Basin Modelling and Thermal History of the Horn River and Liard Basins, Cordova Embayment, and Adjacent Parts of the Western Canada Sedimentary Basin

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Introduction

In sedimentary basins, it is important to gain an understanding of basin evolution. Basin modelling through numerical simulations is a powerful tool in quantifying the burial and thermal history of a basin and hydrocarbon generation, migration and entrapment. Basin modelling requires the integration and knowledge of numerous variables, including regional geology, lithology, stratigraphy, tectonic history and heat flow. The northeastern British Columbia (northeastern BC) portion of the Western Canada Sedimentary Basin (WCSB) is relatively understudied and underexplored compared to most other areas in the basin. Hence, basin modelling can provide significant insights and constraints on the basin history and contribute to predicting the economic potential of this important area.

Previous work in the study area on the Devonian stratigraphy of the Horn River Basin (HRB) and adjacent areas has focused on reservoir properties and resource potential (Stasiuk and Fowler, 2004; Ross, 2007; Ross and Bustin, 2008, 2009a, 2009b; Ferri et al., 2011, 2015; Chalmers et al., 2012; Fiess et al., 2013; Harris and Dong, 2013; Balogun, 2014; Dong et al., 2014; Ferri and Griffiths, 2014; Dong, 2016). There have been few studies that have contributed to understanding the basin evolution and burial history. The few studies that include a basin-modelling component have focused on the Liard Basin and Interior Plains (Morrow et al., 1993; Potter, 1998), on the Peace River arch area (Kalkreuth and McMechan, 1988; Dubey et al., 2017) or farther to the east near the oil-sands deposits (Higley et al., 2009; Berbesi et al., 2012). All of these studies provide important information and methodologies, and lay the groundwork on which the present modelling study is based. Most notably, the Morrow et al. (1993) study of the Liard Basin (mainly within the Northwest Territories) provides key data and insights.

The objective of this study is to use basin modelling to understand the basin evolution and determine the role of various geological properties in the burial and thermal history and subsequent present-day petroleum systems of northeastern BC. One-dimensional (1-D) modelling and sensitivity analysis were performed at 24 well locations throughout the study area, leveraged by publicly available data and a multitude of prior research on the regional geology, lithology and stratigraphy.

Regional Geology and Stratigraphy

Overview and Study Area

This study focuses on the Horn River Basin and the Cordova Embayment in northeastern BC, northwestern Alberta and adjacent areas, as well as a portion of the Liard Basin (Figure 1). This roughly encompasses an area extending from 59 to 60°N and from 118 to 124°W. This large area contains a thick succession of Phanerozoic sedimentary rocks, including the extensive Devonian-age, organic-rich source rocks that are the focus of this research. The main

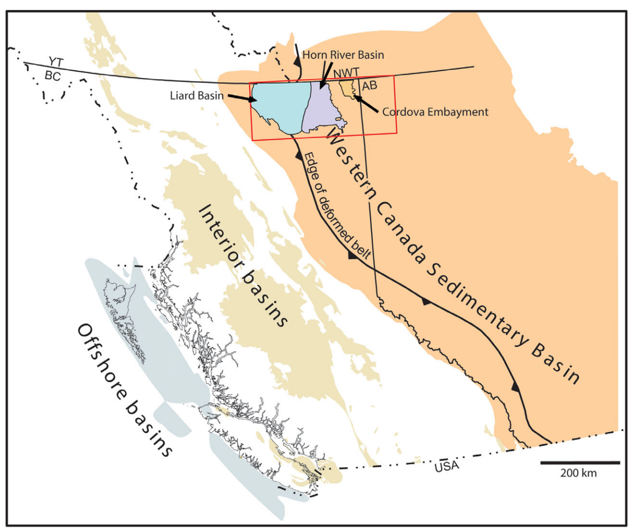

Figure 1. The study area in the geographic context of western Canada (modified from Ferri et al., 2015). The study area is outlined in red and encompasses the Liard Basin (blue), the Horn River Basin (purple) and the Cordova Embayment (orange), as well as western Alberta.

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structural feature of the study area is the Bovie fault complex, which separates the Horn River Basin from the Liard Basin.

Tectonic History

The evolution of the WCSB can be divided into two main tectonic phases: a late Proterozoic to Jurassic continental-margin setting and a compressional Jurassic to Eocene foreland basin. During the Paleozoic, northeastern BC experienced extensive subsidence, block faulting and volcanism (Price, 1994). The study area likely experienced extension behind an east-dipping subduction zone, coeval with the compression of the Devonian-age Antler orogeny occurring to the south. Such extension is thought to have led to the block faulting that formed the Peace River Embayment, Fort St. John graben and Prophet Trough during the Devonian and Mississippian. These salient features affected the Late Paleozoic deposition and clastic provenance (Wright et al., 1994). The first stage of Bovie fault motion occurred during the Late Carboniferous and is interpreted by Maclean and Morrow (2004) to have been a crustal-scale convergent fault. This movement caused the subsequent erosion of the Mattson and Fantasque formations east of the fault within the HRB.

Beginning in the Jurassic, terrane accretion along the western edge of North America formed the Cordilleran fold-and-thrust belt. The tectonic regime during this time can be broadly split into a Jurassic to mid-Cretaceous collision and terrane accretion, and a Late Cretaceous to Paleocene right-lateral transpression phase (Price, 1994). Significant shortening and thickening of the Phanerozoic strata occurred; however, the amount of shortening varies across the margin, with the largest values estimated to be in the south and decreasing toward the north. The decrease in shortening in northeastern BC, relative to southern British Columbia and Alberta, is fundamentally connected to the change in plate motion from compressional in the south to more oblique convergence in the north (Wright et al., 1994). There is a change in structural style in the north due to changes in lithology: the overall lower competency of the area, due to thick shale successions, led to a fold-dominated structural style, rather than thrust-dominated (Wright et al., 1994). The Bovie fault was reactivated during the Laramide orogeny as a shallow décollement (Maclean and Morrow 2004). The tectonic style changed in the early Eocene, and the transpressional regime became transtensional. As a result, subsidence was replaced by uplift and subsequent erosion (Price, 1994).

Stratigraphy

The Phanerozoic stratigraphic succession in northeastern BC is several kilometres thick, varying from approximately 2 km near Alberta to more than 4 km within the Liard Basin, with the majority of the thickness associated with Devonian and Mississippian formations (Figure 2). These periods are characterized by a series of stacked carbonate and mudrock packages related to multiple sea-level changes and continued subsidence. West of the main carbonate platform and the Presqu'ile barrier reef that formed during the early Givetian, the carbonate transitions into shale of the Horn River, Muskwa and Besa River formations. On the cratonic platform, a mixed siliciclastic-carbonate system persisted throughout the upper Devonian (CBM Solutions, 2005). A major transgression and inundation of the entire platform led to the deposition of the Muskwa Formation (Switzer et al., 1994). The Devonian shale units are siliceous in nature due to the accumulation of pelagic radiolarians in a deep-basinal depositional environment (Ross and Bustin, 2008). The Muskwa Formation is overlain by the Fort Simpson Formation and several carbonate formations. The Exshaw Formation and equivalents are present throughout North America and represent another major marine transgression. Above the Exshaw Formation are the siliciclastic and lime-mudstone of the Banff Formation, overlain by the Rundle Group (Kent, 1994). In the Liard Basin, the Besa River Formation was still exposed during deposition of the Rundle Group. During the Late Mississippian, however, the Liard Basin became a dominantly deltaic and coastal-plain environment, resulting in deposition of the Mattson Formation, which is only observed in the Liard area but likely coeval with the Kiskatinaw Formation within the Peace River Embayment (Richards, 1989; Richards et al., 1994). The rock record in the study area becomes sparse from the Permian until the mid-Cretaceous. This is due to a significant drop in sea level during the Late Permian, leading to a period of erosion and the beginning of compressional deformation during the Jurassic, which eroded earlier deposits as the deformation front moved east (Wright et al., 1994). The Cretaceous strata are the deltaic, fluvial and marine deposits of the Fort St. John Group (Stott, 1982). Accumulation of Upper Cretaceous sedimentary rocks is rarely present; the sedimentary section is capped by relatively thick Quaternary overburden.

