1 EXECUTIVE SUMMARY

This report is intended to provide the Alberta Energy Regulator (AER), Alberta Environment and Sustainable Resource Development (ESRD), and the public with an explanation as to the source and flow pathways to the surface at the Canadian Natural Resources Limited (Canadian Natural) Primrose operating sites. Canadian Natural has been working with an independent third-party technical review panel (the Panel) on this report since March 2014. Interaction between Canadian Natural and the Panel has included working sessions, data reviews, feedback on concepts, and open discussions. This *Primrose Flow to Surface Final Report* is intended to address the final reporting requirements as identified in Enforcement Order (EO) No. EO-2013/05-NR, and provide further details and supporting data on the causes of the flow to surface (FTS) events. This report presents Canadian Natural's current understanding of the FTS source, flow pathways, and mechanistic causation based on the new information collected during the course of this study, as well as a complete reassessment of historical data.

1.1 EXECUTIVE OVERVIEW

At Canadian Natural's thermal operation in Primrose, bitumen emulsion was discovered in 2013 on the surface at four locations. Shortly after their discovery, a study was undertaken at each FTS area to understand how these events occurred. The study resulted in the drilling of 78 Quaternary groundwater wells and 58 deeper delineation wells, and the studying of 106 cased holed wells. In addition, several geological, engineering, and geomechanical studies were completed. Using the information gathered from the wells and studies, this final report was prepared to address the mechanisms that are important to understand the most likely pathway(s) from the Clearwater Formation reservoir to the surface at each FTS area. This report is consistent with the Causation Report submitted to the AER and ESRD in June 2014 and provides the data to support the conclusions in the Causation Report. This report replaces the interim Causation Report.

1.2 ENVIRONMENTAL IMPACTS

The environmental impact of the FTS events can be grouped into two broad categories—those that impact the surface and those that impact the subsurface.

1.2.1 Surface

Surface cleanup was completed at all the Primrose FTS areas in accordance with the following regulations.

- *Alberta Tier 1 Soil and Groundwater Remediation Guidelines.* Alberta Environment and Sustainable Resource Development, 2014a.
- *Sediment Quality Guidelines for the Protection of Aquatic Life.* Canadian Council of Ministers of the Environment, 2014.

- *Environmental Quality Guidelines for Alberta Surface Waters.* Alberta Environment and Sustainable Resource Development, 2014b.

1.2.2 Subsurface

Studies to evaluate subsurface impacts that relate to the risk of hydrocarbon and chloride contamination of the groundwater in the Quaternary were immediately undertaken. Laboratory testing results for dissolved hydrocarbons and chlorides encountered by the groundwater wells were below Alberta Tier 1, Natural Area (ESRD, 2014a) criteria for 76 of the 78 monitoring wells, and often below laboratory detection limits. The two wells that are not below the Tier 1 criteria were in close proximity to the surface fracture and contained bitumen emulsion.

Completed studies for the FTS areas to date, have indicated the following.

- Low dissolved constituent concentrations in the surface and groundwater samples showed a lack of produced water impact, thus suggesting that most of the formation water and condensed steam released from the Clearwater reservoir had leaked off before the fluids reached the Quaternary and the surface.
- Significant amounts of bitumen emulsion were not observed in the Quaternary aquifers, thereby suggesting that its high viscosity had limited accumulation in these units and the occurrence of bitumen emulsion was concentrated along fracture pathways.

The detailed documentation from the above subsurface activities will be submitted in separate reports as required by the EO. Those reports include the following:

- Surface Site Containment, Delineation, and Remediation.
- Geology and Regional Groundwater Delineation, Monitoring, and Remediation.

1.3 ENABLING CONDITIONS

This study identified four separate conditions that allowed for the development of flow paths from the Clearwater Formation to the surface. A review of the data from each of the FTS areas showed that the four conditions (enabling conditions) were present at varying degrees in all the areas, except for the 9-21 FTS area where a casing failure in the Colorado Group provided a bypass of the first two enabling conditions and was part of the third condition. With the enabling conditions identified, risk mitigation is tailored to specific areas and addressed in the application process. The four enabling conditions for FTS are:

1) An excessive release of bitumen emulsion from the Clearwater Formation reservoir into the next overlying permeable formation, the Grand Rapids Formation.
2) A hydraulically induced vertical fracture that propagated up to the top of the Grand Rapids Formation.
3) Vertical pathways to facilitate fluid transfer through highly impermeable shales that have in-situ stress states that usually favour horizontal hydraulic fracturing.

