BENNETT RESOURCES

Valhalla Gas Exploration and Appraisal Program

Geotechnical Risk Analysis

BNR_EXP_RE_001

VERSION HISTORY				
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Acronyms / Definition

Acronym	Expansion / Definition
BNR	Bennett Resources Pty Ltd
B.S.	Bachelor of Science
DIF	Drilling induced fracture
DoL	Declaration of Location
e.g.	For example
EP 371	Exploration Permit 371
GISERA	Gas Industry Social and Environmental Research Alliance
HFS	Hydraulic fracture stimulation
ISO	International Organization for Standardization
km	kilometre
m	meter
m AHD	meters Australian Height Datum
mg/L	milligrams per litre
ML	Richter local magnitude (ML) is defined to be used for 'local' earthquakes up to 600 km away
mmscf/d	million standard cubic feet per day, a unit of measurement for gases
SH_{min}	Minimum horizontal stress
SH_{max}	Maximal horizontal stress
Sv	Vertical stress
U.S.	United States
WOB	Wellbore breakouts
2D	Two dimensional
3D	Three dimensional
4D	Four dimensional

1 Summary

This document provides a Geotechnical Risk Analysis for the Bennett Resources Pty Ltd's (BNR) Valhalla Gas Exploration and Appraisal Program (the Proposal) – as required by the Environmental Scoping Document Item 12.

Geotechnical risk assessments are not a single one-off activity. They utilise data acquired from successive petroleum activities to provide a more detailed and comprehensive understanding of the subsurface geology. As they progress, they inform future field design, well design and subsequent mitigations to enable risks are continually reduced to as low as reasonably practicable. One such mitigation that has been implemented is an 'early warning' mechanism that allows a proactive adaptive management approach to be followed in the field during hydraulic fracture stimulation (HFS) activities. This is detailed in Annex A.

As an overview, a geotechnical risk analysis is completed via the following phases:

- **Definition of structural context**: this is where existing data sources are analysed to provide an understanding of the subsurface geology. Specifically, the data sources are "stitched" together to form a picture of the area between data sources
- **Identification of hydrologically active faults**: the subsurface geology data is reviewed and interrogated with other desktop sources to identified if / where any active faults could occur within the field of interest
- **Assessment of well seal effectiveness**: once there is a good handle on the subsurface geology, each of the formations can be reviewed to understand if they provide a suitable geological seal between useable aquifers and targeted formations
- **Definition of potential high-risk zones**: once the subsurface geology and known faults have been understood after review of existing drilling data and new seismic data, specific fault zones or other weak areas will be reviewed or identified.

Based upon the process detailed above, the data for a comprehensive risk analysis is only considered preliminary given data from the wells as they are drilled will be utilised to update the subsurface geological understanding. The data gathered by historical activities are sufficient, when coupled with current regional work, to allow for a generalised risk analysis to be completed. The outcome of this geotechnical risk analysis is consistent with the outcomes of the most recent geotechnical risk evaluation (Buru Energy 2013) conducted by the previous operator of the exploration permit EP 371, Buru Energy. This evaluation concluded the following points:

- "in the Valhalla area, >600 m lies between the deepest recognised aquifer and the shallowest proposed hydraulic stimulation zones" (Buru Energy 2013) that were envisioned at the time. The actual interval between the highest stimulation and potential aquifer was 1,213 m
- in the Asgard area, there was initially planned to be a few hundred meters between the deepest recognised aquifer and the shallowest hydraulic stimulation zones; the actual interval between the stimulations and potential aquifer was 1192 m
- in the northern Canning Basin, "although there is evidence for some hydrocarbons that have naturally migrated into the shallower aquifers over ~200 million years, the very low/lack of hydrocarbon saturations in the Upper Anderson, Reeves, Lower Grant and Mesozoic formations above the Laurel Basin-Centered Gas System demonstrate that hydrocarbons cannot migrate vertically through these rocks" (Buru Energy 2013)
- some faults and fractures have been identified from seismic data and borehole image analysis within the section of interest for hydraulic stimulation. However, all faults identified are closed and strike in a direction that is approximately orthogonal to the maximum horizontal stress (SH_{max}) such that although they may negatively impact upon fracture propagation, they pose no geomechanical hazard for upward propagation of fracturing fluids or hydrocarbons into the recognised aquifers as the activation energy required to dilate faults or fractures in tension will be higher than overburden, which means the fracture growth would rotate to horizontal before opening such faults in tension.

2 Definition of the structural context

BNR has reviewed all the currently available engineering and geoscientific data on EP 371. The review was focused on existing well logs and 2D seismic data using a standard unconventional and petroleum systems workflow. This work built upon the substantial foundation of work and research done by the Western Australian government, and previous permit operators Buru Energy and Mitsubishi Australia. A key document relating to past exploration and engineering results for the unconventional resources on the permit is the EP-371 Discovery Assessment Report Asgard-1 and Valhalla North-1 (Buru Energy 2016). The information contained in the Buru Energy discovery assessment report (2016) and associated documents submitted by Buru Energy are referred to here but not repeated in this document. The EP 371 Discovery Assessment Report notes the key geological and engineering data acquired up through September 2016 which defines the basin-centred gas accumulation and the expected unconventional tight wet gas pool within the permit and Declaration of Location (DoL – refer to Figure 2-3). Two key wells (Asgard 1 and Valhalla North 1) have been drilled, stimulated, and flowed back to demonstrate that wet gas and condensate are present within the permit. Asgard 1 and Valhalla North 1 were located 40 km apart and were truly exploratory as they were drilled outside of any structure.

Leveraging the past efforts of Buru Energy, BNR has progressed in its understanding of the underlying geology and reservoir characteristics. Reviews by BNR continue to be conducted on the existing data. This work includes developing a better understanding of the existing geological formations and the overlying section. It is our intent to advance our understanding with new additional data and interpretations will need to be re-undertaken as additional tests are run on existing wells, new exploration and appraisal wells are drilled, and future seismic data is acquired and brought in-house.

To understand the structural context, the entire geological setting of the Canning Basin has been studied.

2.1 Canning Basin

The Canning Basin is a geologically old basin with Ordovician sedimentary rocks deposited onto Precambrian basement. The Fitzroy Trough is a structural feature on the northern edge of the basin that extends to a depth of up to 18 km (Cadman, et al. 1993). Significant infilling of the basin took place from Carboniferous to Permian and in the Cretaceous, during which period the basin was a shallow seaway. Thick sections of Permian (Grant Group) and Carboniferous terrigenous clastics (Reeves, Anderson, and Laurel Formations) then prograded over some additional deeper petroleum prone targets. Multiple tectonic phases within the basin took place both syndepositionally and post-depositionally, modifying the petroleum systems with an extensive set of both transpressional and extensional fault systems (Zhan and Mory 2013), as seen in Figure 2-1. Tertiary and Triassic sections are notably absent in the basin.

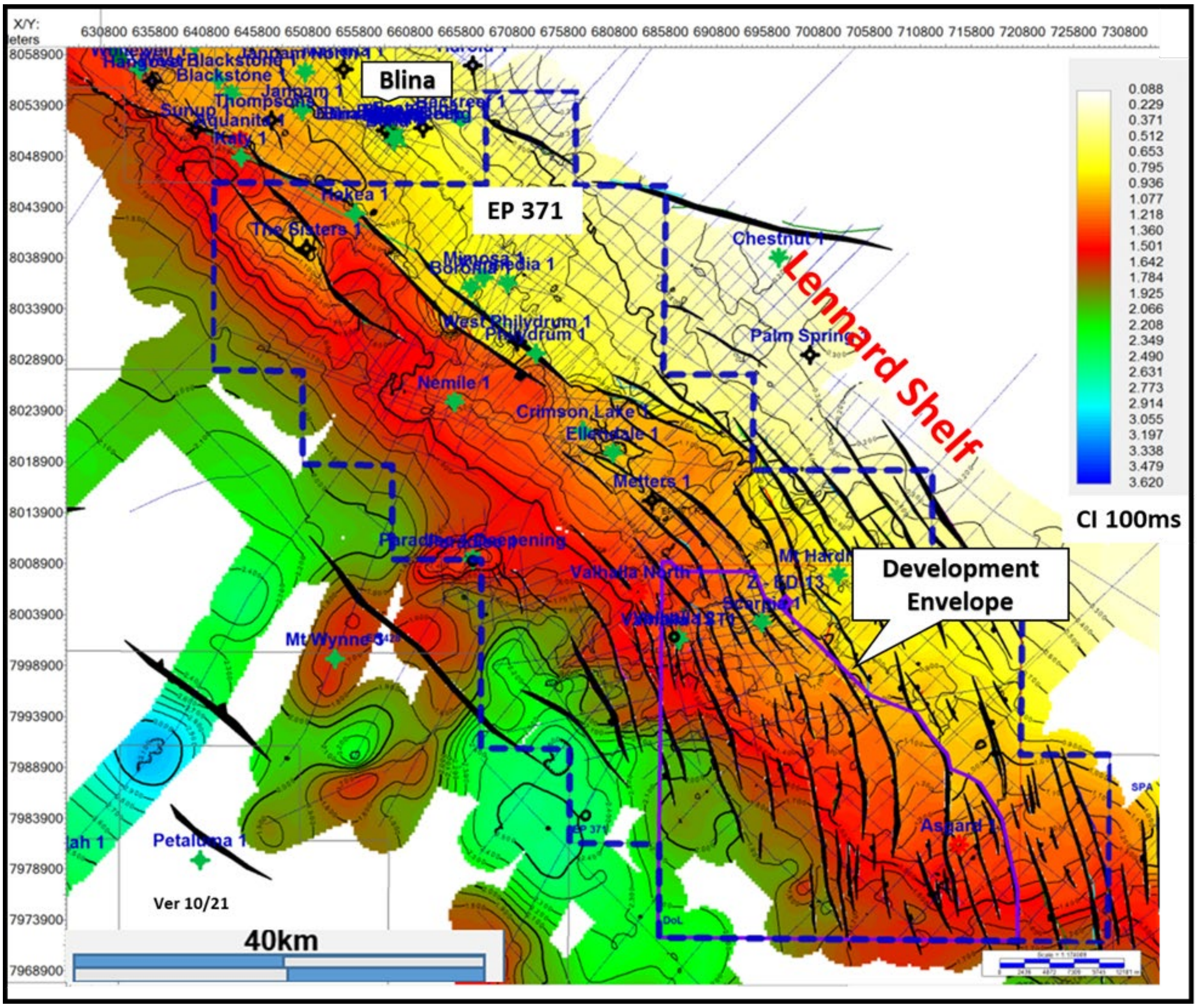

Figure 2-1: Regional Top Laurel Time Structure Map over EP 371 illustrating the deeper basin depocenter related to the underlying Fitzroy Trough to the southwest along with some of the established faulting within the DoL

