Primrose Flow to Surface
Independent Technical Panel

July 14, 2014

Mr. Erin MacZuga
Director, Enforcement & Surveillance
Alberta Energy Regulator
Suite 1000, 250 – 5 Street SW
Calgary, Alberta
T2P 0R4

Re: Independent Panel Review of the Canadian Natural Primrose FTS Causation Report

Dear Mr. Erin Maczuga:

Attached please find the Independent Technical Panel's review of the Canadian Natural Primrose Flow to Surface Causation Report. The review addresses the technical merits of the investigation, analyses and conclusions presented in the Causation Report and recommends additional technical analyses and data collection. The Panel believes not all of this work is required to complete the final report on the FTS events. The additional work will, however, deepen the understanding of these events and improve Canadian Natural's operational integrity in high-pressure CSS operations.

The Technical Panel agrees with the enabling conditions identified by Canadian Natural for the observed Flow to Surface events at Primrose. Canadian Natural has also correctly recognized the majority of the technical factors which influence these conditions. Successful mitigation of future steaming operations can be assessed with the framework of the enabling conditions Canadian Natural has presented. This includes application of low-pressure steaming operations in areas affected by an FTS event.

The Panel would be pleased to make themselves available to staff of AER for discussions of the content of this report. Please do not hesitate to contact us (rick@kry.ca).

Yours truly

Pat McLellan, P.Eng.

Keith Hirsche

Russ Bacon, P.Eng.

Rick Kry

Independent Panel Review of the Canadian Natural Primrose Flow to Surface Causation Report

Preface

Subsequent to the four Flow to Surface (FTS) events in 2013 at Canadian Natural's Cyclic Steam Stimulation (CSS) operation at Primrose, Canadian Natural and the AER agreed to appoint an independent third party panel to review the technical merits of the FTS investigation, analyses and conclusions. Canadian Natural appointed the Panel in March, 2014. Three workshops with the Canadian Natural FTS team, the Panel, and key personnel from the AER were completed prior to writing this report. The Panel also held several additional working meetings with Canadian Natural personnel to discuss the data and analyses in more detail, and identify activities to more fully investigate the FTS events.

The Panel members have expertise in the key areas of geomechanics, wellbore and caprock integrity, geophysics, and thermal recovery; their combined work experience in the oil and gas industry is greater than 120 years. Collectively, the goal of the Panel is to aid both the AER and Canadian Natural in the Source Flow and Pathway investigation, as well as provide technical review of the Canadian Natural investigation findings and final report.

This document describes the Technical Panel's views on the results of the investigation to date and in particular, the Causation Report prepared by Canadian Natural.

Independent Panel Review of the Canadian Natural Primrose FTS Causation Report

Summary

The Technical Panel agrees with the factors related to the cause of the Flow To Surface (FTS) events as expressed in the Canadian Natural Report:

- Excessive release of bitumen emulsion from the Clearwater reservoir into the next overlying permeable formation, the Grand Rapids Formation.
- A vertical hydraulically induced fracture that propagates up to the top of the Grand Rapids Formation.
- Vertical pathways to facilitate fluid transfer through generally impermeable shales that have in-situ stress states that usually favour horizontal fracturing:
    - Wellbore(s) for segments of the path to surface (where inadequate cementing left a gap or open channel, a wellbore can be an efficient conduit).
    - Natural fractures and faults in the shales.
    - Vertical hydraulically induced fractures.
- An uplift of the overburden above the Clearwater reservoir that changes stress in the overlying shale such that the minimum horizontal and vertical principal in-situ stresses approach each other.

The Technical Panel regards these factors as enabling conditions for the observed Flow to Surface (FTS) events within Canadian Natural's Primrose operations. Of the enabling conditions identified by Canadian Natural, three are controllable.

- The existence of a cased well or open hole wellbore with poor sealing along at least a portion of its path.
- Excessive uplift generated by operational steaming of the Clearwater reservoir.
- Excessive fluid volume released from the Clearwater reservoir into the Grand Rapids Formation[1].

Uncontrollable enabling conditions such as the propensity for hydraulic fractures to be vertical in the Grand Rapids and natural fracture and fault distributions in the Colorado Group also need to be sufficiently understood to properly assess operational risks. Naturally occurring geologic features may be of particular importance in Primrose East where the formations have been affected by salt dissolution and four of the five FTS events have occurred.

Introduction

The Panel recognizes Canadian Natural has collected an impressive amount of data and performed significant technical analyses to investigate how the FTS incidents came to be. To this point in the investigation, Canadian Natural has identified the primary components of a flow path to surface and correctly recognized the key technical factors which influence the enabling

[1] The Panel has tried to be consistent with the stratigraphic nomenclature selected by Canadian Natural in their Causation report

conditions. As such, Canadian Natural has defined the context required to review past operations at Primrose and demonstrate how new mitigation proposals might avoid or pro-actively detect the enabling conditions for a FTS incident.