Materials and Methodology

This study focuses on reconstructing the basin through a series of 1-D basin models across the study area (Figure 3). The models were built using Schlumberger's PetroMod® 2015 software suite. In order for the models to be fully representative of the basin, all of the inputs need to be defined according to the best available knowledge and data. Important modelling inputs include lithology for the entire stratigraphic column, source-rock properties, boundary conditions (heat flow, surface-water interface temperature and paleo–water depths), erosion and hiatus events, and any thermal-maturity calibration data available (mainly vitrinite reflectance). Some inputs, such as heat flow, are particularly difficult to constrain; therefore, sensitivity analysis was performed on each model to address these uncertain-

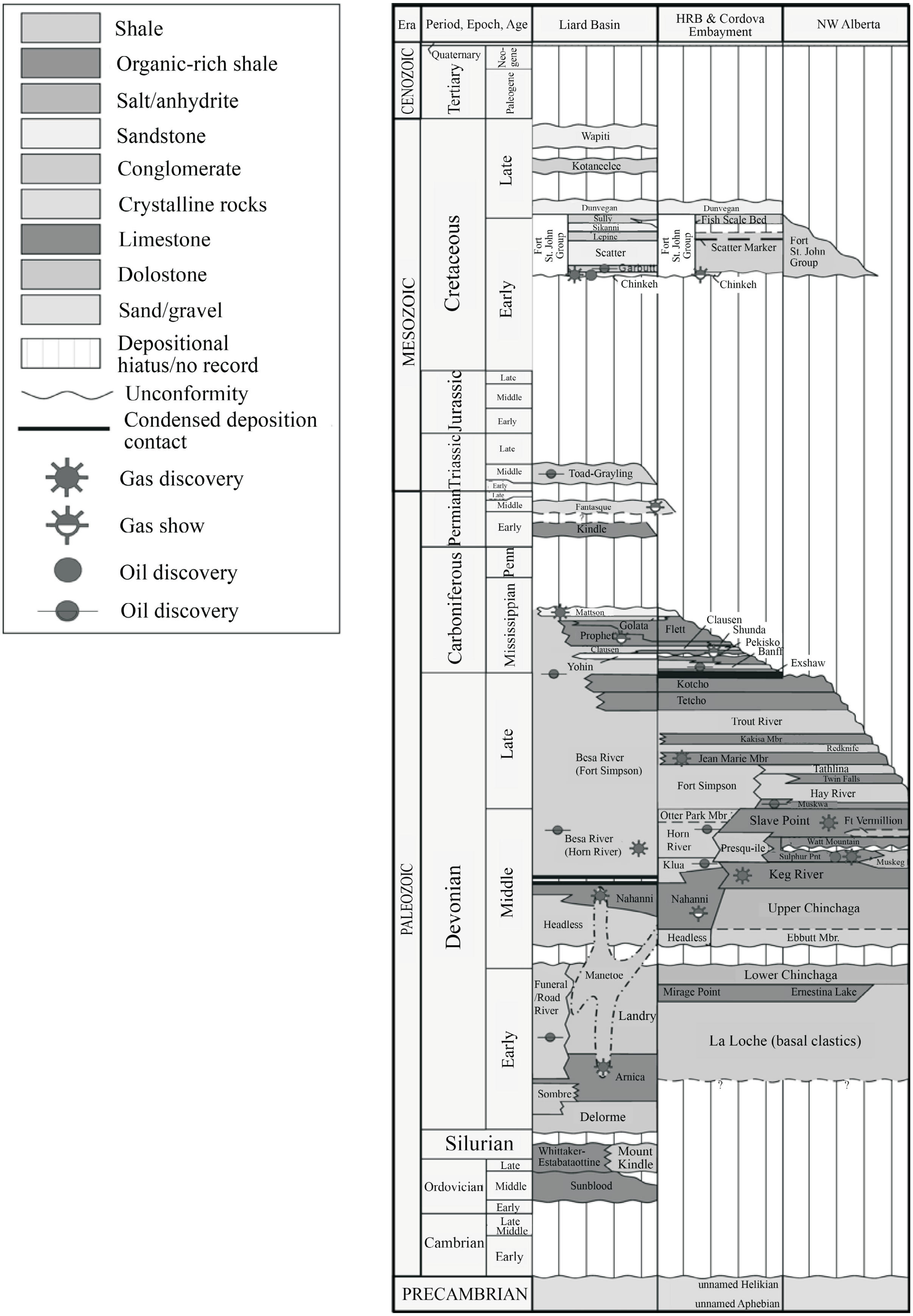

Figure 2. Phanerozoic stratigraphy of northeastern BC and Alberta (modified from Maclean and Morrow, 2004).

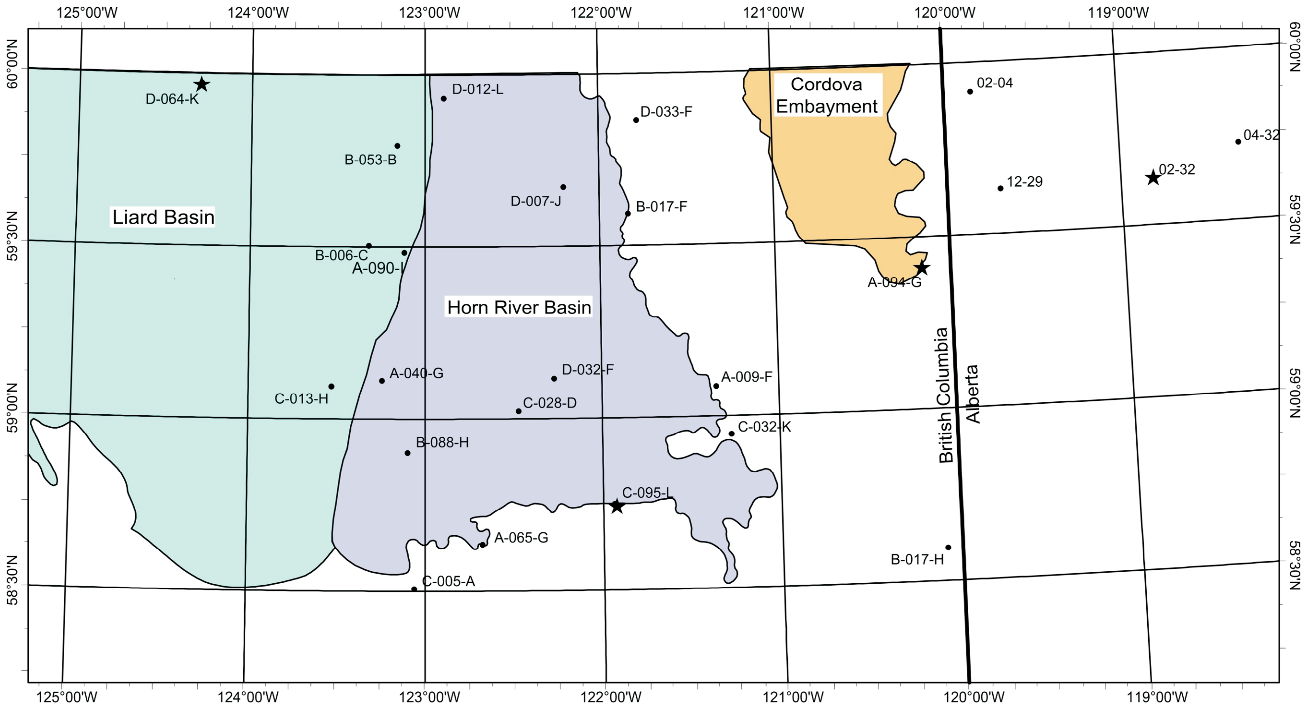

Figure 3. Location of 1-D models within the study area in northeastern BC and adjacent areas. Model locations are represented by black dots, and the models discussed in this paper are represented by black stars.

ties and ensure that the final models reflected the most likely case.

Lithology

Accurately defining the lithology of individual stratigraphic intervals (Devonian to present) is critical during basin modelling. Different rock types exhibit different petrophysical properties (chemical, mechanical and thermal), which affect the simulation of the numerical models. User-defined rock types were created within PetroMod® for each stratigraphic unit by mixing several predefined rock types. The Lexicon of Canadian Geological Names (Natural Resources Canada, 2018) was the main source for generalized lithological descriptions. In general, the rock types were kept laterally consistent across the study area. The default Athy's law (Athy, 1930) was used as the mechanical compaction model and the default Sekiguchi model (Sekiguchi, 1984) was used for thermal conductivity. The thermal conductivity of mixed rock types is calculated internally by geometrically averaging the rock-matrix and pore-fluid values. The calculated thermal-conductivity values were used for each mixed lithology. Table 1 illustrates the stratigraphic formations and ages, and their respective rock types, and thermal and mechanical properties.

Source Rock Properties

In the study area, the main identified Devonian-age petroleum source rocks are the Evie Member and the Muskwa and Exshaw formations (National Energy Board and BC Ministry of Energy, Mines and Petroleum Resources, 2011). The default Burnham 1989 TII kinetic model built within PetroMod® was used for all three source-rock intervals. Based on whole-rock pyrolysis analysis, hydrogen indices are generally <50 mgHC/g of rock, and TOC averages 3 wt. % for both the Muskwa and Evie intervals, and slightly higher for the Exshaw Formation (Wilson and Bustin, 2017).

Boundary Conditions

The PetroMod® software requires three boundary conditions to be defined before any simulations can be completed. These conditions are heat flow, sediment-water interface temperature (SWIT) and paleo–water depth (PWD). Both present-day and paleo values must be defined. All of the boundary conditions help to define the thermal constraints of the model, with heat flow being the most important of the three. Figure 4 represents the generalized trend of these three parameters versus time.

Sediment-Water Interface Temperature and Paleo–Water Depth

The SWIT values throughout the history of the basin were defined by using the Wygrala (1989) model for global mean temperature at sea level. This method is built into PetroMod® and uses present-day latitude and paleo–water-depth data to extract the temperature at sea level over a series of geological time steps. The SWIT values range from 5 to 25.3°C, with peak temperatures at 100 Ma. The PWD was based on the paleogeographic maps and the evolution history of the basin (Mossop and Shetsen, 1994; Wright et

Table 1. Stratigraphy, lithology, and thermal and mechanical parameters used for the model simulations.