2.2 Geological summary of the Laurel Formation and above geological section within EP 371

A review of the geochemical, petrophysical and existing 2D seismic data establishes an extensive basin-centred gas fairway beginning at 2,000 m and continuing to over 4,500 m in depth which is significantly deeper than any take points in the aquifer for water wells. This fairway steps down from the basin margins (Figure 2-1) into the depths of the Fitzroy Trough and is analogous and correlative to a similar petroleum system that hosts gas discoveries on the opposite margin of the trough (Yulleroo-2, a 3 stage frac that produced up to 1.5 mmscf/d).

The seismic data demonstrate a steep deepening of the Laurel Formation section into the basin with numerous normal downthrown faults parallel to the shelf margin that typically have throws (vertical component of the separation) of over 100 m (Figure 2-2 and Figure 2-3). Complex structuring that occurred during the basin's extensional phases controlled and influenced the carbonate sequences. The Permian Carboniferous Meda transpressional (strike slip and compressional structuring) event followed by the later Fitzroy Transpression in the Triassic-Jurassic caused reactivation and inversion on several the basement faults. Within the area of interest is located the Meda unconformity between the Reeves and Anderson Formations with an additional unconformity between the Reeves and overlying Grant Group formations.

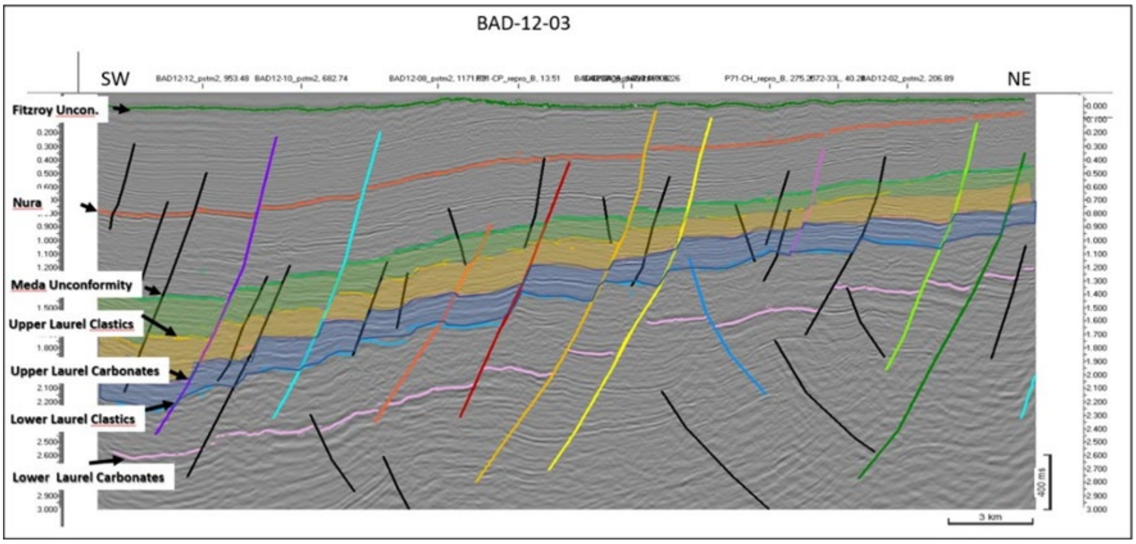

Figure 2-2: A 2D seismic line in two-way time along the northern edge of the Fitzroy Trough showing the Anderson (Green) and Upper Laurel Formation (Yellow and Blue) benches down stepping into the basin. Some expansion of the Laurel and Anderson Formation sequence is shown. An extensive database of 2D seismic was used to map in three dimensions the structural style of the basin margin. Location of this 33 km long line is shown in Figure 23.

The Grant is the deepest know aquifer in this part of the basin; the Betty Unit is in the lowermost part of the Grant Formation. The base of the Grant to uppermost Reeves is often difficult to recognize on 2D seismic. New 2D data and a potential 3D seismic program should better define the shallow sections.

2.3 Structure of the Laurel Formation and shallower section within the DoL of EP371

The structural evolution of the section of interest in this study is tied to the deformation within the Fitzroy Trough. The Fitzroy Trough has several major transtensional (strike slip and extensional structuring) and transpressional faults within it that may have strike slip offsets more than several kilometres. Within the trough are several large-scale synclines and anticlines, some with surface expression (St. George Ranges). Faults imaged within the trough downdip of EP 371 on 2D seismic data can be interpreted as exhibiting complex flower structures.

A series of normal and strike slip faults down to the southwest is noted across the DoL that have had movement up through Noonkanbah (Permian) time (Figure 2-2) which is marked as the Fitzroy Unconformity. Some normal faults have potentially more than one episode of movement as evidence by changes in dip regarding depth. There are also some antithetic faults noted into the larger master faults. Overall faults change their orientation from north-west to south-east to a more north-south strike orientation within the southern portion of the DoL (Figure 2-3). The fault orientation for most faults is 90 degrees off of the north-east / south-west oriented SH_{max} orientation which should reduce the risk of fault slippage during HFS. Further review of fault slip tendances can be conducted when additional 2D and or 3D seismic data are acquired.

Typical fault blocks are 4-6 km in breath and often 5-10 km in length based on the current 2D data. The Laurel Formation steps down as a series of terraces into the trough along these faults. Current 2D data allows BNR to tie together major faults between seismic lines but there are several faults that are less substantial that are difficult to correlate out beyond a one- or two-line interpretation. It is important to note the lack of faults on the map in the south-western corner of the DoL does not indicate that no faults are present, BNR does not have any data currently there to map the faults. BNR will continue to map the subsurface geology in accordance with EP 371 permit conditions. Specifically, future seismic program data will highlight fault blocks that are smaller in nature and potentially more complex.