Canadian Natural responded to the FTS events by identifying the immediate surface, Quaternary soil and groundwater impacts and remediating these (where required) to current regulatory standards. Canadian Natural also identified the bitumen emulsion at surface as Clearwater Formation sourced. It undertook both an extensive drilling and coring program to identify the elements of the flow path from the reservoir to surface and acquired additional 4D seismic to image the subsurface. In conjunction with this data acquisition, technical efforts were commissioned to further understand the enabling conditions for FTS events.

Canadian Natural's plan for documenting the results of the FTS investigation is to issue a causation report which will be followed by a final report. The Causation report is complete and focuses on presenting an overview of the current understanding of the causes of the incidents and further outlines work areas to be addressed and presented in a final report. This document contains the Independent Panel's response to Canadian Natural's Causation report.

FTS Pathway

The Panel felt it important to describe the components and relevant properties of the pathway for a FTS event to provide context for understanding bitumen emulsion flow to surface. Although this is somewhat redundant with Canadian Natural's Causation report, the Panel felt it appropriate to express the components of the pathway in the terms arising from their collective experience.

Three general factors influence the flow path: in-situ stress magnitudes, improperly cemented wellbores and pre-existing discontinuities (natural fractures, faults and bedding planes).

- In the Canadian Natural operations area, in-situ stress states have been determined that support the commonly understood mechanisms which help contain CSS operations in the Clearwater and avoid releases of fluid from the reservoir to the surface. Stresses and potential stress contrasts typically increase with depth. With a larger stress contrast present, there is a decreased likelihood of a vertical feature allowing significant vertical flow to occur deeper in the Colorado Group. This relationship predicts horizontal hydraulic fractures lower in the section will tend to be larger than those found higher. No matter where a horizontal hydraulic fracture is located, however, natural fractures connecting to the propagating hydraulic fracture plane can receive some amount of bitumen emulsion. As a result oil staining on natural fractures can be an indicator of a nearby flow path but not necessarily an observation of the main flow path.
- Inadequate placement of cement at an abandoned, open hole wellbore will leave a gap which can transmit fluid just by pressure differential. In that sense, a wellbore (or cased and cemented well) that does not meet its cementing requirements is an easier pathway for fluid to travel vertically through a formation. However, it must be noted that a bitumen show at a cased well might simply be the intersection with a horizontal hydraulic fracture

and not an indicator of a behind casing channel path. Perforation, flow tests and production log analyses are required to discern if the show is the result of a fracture, or due to flow through a significant channel behind casing.

- Natural fractures and faults of varying densities and properties exist in all of the geological strata at Primrose, however, it can be difficult characterizing their relative connectivities and conductivities (aperture–permeability product). Based on field evidence from the Primrose FTS sites the Panel believes that these natural discontinuities, when subjected to changing in-situ stresses, and high fluid pressures, can provide the critical vertical flowpath across strata where the original stress state favours a horizontal hydraulic fracture.

At initial conditions, the Clearwater Capping Shale normally is competent in that there is the expectation of a minimum horizontal stress contrast with the underlying reservoir to provide a seal during steaming operations. Excessive uplift caused by CSS operations in the Clearwater, however, changes the initial in-situ stresses enough in localized areas to bring this into question. Seismic imaging of post steam 4D anomalies in the Grand Rapids supports the breach of the Clearwater Capping Shale in locations with no through-going wellbores.

In most thermal operations, small fluid releases to the Grand Rapids can be absorbed by the porosity of the water sands. In the event of a larger but still limited fluid release, minor pressure excursions may be observed at propitiously sited pressure observation wells. The apparent stress state in the Grand Rapids has the minimum in-situ stress being horizontal so that a leak-off dominated fracture will grow vertically in response to sufficiently high injection rates. Fluid leak-off from such a fracture will appear radial away from it and the fracture will grow as needed in the direction requiring least work, namely upwards. It will eventually reach the base of the Joli Fou Formation. With continuing volumes entering the Grand Rapids, stresses on the fracture face will increase and pore pressure at the base of the Joli Fou will therefore also increase.

The transition of the FTS pathway from the Grand Rapids to the Joli Fou is not trivial because the in-situ stresses strongly favour horizontal fracturing at this interface. As Canadian Natural shows in their causation report, a wellbore with inadequate cement placement can be an effective mechanism for transferring fluid to a higher elevation. However, it is not the only possibility. A vertical fracture can, for a few meters, penetrate a formation with a higher horizontal stress before re-orienting to a horizontal fracture. This then puts the first horizontal fracture in the Joli Fou from the Grand Rapids. High-pressure fluid from the Grand Rapids might also find and influence a natural fracture or fault which is optimally oriented, located where the pre-steam horizontal and vertical stresses in the shale are closer than normal, or just where the change in stresses caused by formation uplift contributes to failure of the natural fractures. The combination or alignment of these conditions is expected to be uncommon but considering the presence of seismic scale faulting and the potential for localized stress variations, for example as related to the salt dissolution from the underlying the Prairie Evaporite Formation, in Primrose East or differential compaction across sand-filled channels in the Grand Rapids, these conditions are not impossible.

