of maturity	←	**Thermal maturity map**, kinetics curve
Convertible carbon (Cc) = (0.085*HI_o)/100	←	Hydrogen Index (immature) from core
TOC_o = TOC_{pd}/(1-(TR*Cc))	←	**TOC_{pd} map (shales)**
Full generative potential $S2_o$ = (HI_o*TOC_o)/100 mg HC/g rock		
Full generative potential $S2_o$ in **HCPV** (MMRBO/Sec) = ($S2_o$ mg HC/g rock map*20.082[1]*640*thickness map)/1,000,000	→	**Basin-scale OGIP/OOIP maps (reservoirs)**
Hydrocarbons generated = Generative Potential map*Transformation Ratio map	→	Produced oils data

Figure 4. Mass balance equations and their relationship to required elements. Critical input maps are in blue. HC generation is derived from source rock facies, and resource in place is from reservoir facies. [1]20.082 (bbl-g)/(ac-ft-mg HC) from Fujine, K., 2014.

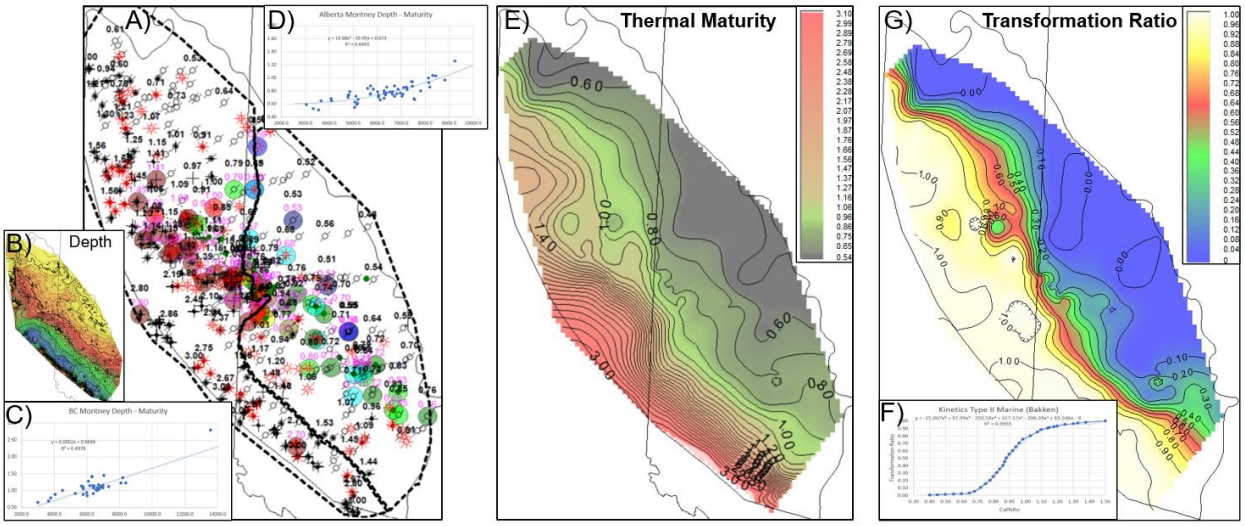


Figure 5. A) Thermal maturity well control and values (%Ro and calculated %Ro) derived from screened core data (bubbles) from several public and academic sources (Ferri et al, 2013; Alberta CRC, Egbobawaye, 2017; Feng, 2022). B) Montney TVD map. C) and D) Depth-maturity gradients for areas with little to no core data. E) Regional Montney thermal maturity map in %Ro equivalent. F) Type II kerogen kinetics curve for Bakken analog: transformation ratio and thermal maturity (after Waples and Marzi,1998). G) Montney transformation ratio map as a function of thermal maturity using analog Type II kerogen kinetics.