Stratigraphic nomenclature	Depositional age (Ma)	Lithology	Thermal conductivity @ 20°C/300°C (W/[m•K])	Heat capacity @ 20°C/300°C (kcal/[kg•K])	Mechanical properties		
					Density (kg/m^3)	Initial porosity (%)	Athy's factor (1/km)
Overburden	0.4	sst (subarkoze, typical)	4.55/2.90	0.21/0.29	2680	41	0.28
Upper Cretaceous	65	sltst (organic lean), sh (organic lean), siderite, kaolinite	1.87/1.85	0.21/0.3	2743.3	58.81	0.42
Fort St. John Gr.	100	sst (clay rich), sh (organic lean), sst wacke), coal, sltst (organic lean)	1.85/1.84	0.21/0.3	2717.4	46.97	0.6
Bullhead Gr.	110	Cnglm (typical), sst (typical), coal, sltst (organic lean), sh (organic lean)	2.45/2.08	0.21/0.30	2656	49.05	0.44
Doig/Toad Fm.	230	sh (organic lean), sst (typcial), lmst (shaly), sltst (organic lean)	2.03/1.91	0.21/0.3	2716.9	57.17	0.59
Fantasque Fm.	252	Chert, sh (typical), sst (typical)	4.42/2.84	0.21/0.3	2663	45.65	0.41
Belloy Fm.	270	sst (typical)	3.95/2.66	0.2/0.29	2720	41	0.31
Mattson Fm.	325	sst (typical), sst (quartzite), sh (typical), dlm (typical), chert, coal	3.85/2.62	0.21/0.3	2650.7	43.49	0.34
Golata Fm.	325	sst (typical), argill. carb. mdst (marl), anhydrite, coal	3.5/2.47	0.21/0.29	2706.95	47.95	0.43
Rundle Gr.	335	Lmst (ooid grainstone), dlm (typical)	3.2/2.37	0.2/0.29	2770	35	0.24
Banff Fm.	347	sh (organic lean, silty), carb-rich arg mdst, lmst (shaly), sltst (organic lean)	2.70/2.18	0.21/0.29	2716.9	58	0.63
Exshaw Fm	360	Sh. (black), pyrite, tuff (felsic)	1.00/1.51	0.22/0.31	2584.3	67.33	0.78
Kotcho Fm.	361	Carb. silic. mdst, Sh (black), carb-rich argill. mdst, lmst (micrite)	3.50/2.49	0.21/0.29	2712.85	57.6	0.61
Tetcho Fm.	362	Lmst (micrite), sh (typical), sltst (organic lean)	2.86/2.24	0.2/0.29	2737	52.15	0.54
Trout River Fm.	363	sltst (organic lean), lmst (shaly), shale (typical)	2.9/2.25	0.21/0.3	2720	55.2	0.57
Red Knife Fm.	369	lmst (shaly), sst (subarkose, dlm rich), sltst (organic lean)	2.44/2.07	0.21/0.29	2724.5	48.55	0.47
Jean Marie Fm.	369	Dlm (organic lean, silty), lmst (micrite), lmst (mound)	3.00/2.29	0.2/0.29	2752	34.4	0.34
Fort Simpson Fm.	371	Sh (organic lean, typical), carb. silic. Mdst, sltst (organic lean), sst (typical)	3.45/2.47	0.21/0.30	2710.6	61.8	0.67
Muskwa Fm.	376	Carb. silic. mdst, sh (typical), pyrite	1.5/1.71	0.2/0.29	2781.78	60.73	0.68
Watt Mountain Fm.	376	Sh (typical), lmst (micrite), sst (arkoze, typical), dlm (typical), anhydrite	3.13/2.34	0.2/0.28	2761.5	42.4	0.44
Slave Point Fm.	376	lmst (micrite), dlm (typical), sh (typical)	3.12/2.34	0.2/0.29	2751	48.1	0.51
Otter Park Mbr.	378	Carb. silic. mdst, sh (typical), pyrite	2.8/2.21	0.21/0.29	2760.24	60.52	0.67
Evie Mbr.	380	Sh (black), sltst (organic lean), lmst (micrite), pyrite	1.27/1.62	0.22/0.3.1	2948.1	62.65	0.7
Dunedin Fm.	380	dlm (typical), sst (tyical), lmst (ooid grainstone)	2.9/2.24	0.2/0.29	2774.2	35.24	0.29
Muskeg Fm.	381	Salt, lmst (micrite), dlm (typical), anhydrite	4/2.68	0.2/0.28	2801	21.2	0.22
Keg River Fm.	382	dlm (typical), sst (typical), lmst (ooid grainstone)	2.9/2.25	0.2/0.29	2774.2	35.24	0.29
Besa River Fm.	380-345	Sh (organic lean, typical), carb. silic. Mdst, sltst (organic lean), sst (typical)	3.45/2.47	0.21/0.30	2710.6	61.8	0.67

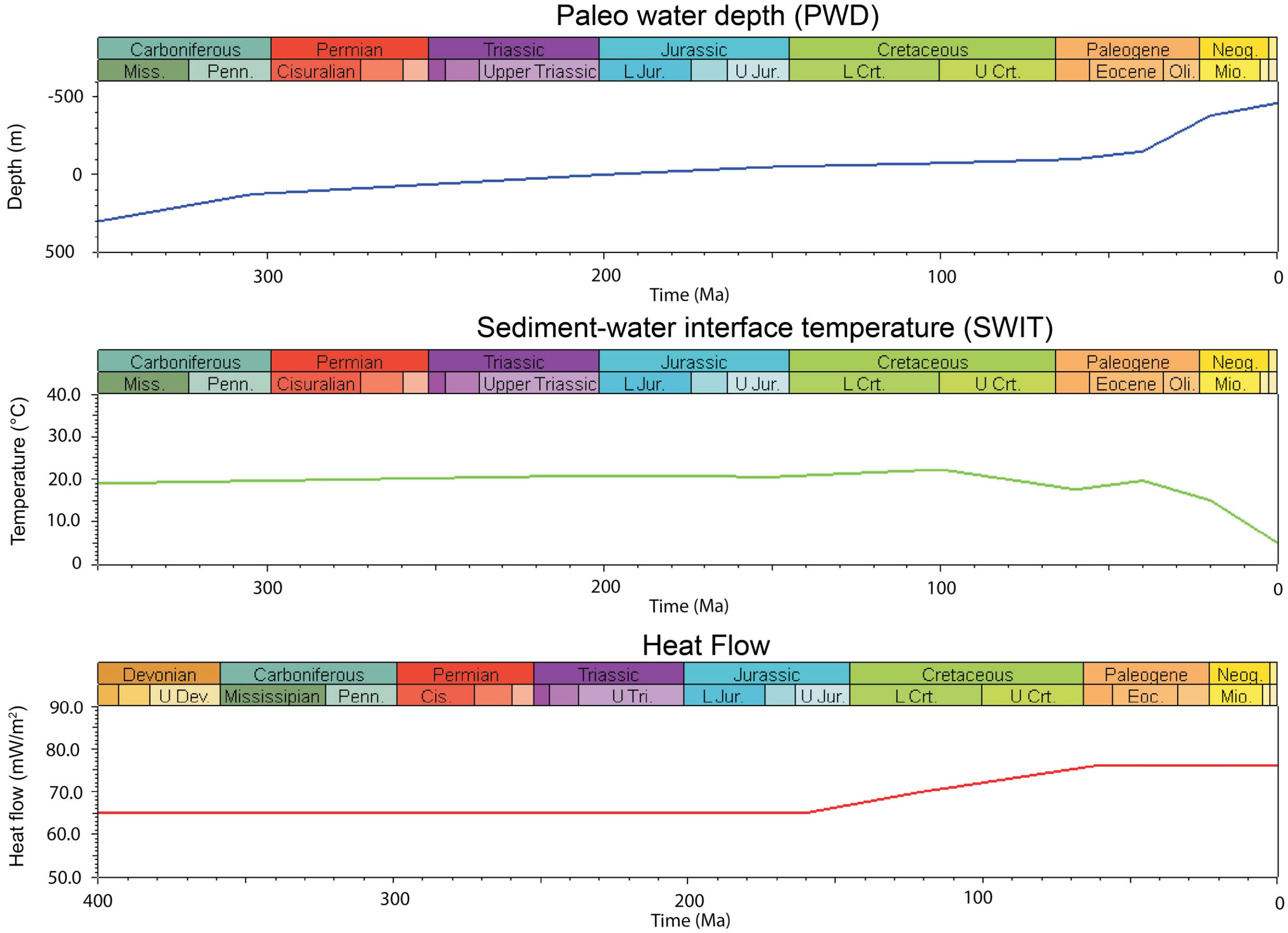

Figure 4. Examples of boundary conditions used for the modelling: **Top**, paleo–water depth (PWD); **Middle**, sediment-water interface temperature (SWIT); **Bottom**, heat flow (HF).

al., 1994). It is known that the PWD is an important parameter for compaction and pressure effects, along with SWIT (Bruns et al., 2016). The PWD during deposition of the Evie and Muskwa may have been in excess of 100 m (Stasiuk and Fowler, 2004); however, due to the difference in magnitude of PWD and the overall thickness of the WCSB of several kilometres, its impact is not very significant.