The in-situ stress state implied by determinations which Canadian Natural has done in the Colorado Group from the Joli Fou to the Second White Specks Formation shows the vertical stress to be a minimum, so induced hydraulic fractures caused by fluid incursion should be horizontal. However, as more fluid is injected to such a fracture, it will grow according to variations in the local vertical stress. As the area of the fracture increases, the fracture is effectively increasing the search area for the best feature that allows significant vertical growth. Depending on placement, that might be a wellbore (or well) with inadequate cement placement, or natural fractures or faults that have sufficient connectivity and conductivity and are optimally oriented. If the main intersecting discontinuities are also located in regions where the stresses and pore pressures are modified sufficiently, then a combination of tensile and shear failure can occur. The high pressure in the induced fracture decreases the local effective stresses resulting in an increase in aperture and potentially significant permeability enhancement. Fluid can then flow up this newly discovered relatively uncommon feature and start a new horizontal fracture once any of the necessary conditions for significant vertical flow are absent. The process then repeats from the new, higher horizontal fracture.

Above the Second White Specks, the stress determinations in the Niobrara and Lea Park Formations indicate that the horizontal minimum stress may be the minimum principal in-situ stress and if so, vertical hydraulic fractures will be preferred. This assumption is further supported by the relatively frequent occurrence of vertical fractures in the shallower Quaternary deposits (where there are no stress determinations) and the vertical surface fissures observed at the FTS sites. These surface fissures are dominantly aligned in a NE-SW orientation and consistent with the regional maximum horizontal in-situ stress. Natural fractures in the Niobrara and Lea Park are also sufficiently frequent that they may provide effective local storage for bitumen emulsion.

Implications of the Pathway Model

Canadian Natural has performed Diagnostic Fracture Injection Tests (DFITs or minifracs) over intervals in the Colorado group that contained oil shows in natural fractures. The results of these tests provide some support for Canadian Natural's belief that the effective permeability of natural fractures that contain oil is too low to allow significant fluid flow rates.

Two important caveats on these results exist. First, these tests were performed when the formations were not being influenced by injection-related uplift. Secondly, because the volume of formation sampled by each evaluation well is small compared to the total area being investigated it is not possible to test a very large number of natural fractures with a DFIT. Thus, the distribution of native conductivities determined by these tests may not be representative of the actual conductivities when the FTS events occurred. In other words, the vertical connectors between successively shallower horizontal fractures likely are not representative of the average natural fractures. Instead, it appears they must be end members of the set of fractures in terms of their connectivity, conductivity, orientation and their placement relative to operations-induced stress changes and local effective stress conditions imposed by high-pressure fluids contained in the pathway.

Canadian Natural has completed their causation investigation which has identified the primary components of a flow path to surface. They are now in the process of determining the most likely pathways at each FTS site along with alternate pathways of more limited probability. It is important that these interpretations honour all observed oil shows and no-shows with a framework that contains elements that either are present or possible. For those elements which are possible, the confidence limit should be noted.

Canadian Natural has identified knowledge gaps in their analysis and will undertake work to address these before their investigation is completed. These activities are described in the next section. They also have correctly recognized the majority of technical factors influencing the enabling conditions. Successful mitigation of future steaming operations can be assessed within this framework of the enabling factors which they have presented.

Canadian Natural has also thus defined the context with which they need to review past operations at Primrose to demonstrate how new mitigation proposals might have influenced prior events, to avoid or pro-actively detect the enabling conditions in each FTS incident. In setting the stage for any mitigation plan, Canadian Natural needs to more precisely identify what relevant operating conditions triggered the existing FTS events and this will provide confidence that future operations can be monitored and managed in a way that minimizes the likelihood of another such event.

Canadian Natural states that the four enabling conditions are commonalities at the five FTS sites. The independent Panel considers that while all of the enabling conditions can be commonalities, not all are required to initiate a flow to surface. Regardless, the implication is that future operations at PAW must be designed to provide confidence that none of the enabling conditions rises to sufficient prominence to activate another release. For example, previous operations may have left bitumen stored in shallow intervals and this could be released if future operations activate one of the enabling conditions. A prime example of this time delay effect is suggested at the 9-21 site where bitumen emplacement in the Westgate Formation most likely happened approximately four years before the actual FTS event. In 2013, the operating conditions, which caused excessive injection-related uplift, changed the stresses sufficiently to allow the extension of the flow path to surface.

Specific Review Comments on Canadian Natural Causation Report.