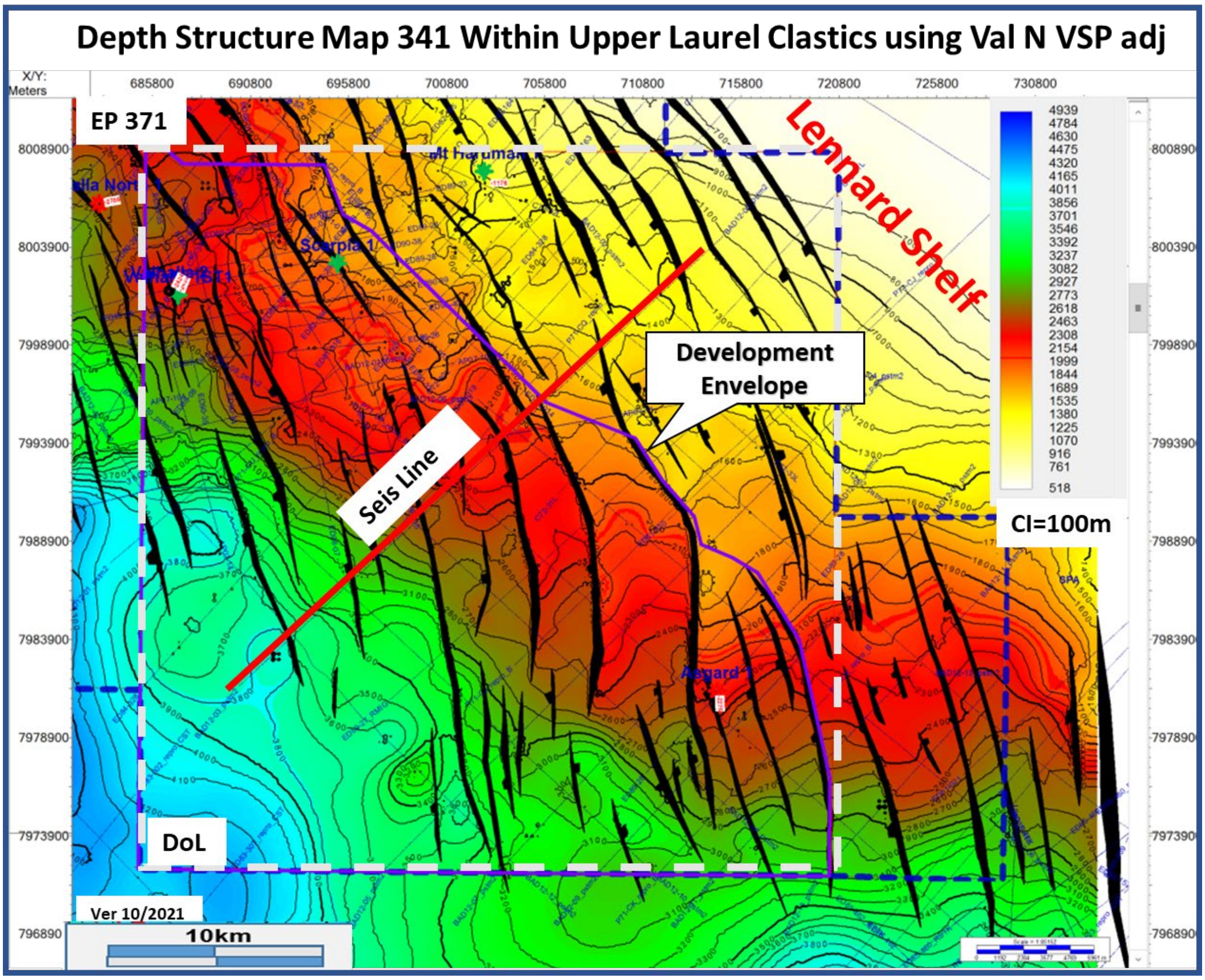

Figure 2-3: The 341 surfaces just above the Upper Laurel Carbonate is shown highlighting a number of downthrown normal faults stepping into the basin. The DoL is marked with the box. The location of the seismic line from Figure 2-2 is also marked

2.4 Definition of subsurface state of stress

BNR's current understanding of stress is based on data from the recently drilled Asgard 1, Valhalla North 1 and other Valhalla wells as well as the world stress map (WSM 2016). SH_{max} is anticipated to be in a north-east to south-west direction based on existing well data (Figure 2-4) and a review of the world stress map (WSM 2016). BNR's understanding of the subsurface state of stress is as follows:

- the stress regime is considered strongly to mildly anisotropic with fractures propagating in tension primarily in the SH_{max} direction.
- per Schlumberger (Figure 3-7), the Valhalla region (area between the Valhalla wells) is likely to be in strike-slip stress regime ($SH_{min} < Sv < SH_{max}$). Image logs identified both wellbore breakouts (WBO) and perpendicular drilling induced fractures (DIF) simultaneously, indicating high horizontal stress anisotropy. The occurrence of both WBO and DIF in the vertical plane, where identified, eliminates reverse faulting as a potential current day stress regime
- the amount of tectonic stress is not known but further work can be done on the past completions to better understand and calibrate a mechanical earth model
- there is significant vertical heterogeneity within the Laurel Formation. Significant variations are noted in the static Young's modulus and unconfined compressive strength which can provide potential vertical frac barriers.

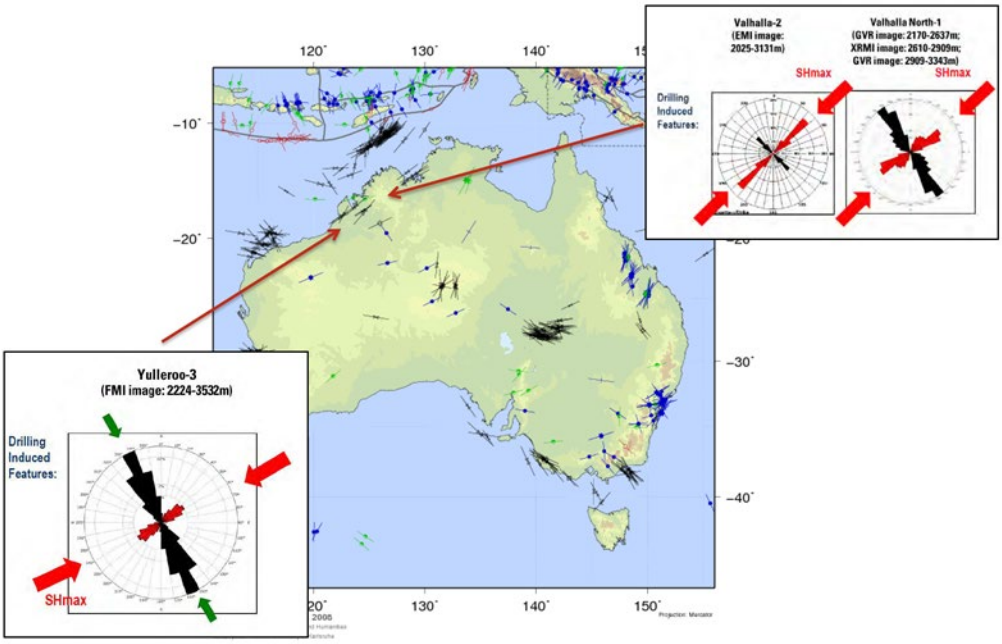

Figure 2-4: SH_{max} for three wells within the northern portion of the Canning Basin along with the world stress map. SH_{max} is north-east to south-west, and is consistent across this part of the Fitzroy Trough

Downhole geomechanical logs obtained on Valhalla North 1 and Asgard 1 wells and their interpretation and analyses are highlighted in the final well reports and not included here. In short, drilling induced tension fractures and borehole breakouts are common in the wells like Valhalla North 1 based on the image logs. The orientation of these features indicates a regime with a broadly north-east to south-west oriented present day maximum SH_{max}.

2.5 Future wells

As a part of the Well Management Plan development and the International Organization for Standardization (ISO) ISO 16530-1-2017 requirement, a prognosis will be prepared for each well location (Figure 2-5). Per the ISO, the prognosis provides a “description of the expected formations and fluids, pore pressures, formation strength and temperatures to be encountered, including their uncertainty” (ISO 2017). Furthermore, “the information should cover subsurface aquifers and hazards, faults and high-pressure stringers, i.e., pore pressure prediction, freshwater zone protection, stratigraphic prognosis, well orientation and length of penetration through production zone” (ISO 2017).

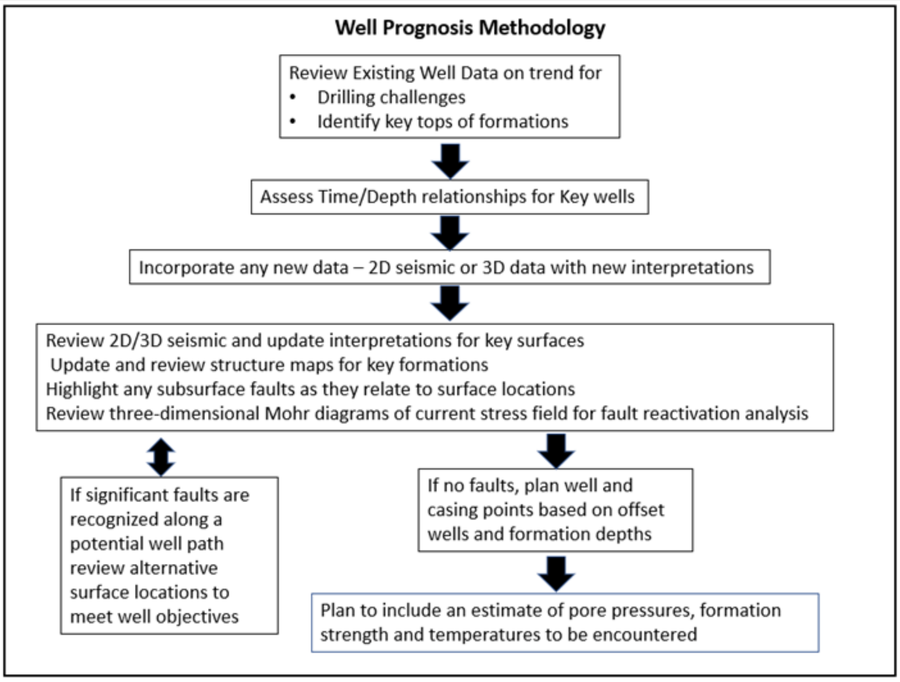

Figure 2-5: Well prognosis methodology

After drilling the future wells but prior to HFS, a workflow examining the key formations and zones is followed. Here stimulation models are produced to understand fracture height and lengths. Figure 2-6 highlights an example workflow that is likely to be followed through.