Heat Flow

The SWIT and PWD define the upper thermal boundary of the basin. The lower boundary requires mapping of the heat flow. Within the study area, present-day heat flow varies significantly, with values generally the highest in the northeastern corner of BC and lowest within the Liard Basin (Majorowicz and Jessop, 1981; Majorowicz et al., 2005). Heat flow within the Liard Basin represents a localized low (Majorowicz et al., 2005). Heat flow in the HRB, Cordova Embayment and western Alberta area are significantly elevated, reaching values near 100 mW/m^2. Heat-flow maps (Majorowicz, 2005; Weides and Majorowicz, 2014) were important references for the determination of present-day heat flow (Figure 5), with the continental average value of 65 mW/m^2 (Allen and Allen, 2005) being used for the basin from 350 to 65 Ma. Heat flows are often elevated during times of inversion due to the exhumation and removal of relatively hot rocks (Bruns et al., 2013), such as during the Tertiary[1] when heat-flow values were above 65 Mw/m^2 in the HRB, Cordova Embayment and western Alberta. Due to the large uncertainty around heat-flow evolution through geological history, sensitivity analysis was instrumental in constraining this parameter and increasing confidence in the final models. Due to present-day elevated values, however, the ultimate impact of heat flow during the Mesozoic and Paleozoic is minimized.

Erosion and Hiatus Events

The main tectonic event in western Canada was the uplift and erosion associated with the Laramide orogeny. Attempts at quantifying Cenozoic erosion have been made

[1] *'Tertiary' is an historical term. The International Commission on Stratigraphy recommends using 'Paleogene' (comprising the Paleocene to Oligocene epochs) and 'Neogene' (comprising the Miocene and Pliocene epochs). The author used the term 'Tertiary' because it was used in the source material for this report.*

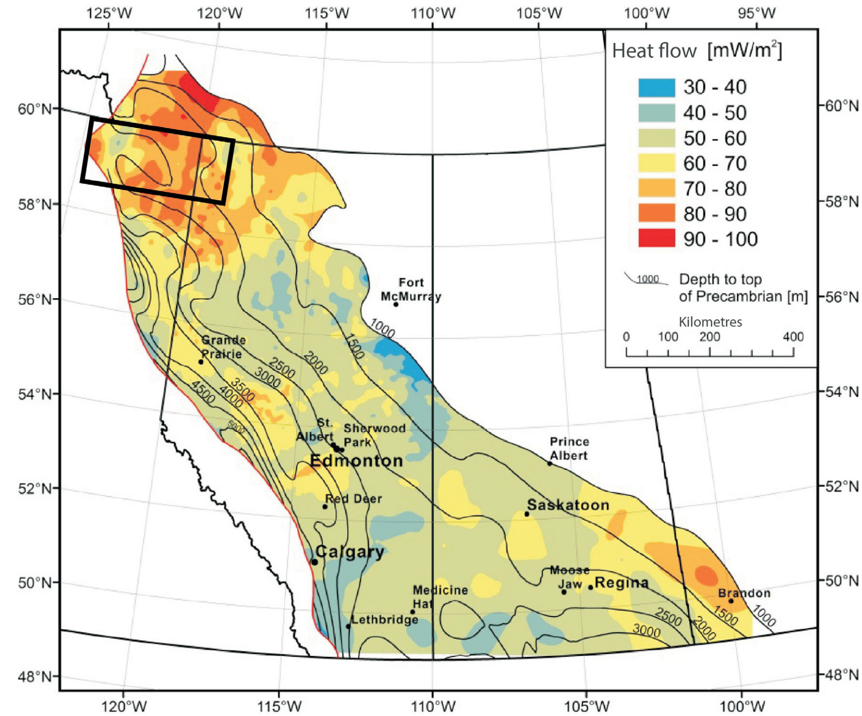

Figure 5. Present-day heat flow for the Western Canada Sedimentary Basin (from Weides and Majorowicz, 2014). The study area is outlined in black.

by many studies, through both compaction-based methods (Magara, 1976; Connolly, 1989; Poelchau, 2001; Aviles and Cheadle, 2015) and organic-maturity–based methods (Hacquebard, 1977; Nurkowski, 1984; England and Bustin, 1986; Osadetz et al., 1990). The limits of erosion range from 520 m (Magara, 1976) to more than 4 km (England and Bustin, 1986), depending on the method used by the researchers and the proximity of their study area to the fold-and-thrust belt. Within the Alberta Deep Basin, many of the values cluster around 1500–2000 m (Poelchau, 2001), and a basin model for the same area suggested that 2000 m of erosion was required to match the observed thermal maturity of the Cretaceous Blackstone Formation (Aviles and Cheadle, 2015). It is important to note that the tectonic regime during this time varied along the length of the fold-and-thrust belt, with a higher degree of strike-slip motion being exhibited in the northeastern BC area. This change of tectonic style may have affected the erosion. The limits for the eroded section at the modelled well locations for this study ranged from 440 to 2250 m. This range was informed by prior knowledge of geological history and results from well-defined and -calibrated models. Minor hiatus and erosion events were input throughout the model, according to the stratigraphic record.

Thermal-Maturity Calibration Data

Calibration to thermal-maturity data is paramount for an accurate model. Since the inception of basin models in the early 1970s, vitrinite reflectance (VR) has been the most common calibration parameter (Mukhopadhyay, 1994). Well locations for this study were preferentially picked based on the availability and number of VR data points. Unfortunately, reliable VR data are sparse throughout the study area. The main source rocks of interest were deposited in marine environments, so many of the reflectance measurements were completed on indigenous bitumen or bitumen-like substances, not vitrinite. There is sufficient support available in the literature to confidently use bitumen-reflectance values in place of vitrinite (Gentzis, 1991; Reidiger, 1991; Landis and Castano, 1995). However, the reflectance measurements from the public database do not always explain the methodology behind the values, which reduces confidence in the data. Nonetheless, these VR values are still the best calibration data available. In instances where VR data points were not available, T_{max} values were converted to % R_o values using the Jarvie et al. (2001) equation. These values should be taken with caution, since it has been shown that such formulas are not ideal, particularly when used on formations on which they were not strictly based (Wust et al., 2013). Although the study is focused on Paleozoic source rocks, data from younger formations were used when available. The assumption that the Laramide orogeny affected the entire Phanerozoic sedimentary succession warrants the use of data from younger formations when reliable Devonian data are unavailable. Table 2 shows the well locations of the 1-D models and their associated calibration data.

Table 2. Well locations and associated calibration data for 1-D models used in this study.

UWI	Area	Type of calibration data	Number of data points and formations
100/02-04-126-11W6/0	Alberta	Calculated Ro from Tmax	Muskwa (1)
100/02-32-122-05W6/0	Alberta	Calculated Ro from Tmax	Muskwa (4)
100/04-32-123-02W6/0	Alberta	Calculated Ro from Tmax	Muskwa (3)
100/12-29-122-10W6/0	Alberta	Calculated Ro from Tmax	Muskwa (4)
200/A-094-G/094-P-08/0	Cordova	VR in situ	Slave Point (1), Muskwa (2)
200/A-040-G/094-O-03/0	Horn River Basin	VR in situ, Calculated Ro from Tmax	Exshaw (2), Kotcho (1), Muskwa (2)
200/A-065-G/094-J-10/0	Horn River Basin	VR in situ	Fort Simpson (1)
200/B-017-F/094-P-12/0	Horn River Basin	VR in situ	Muskwa (2)
200/B-088-H/094-J-14/0	Horn River Basin	VR in situ	Muskwa (3)
200/C-028-D/094-O-01/0	Horn River Basin	VR in situ	Otter Park (1), Muskwa (1)
200/C-095-L/094-I-12/0	Horn River Basin	VR in situ	Klua (1), Redknife (1), Kotcho (1), Exshaw (1)
200/D-007-J/094-O-09/0	Horn River Basin	VR in situ	Otter Park (1)
200/D-012-L/094-O-15/0	Horn River Basin	VR in situ	Muskwa (3), Otter Park (1)
200/D-032-F/094-O-01/0	Horn River Basin	Calculated Ro from Tmax	Exshaw (3), Fort St. John (2)
200/A-090-I/094-O-06/0	Liard	VR in situ	Kotcho (3)
200/B-006-C/094-O-11/0	Liard	VR in situ	Garbutt (5)
200/B-053-B 094-O-014/0	Liard	VR in situ	Fort St. John Group (3)
200/C-013-H/094-O-14/0	Liard	VR in situ	Garbutt (3)
200/D-064-K/094-N-16/0	Liard	VR in situ	Golata (10), Banff (2), Besa/Muskwa (3)
200/A-009-F/094-P-03/0	Other	VR in situ	Muskwa (3)
200/B-017-H/094-I-09/0	Other	VR in situ	Muskwa (2)
200/C-005-A/094-J-11/0	Other	VR in situ	Slave Point (1)
200/C-032-K/094-I-14/0	Other	VR in situ	Fort Simpson (2)
200/D-033-F/094-P-13/0	Other	VR in situ	Garbutt (2)

Sensitivity Analysis

Although basin modelling is a powerful tool, it is a probabilistic method that yields non-unique results. In order to increase confidence in the results, it is paramount to run sensitivity analysis of each model to determine the main factors that control the model and how these factors relate to one another, and to ensure that the final model represents the most likely case. For each 1-D model, dozens of iterations were completed with slight changes to variables such as boundary conditions, rock types and erosion amounts, in order to determine the influence of these variables on one another. The main iterations in this sensitivity analysis involved varying heat flow and erosion. In order to understand the importance of each variable, heat flow or erosion was held constant while the other was varied systematically. This approach allowed for the most likely solution to be modelled with confidence and provided quantitative results for the effects of heat flow and erosion on the present-day thermal maturity of the study area.

Results

In this paper, a single model from each area—Liard Basin, HRB, Cordova Embayment and western Alberta—will be discussed. Table 3 shows an example of the primary inputs for the finalized models, including stratigraphy, age and lithology.