There has been a dedicated focus by Canadian Natural on obtaining high-quality data in the FTS areas. This has allowed the identification of the enabling conditions, both controllable and uncontrollable that lead to the FTS events.

The Technical Panel recognizes the particular steaming strategy employed by Canadian Natural during the FTS events, namely large volumes above fill-up with closely-spaced wells, resulted in the excessive uplift and further enabled the excessive fluid release to the Grand Rapids. In this sense large volumes above fill-up, considering the close spacing of the wells, is a more fundamental cause of the FTS events. The Panel recognizes that this cause leads to the conditions presented by Canadian Natural in their Causation Report, but Canadian Natural could be clearer in explaining the underlying conditions leading to the FTS events. Since similar steaming strategies appear to have been applied successfully in large regions of the Primrose area without causing FTS events, identifying the reason(s) for the different FTS outcomes is of crucial importance in minimizing the risk of future events.

The conditions presented by Canadian Natural also address the practicality of initiating a low-pressure steamflood in the affected areas. At low operating pressures, the Technical Panel considers three of the four enabling conditions – an excessive release of bitumen emulsion from the Clearwater reservoir, vertical hydraulically induced fractures, and uplift of the overburden that changes stress in the overlying shale – cannot occur. And although a vertical pathway to facilitate fluid transfer through generally impermeable shale might be present, this should not be a factor at low reservoir pressures

Sections 1-3 of the Causation report provide a good summary of the FTS events and their investigation. Conditions which facilitated the release of bitumen emulsion at surface are defined and the FTS delineation program, technical evaluations, and industry/regulatory collaboration activities are summarized in Table 3-1 of the Causation report. Since most activities are described in a single line, this brief summary understates the impressive amount of high-quality data obtained and breadth of the analyses undertaken by Canadian Natural.

The Geological overview presented in Section 4 is sufficient to understand the formations and their geological character. The introduction of fracture statistics is a start at developing an understanding of the distribution of natural fractures and faults in the Colorado Group. This characterization and modelling work is important since these features play a strong role in the vertical transmission of fluid through the Colorado. Without a quantitative understanding of them, assessment of the risk for vertical transmission of fluids through this section is limited to a search for wellbores. Considering the high correlation between FTS events in Primrose East where salt dissolution has had the greatest impact, Canadian Natural is currently working to improve this understanding.

The Hydrogeological section of the report briefly notes the apparently limited impacts of the FTS events on groundwater. Further reporting on groundwater monitoring and hydrogeological activity is completed each month. A separate hydrogeological report will be prepared for the Geology and Regional Groundwater Delineation, Monitoring and Remediation Plan as required by the Enforcement Order.

The Geomechanics discussion in Section 6 begins with a summary of several mechanisms or conditions which can allow fluid to travel through the Colorado Group. The Panel recognizes and agrees with the points listed in the summary section. Data and analyses then are presented to demonstrate the discussion of where – and how – horizontal or vertical hydraulic fracturing can occur in the Colorado. The example of how a wellbore can facilitate vertical fluid transfer when formation stress states favour horizontal hydraulic fracturing clarifies why wellbores should be investigated as potential conduits.

Section 7 ”Wellbores” describes how flow can result at an abandoned wellbore or cased and cemented well, and notes some problem wellbores and potential problem wells and their status relevant to the observed FTS sites.

Section 8 displays factors relevant to initiation of the FTS events and data confirming the bitumen found at surface was sourced from the Clearwater. The tables showing Formation Expansion Indices (FEI) when the FTS events occurred and maps showing the operating wells state of steam injection when the maximum FEI's were achieved, helps place the location of the FTS with respect to these conditions. Although details of the calculations for the volumes released to the Grand Rapids are not presented in Canadian Natural's Causation report, the methodology is briefly noted and it is clear that excessive volumes of fluid were injected into the Grand Rapids.

Section 9 “Flow Path to Surface” describes how the flow paths were defined, and the varied or different components which can comprise a single path to surface. The discussion also highlights the difficulty of establishing a definitive flow path, given the limitations of the tools available to probe the subsurface. Nonetheless, based on their observations Canadian Natural has presented a very reasonable picture of the likely elements of each flow path. The map and cross-section views of the FTS events are highlights of the investigative work to date.

Section 10 presents the site-specific components of each flow path. This includes the best estimates of the relevant fluid releases and the observed anomalies that may be associated with each event. One important observation is there can be a different level of certainty for each portion of a path. However, although the proposed flow paths might not be precisely defined, the discussion and visualizations do represent the more likely cases. Definition can be enhanced with more work. This enhancement will not change the causes but will improve the certainty of mitigation measures to prevent future occurrences. Including the 2009 Flow to Surface event in this report is essential to the understanding of these measures, and it would be helpful if this initial FTS event was consistently included in all the various sections of the report.