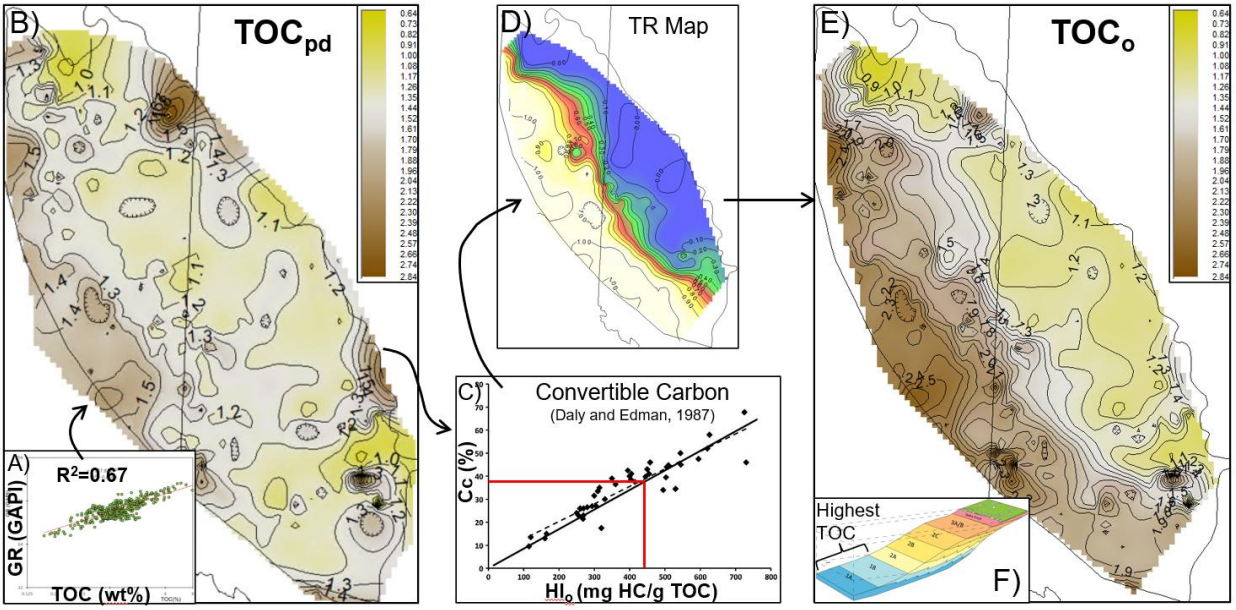


Figure 6. A) GR-TOC relationship from Montney core (Feng, 2022). B) Average TOC_{pd} for the full Montney section. C) Percent convertible carbon (Cc) (0.376) as a function of HI_o (442) (after Daly and Edman,1987). D) Montney transformation ratio map. E) Calculated original TOC map, where $TOC_o = TOC_{pd}/(1-(TR*Cc))$. F) Model for Montney sequences with highest TOC occurring in the deep basin shelf facies (blues) compared to the distal facies (yellows) and proximal prodelta facies (oranges) (from Proverb et al., 2018). Note that the TOC_o map matches well with the sequence model.