Sensitivity Analysis

Heat-flow and erosion values are the two most important variables that must be constrained. Sensitivity analysis allows these variables to be determined more accurately and provides a quantitative understanding of the magnitude of impact these variables have on the overall petroleum systems. Many basin-modelling studies use some form of sensitivity analysis (Bruns et al., 2013; Grobe et al., 2015; Bruns et al., 2016), often isolating heat flow and erosion, as this study does. For each of the models discussed here, erosion values were changed in 200 m increments between iterations, and heat-flow values by 5 mW/m^2. Heat flow was

Table 3. Example of primary inputs for the finalized models.

Age	Formations/ events	Depth (m)	Thickness (m)	Event type	Paleodeposition/ erosion	Lithology
0	hiatus	-459.6	0	Hiatus		
0.4	Overburden	-459.6	391.7	Deposition		Sandstone (arkose, typical)
10	Hiatus 10	-67.9	0	Hiatus		
25	Uplift	-67.9	0	Erosion	-1565	
55	Hiatus 9	-67.9	0	Hiatus		
65	Upper Cretaceous	-67.9	0	Deposition	790	Smoky River
88	Hiatus 8	-67.9	0	Hiatus		
95	Spirit River	-67.9	204.49	Deposition	775	Spirit River (FSJ)
115	Hiatus 7	136.59	0	Hiatus		
140	Erosion	136.59	0	Erosion	-275	
200	Hiatus 6	136.59	0	Hiatus		
230	Doig/Toad	136.59	0	Deposition	150	Toad/Doig
245	Hiatus 5	136.59	0	Hiatus		
252	Fantasque	136.59	0	Deposition	125	Fantasque
280	Hiatus 4	136.59	0	Hiatus		
290	Erosion	136.59	0	Erosion	-300	
305	Hiatus 3	136.59	0	Hiatus		
310	Mattson	136.59	0	Deposition	250	Mattson
335	Rundle Group	136.59	196.32	Deposition	50	Rundle Group
347	Banff	332.91	306.9	Deposition		Banff
360	Exshaw	639.81	8.2	Deposition		Exshaw
360.5	Hiatus 2	648.01	0	Hiatus		
362	Kotcho	648.01	81.99	Deposition		Kotcho
364	Tetcho	730	55.51	Deposition		Tetcho
366	Trout River	785.51	25.88	Deposition		Trout river
367	Hiatus 1	811.39	0	Hiatus		
368	Kakisa	811.39	14.32	Deposition		Kakisa
369	Redknife	825.71	168.59	Deposition		Redknife
369.5	Jean Marie	994.3	44.8	Deposition		Jean Marie
370	Fort Simpson	1039.1	418.49	Deposition		Fort Simpson
374	Muskwa	1457.59	13.72	Deposition		Muskwa
374.5	Otter Park	1471.31	1.8	Deposition		Otter Park
375	Slave Point	1473.11	80.8	Deposition		Slave Point
376	Watt Mountain	1553.91	2.1	Deposition		Watt Mountain
377	Muskeg	1556.01	164.29	Deposition		Muskeg
378	Klua	1720.3	96.99	Deposition		Evie
380	Keg River	1817.29				

kept constant at 65 mW/m^2 while erosion was varied, and heat flow was varied while erosion was held constant.

Increasing erosion thicknesses shifts the vitrinite reflectance trend to higher maturities, as the thicker overburden section would have caused the interval in question to have been buried deeper. With each increment in erosion (keeping heat flow constant), the slope of the vitrinite reflectance as a function of depth remains constant (at 0.5% R_o/km) and there is a bulk shift in maturity of 0.2% R_o for every 200 m increment in erosion (Figure 6a). For the example in Figure 6a, the lower and upper brackets of the eroded section are 2200 and 3200 m, which causes a range of change in maturity of 1.0% R_o. The values that best fit the calibration data are erosion thicknesses of 2600–2800 m. In all iterations, however, the slope of the line must be increased in order to match the calibration, which requires an increase in heat flow. Although a constant–heat-flow scenario is unlikely due to the time span encompassed by this model and the various tectonic regimes acting through the geological history, keeping heat flow at 65 mW/m^2 for the entirety of

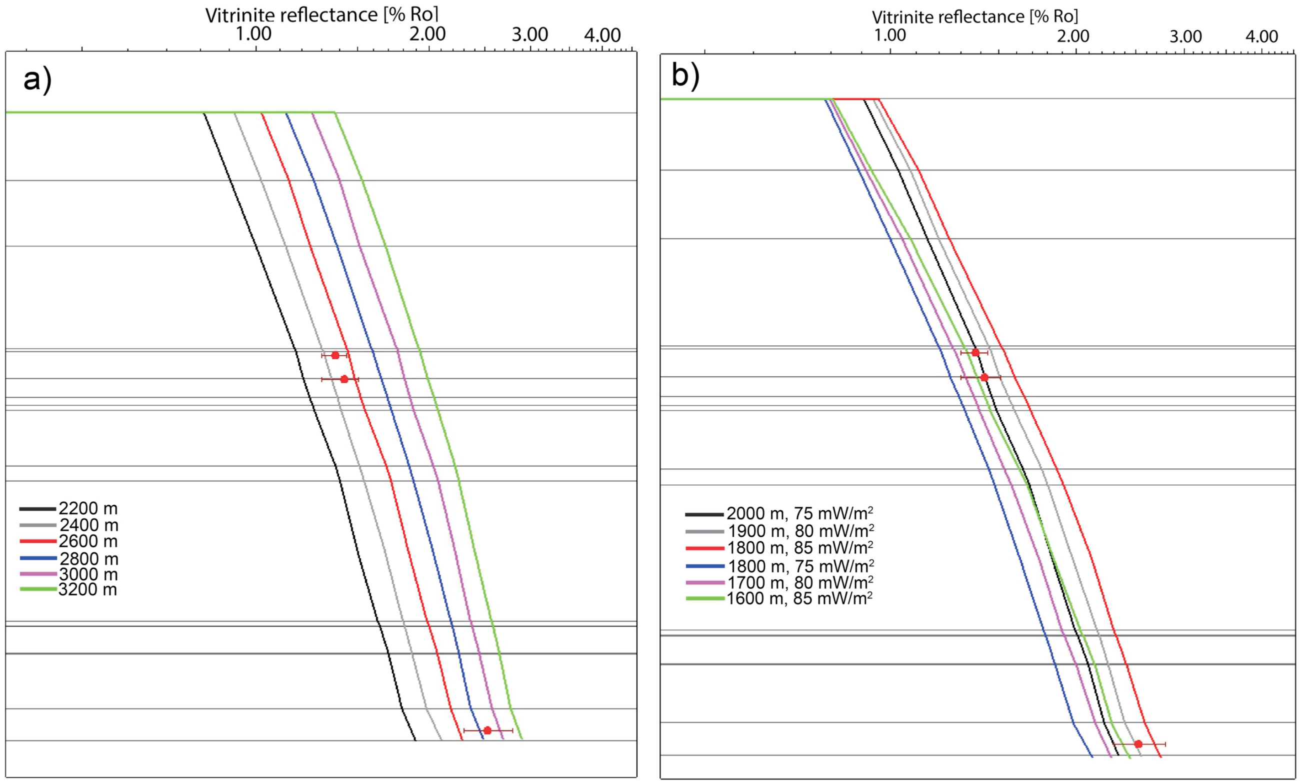

Figure 6. Results of sensitivity analysis for the Direct Gunnel C-095-L model: **a)** vitrinite reflectance versus depth for variable erosion thickness at a fixed heat flow of 65 mW/m^2; **b)** vitrinite reflectance versus depth for variable present-day heat flow. The points on the graph represent calibration data and the lines represent the calculated vitrinite reflectance for each different iteration.

basin evolution provides insight into the quantitative importance of erosion.

Increasing heat flow also has the effect of increasing the thermal-maturity trends. However, as can be seen in Figure 6b, the maturity trends for different heat-flow values are not parallel, as the slope increases from 0.5% R_o/km to 0.85% R_o/km for a heat-flow change from 65 mW/m^2 to 80 mW/m^2. Using the same erosion thickness and increasing heat flow by 5 mW/m^2 can shift thermal maturity by 0.3% R_o in the Devonian shales. In the example illustrated in Figure 6b, the range of heat flow is from 75 to 85 mW/m^2, spanning an increase of nearly 0.6% R_o. The trend that most closely matches the data is associated with 1600 m of erosion and a present-day heat flow of 85 mW/m^2. In the final model for this example, values of 1565 m of erosion and 88 mW/m^2 for heat flow were used. Based on the detailed sensitivity analysis, confidence in the erosion and heat-flow values for the final models is within 50 m and 1 mW/m^2, respectively.