Section 11 is a list of future work, much of which is required to complete the FTS investigation and prepare the final report. There should, however, be two more goals. One is completing work that will deepen the understanding of all enabling conditions (controllable and uncontrollable) so mitigation plans can be more effective. The second is establishing new, evergreen work methodologies so future operations will be monitored and managed more effectively to limit the potential for FTS events.

With these three goals in mind, the Panel presents the following recommendations and detailed proposals. We believe this additional work which is not all necessary for completion of the final report will assist with:

- Determining the best course to arrive at a successful conclusion to the FTS investigation,
- Designing appropriate mitigation plans for future steam stimulation operations, and
- Improving knowledge and techniques to improve the integrity of future steam stimulation operations

Recommended Data Collection and Technical Analyses

The Panel recognizes Canadian Natural has collected an impressive amount of data and performed some significant technical analyses to investigate how the FTS incidents came to be. Not all of this work has been completed. Some of it only requires partial completion to arrive at final conclusions for the investigation into the FTS events. However, extending this work will deepen the understanding and should improve Canadian Natural's operational integrity. The data gathering and analysis activities will continue with ongoing production and monitoring so as to provide an evergreen basis of knowledge and understanding that will improve future mitigation measures and ongoing operations.

An example of work needed for the final report is an assessment of the possible areal changes in stress states in the Colorado Group due to salt dissolution of the Prairie Evaporite. The Panel expects that Canadian Natural's processing and upcoming analysis of recent seismic to address this issue will cover this important topic adequately for the final report. Work that will increase Canadian Natural's understanding but is not essential for the final report is work with formation strain measurements that will provide reliable data on actual formation uplift responses to steaming. Better incorporation of Interferometric Synthetic Aperture Radar (InSAR) data into the operation will also provide future checks on actual steaming results and enhance operations integrity to limit future possible problems.

The following is a list of topics that the Panel believes should be examined and discussed in concert with AER and Canadian Natural. It is noted that Canadian Natural has already begun many of these crucial projects and the work is ongoing. The Panel also recognizes that not all of the work is required to bring the FTS investigation to a close.

- Salt Dissolution and Geological Hazards
- Seismic Anomaly Property Determination
- Enhanced Analysis and Integration of Seismic Data
- Characterization and Modelling of Natural Fractures and Faults
- Wellbores
- Coupled Reservoir-Geomechanical Simulation of the CSS Process
- Bitumen Emulsion Flow in Grand Rapids
- Microseismic
- Interferometric Synthetic Aperture Radar (InSAR)
- Vertical Strain Monitoring

Salt Dissolution and Possible Geological Hazards

The Primrose East area contains unique geological conditions that could influence shale integrity, fracture permeability and in-situ stresses. The local geologic anomalies associated with this area include a thicker and more recently deposited sand channel in the Clearwater, higher sand content in the Grand Rapids and local thickening of formations as recently deposited as the Cold Lake Member of the late Cretaceous Niobrara. Many of these geologic features are likely connected and related to salt dissolution of the Prairie Evaporite and the subsidence that occurred.

This salt-related subsidence, which was active over a very long time period – being pre-, post- and syn-depositional with the Cretaceous formations – has most likely resulted in localized changes in the paleo in-situ stresses and potentially weakened overlying formations due to post-lithification stress unloading, erosion and relaxation. Secondary effects, due to processes like differential compaction of the sands and shale across this area, have also occurred. These changes can also lead to contemporary variations in the in-situ stress field that need to be quantified.

There is a definite advantage in making a more detailed examination of the potential geologic risk factors related to the FTS events. Four out of five of the FTS events happened in Primrose East and three of the five of the events occurred within a circle of 1.5 km radius. If the local geology is a major factor in these events, and if the clearly identified geologic risks are not present in other parts of the field, then the overall probability of FTS events in other parts of the field is immediately reduced.

Clearly identifying these potential geologic hazards also provides the opportunity of locally adjusting a CSS or steamflood recovery process to accommodate the magnitude of geologic risk. For example, this might allow for a customized, albeit slightly less efficient recovery strategy in areas that have greater geologic risk while allowing Canadian Natural to use more efficient production practices over the majority of the project area.

The fact that four out of the five FTS sites are in Primrose East indicates completeness of the investigation requires a thorough assessment of possible stress state changes, faulting and fracturing that may be related to valley incision, glacial loading and salt dissolution in this part of the field.

Seismic Anomaly Property Determination

Significant 4D seismic anomalies have been observed in the Grand Rapids during the interpretation of seismic monitoring data. These anomalies are characterized by a significant increase in seismic reflection amplitude and a delay in the reflection times from deeper events. Both of these characteristics are consistent with a significant decrease in seismic velocity through the Grand Rapids.