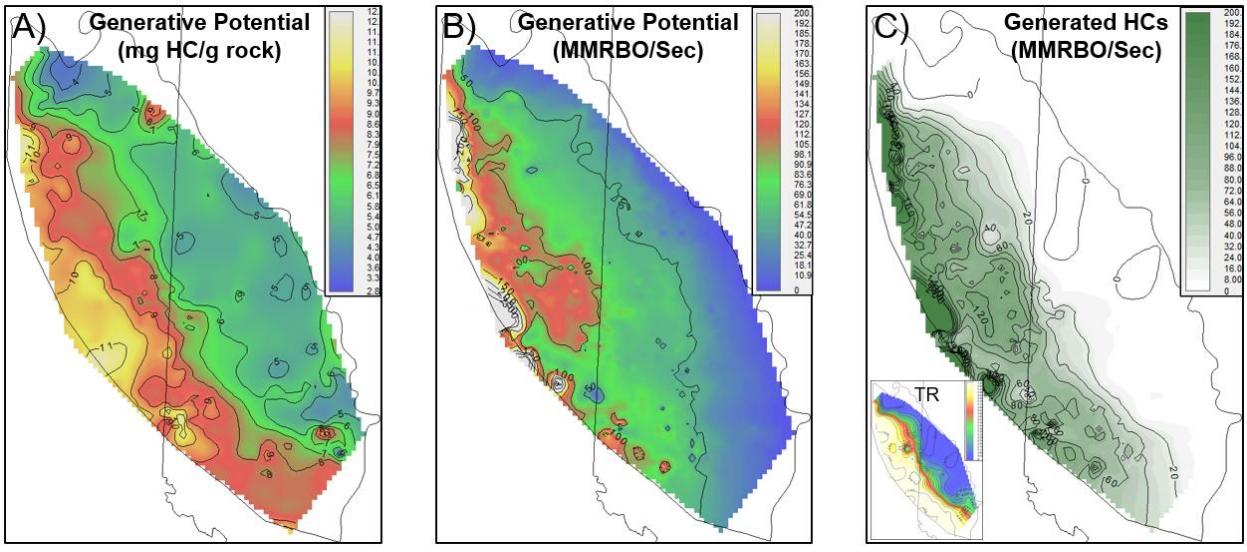


Figure 7. A) Generative potential in mg HC/g rock, where $S2_o=(HI_o*TOC_o)/100$ mg HC/g rock. B) Generative potential expressed in HCPV (MMRBO/Sec), where $S2_o$ HCPV = ($S2_o$ mg HC/g rock map*20.082*640*TVT map)/1,000,000 and 20.082 (bbl-g)/(ac-ft-mg HC) from Fujine, K., 2014. C) Generated hydrocarbons expressed in MMRBO/Sec, where HCs generated = generative potential map*transformation ratio map (inset).

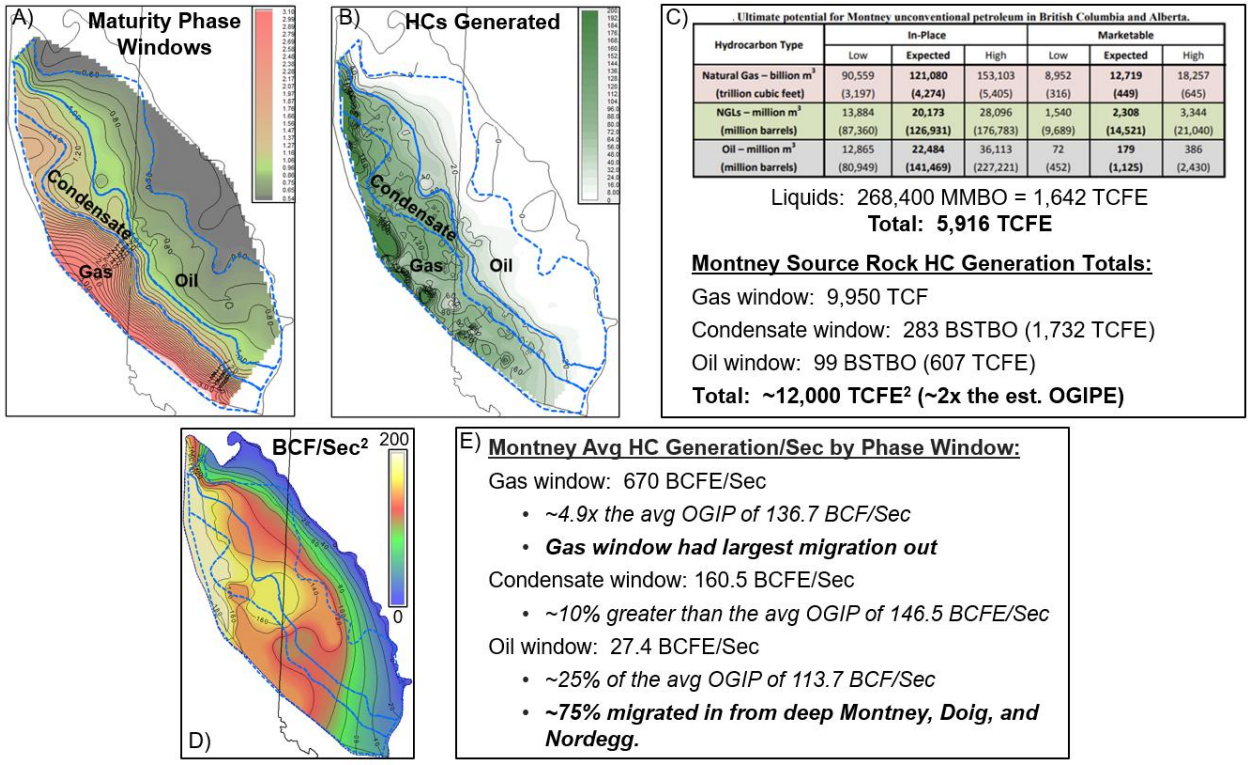


Figure 8. A) Montney thermal maturity map with gas, condensate, and oil window phase windows. B) Montney HCs generated map in HCPV (MMRBO/Sec) in context of thermal maturity phase windows. C) Total hydrocarbons in place for the Montney across the WCSB (National Energy Board, 2013). Liquids are converted to TCFE to total Montney OGIPE. Totals of Montney source rock HCs generated by phase window are converted to stock tank volumes using simple FVFs: gas B_g = 0.001, condensate B_o = 3.0, oil B_o = 1.5. These volumes are in turn converted to TCFE, for comparison purposes, and total ~2x the Montney OGIPE in the WCSB. D) Montney OGIP map (after Jarrah, 2016) in context of thermal maturity phase windows. E) Montney average HC generation/sec in BCFE by phase window compared to average OGIP/Sec (after Jarrah, 2016) by the same phase windows.