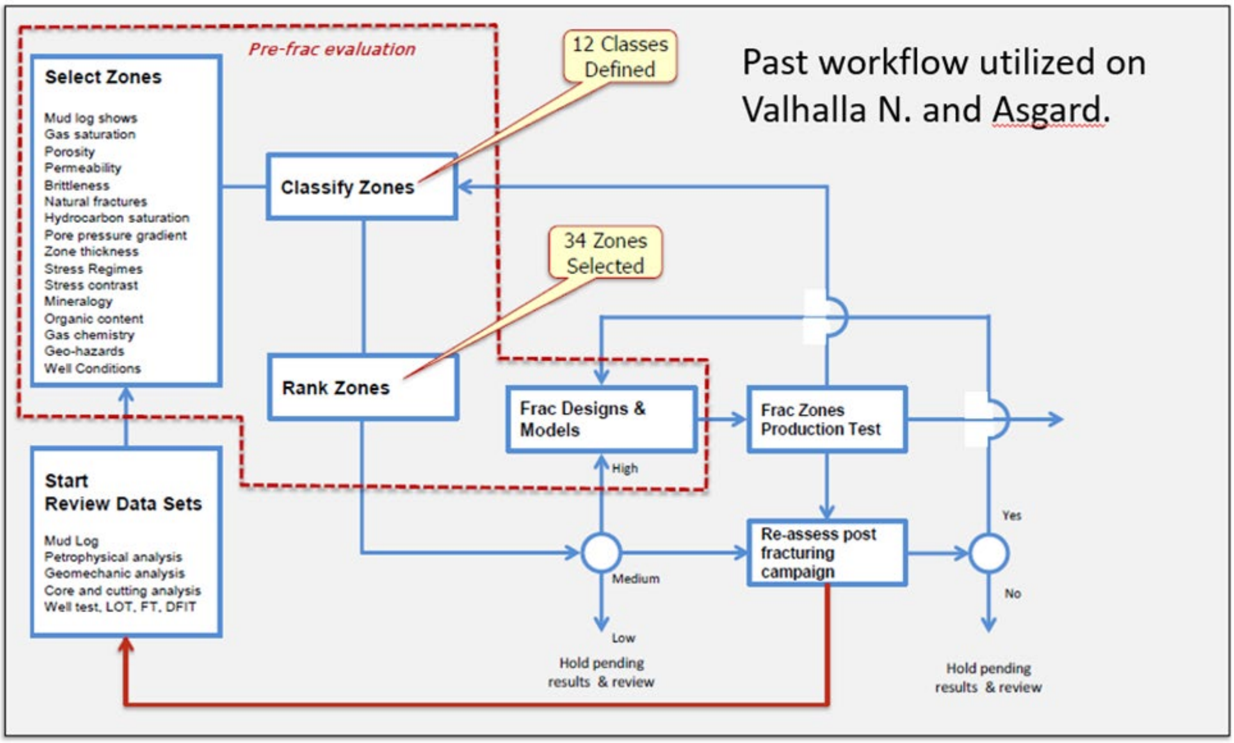

Figure 2-6: Example workflow for considering the zones to be tested for the HFS

A risk analysis is then reviewed for key HFS zones and utilises offset well geomechanical and geotechnical data. Such a risk analysis workflow used in the past is highlighted below in Figure 2-7.

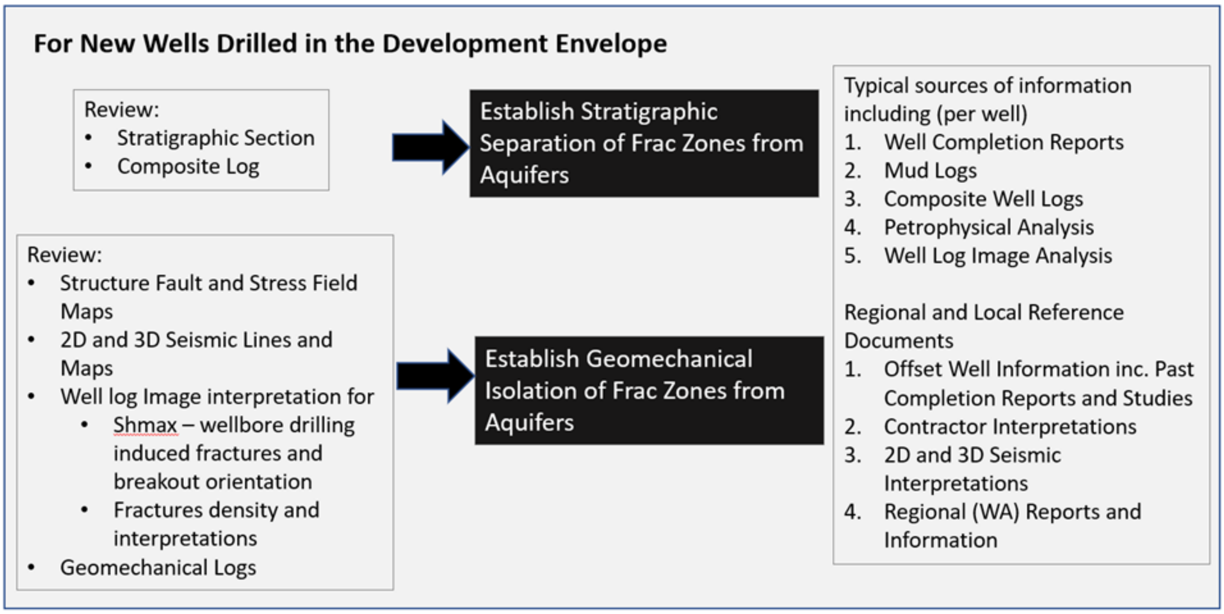

Figure 2-7: Example of data that is considered for a risk analysis for any HFS as it relates to the relationships between the HFS and aquifers

3 Identification of hydrologically active faults or fracture zones

Based on the observation that most wells drilled below the Anderson Formation shale contain hydrocarbons, it is believed that the shale within the Anderson Formation can be considered a seal. There is no conventional core in the nearest offsetting wells, but core in Yulleroo noted cemented fractures at depth.

Based on the current data from the Valhalla and Asgard areas, it is also likely that faults appear to be mainly sealing. Some faults do cut through to the near surface based on seismic data. There is some gas presence noted in the shallower Grant Group units in the Valhalla area but not encountered in the Asgard 1 well. It can be inferred that through geological time there has been some hydrocarbon migration into the shallower Grant Group. The industry has however not noted natural petroleum presence on the surface, thus suggesting that the regional faults are not significantly open and conductive. There is potential for open and conductive fractures within the Laurel Formation based on formation micro-imager data, however pressure data support an overpressured Laurel Formation section so hydrocarbons appear to be contained.

Prior to drilling, a WMP along with a well prognosis will be created to review the existing and future seismic data to ascertain and/or minimise drilling through significant faults.

3.1 Historical analysis

Buru Energy previously characterised the subsurface geology using the most recent well data that exists on EP 371 (Buru Energy 2013). A few key figures of this past work demonstrate the existing well data and their interpretation. BNR plans to follow a similar workflow for the wells associated with the Proposal.

The following interpretations can be made from Figure 3-1 to Figure 3-4, relating to the Valhalla North 1 area:

- the Valhalla North 1 well was drilled into the Lower Laurel Clastics. There are three or four down to the south-west normal faults within a few kilometres of the well. SH_{max} is north 50° east.
- the base of potential Grant Group aquifer (Betty unit) is located at 1,614 m. The highest planned stimulation considered was at 2,355 m in the upper Laurel Clastics (planned 741 m apart); the actual uppermost stage was at 2,827 – 2,872 m resulting in a separation from the Grant Group aquifer of 1,213 m.
- hydrocarbon saturation increases just below the Anderson Formation shale, which provides a seal for the gas as well as a fracture barrier
- the more quartz-dominated rock generally has a lower stress than the clay-rich rock. Carbonate units have an even higher stress.

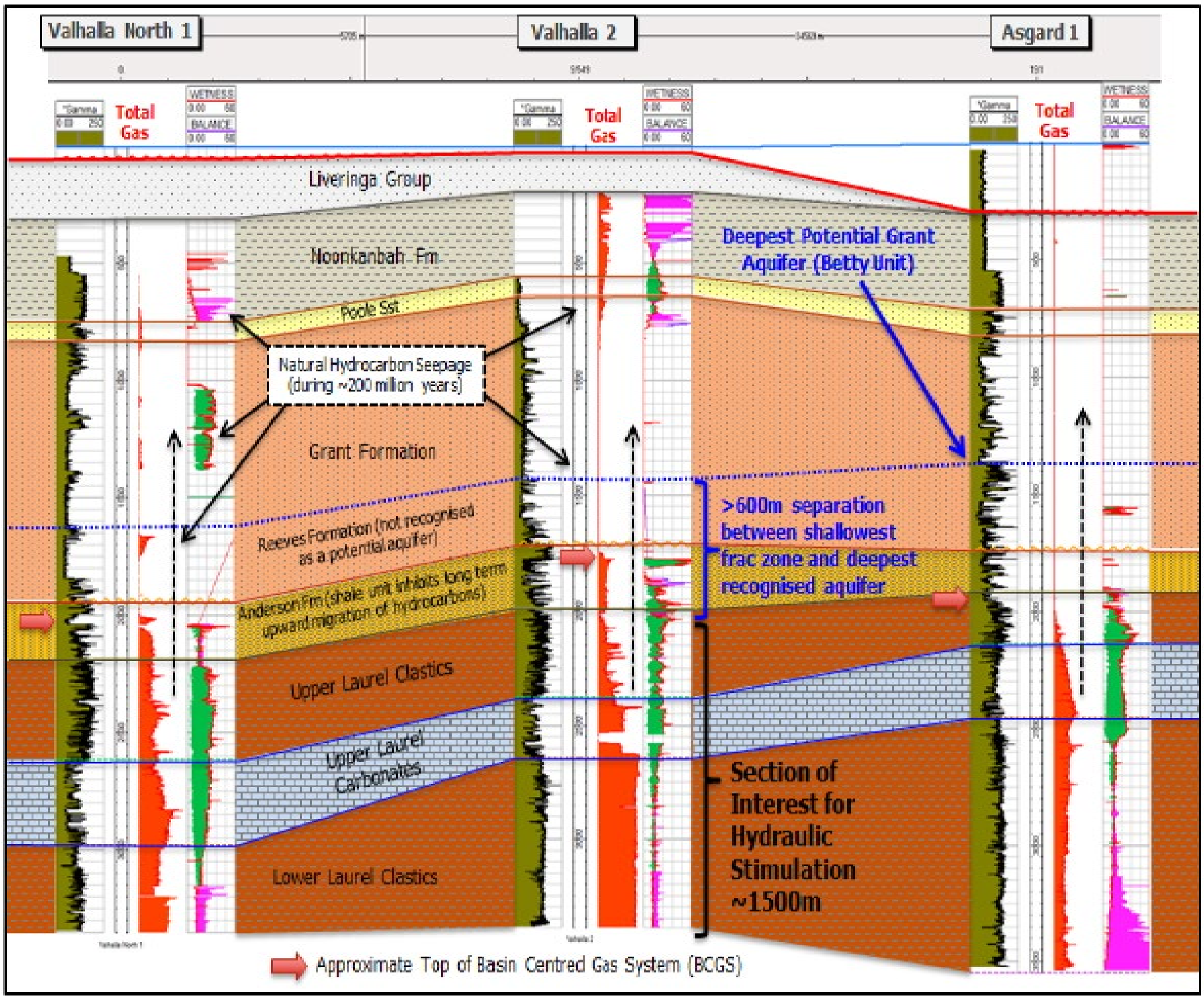

Figure 3-1: Relationships of the Laurel Formation to the overlying Grant and Reeves formations