Liard Basin

The Nexen Beaver D-064-K well is located in the north-central part of the Liard Basin, near the deformation front. This model uses present-day heat-flow values of 67 mW/m^2. The burial history of the Upper Paleozoic comprises several kilometres of sediment due to the thicknesses of the Besa River, Golata and Mattson formations. The organic-rich Evie and Muskwa members within the Besa River Formation were buried to depths of 3225 m and 3110 m, with corresponding temperatures of 101 and 105°C, respectively, by the end of Mattson Formation deposition (Figure 7a). These depths were obtained by backstripping the model to Carboniferous/Permian time. This model entered the oil window (0.60% R_o) by 310 Ma. Throughout the Permian to Jurassic, the Fantasque and Toad formations were deposited, along with multiple hiatus/nondepositional periods. Thermal maturity was held fairly constant throughout this time, reaching 0.90% R_o by Late Jurassic. During foreland subsidence, the Evie and Muskwa horizons reached maximum burial depths 5375 and 5260 m, and maximum temperatures of and 238 and 234°C, respectively. During foreland subsidence, thermal maturation increased from 0.9% R_o (oil window) to 3.3% R_o (overmature). By Late Cretaceous, all of the formations had reached thermal maturities necessary for hydrocarbon generation, with the majority of strata within the gas window or overmature. The erosion thickness for this model is 2250 m, corresponding to an erosion rate of 85 m/m.y. Present-day maturities range from 1.7% R_o in the Mattson Formation to 3.4% R_o in the Muskwa member (Figure 7b).

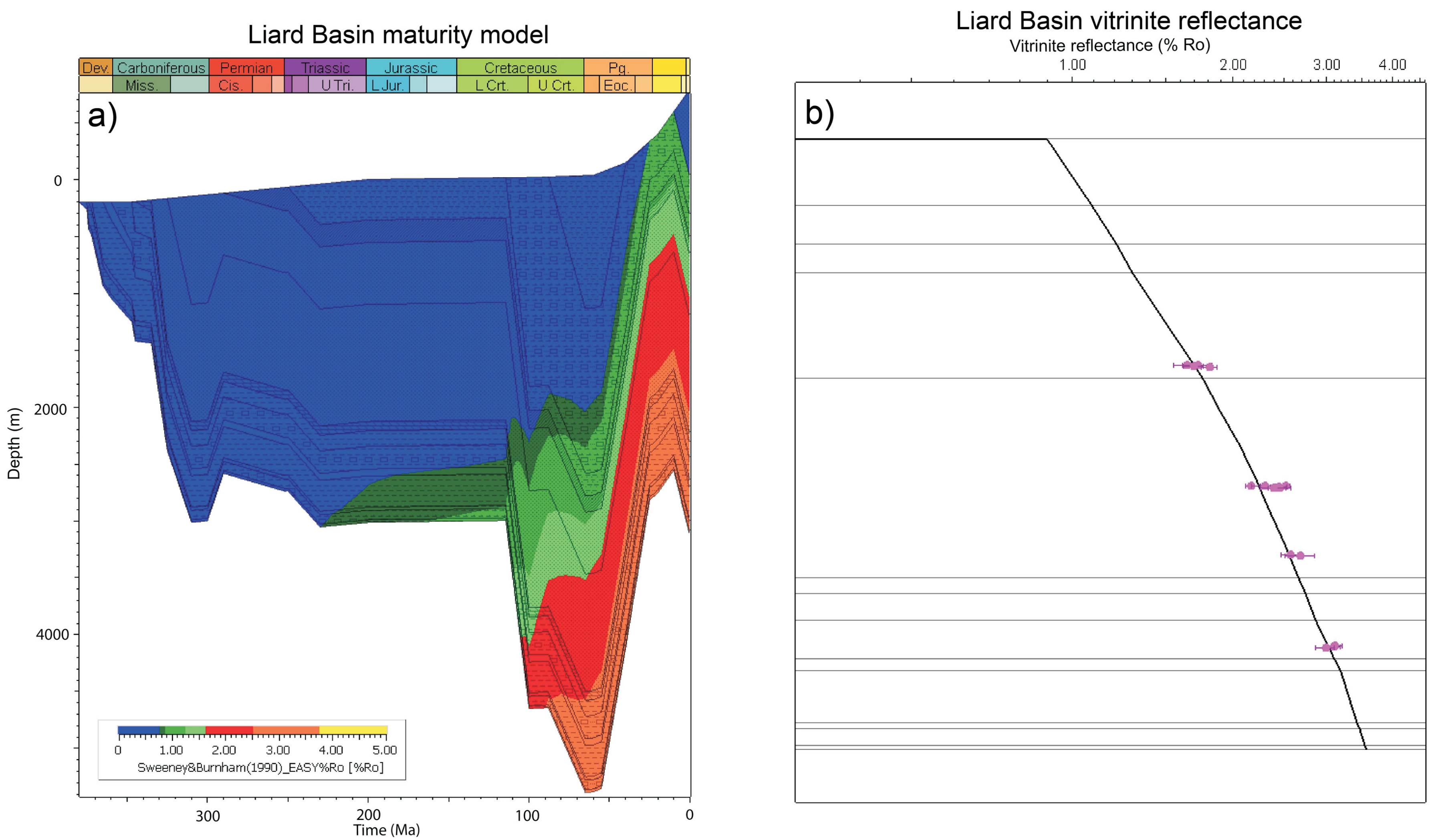

Figure 7. Liard Basin maturity model for the Nexen Beaver D-064-K well: **a)** burial-history plot with vitrinite-reflectance overlay; **b)** vitrinite-reflectance versus depth plot. The calculated vitrinite line (black) matches well with the calibration data points (pink).

Horn River Basin

The Horn River Basin (HRB) model presented here (Direct Gunnel C-095-L well) is located in the southeastern portion of the basin. This model uses a present-day heat flow of 88 mW/m^2. The Muskwa Formation was buried to a depth of 2025 m and a temperature of 83°C by Late Carboniferous, beneath the thick accumulation of the Fort Simpson and Mattson formations (Figure 8a). The Mattson Formation was subsequently eroded due to movement along the Bovie fault, as were the Toad and Fantasque formations (Maclean and Morrow, 2004). Hydrocarbon generation began in the Lower Jurassic for the Muskwa Formation. Maximum burial depths and temperatures of 3035 m and 195°C, respectively, are reached during foreland subsidence. Thermal maturity for the Muskwa Formation increased from 0.6 (early-oil window) to 2.0% R_o (wet-gas window) during this time. The amount of erosion for this model is 1565 m, with an erosion rate of 52 m/m.y. Present-day maturities range from 1.4% R_o in the Exshaw Formation to 2.6% R_o in the Klua Formation (Figure 8b).

Cordova Embayment and Adjacent Areas

The featured Cordova Embayment model (Ioe Union Shekilie A-094-G well) is located in the southern part of the embayment and uses a present-day heat-flow value of 88 mW/m^2. The burial history for this model is similar to many of the models within the HRB. During the Paleozoic, the Muskwa Formation reached depths of 1830 m, corresponding to a temperature of 76°C (Figure 9a). Depths remained fairly constant throughout the Permian, Triassic and Jurassic. The Klua Formation entered the oil window in the Late Triassic, and the Muskwa Formation in the early Cretaceous (at the start of foreland subsidence). Maximum burial depths and temperatures for the Muskwa Formation were of 2920 m and 183°C, respectively. During maximum burial, thermal maturity increased from 0.6 to 1.8% R_o (early-oil to wet-gas window). The thickness of the eroded section for this model is 1650 m, corresponding to an erosion rate of 55 m/m.y. Present-day maturities for the Muskwa and Klua formations are 1.9 and 2.1% R_o, respectively (Figure 9b).

Western Alberta

The models in western Alberta present significantly shallower burial and therefore lower maturities than those calculated in the models in British Columbia. The 100/02-32 well, located east of 119°W, has a present-day heat-flow value of 66 mW/m^2. The model was buried to a depth of 1400 m and a corresponding temperature of 70°C during the Paleozoic (Figure 10a). As with the Cordova Embayment model, depths and temperatures stayed fairly constant throughout the Permian to Jurassic. Maximum foreland-subsidence burial depths and temperatures for the Muskwa Formation are 1830 m and 92°C, respectively. The Muskwa Formation did not reach the oil window until the Latest Cretaceous. The thickness of the eroded section for this location is 525 m, corresponding to an erosion rate of only 17.5 m/m.y. The present-day maturity for this model is 0.62% R_o for the Muskwa Formation, with all younger strata remaining immature (Figure 10b).

Discussion

Impact of Peak Hydrocarbon Generation on Present-Day Distribution

In all of the models, peak burial depth and temperature were reached during the Late Cretaceous and beginning of the Paleocene. However, the onset of hydrocarbon generation (specifically the onset of oil generation) varies by hundreds of millions of years over the spatial extent of the study area. In the Liard Basin, the Devonian shales have been generating since the Carboniferous, reaching peak oil generation (transformation ratio = 50%) in the early Triassic (Figure 11). Conversely, the onset of oil generation in the Alberta wells occurred at 100 Ma at the earliest (if oil generation occurred at all), and peak generation occurred during the Late Cretaceous (Figure 11). Areas that have been in the maturity window for longer have a lower likelihood of containing extensive volumes of generative hydrocarbons today, since the organic matter has been generating for hundreds of millions of years. In the Liard Basin, many of the areas have reached maturities high enough, and sustained high temperatures long enough, that the organic matter no longer has any generating potential left but may still have producing potential. Age of maturation generally decreases toward the eastern and southeastern portions of the study area—in locations where production shows larger fractions of produced condensate than farther west. The temporal constraints provided by basin modelling can be used in conjunction with maturity to deduce the potential producibility of different areas. In nearly all of the well locations modelled, the transformation ratio reached 100% during foreland subsidence, which is expected due to the dominantly dry-gas nature of the Devonian petroleum system.