4) An uplift of the overburden above the Clearwater Formation reservoir that changed stress in the overlying shale, such that the minimum horizontal and vertical principal in-situ stresses approached each other.

Each enabling condition allowed for the development of a segment of the flow path using the unique circumstances for that given interval of strata. In the absence of a through-going or bypassing conduit, sufficient overlap of all four enabling condition will significantly increase the chance for a pathway to extend to the surface.

Primrose and Wolf Lake Cyclic Steam Stimulation (CSS) started some 50 years ago, and current development design and execution of CSS operations have been undergoing continuous refinement for the past 13 years in the area. The occurrence of multiple FTS events over a broad area, in a narrow time period, strongly suggests a repeatable cause (Figure 1.3-1). The fact that the four FTS events all occurred in recent history, suggests that the enabling conditions only existed with sufficient overlap in this same time period, which allowed the FTS events to occur.

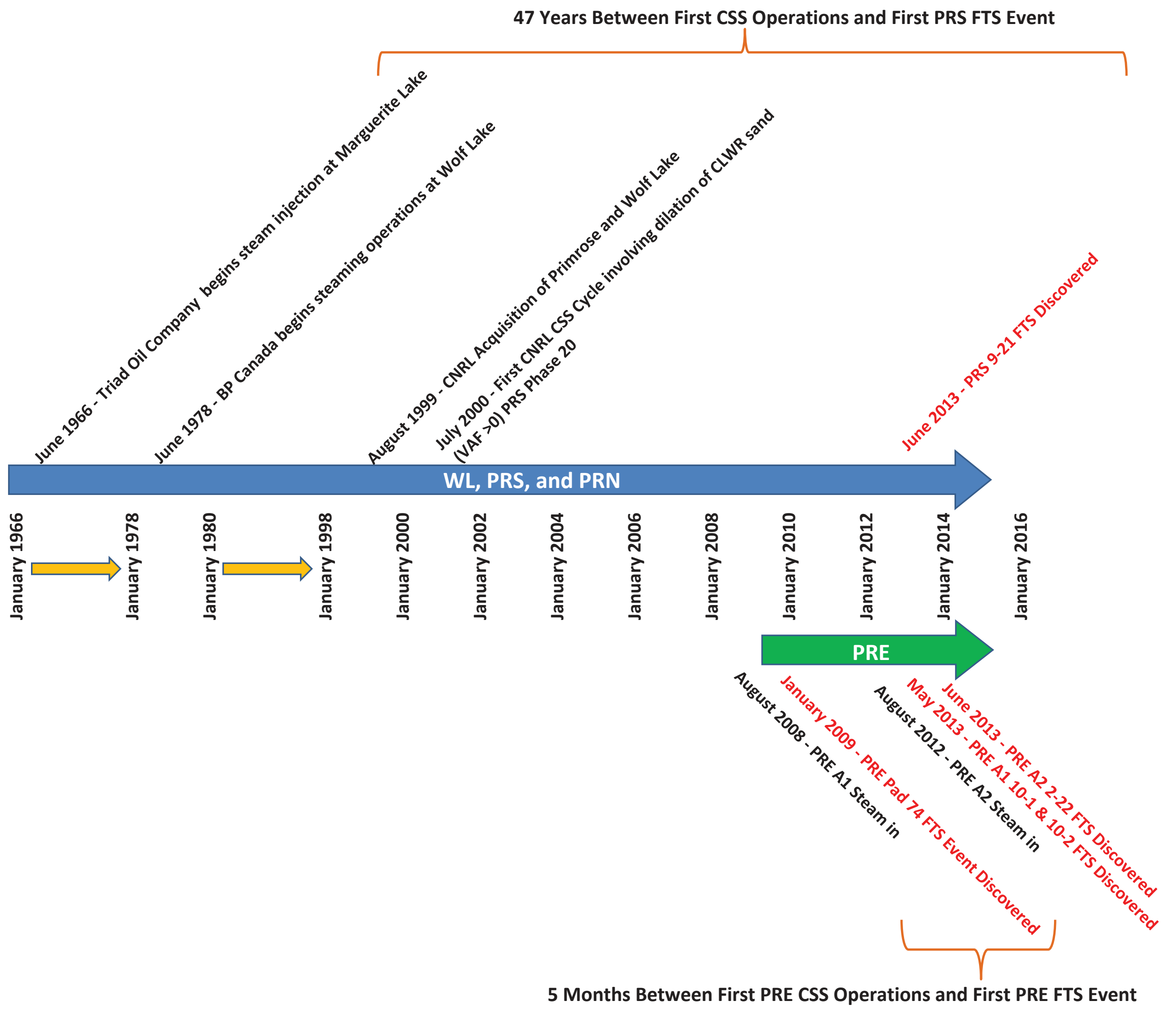

Figure 1.3-1 Timeline of Primrose and Wolf Lake (PAW) operation with FTS events.

The four enabling conditions were deduced from the systemic patterns observed in the field data. Evidence of the four enabling conditions appeared repeatedly in the field data for the FTS areas. In many instances, field observations forced a reassessment of industry understandings of the nature and mechanistic behavior of overburden. Simulations and laboratory measurements helped to understand the underlying mechanisms for three of the four enabling conditions.

Figure 1.3-2 provides a schematic of the pathway the bitumen emulsion took as it travelled from the Clearwater Formation to the surface.