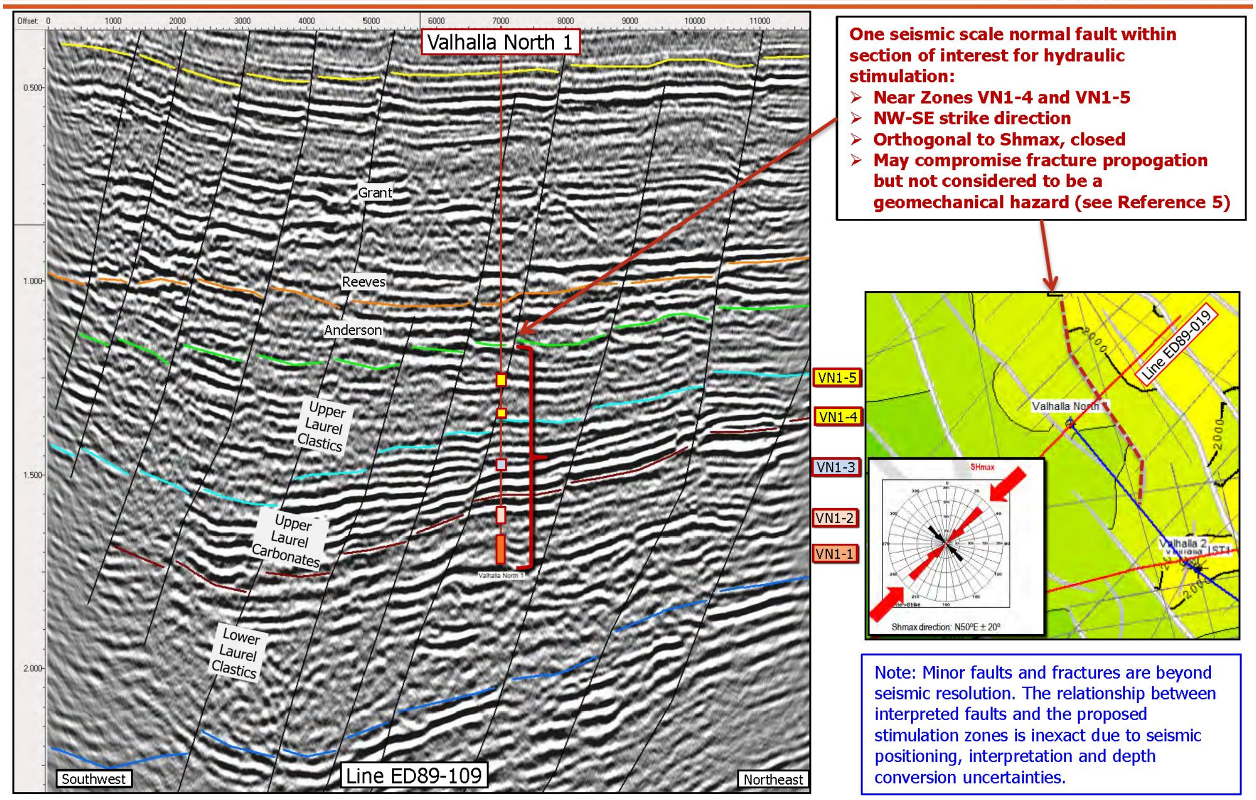

Figure 3-2: Valhalla North1 – 2D Seismic section showing the detail of the Upper Laurel Formation and faults as well as the relationship to the overlying Anderson, Reeves and Grant Group formations. The base of the Reeves Formation is noted as not a consistent reflector

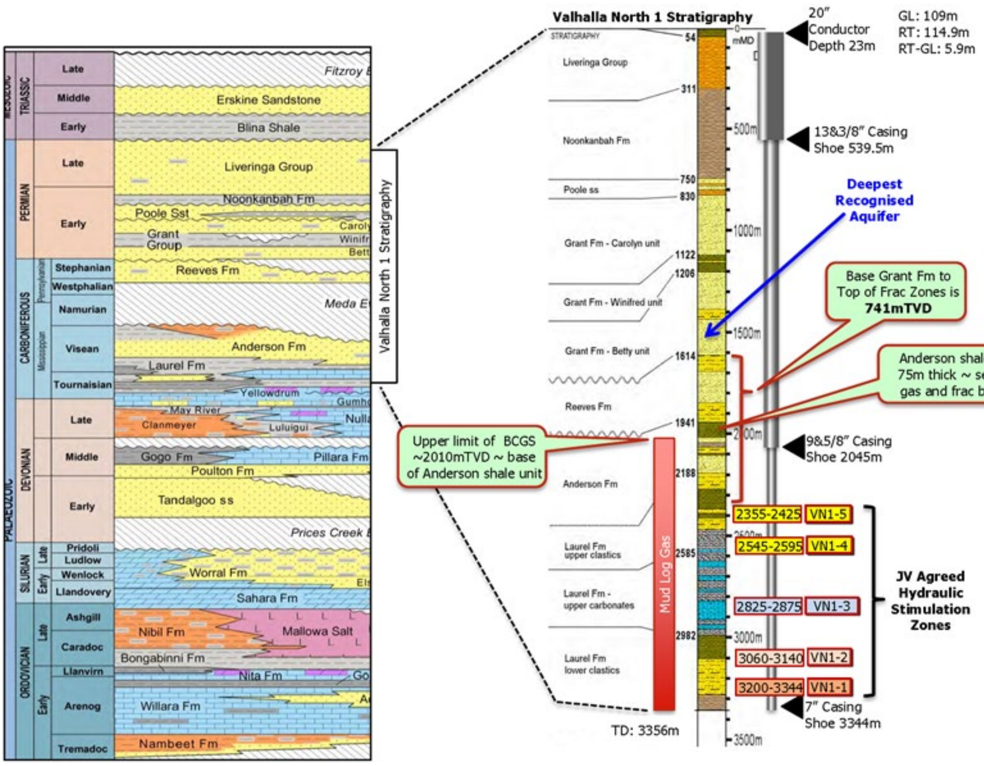

Figure 3-3: Valhalla North 1 stratigraphic section highlighting the Anderson Formation shale seal between the hydrocarbon bearing zones of the Anderson and Laurel Formations, and the Grant / Reeves sections above along with proposed hydraulic stimulation zones. Actual zones for the stimulations were deeper than the shallowest ones illustrated here

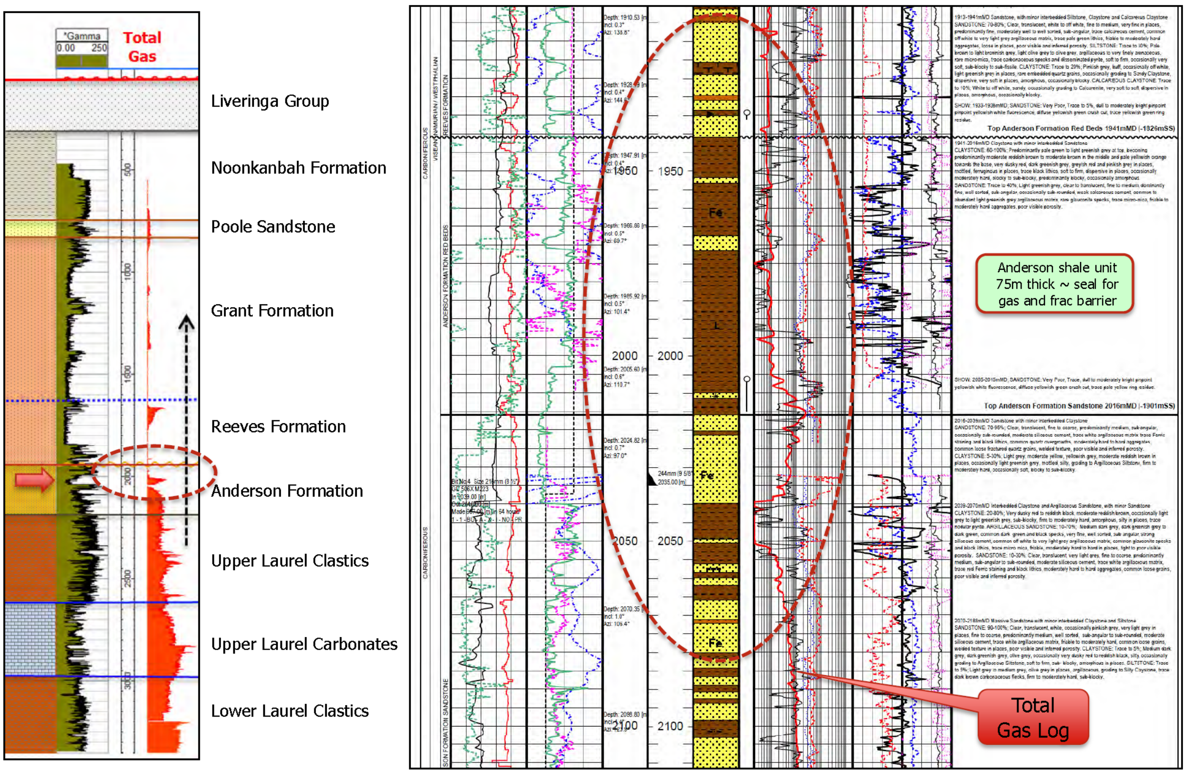

Figure 3-4: Composite well log for Valhalla North 1 showing the shale seal and the top of the gas section

From Figure 3-5 to Figure 3-7 below, the following can be interpreted for the Asgard 1 well:

- the deepest Grant Group layer is at 1375 m; the shallowest proposed stimulation was at 2045 m (actual shallowest stage was at 2567 m (planned distance from Grant Group – 670 m; actual distance was 1192 m)
- gas saturation increases in the upper Laurel Formation below the shale sealing Reeves Formation from the Anderson Formation
- SH_{max} is similar to the Valhalla area and is north-east to south-west.