Results and Discussion

The basin-scale thermal maturity map honors available core data and shows a dry gas window along the basin axis that grades to the early oil window along the shallow eastern extent of the Montney (Figure 5). The TR map, which is a function of thermal maturity, shows similar spatial trends that range from 100% transformation to little or no transformation. The largest restoration from TOC_{pd} to TOC_o corresponds to highest TR (highest thermal maturity) in deepest part of the basin, where the elevated TOC_o values are consistent with Montney depositional models of higher TOC preservation in distal source facies (Figure 6). The highest TOC_o, thermal maturity, transformation ratio, and thickest Montney section all align along the basin axis. The HC generation map strongly reflects the alignment of these attributes, with the largest generated volumes in the west (as high as 200 MMRBO/Sec), strongly contrasting with negligible generated volumes in the east (Figure 7).

Published basin-scale resource in place estimates for the Montney (National Energy Board, 2013; Jarrah, 2016) - when all HC types are converted to gas equivalent - total 5,916 TCFE (Figure 8).

Total HCs generated, however, total ~12,000 TCFE, which is double the estimated resource in place. This comparison strongly suggests that Montney source rocks were far more than sufficient to charge the entire Montney reservoir system. Parsing generation and in-place totals by phase windows, importantly, reveals the HC generation surpluses and shortfalls compared to OGIP (Figure 8). The gas window has generated ~4.9x the average OGIP. The condensate window has generated ~10% more than the OGIPE, and the oil window has generated only ~25% of the OGIPE. Generation in the gas window greatly exceeds in-place volumes, requiring migration out of the local system. In-place volumes in the oil window exceed generation, so ~75% of the OGIPE in the oil window has necessarily migrated into the system from the source rock of the deeper, higher-maturity Montney and the overlying Doig and Nordegg.

The results presented here highlight regions with excess and deficit HC generation in relation to resource in place, with further respect to depth, erosional surfaces, and subcrop edges. Where maximum generation has taken place, most of the HCs have necessarily left the local system (migrated out vertically and/or horizontally). Where reservoired volumes exceed generation, migration into the local system is required (from down-dip Montney and overlying Doig and Nordegg source rocks) to fill the HC generation shortfall. The above observations appear consistent with available oil family data.

Oil families of produced oils from Montney reservoirs reveal migration patterns in relation to erosional surfaces, subcrop edges, and overlying source rocks (Figure 9). Typing HCs in the gas window is not possible, but the high thermal maturity and maximum HC generation strongly suggest surplus generation and necessary migration to adjacent formations and updip along carrier beds to shallower Montney reservoir rock. The Doig PZ is positioned mainly over the gas and condensate phase windows, but no Doig oils are reported in the limited dataset. Montney reservoirs in the oil window produce Montney and mixed Montney/Doig oils. Doig oil detection is restricted to Doig extents. Nordegg and mixed Montney/Nordegg oil from Montney reservoirs only occurs in the early oil-to-thermally immature/negligible HC generation region east of the main oil window, and east of the Doig subcrop edge, where the Nordegg unconformably overlies the lower Montney (Figure 9).