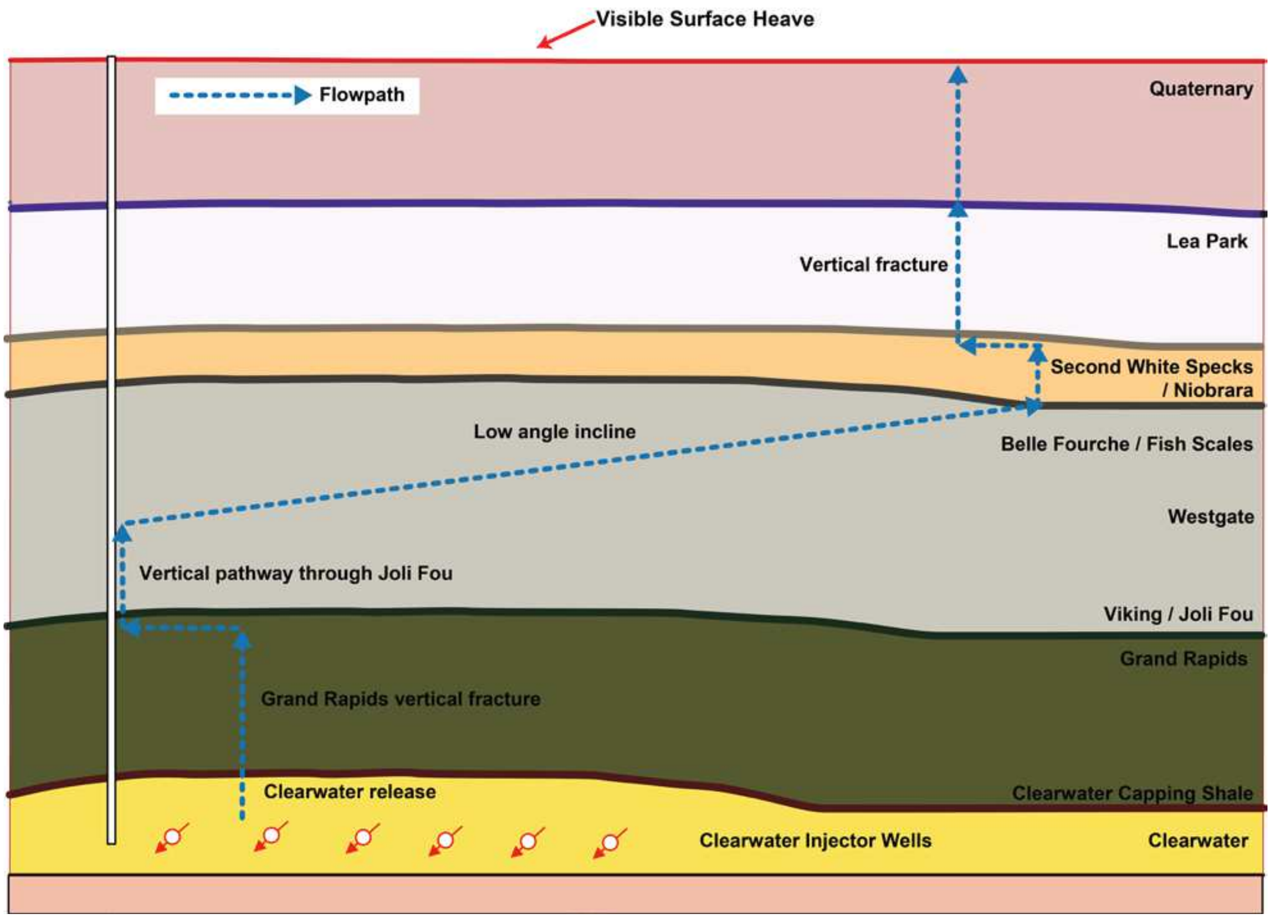

Figure 1.3-2 Schematic of the four enabling conditions showing the flow path to the surface.

1.3.1 An Excessive Release of Bitumen Emulsion from the Clearwater Formation Reservoir into the Next Overlying Permeable Formation, the Grand Rapids Formation

The upward flow of fluid to the surface begins with an excessive release of bitumen emulsion from the Clearwater Formation into the next overlying permeable formation, which in the Primrose area is the Grand Rapids Formation.

Observation systems in the field, have shown that excessive bitumen emulsion releases from the Clearwater Formation are characterized by multi-well injectivity events observed through the injection monitoring system. They are also characterized by regional pressure responses in the overlying Grand Rapids Formation water sand, which are observed through the B12 monitoring array. The B12 monitoring array can detect pressure responses over large distances with the ability to locate events. An excessive release on its own will not cause a flow path to the surface to develop. Most releases from the Clearwater Formation do not correlate to FTS events. However, all of the FTS events with excessive releases have been sourced by some of the largest releases observed.

1.3.2 A Hydraulically Induced Vertical Fracture that Propagates Up to the Top of the Grand Rapids Formation

When fluids enter the Grand Rapids Formation, the bitumen emulsion must make its way up through more than 100 m of the formation to reach the top. The Grand Rapids Formation contains significant water-saturated sands and muds. Within the FTS areas of interest, there are no observations of pre-existing natural vertical pathways where the released fluids could flow up to the top. Thus, for any fluid released from the Clearwater Formation