Seismic modelling results, determined by Canadian Natural, have shown that these anomalies are consistent with an increase in gas saturation within the Grand Rapids. Unfortunately, the conventional compressional wave (P wave) seismic velocity response is non-unique; i.e., the same response can be generated by an increase in gas saturation, an increase in heated bitumen saturation, an increase in pore pressure or a combination of all these effects. It is also impossible to determine the percentage of gas saturation from the P wave data alone because a very small or very large increase in saturation can cause the same decrease in velocity.

Additional modelling and analysis can potentially improve the determination of saturation and pressure conditions within these 4D seismic anomalies by analysis of the shear wave (S wave) velocity information embedded within the P wave seismic signal.

To further quantify the properties of the 4D seismic anomalies in the Grand Rapids, it is recommended that Canadian Natural undertake a program that includes rock physics modelling, synthetic seismic generation and pre-stack 4D seismic analysis to estimate the pore pressure, temperature and pressure changes related to these features.

Once the reduction in the P wave seismic velocity has been validated through the modelling process, it will be possible to estimate the vertical thickness of the anomaly features. This thickness estimate, combined with the areal dimension of the anomalies, should be used to constrain the estimate of the volume of fluids released into the Grand Rapids that has been made from the pressure monitoring, injection and production data. This combination of 4D seismic and engineering data can often reduce uncertainty in the overall interpretation process

Enhanced Analysis and Integration of Seismic Data

Canadian Natural has made impressive progress in identifying and mapping seismic scale faulting, particularly in the Primrose East area. The existing data should be better integrated with data from logs and cores and the analysis should be extended to areas outside of Primrose East to help confirm any fingerprint of salt dissolution effects on the Colorado Group.

Smaller scale faults, for example with offsets less than 3 m, while not totally resolvable due to the frequency content of the propagating seismic wave, may still be detectable through subtle changes in the seismic signal response. The polygonal fault structure mapped in Primrose East is an example of this. Further analysis based on two different approaches can extend seismic interpretation of small scale faults and fractures to a wider area.

One approach combines the extensive well control with high spatial resolution seismic time horizons to generate seismically-constrained depth structure maps. These maps can then be analyzed to highlight areas with the greatest structural curvature. This should be important because these areas are more prone to fracturing and localized stress variations.

A second approach examines the azimuthal variations in the P wave and S wave seismic data. Unequal horizontal stresses in the subsurface often result in azimuthal variation in velocity (azimuthal anisotropy) because the cracks and grain contacts within the rock tend to be more compacted when subjected to higher levels of stress. This means that the velocity of the rock medium tends to be faster in directions parallel to the maximum principal horizontal stress and slower parallel to the minimum principal horizontal stress. The azimuthal velocity variation can be a useful technique for determining spatial variations in the dominant stress direction and the magnitude of the difference between the minimum and maximum horizontal principal stresses.

The converted S wave data from Primrose is still in the processing stages, however, a preliminary review indicates that there is an unusually high level of S wave splitting in parts of Primrose East. Further analysis is required but at this stage, it appears that the S wave data has the potential to provide information related to the in-situ stresses and indications of conductive fractures in the FTS areas at the time the survey was recorded. This analysis has the potential to provide important information related to the effect of salt dissolution in Primrose East and the data is potentially useful in determining the level of geologic risk present in other parts this producing trend.

P wave azimuthal anisotropy analyses can also provide information relating to the velocity anisotropy across the field area. While the converted S wave data is theoretically more sensitive to the effects of azimuthal anisotropy, it could potentially be even more significant if the P wave azimuthal data proves helpful in identifying key parameters in the in-situ stress. Due to its more widespread use, the P wave azimuthal data could be major aid in determining regions of the heavy oil resource area which are at the highest risk for future FTS events.

Geostatistical techniques provide a methodology that allows for the integration of diverse types of data, which are taken with different types of spatial sampling, into a single unified interpretation. Canadian Natural has amassed a data set that is well suited to the application of geostatistics to explore the inter-relationship between the engineering and borehole-derived fracture information and co-located seismically derived attributes. When reliable relationships can be found between these sources of data, the spatial density of the seismic attribute information can be used to spatially propagate the information from the discrete well locations.

Characterization and Modelling of Natural Fractures and Faults

Core and Image Log Analyses

A discrete fracture network (DFN) approach is strongly advocated for characterizing the frequency, geometry, orientation and flow properties of the major discontinuities in the Colorado Group (natural fractures, bedding planes and faults). Suitable commercial software for this purpose exists on the market and specialized consultants skilled in its application should be used to fast track this in the Canadian Natural workflow.

Laboratory Determination of Natural Fracture and Fault Aperture and Permeability under Stress

Canadian Natural has acquired considerable core and image log data to date and since additional cores are planned, we recommend that a high quality laboratory program be undertaken to investigate the aperture-permeability-effective stress behaviour of natural discontinuities from the various geological units in the Colorado Group and Niobrara and Lea Park Formations. The information from such a program would be used for understanding DFIT injection tests, ranking flow paths for escaping fluid under field conditions, and conducting DFN flow simulations.