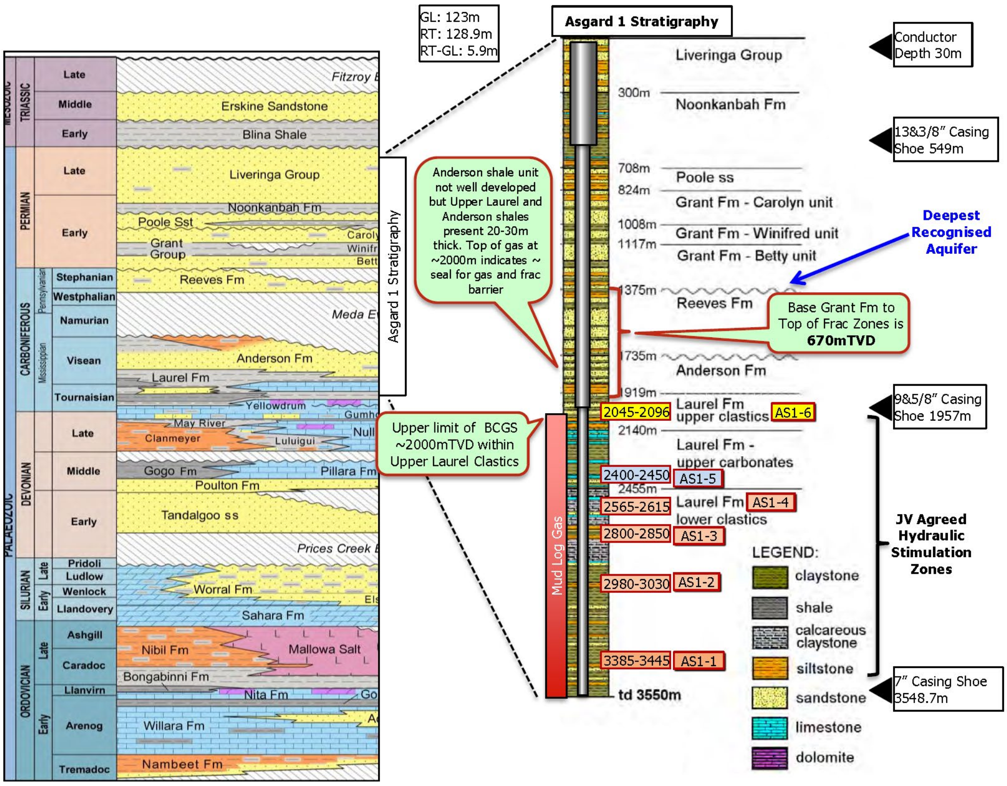

Figure 3-5: Asgard 1 stratigraphic section noting the deepest aquifer and the underlying siltstones of the Reeves and Anderson Formation shales and hydrocarbon zones within the Laurel Formation

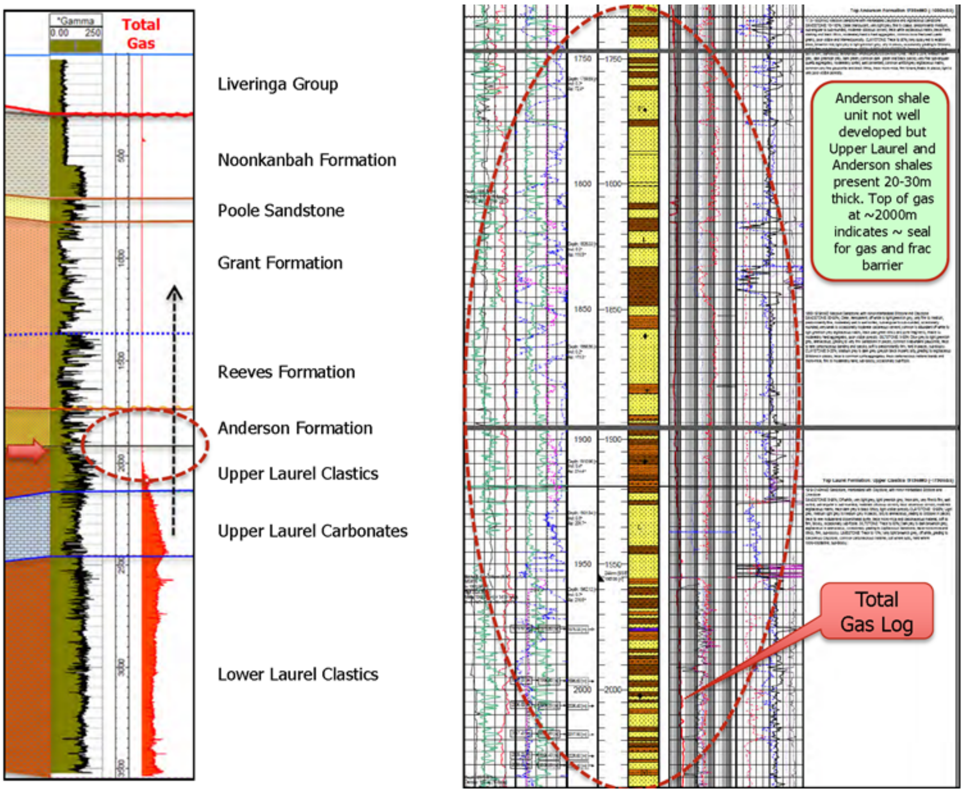

Figure 3-6: Asgard 1 composite well log showing the top of gas in relationship to the upper Anderson and Reeves Formations

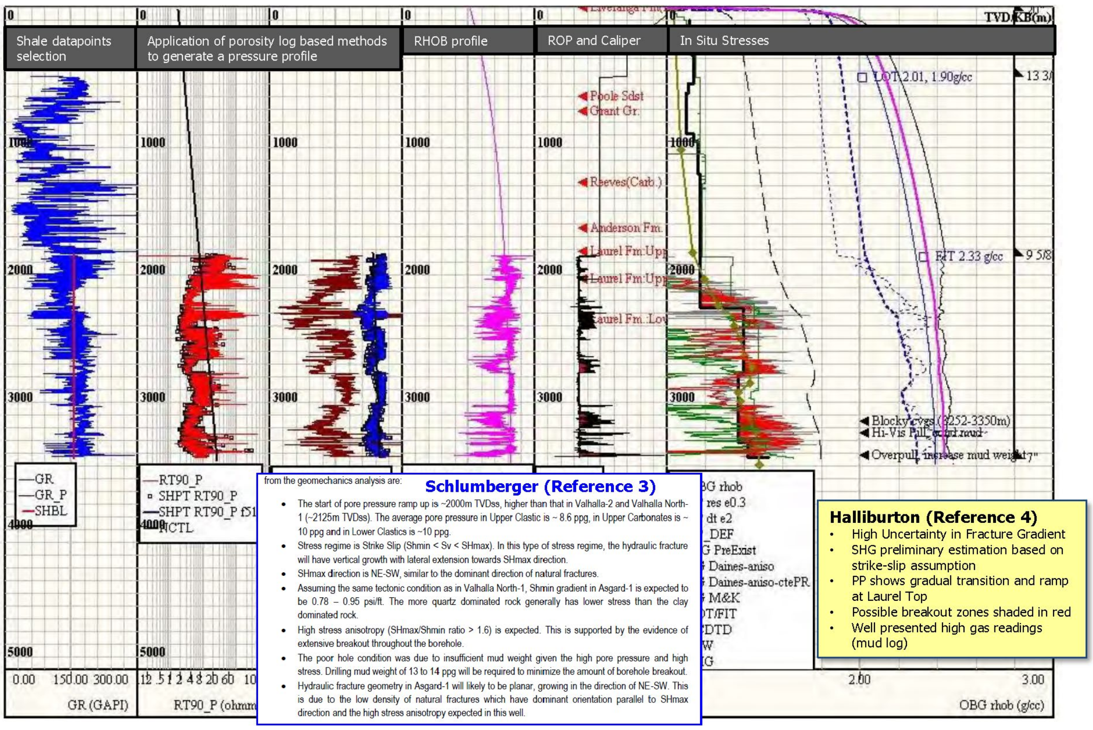

Figure 3-7: Asgard 1 geomechanical log from Haliburton as well as notes from Schlumberger

4 Assessment of well-seal effectiveness

Data of three petroleum wells (Table 4-1) drilled within the Development Envelope by the previous operator of EP 371 provides a detailed two-dimensional cross section of the formations located beneath the Development Envelope, shown in Figure 16.