reservoir to reach the top of the Grand Rapids Formation, it must use a non-porous media pathway. The mechanism that results in the development of a flow path through the Grand Rapids Formation is a hydraulically induced vertical fracture. It is possible that a wellbore conduit can provide a bypassing pathway for fluid to reach the top of the Grand Rapids Formation.

There have been four general field observations noted for this enabling condition. Those observations are noted below.

1) Diagnostic Fracture Injection Tests (DFIT) in the Grand Rapids Formation show that the stress state favours vertical fracturing.
2) The Grand Rapids Formation pressure monitoring systems record transient pressures for some excessive fluid releases that are consistent with fracture pressures at the release source points.
3) The identification of circular to elliptical seismic anomalies in the Grand Rapids Formation, which appear in post steam seismic. Seismic modeling show Post Steam Seismic Anomalies (PSSAs) to be consistent with the predicted seismic changes expected from fracture leak off of reservoir fluids containing solution gas. Drilling has confirmed the presence of heated Clearwater Formation sourced bitumen in the Grand Rapids Formation at the centre of one such anomaly (102/16-2-67-3W4). Mapping shows how far such anomalies extend vertically in the Grand Rapids Formation, and confirms that only a small subset of excessive releases reach the

top of the Grand Rapids Formation. Mapping also shows that not all PSSAs that reach the top of the formation become FTS events.

4) The observations of linear patterns of microseismic events running northeast/southwest. These patterns are consistent with hydraulically induced vertical fractures propagating laterally at the Grand Rapids and Joli Fou formations interface.