Discrete Fracture Network (DFN) Modelling

For fractured rock masses there has been considerable progress in the last decade in the modelling of natural fracture connectivity and flow at different scales, especially as applied to shale gas stimulation. Using this capability, we encourage Canadian Natural to develop calibrated realizations of the discontinuities in the various strata of the Colorado Group where changing horizontal stress and pore pressure profiles appear to control the release of bitumen emulsion from the upper Grand Rapids into the lower Colorado Group. Once laboratory testing has constrained the fracture apertures likely to exist under shear and tensile conditions (as recommended above) it would be possible to model probable flow pathways in networks of intersecting discontinuities and induced hydraulic fractures. Stochastic Monte Carlo approaches to this problem are advocated since the defining discontinuity properties are quite variable making deterministic solutions limited in their applicability.

Wellbores

Canadian Natural successfully identified, with high probability, two wellbores that provided a flow path for fluid releases from the Clearwater reservoir. Each time, the path is believed to have been enabled by inadequate placement of cement plugs when the open hole section of each exploration well was abandoned. "High probability" is noted by the positive oil shows at each location. However, the full extent and flow capacity of each path are not certain since (a) the plug tracking operation – which can be very difficult to complete successfully – was not able to reach the lower cement plug(s) at 07-22-067-03, and (b) the "twin" well drilled at 09-01-067-03 did not access the original well.

Operating (cased and cemented) wells also are suspected of playing a role in the flow path in at least two of the FTS areas.

As noted in Table 7-1 of the Causation report, inspections have been completed at several CSS wells in the FTS areas. To help understand the implications of the diagnostics results, Canadian Natural should describe how wells were selected for these checks.

- Proximity to oil shows and expected flow paths; steam injection, passive seismic, and 3D/4D seismic monitoring results; and casing connection make-up & well installation results (including casing rotation and cement bond log analyses) are assumed.

Channel Behind the Casing:

Pad AC21 wells and 09-02-067-03 are identified as likely providing a flow path due to inadequate placement of primary cement during the well completion. To help define this potential, where available the following should be presented:

- Flow rates calculated for a reasonable range of path dimensions (length and cross-sectional area), fluid viscosity (fluid type and temperature), and pressure differential.
- Flow rates established between different sets of perforations, during well testing.
- Cement bond log results in the unpressured (0 MPa) and pressured (e.g., 21 MPa or another value as defined in the logging program) passes. The different results can be used to estimate the width of an annular gap.
- Well status when flow through the behind-casing channel was suspected. Casing temperature is important since the radial expansion induced by a 100 C rise above ambient is equivalent to the expansion imposed by a 21 MPa pressure test.
- RST analysis summary including the detection limit, whether the tool was centered or eccentered during the run, and logging speed. If a bitumen-filled channel is small, the RST

most likely will not detect it. But if the channel has a flow area equivalent to a 1 inch diameter tube and is seen by the logging tool, detection is possible.

Casing Failures:

Casing failures are suspected of contributing to the fluid volume releases, and possibly acted as a flow path, in at least two locations. To complete this evaluation, the following should be presented for all known casing failures in the FTS areas:

- Fluid Losses to the Colony gas sand or Colorado Group through (a) cross flow from a casing failure at the Clearwater top, or (b) a casing failure opposite the Colorado. The range of the fluid release volume for each event should also be documented.
- Casing Integrity pressure test results for all wells in the FTS areas. Table 7-2 notes 58 of 66 wells pre-FTS wells were pressure tested: a successful pressure test is assumed, but the interval isn't known. Since a casing failure at the top of the Clearwater reservoir can allow fluid to bypass the capping shale and enter the lower Grand Rapids, the depth of each test and whether or not the pressure test assembly could reach into the Clearwater, should be noted.

Casing Caliper Surveys and Formation Movement:

Computer analysis of multi-sensor casing caliper surveys can identify the magnitude and direction of casing and formation shift from a casing deformation. This can be especially useful for discerning how long fluid might have been stored in a fluid-supported horizontal fracture or other weak interval in the overburden while high-pressure CSS operations were conducted in the area. Furthermore, quantitative casing deformation data can be used to map the spatial and vertical pattern of shearing displacements on bedding planes and faults, which in turn sheds light on the deformations produced by the uplift caused by operations in the Clearwater reservoir.

- The 9-21 area is the most obvious location to conduct these surveys and analyses, as fluid is believed to have been stored in the overburden for at least a few cycles before the actual release to surface.
- Other sites where there have been 2 or more CSS cycles also are good candidates. At least 1 high-pressure CSS cycle after fluid has been released to the overburden is needed to have any reasonable chance of seeing formation movement along a fluid-impacted horizontal feature. Ideally, the MSC-surveyed well will have been steamed so high thermal stresses / strains will have been imposed on the casing string, making it less resistant to formation movement and thus more likely to incur plastic deformation.