Limitations of the Model

Basin modelling is a powerful tool for understanding basin evolution, burial history, thermal maturation and the multitude of dependent relationships that exist between input variables. However, because the models require that such an extensive suite of factors be defined, there is a large amount of uncertainty involved, even in well-calibrated models. The results of this study are geologically plausible but not necessarily correct. Each model provides abundant information for each stratigraphic unit and each important time step, but the nuances of variables such as lithological variability are not captured, thereby decreasing the accuracy of the modelling. This study used only 24 models to

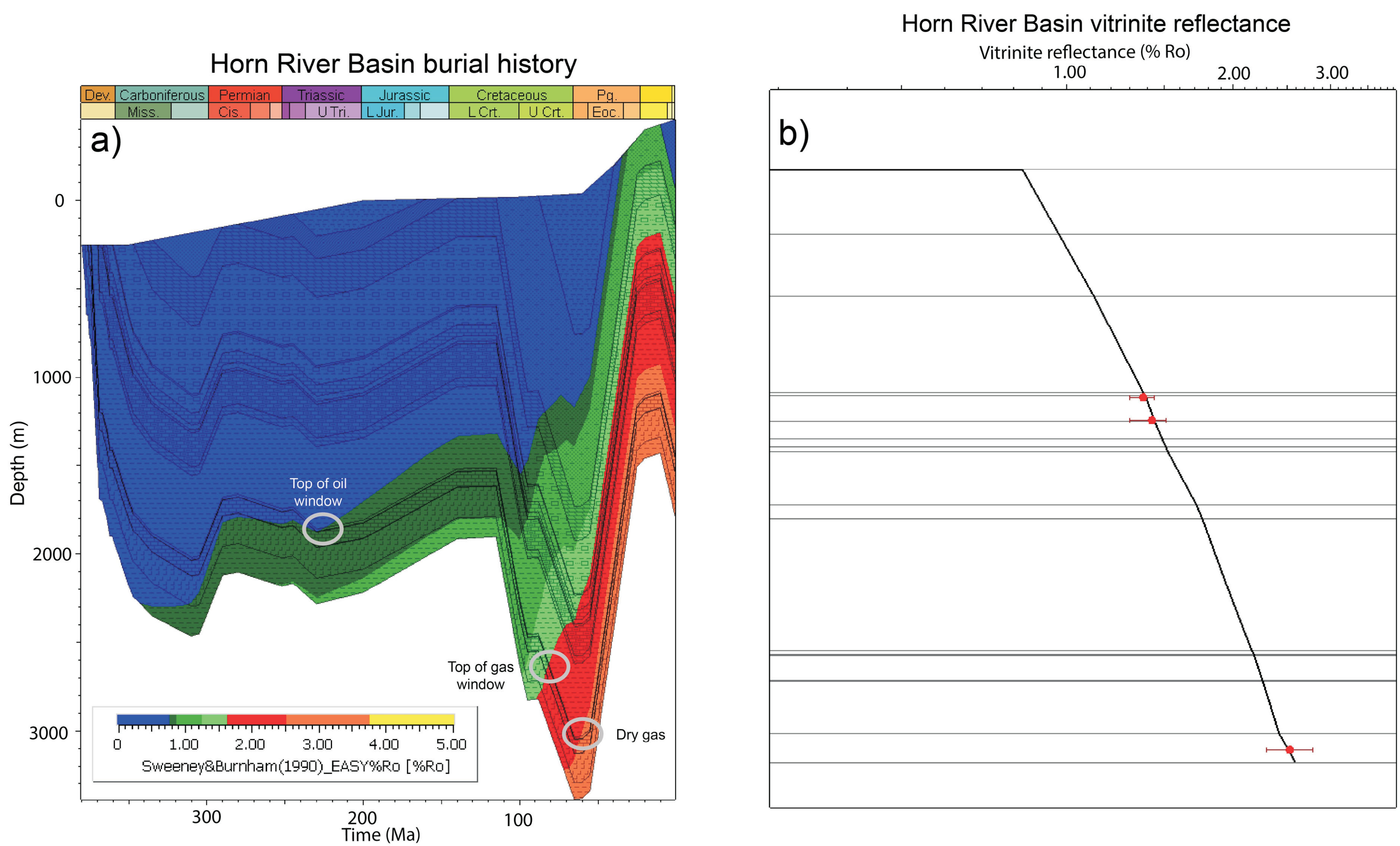

Figure 8. Horn River Basin maturity model for the Direct Gunnerl C-095-L well: **a)** burial-history plot with vitrinite-reflectance overlay; **b)** vitrinite-reflectance versus depth plot. The calculated vitrinite line (black) matches well with the calibration data points (red).

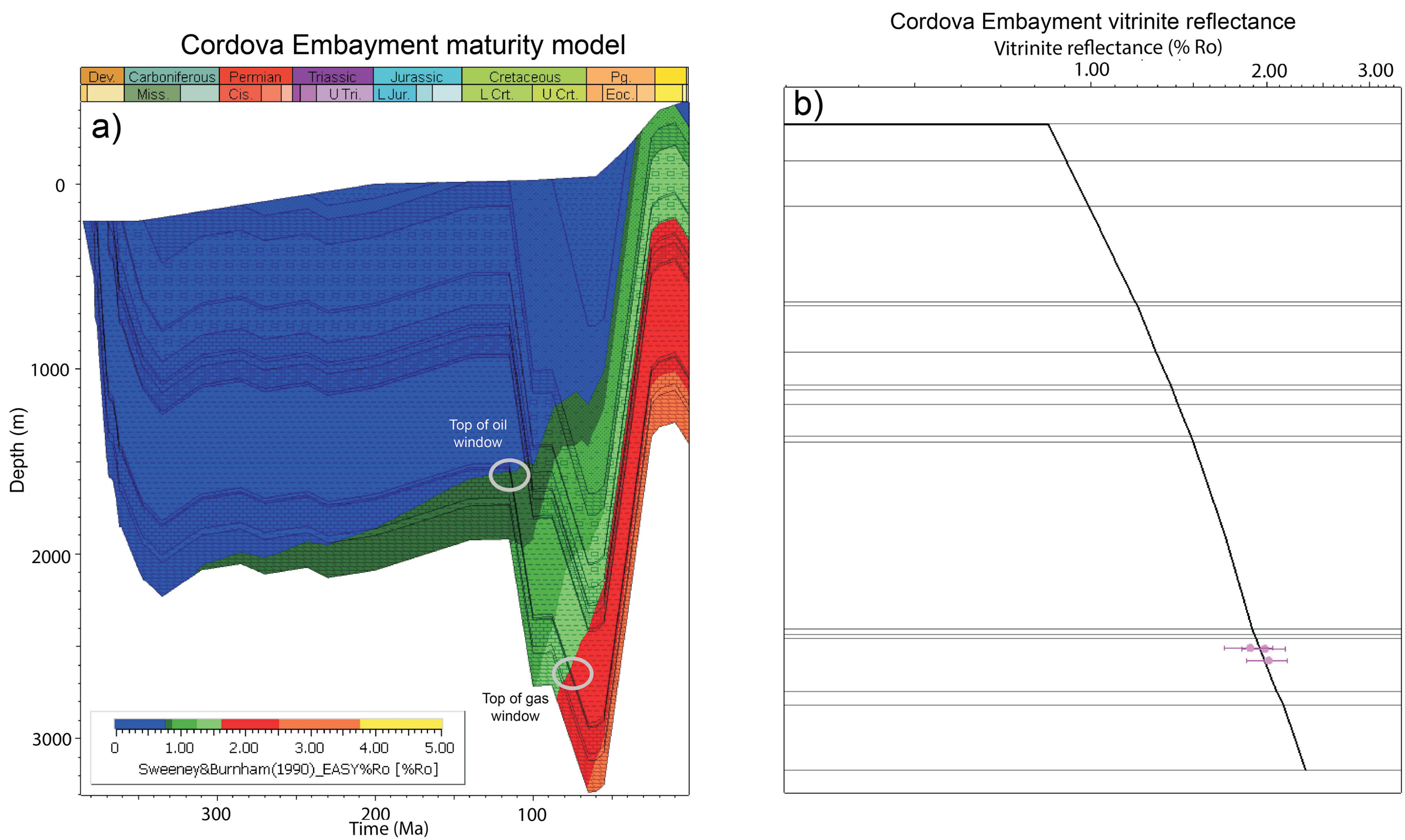

Figure 9. Cordova Embayment maturity model for the Ioe Union Shekilie A-094-G well: **a)** burial-history plot with vitrinite reflectance overlay; **b)** vitrinite-reflectance versus depth plot. The calculated vitrinite line (black) matches well with the calibration data points (pink).