Additional conditions are required for an FTS pathway to continue to develop.

1.3.3 Vertical Pathways to Facilitate Fluid Transfer through Highly Impermeable Shales that have In-Situ Stress States that Usually Favour Horizontal Hydraulic Fracturing

The Joli Fou Formation is a natural barrier to fluid flow and is the regional capping seal to the Mannville Group hydrocarbon system. It is because of the high mud content that these formations lack the permeability for fluid to flow through them (even over geologic time). In addition, these mud-dominated formations have much higher horizontal stresses because of the markedly different material properties of the mud (as compared to sand). The sharp contrast in horizontal stresses between the Grand Rapids and Joli Fou formations acts as a barrier to the upward growth of vertical fractures in the Grand Rapids Formation. Any hydraulically induced vertical fracture that overcomes leak off and propagates to the top of the Grand Rapids Formation, cannot climb any farther because hydraulically induced fractures created in the overlying Joli Fou Formation would be horizontal. Despite these characteristics, the field evidence indicates that the FTS pathways through the Joli Fou Formation were vertical.

Vertical pathways through the Joli Fou Formation can include an open conduit (such as the inadequate placement of cement around a wellbore), conductive natural fractures or faults, or induced pathways (such as shear failure of a natural fracture or fault as a result of CSS operations). The simplest (lowest required pressure) and most likely explanation for this vertical pathway is an inadequately cemented wellbore. This is consistent with other industry studies (Dusseault & Jackson, 2014).

One example is shown by the 100/7-22-67-3W4 wellbore. Field evidence from the abandoned 100/7-22-67-3W4 wellbore at the 2-22 FTS area, strongly supports this conclusion. The well is in close proximity to the release point from the Clearwater Formation. A flow rate of 200 L/min of bitumen emulsion was sustained for several days in the Westgate Formation when the well was re-entered. A twin well drilled 10 m away encountered oil at the same depth, but at a flow rate of only 2 L/min. This 2 L/min flow rate is consistent with the flow from fractures in other delineation wells.

Another example consistent with a wellbore pathway is the 108/9-2-67-3W4 well at the 10-2 FTS area. In this well, the volume of bitumen recovered during a perforation program in the Joli Fou Formation was larger than observed during the drilling of nearby wells. Although the potential for a FTS flow path vertically up through the Joli Fou Formation using natural fractures and faults cannot be dismissed, the data collected does not appear to support this possibility. The identified pathways are interpretations based upon a mechanistic framework, which fits well with the FTS study field observations. Alternate pathways could exist and are explored in Appendix F.

1.3.4 An Uplift of the Overburden Above the Clearwater Formation Changed Stress in the Overlying Shale, such that the Minimum Horizontal and Vertical Principal In-Situ Stresses Approached Each Other

Hydraulically induced fracture growth is controlled by in-situ stresses. Determinations of in-situ stresses from the majority of the Colorado Group shales, indicate that bitumen emulsion would hydraulically induce horizontal fractures. Despite this, bitumen emulsion shows from the four FTS areas demonstrate that the flow path follows a net low angle (< 10°) climb through the Westgate, Fish Scales and Belle Fourche formations (Table 1.3-1). This pattern of net low angle climb is also evident in core data, where bitumen filled fractures are predominantly in a small subset of low dip angle fractures representing 5% or less of the total available natural fractures (Figure 1.3-3).

The findings suggest that stress states were altered by dynamic loading during the FTS events.

Table 1.3-1 Net Low Angle Inclined Pathway

FTS Area	Formations	Gross Distance	Angle
2-22	Westgate to Second White Specks Formation	478 m	4.8°
10-2	Viking to Second White Specks Formation	573 m	8.6°
10-1	Joli Fou to Niobrara Formation	1056 m	6.5°
Pad 74	Joli Fou to Niobrara Formation	1302 m	4.6°
9-21	Joli Fou to Second White Specks Formation	1365 m	4.3°