Given the presence of trapped hydrocarbons in the lower Anderson and Laurel which are not significantly found above, along with evidence of overpressure below, BNR determined that the Anderson Formation provides a geological seal between the targeted Laurel Formation and shallower formations.

Data from these historical wells indicate that Anderson Formation is between 184 m and 279 m thick, this is similar to the thickness of the Kolkata shale present in the Perth Basin which also acts as a geological seal for the targeted formation.

Table 4-1: Subsurface formation data

Formation	Dominant lithology	Classification	Elevation – base of formation (m AHD)			Thickness	Total Dissolved Solids (mg/L)
			Valhalla 2	Valhalla North 1	Asgard 1		
Liveringa	Carbonate / shale	Minor aquifer, Aquitard	-84	-196	-171	84 to 196 m	500 to 12,400
Noonkanbah	Shale	Aquiclude	-441	-635	-579	357 to 439 m	550 to 800
Poole Sandstone	Sandstone and Shale	Aquifer or Aquitard	-524	-715	-695	80 to 116	300
Grant Group	Sandstone	Aquifer	-1,332	-1,499	-1,240	545 to 808	800 – 1,000
Reeves	Sandstone	Aquifer	-1,588	-1,826	-1,606	270 to 366	No data available
Anderson	Sandstone, siltstone, shale	Minor aquifer, Aquitard	-1,858	-2,105	-1,790	184 to 279	70,000 – 100,000
Laurel	Limestone, shale, siltstone and sandstone	Minor aquifer, Aquitard	<-3,350	<-3,241	<-3,400	1136 to 1610	70,000 – 100,000

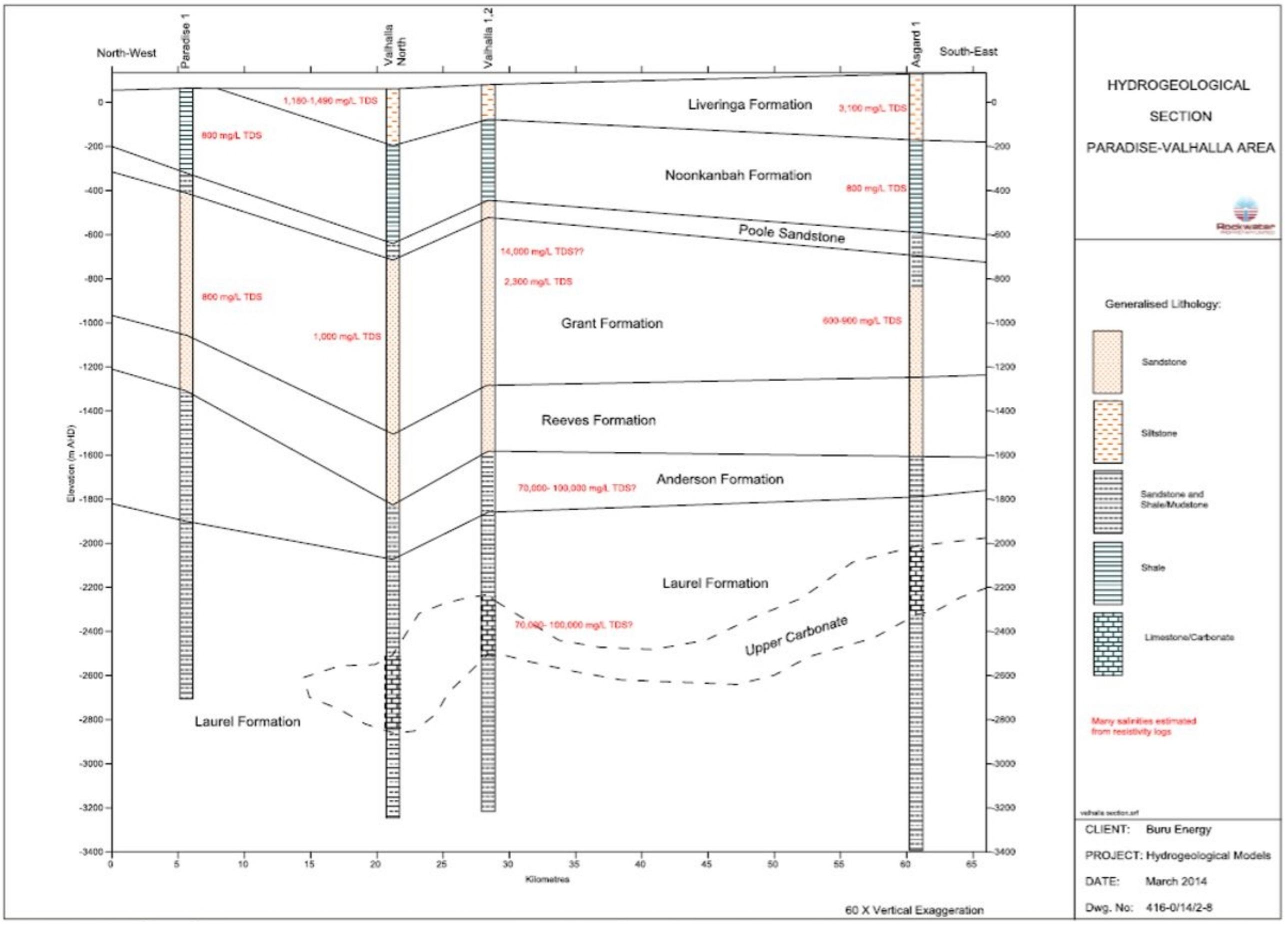

Figure 4-1: Hydrogeological cross section of the Valhalla and Asgard areas

5 Definition of potential high-risk zones

Currently this geotechnical risk assessment indicates substantially thick Grant Group and Poole Sandstone formations, along with the Reeves Formation section overlying the unconventional Laurel and Anderson Formations. Based on past drilling of the Laurel Formation section with no major drilling issues, BNR does not anticipate any significant high-risk zones directly related to drilling through the overall section. For the shallow formation section, through the aquifers, appropriate mud weight and casing design will be implemented to cover the shallow interval. For the deeper Laurel Formation section, BNR expects there should be little flow into the well during drilling operations over the hydrocarbon bearing intervals as the unconventional resources are noted as extremely tight with low permeability.

BNR has not noted any significant reverse faults providing juxtaposition of the Grant Group's potential aquifers adjacent to the Anderson or Laurel Formation sections in the downdip areas within EP 371.

The wellbore design and location will be optimised to minimise drilling through structurally weak geological zones that could shear and deform the well casing. The Canning Basin rocks on the Lennard Shelf are old. BNR does not anticipate drilling through salts or coals. Faults and a potentially weak shear zone surrounding them are the most likely weakest zone that may be encountered during the Proposal. It is our intention to not drill extensively through fault zones. Hydraulic stimulations in the proposed horizontal wells will be modelled prior to a stimulation and designed within the engineering tolerances.

BNR has not recognised any high-risk zones as such.

6 Expertise of current review

This geotechnical risk analysis has been prepared and reviewed by BNR using internal expertise.

6.1 Jay Moore, P.G

Chief Geoscientist, with over 24 years of diversified upstream oil and gas experience as an exploration and development geologist for companies in the United States (U.S.) such as Denbury, Encore Permian, XTO, BMOG). His experience includes prospect generation, planning, and drilling oversight of hundreds of vertical and horizontal wellbores in both conventional and unconventional plays (Wolfcamp, Bone Spring, Barnett Shale, Haynesville, Cotton Valley and others). Well versed in cross-discipline integration with experience in drilling, completion, and production operations.

6.2 George Witman

Vice President Drilling and Completions, with 22 years of upstream oil and gas experience, focused exclusively on high-efficiency development of U.S. unconventional resources including the Barnett, Eagle Ford, and Permian Basin. He managed EOG Resources' completions operations and water resources for the Permian Basin from 2016-2019. Responsible for a >$900 milliong annual completions budget, 6-8 operated frac fleets, and over 100 employees / contractors. Reduced completions costs by 29% and increased completions efficiency by 43% over a 3-year time frame. George holds a Bachelor of Science (B.S.) in Mechanical Engineering from Cornell University (Magna Cum Laude).

6.3 Mark Mueller

Drilling Supervisor after spending 7 years with BHP Billiton. He held roles in engineering and operations supervision across the drilling and completions function, and has planned and executed drilling projects in North American Shale, Australia, and the Gulf of Mexico. Mark holds a B.S. in Petroleum Engineering from Texas A&M.

6.4 Jon Holt

Director of Completions, with over 16 years of experience in the oil and gas industry. He spent 8 years with EOG Resources creating various completion strategies including: parent/child development, reservoir geomechanics evaluation, and exploration play design. Jon holds a B.S. in Chemical Engineering from Colorado School of Mines and an Master of Business Administration from University of Denver Daniels School of Business.

6.5 Rob Hull

Geophysical Consultant, with 27 years upstream oil and gas experience as a geotechnical specialist (for companies such as Pioneer Natural Resources, Maxus Energy, YPF- Repsol). He is a leader in 3D seismic, microseismic, geomechanics and fibre optics. He has experience in the unconventional Permian Basin, and Barnett Shale as well as conventional plays of West Africa, South Africa, and Indonesia. Rob holds a B.S. in Geology from the University of Rochester and a Master of Science. in Geosciences from the University of Texas at Dallas.

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Annex A. Early warning mechanism

The purpose of implementing an early warning mechanism process is to enable efficient and consistent decision making when responding to anomalous seismic events during HFS operations.