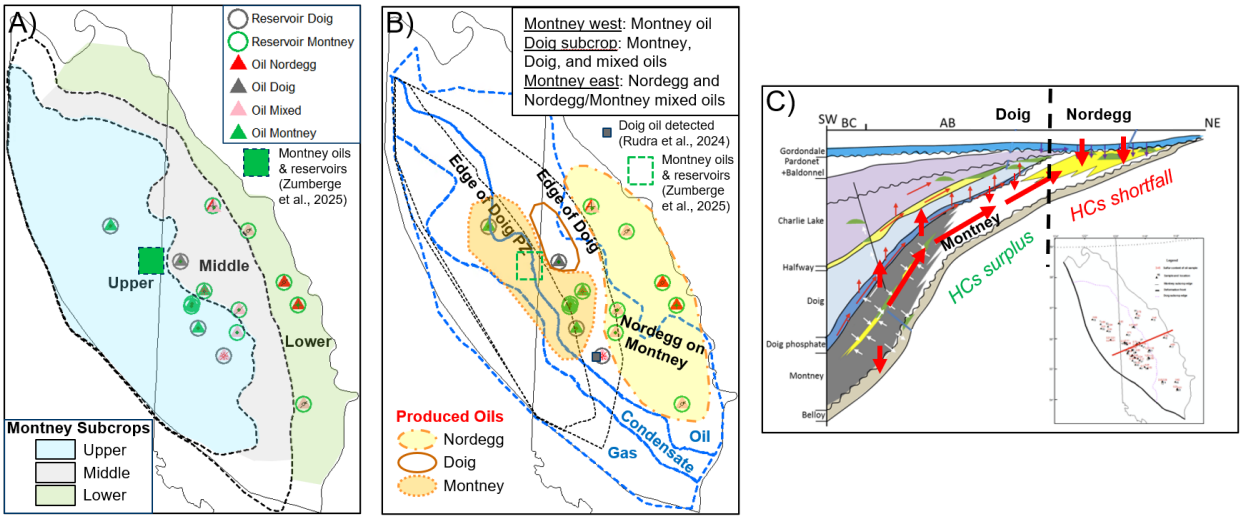


Figure 9. A) Produced oils from Montney and Doig reservoirs in relation to upper, middle, and lower Montney subcrops. All data from Feng (2022), except numerous Montney oils Zumberge et al. (2025) within green square. B) Produced oils in relation to phase windows, Doig PZ extent and Doig subcrop, and Nordegg source rock (east of Doig subcrop edge). Note generalized regions of dominantly Montney oils, Doig oils, and Nordegg oils. Montney thermal maturity phase windows - dashed blue lines; Doig PZ extent and Doig Formation subcrop - dashed black lines. C) Montney HC generation and migration model showing (SW) where generated HCs surplus and migration out of the local system occur vs (NE) where generated HCs shortfall and migration into the local system occur (modified from Feng, 2022).

Limitations and Implications

This evaluation provides a first-order delineation of where HC charge of Montney appears to be fully self-sourced and where it requires migration. The findings are generalized for the basin scale and include some limitations. For example, improved resource in place estimates may be possible and would vary depending on petrophysical technique. But assuming the published OGIPE estimates are reasonable, and key mapped elements such as TOC_{pd} and thermal maturity are broadly accurate, the observations presented here are informative. Inclusion of additional oil family data for oils produced from Montney reservoirs would improve the HC migration model.

The basin-scale analysis presented here helps answer the question of whether Montney source rocks have generated sufficient HCs to charge the entire Montney reservoir system. And the phase window breakdown of HC generation vs in-place volumes explains known complexity such as the presence of Doig, Nordegg, and mixed oils in the oil and immature phase windows. This methodology may be useful for identifying and explaining migration pathways, such as those with anomalously high GORs, and areas with Montney oil maturities that exceed local source rock thermal maturity.

Conclusions

A mass-balance organic geochemistry approach is presented here to spatially quantify Montney hydrocarbon generation as a function of original TOC, generative potential, and thermal transformation. The totals for each phase window are compared to today's basin-scale estimated resource in place for the Montney. Calculations indicate that the Montney Formation has

generated more than twice the in-place volumes of today, more than sufficient volumes needed to charge the entire system. In the gas and condensate windows, generation exceeds OGIPE and requires migration of surplus hydrocarbons out to stratigraphically adjacent formations and to updip Montney reservoir facies. Important unconformities and subcrop edges of the Montney, Doig, and Nordegg are located in the oil and thermally immature windows. Here, a hydrocarbon generation shortfall relative to in-place volumes suggests necessary hydrocarbon charge by migration from overlying source rocks and downdip Montney source rock facies. These results are consistent with available oil family data for oils produced from Montney reservoirs. The above variability in HC generation and migration is the result of variability in TOC_o, thermal maturity and transformation ratio, and unconformities and subcrop edges. This evaluation underscores the importance of regionally characterizing the lateral variability in source rock hydrocarbon generation in unconventional systems.

Acknowledgements

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