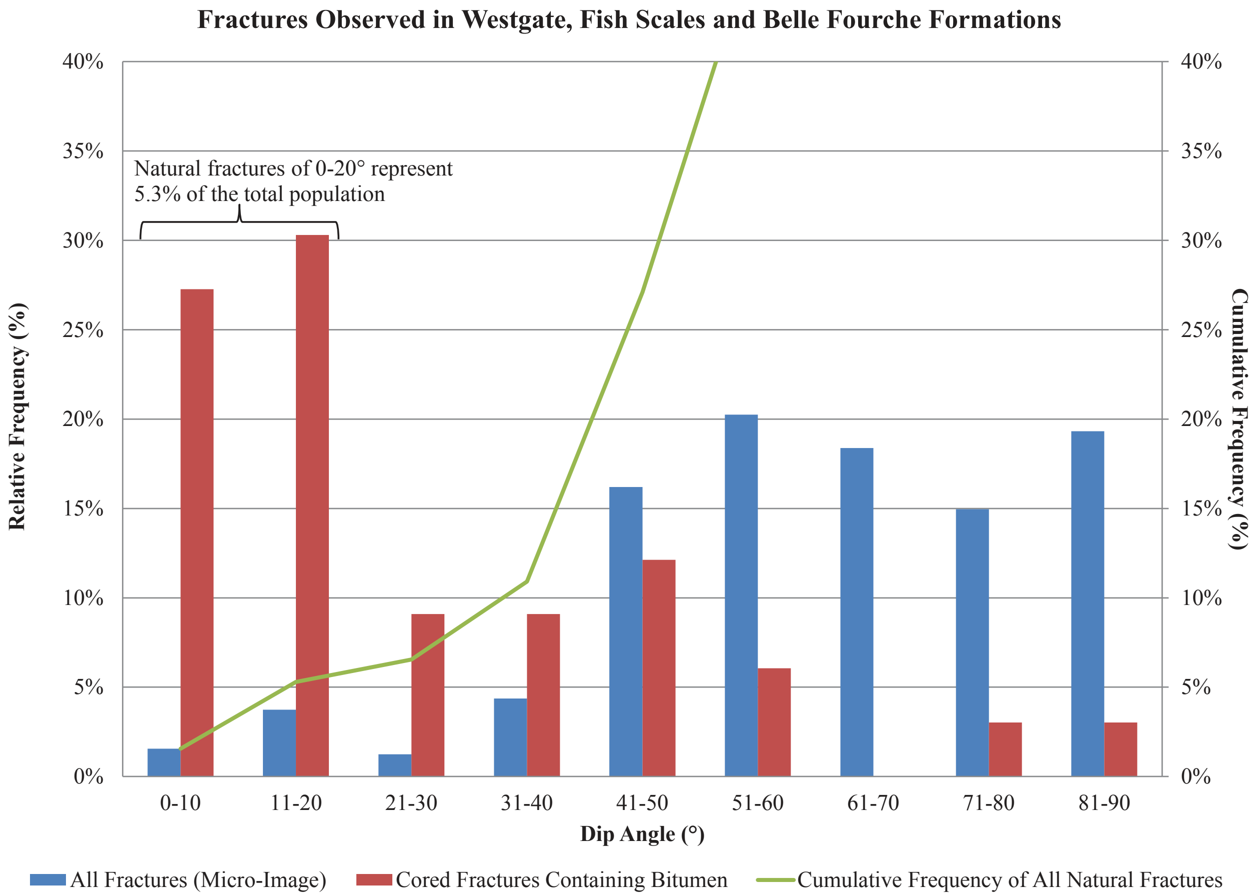

Figure 1.3-3 **Dip angles of cored fractures containing bitumen emulsion. The low angle inclined FTS pathway likely used 5% or less of the total natural fracture population in the Westgate to Belle Fourche formations.**

This change in stress state can be explained by an uplift of the overburden during CSS operation. A large uplift results in substantial stress changes, which reduces the contrast between the vertical and minimum horizontal stresses. As the contrast between the vertical and minimum horizontal stresses narrows, the cohesion of the shales becomes increasingly more important to the fracture orientation. Since natural fractures and faults have little to no cohesion, it becomes easier to open pre-existing low dip angle natural fractures and faults, than to propagate hydraulically induced horizontal fractures. Once injection has ceased and production commences in the Clearwater Formation, compaction occurs and the dynamic loading of the stress state diminishes.