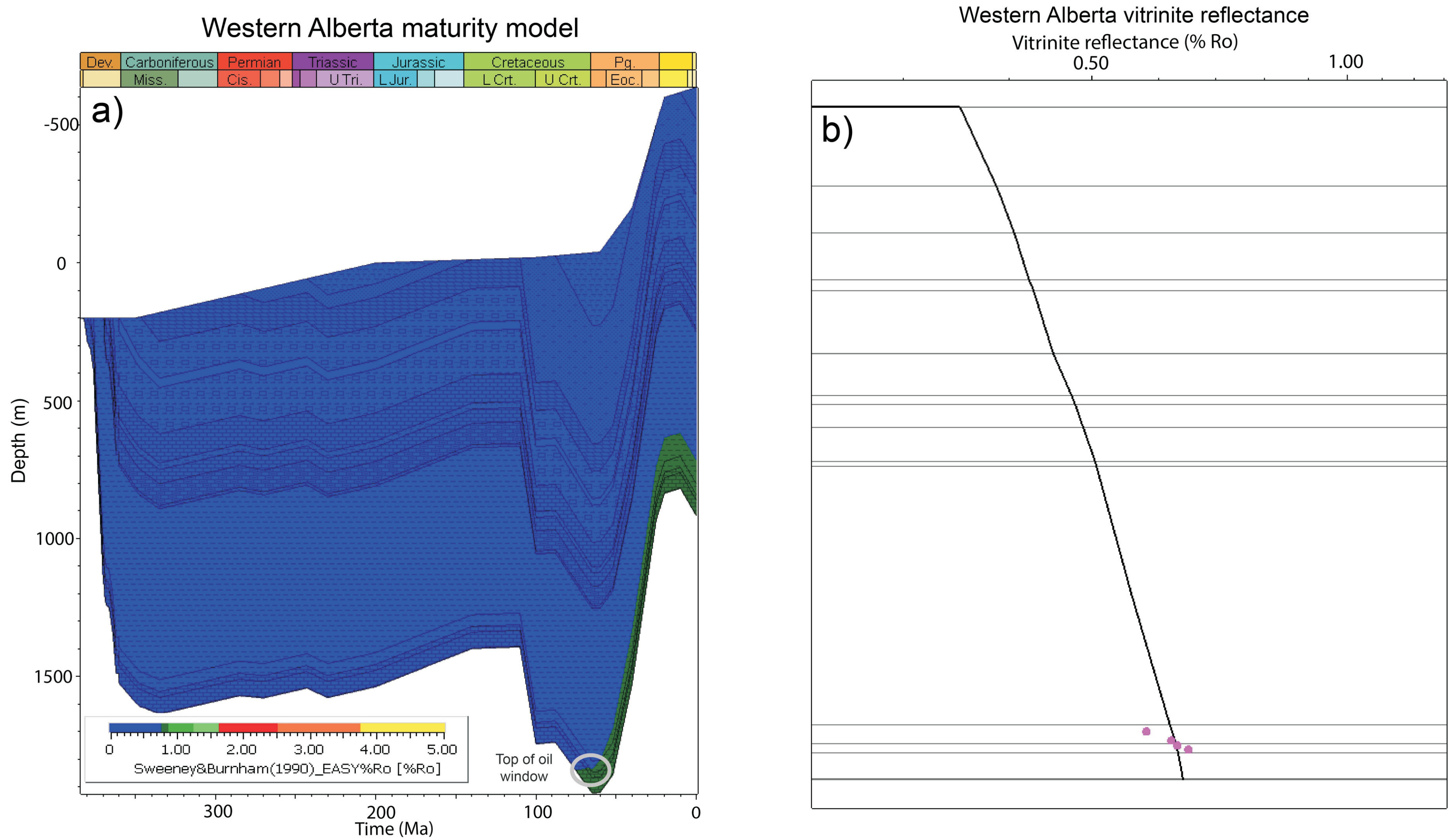

Figure 10. Western Alberta maturity model for the 100/02-32 well: **a)** burial-history plot with vitrinite-reflectance overlay; **b)** vitrinite-reflectance versus depth plot. The calculated vitrinite line (black) matches well with the calibration data points (pink).

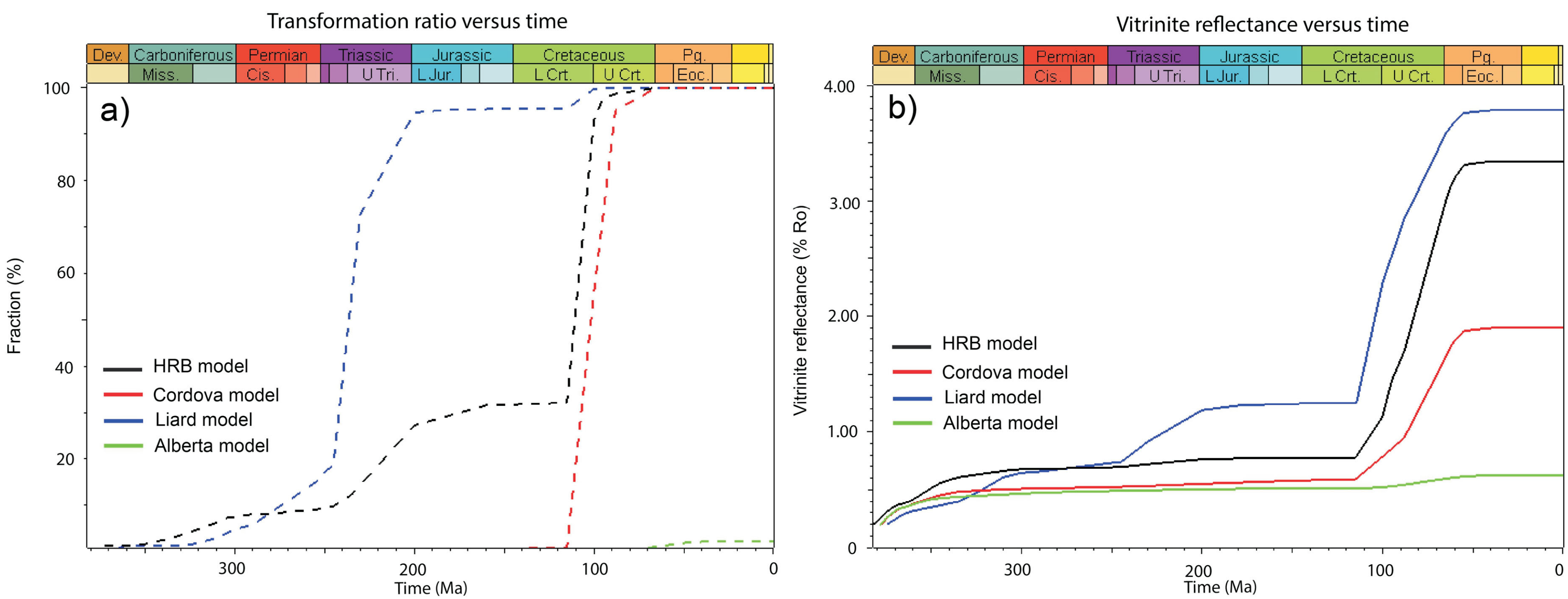

Figure 11. Relative timing and phases of maturation across the four main areas of this study: **a)** transformation ratio versus time, and **b)** vitrinite reflectance versus time. Dotted lines represent the calculated transformation ratios over time and solid lines represent the calculated vitrinite reflectance over time.

define an area that encompasses hundreds of square kilometres. The models provide considerable information in the direct vicinity of the well location, but caution should be taken when upscaling to a regional scale. The calibration data used for this study were relatively sparse and not all of the data could be used with complete confidence. Basin modelling can help identify suspicious and erroneous data. For example, some reported vitrinite-reflectance and pyrolysis values required erosion levels, heat flow or the thermal conductivity of formations to be outside the geologically plausible limits of the model. Although this method helps flag bad data, it is difficult to determine how accurate the 'good' data are and therefore how accurate the overall model is. However, basin modelling is a quantitative approach that provides valuable information even with limited data or well control.

Conclusions and Future Work

Basin modelling of the Liard and Horn River Basins, Cordova Embayment and western Alberta provides insight into burial history, thermal maturation and how the evolution of the basin has affected the present-day Devonian petroleum systems. Important conclusions of this ongoing study include the following:

- The Devonian shales were buried to depths of 1500 to 3200 m by the end of the Carboniferous Period, and reached temperatures of up to 100°C during this time. Burial depths and temperatures are greatest within the Liard Basin, which experienced the additional accumulation and preservation of the Mattson Formation due to movement along the Bovie fault.
- Tectonism related to the Laramide orogeny was the dominant control on the present-day petroleum system. During deepening of the foreland basin and subsequent uplift and erosion, all of the models experienced rapid increase in maturity. The majority of the 1-D models experienced an increase in reflectance of approximately 2% Ro over a 50 m.y. time span.
- Based on the sensitivity analysis, confidence in the heat-flow values is within 1 mW/m^2 and within 50 m for erosion. Eroded-section thicknesses range from 2250 to 440 m across the study area, and heat flow ranges from 48.5 to 88 Mw/m^2. Heat flow is highest within the Cordova Embayment and lowest within the Liard Basin, and erosion thicknesses generally decrease toward the east, away from the deformation front.
- Lithology has a relatively minor effect on the burial history and thermal maturation of the Western Canada Sedimentary Basin. Most of the stratigraphic interval comprises carbonate or sandstone, both of which have moderate values of thermal conductivity and therefore do not greatly impact the maturity profile.
- The timing of the onset of oil generation varies greatly across the study area. In the Liard basin, the Muskwa member of the Besa River Formation entered the oil window in the Carboniferous and, in Alberta, the Muskwa Formation began generating oil in the Upper Cretaceous. This large time span of hydrocarbon generation affects the present-day distribution and potential of the study area. The organic matter within the Muskwa of the Liard basin has been generating hydrocarbons for hundreds of millions of years and, as a result, its production potential today is poor. Areas that have only experienced generation since the onset of foreland subsidence (eastern Horn River Basin, eastern BC and western Alberta) will have greater potential for present-day in situ production.

In order to further constrain maturity trends and quantify erosion and hydrocarbon distribution, additional 1-D models need to be simulated, along with further sensitivity analysis. Taking the 1-D models into 2-D and 3-D should be completed in future studies to further enhance the understanding of the basin and gain further insight into hydrocarbon migration in northeastern BC.

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