In addition, more complete data should be provided for the evaluations conducted at the suspended water disposal well 1F1/11-02-067-03 and casing failed CSS well 4D21 as the failures / damage at each location could also have contributed to the flow path of release of fluid from the Clearwater, at each site. A schematic for 4D21 showed a "suspected shale loss zone" above the casing failure and the well recompleted for pressure and temperature monitoring below the failure.

Coupled Reservoir-Geomechanical Simulation of the CSS Process

The Panel did not see much evidence of thermal reservoir simulation modelling of the Clearwater CSS process, with an account for geomechanical processes that enhance reservoir uplift and deformation. This modelling is typically a component of a thermal reservoir modelling workflow. Detailed investigations should be conducted of lateral and vertical deformations of the reservoir that result from the combination of thermal expansion, pore pressure increase (hence effective stress decrease) and shearing deformation with concomitant porosity and permeability changes. Several commercial simulation tools on the market today have enhanced geomechanical coupling features. Ultimately, this type of simulation should be used to predict caprock deformations, which would in turn be calibrated against actual reservoir and caprock strain measurements. A more rigorous approach to predicting caprock movements could provide justification for the modification of empirical uplift predictions that do not rigorously model all physics of the problem, but are fast and easy to use.

Bitumen Emulsion Flow in Grand Rapids

The details of the triangulation methods using existing observation wells to estimate flow volumes and locations in the Grand Rapids needs to be presented in detail for all the flow events observed. The combination of well testing to characterize an observation point, then comparative timing of pressure responses to triangulate a source is an innovative approach to estimating fluid incursions. The final report needs to address the confidence limits of such estimates.

The leak-off behaviour from a vertical fracture in the Grand Rapids should be studied by reservoir simulation. The objectives are to determine the extent to which bitumen, as it cools, tends to reduce the transmissibility of the Grand Rapids sand. The objective would be to use reservoir models to provide a physical basis for the observed size of 4D seismic anomalies in the Grand Rapids. Ideally, this would provide data on the size of the heated zone and estimates of the volume of fluid necessary to create a seismic anomaly of the observed size. This information could then be used to assess the potential for stress changes in the overlying Joli Fou to provide an estimate of the stress changes that might occur and hence provide data for a mitigation plan.

Microseismic Data

Canadian Natural has utilized passive seismic successfully for monitoring wellbores above the reservoir. Nevertheless they should improve their microseismic monitoring hardware and software in order to enhance the use of this technology as an alarm to alert operations to reservoir, and caprock phenomena such as: vertical and horizontal hydraulic fracture propagation, shear versus tensile movements on intersecting discontinuities, and whether fracture or fault networks are involved. Full coverage over an entire horizontal section of a pad may not be feasible or warranted.

Interferometric Synthetic Aperture Radar (InSAR) Data

Canadian Natural should enhance their InSAR monitoring by the addition of installed reflectors to greatly improve the resolution of the ground surface heave data that can be collected over an area. For new steaming areas or previous FTS locations where reactivation of these events is a possibility, reflector calibrated uplift measurements could be valuable in ascertaining the reliability of simple through to complex models-based predictions of uplift, and the resulting stress changes.

Regular comparisons of observed uplifts, even without reflectors, to simple-to-apply models predicting the heave caused by the actual injection schedules have the potential to indicate potential deviations from normal responses. When used as a regular part of operations, this can help improve the empirical models and provide a basis for assessing the importance of other indicators of potential problems. This recognizes that the data from InSAR can now be obtained several times a month, which is a reasonable time interval to assess steam injection cycles.

Vertical Strain Monitoring

Canadian Natural should conduct a pilot program using proven technology to provide accurate, in-situ vertical deformation data associated with steam injection and fluid production cycles. If successful, this type of monitoring should be extended to areas where the geologic setting or operating conditions present an increased risk for future FTS events.

- Maintaining hydraulic isolation at the strain monitoring wells is important, thus, the installations should only consider wells where the casing can be reciprocated or rotated during primary cementing to enhance cement placement.
  - In this regard, placing radioactive or magnetic markers at the required depths is preferred to installing a well with multiple anchors and slip joints.
- Reference points should be included to help further define the vertical strains which result from reservoir operations.
  - Consider a tie-in to InSAR monitoring with installed reflectors.
- Formation strain can also result from change(s) in pressure and temperature from fluid influx, or withdrawal.
  - Consider installing “dual service” wells with retrievable (or permanent) P – T sensors. If the sensors are retrievable, other logs can be run on an “intervention” basis.
- P – T sensors could also be included with passive seismic wells by cementing-in a small diameter tubing string as the geophones are firmly cemented in-place.
- Where dual service monitoring wells are installed, the increased functionality needs to be balanced with the incremental cost and (potential) impacts to the primary monitoring system.