A review of the estimated uplift (as represented by the Formation Expansion Index [FEI]) in Primrose, shows that a high FEI (large uplift) is associated with the flow to surface events. Figure 1.3-4 shows the distribution of individual well FEIs from a total of 123 phase cycles. The distribution of all the flow to surface events is noted in this population. It can be seen that FTS events are confined to the top 27% of this distribution, with the majority in the top 10%. The correlation of FTS to significant uplift induced stress changes is supported by this pattern.

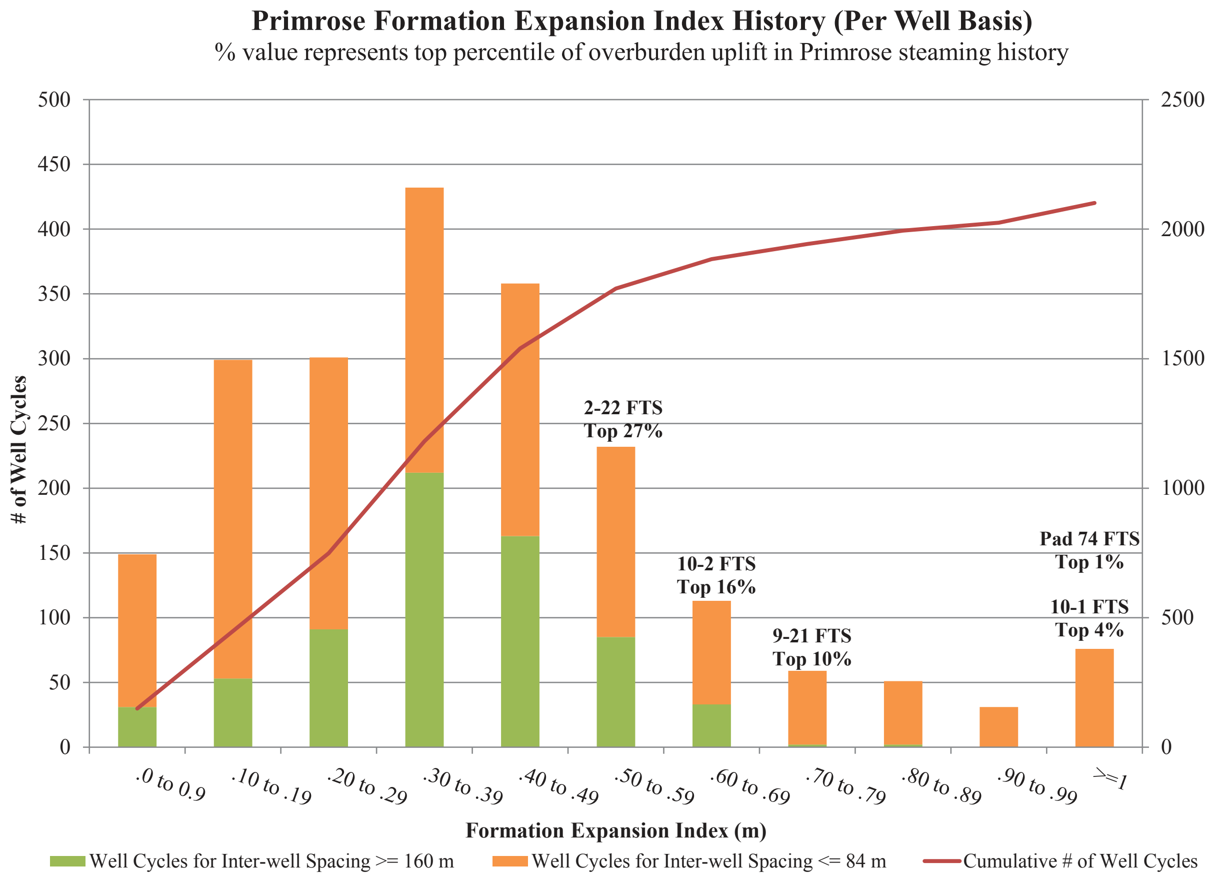

Figure 1.3-4 Primrose FEI distribution with the FTS events confined to the top 27%.

Similar to the previous enabling conditions, a large uplift induced stress change allowed part of the flow path to develop. This pathway will only be used if bitumen emulsion reaches the Westgate to Belle Fourche formations.

1.3.5 Second White Specks Formation to the Surface

The flow path from the Second White Specks Formation through to the Lea Park Formation, and then through the Quaternary to the surface is essentially vertical, using both natural fractures and hydraulically induced vertical fractures. Image logs and cores show the Second White Specks, Niobrara, and Lea Park formations having bitumen emulsion present in fractures with high dip angles (70–90°). Both the higher natural fracture densities and the conductive nature are unique in comparison to the underlying formations. In addition, Diagnostic Fracture Injection Test results for these formations indicated both connected and conductive natural fracture networks in at least limited vertical zones (a unique feature and in contrast to the rest of the Colorado Group shales). These zones can store fluids, if the fluid pressures are below that which would induce hydraulic vertical fractures. The containment and lateral movement can result in a time delay between the FTS pathway arriving in a zone and departing from it. This latter characteristic is evident in time delays between the Clearwater reservoir release and its arrival on the surface via hydraulically induced vertical fracturing through the Quaternary strata. In some instances, the bitumen emulsion may have stayed in the Second White Specks to Lea Park formations for a significant time before fracturing to the surface. This phenomenon was most evident at the 10-1 FTS location.

1.3.6 9-21 FTS Area—Exception to the Four Enabling Conditions

The 9-21 FTS area is unique among the FTS areas in that a significant portion of the flow path from the Clearwater Formation to the Westgate Formation was inside a wellbore. An uphole casing failure and subsequent fluid release in Phase 21 many years ago, provided a direct conduit from the Clearwater Formation to the Joli Fou and Westgate formations—with no contact between the released fluids and the strata in between. This unique bypass left bitumen emulsion in the Joli Fou and Westgate formations at the pad. It is possible that the release of bitumen emulsion may be related to casing impairments in this area. From the Westgate Formation to the surface, the 9-21 FTS event exhibited the final enabling condition that involved a net low angle elevation gain to the Second White Specks Formation and then an essentially vertical pathway to surface.

1.4 SUMMARY OF ENABLING CONDITIONS

The findings in this study are based primarily on field observations; supplemented with laboratory, engineering, and simulation work to provide additional insights and to confirm observations. The fact that the four FTS events all occurred in recent history suggests that the enabling conditions only existed with sufficient overlap in this same time period (Table 1.4-1).

Table 1.4-1 Flow Path Location and Mechanism Summary by Site

FTS Area	Enabling Condition 1 (Clearwater Capping Shale)	Enabling Condition 2 (Grand Rapids Formation)	Enabling Condition 3 (Joli Fou/ Westgate Formations)	Enabling Condition 4 (Westgate to Belle Fourche Formation)	Second White Specs Formation to Surface
2-22	Non-wellbore release near 16A94	Vertical fracture/bypass by wellbore 100/7-22-67-3W4	Bypass by no cement in 100/7-22-67-3W4	Low angle climb at 4.8°	Vertical
10-2	Non-wellbore release near 12A75	Vertical fracture at 16-2	Inadequate placement of cement in 108/9-2-67-3W4	Low angle climb at 8.6°	Vertical
10-1	Non-wellbore release near 10A77	Vertical fracture near 1AA/9-1-67-3W4	Inadequate placement of cement in 1AA/9-1-67-3W4	Low angle climb at 6.5°	Vertical
Pad 74	Non-wellbore release near 10A77	Vertical fracture near 1AA/9-1-67-3W4	Inadequate placement of cement in 1AA/9-1-67-3W4	Low angle climb at 4.6°	Inadequate Placement of Cement and Heat at 1A74
9-21	Bypass by Casing Failure at Phase 21	Bypass by Casing Failure at Phase 21	Casing Failure at Phase 21 well	Low angle climb at 4.3°	Vertical

1.5 Conclusion

In accordance with Enforcement Order EO-2013/05-NR issued on October 21, 2014, Canadian Natural initiated this study to determine the source and flow path of bitumen emulsion discovered on the surface at Primrose. This report documents the findings and data gathered for the study, describes the origin and flow path to the surface for each FTS location, and describes the enabling conditions and flow mechanisms associated with each event.