1. Overview

Microseismic monitoring is the passive observation (magnitude and location) of very small-scale ground movements or stress drops which can occur during HFS activities. Unlike traditional 3D seismic technologies, which measure acoustic reflections from an energy source, microseismic monitoring is a passive method, meaning it listens and measures the occurrence of natural and man-made seismic events within the earth. Passive methods provide a continuous 4D record of seismicity in the monitoring area, rather than individual snapshots in time obtained by conventional 3D seismic methods. These micro seismic events, often with magnitudes less than zero, are too small to be felt on the surface, but can be recorded by sensors called geophones or seismometers.

A microseismic event can occur from a natural build up and release of stress in the subsurface. Typically, as compaction and sedimentary processes take place within the earth, unequal distributions of lithology and fluids occur which can result in natural slippage and stress release along discontinuities or faults. Seismographic networks on the surface locate these natural slippages through time, highlighting the locations of these earth movements. Significant earth movements often greater than a magnitude of 3.5 on the Richter scale can be felt on the surface but seismometers can detect events that are far weaker. In oil and gas operations, during a hydraulic stimulation we modify the local pressure and stress at a given injection point along the well to create a hydraulic fracture. The hydraulic fracture opens up against the minimum horizontal stress direction and propagates away from the wellbore. As the fluid and pressure increase, the fracture forms and extends into the unconventional shale providing a conduit of hydrocarbons back into the well. The hydraulic fracture during its formation introduces local stress changes, which may generate microseismic events that can be monitored with a sensitive network of seismometers. These events can be mapped as the HFS operations progress. After pumping stops, the fractures begin to close and the localised fluid begins to diffuse in the host rock. Minor stress redistributions can further occur generating a falling off of microseismic events through time.

Microseismic monitoring has the ability to tell us the time, location and magnitude of microseismic events. During hydraulic stimulation, microseismic monitoring can be used to determine the fracture geometry and azimuth, identify out-of-zone events, evaluate fracture complexity and intensity, optimise injection strategies and staging, estimate stimulated reservoir volume, understand fracture development and stimulation effectiveness.

Microseismic monitoring utilises microseismic monitoring stations arranged in an array around the well to be stimulated. Receivers can be placed in different location, such as on the surface, buried under shallow earths, in shallow monitoring wells (10-30 m below ground level) or in deep boreholes. Depending on the design and purpose, a typical microseismic monitoring station consists of a sensor, data acquisition unit and radio (for real time).

2. Monitoring

The CSIRO's Gas Industry Social and Environmental Research Alliance (GISERA) is undertaking setting up a baseline study for the northern Canning to characterize the current natural seismic activity for the basin (GISERA 2021–). The collection of baseline information is important to help distinguish between natural and man-made events (e.g. quarry blasts or oil and gas extraction activities). Currently there are national catalogues available for the Canning Basin showing past natural earthquake activity. This GISERA work with an additional fourteen seismometers will enhance the understanding of natural earthquakes. The current national sparse network of receivers (currently three in the northern Canning Basin) cannot detect and locate events less than a magnitude of 2.5 within the basin. The new network should resolve events down to a 1.5 magnitude. This project will be set up from 2021 to 2025 and is currently 10% complete (GISERA 2021–). At least one monitoring station is proposed to be located in EP 371. GISERA notes that "increased seismic activity associated with hydraulic fracturing is an area of community concern and this baseline study will distinguish any potential increase in seismic activity due to planned gas extraction operations from other seismic sources" (GISERA 2021–). Furthermore, this research addresses recommendations from the 2018 Independent Scientific Panel Inquiry into Hydraulic Fracture Stimulation in Western Australia (Independent Scientific Panel Inquiry 2018).

It should be noted that the Development Envelope is located in a remote area of the Canning Basin. There are no inhabitants within the Development Envelope as well as no significant man-made structures. Hundreds of natural earthquakes have been recorded in the Canning Basin in the past, with at least one 6.6 magnitude event occurring off of Broome in 2019. With the addition of additional instrumentation by GISERA there will likely be a significant jump in the number of weak natural earthquakes that can be detected within the basin.

2.1. Timing of monitoring

Given GISERA's efforts for the basin and locating a seismometer within EP 371 prior the Proposal's stimulations, BNR does not anticipate needing substantial additional baseline information. The GISERA data should produce a catalogue of the naturally occurring low-level events over multiple years. BNR does plan on recording some additional baseline information at an even lower magnitude than GISERA, however over a limited time around HFS. The GISERA work utilising standard seismometers can record for months or years prior to the shorter-term local collection of microseismic events that BNR will record. Prior to the deployment of surface HFS equipment, BNR will set up a monitoring program to record events that might occur down to a magnitude of around -1 Richter local magnitude (ML). The scope of microseismic monitoring during the different phases of the HFS operations may involve different methodologies. An example of proposed monitoring program is provided in Table A.

Table A: Example of microseismic monitoring during the different phases of HFS operations

Location of loggers	Proposal phase		
	Baseline	Operations	Post-operations
Surface – GISERA Study	Deployed around the northern Canning with 14 seismometers over multiple years		
Surface – BNR	Array of typically 3 to 5 seismometers around the well to be stimulated, usually for 3-5 days prior.		
Post hole – BNR	Array of typically 3 to 5 seismometers around the well to be stimulated, usually for 3-5 days prior.		

2.2. Project set-up

2.2.1. Objective and initial short baseline program

The GISERA Western Australian surface seismometer program (GISERA 2021–) should be sufficient to understand events down to a 1 (ML). BNR will set up a short-term baseline program to detect and identify background levels of microseismic activity should these levels exist around the wells prior to HFS operations occurring. The array utilised should record down to a -0.5 to -1 ML and be more than sufficient for any induced events. This same array will record events during and after the stimulation for a short period. Depending on operations and logistics, BNR may maintain the network to record a longer duration of the baseline and post operations.

2.2.2. Monitoring stations

Typically, between 3 to 5 surface seismometers may be arranged around the well to be stimulated and may be situated in a low noise environment within a few kilometres of the surface location. Some post hole seismometers may also be situated away from the stimulation.

2.2.3. Recording

Data will be stored internally on data loggers. Data will be retrieved periodically for analysis. Given the short time intervals, most data will be transmitted to a base station via radio as will occur during the HFS operations.

2.2.4. Outputs

Results of the short term baseline microseismic monitoring program along with the GISERA data will be used as inputs into the operational monitoring program and can also be used for comparative purposes during later analysis of microseismic data.

2.3. Operations during HFS

2.3.1. Objective

The objectives are to:

- collect information on microseismic events during HFS operations
- provide data for the monitoring of hydraulic fracture development in real time.

2.3.2. Monitoring stations

A variety of methods can be used to monitor microseismicity during HFS operations. Between 3 to 5 surface seismometers may be set up, and up to 10 post hole powered downhole seismometers may be arranged around the well site at depths depending on soil type, level of detection desired, along with operations capability. Seismometers may also be buried in shallow soil away from the well site.

All sensors will be connected into a radio array network which will broadcast to the microseismic office. Arrays will be tested to ensure they are functional prior to starting pumping.

2.3.3. Recording and processing

Events greater than a certain magnitude (to be determined from baseline data) will be sent directly to the microseismic office on the well site to be processed in real time (refer to Section 2.3.3.1). Events below this threshold will be stored on internal data logger for later processing.

2.3.3.1. Real time processing

The microseismic office will be located at the central well site. This office will contain the central recording facility for the real time monitoring of the fracture stimulation. Incoming data will be analysed by geoscientists to assess the real time propagation of the stimulation. Collected information will then be fed back into the frac data van and correlated against the pumping rate.

2.3.3.2. Management response

A traffic light assessment tool (stop light system) will be developed to risk assess and ensure safe downhole fracture operations, incorporating the magnitude of events from the seismometer array. If thresholds are exceeded during stimulation activities, the operator will have various methods to respond including pausing the stimulation, lowering pressure, injection rates, and volumes as well as skipping a stage.

2.3.4. Outputs

All data will be stored and downloaded for post-operations analysis. Post-operations analysis will examine the data at a higher sampling rate and lower event threshold to ensure no microseismic events were missed during the real-time operation.

Analysis of continuous data collected during the program will be undertaken following the completion of operations. This analysis will include a review of all events along with a review of all waveform data and retriggering of events to see if events were missed. This report will provide an in-depth review of all events recorded prior-to, during and following the hydraulic stimulation, and will be correlated against the pump rates to understand the nature and lateral continuation of HFS activities. The results learnt from the microseismic program implemented during the well monitoring will then be applied to future programs.

Outputs from post processing will consists of copies of all extracted event waveforms, event pick files, event locations files, catalogue of events, updated models and stations corrections, plots of events, and a final report. The following interpretive products might also be developed from the microseismic monitoring program:

- basic engineering report of the interpreted fracture geometry

- advanced engineering report incorporating basic geophysical analysis of sensitivity and accuracy to interpret fracture geometry and evaluate the HFS
- basic geophysical processing and quality control report describing the workflow employed and corresponding data accuracy and confidence attribute
- advanced processed report described the workflow and corresponding interpretation.

2.4. Post-operations

2.4.1. Objective

The objective of post-operations monitoring will be to collect information on microseismic events following the HFS program as the stress is released from the geological profile. Typically, there are few events after pumps shut down with the majority occurring within a few hours of the end of operations.

2.4.2. Monitoring stations

Using the same equipment that was used during the stimulation, the data will be recorded post stimulation shut down for a short period typically on the order of a few days.

2.4.3. Recording

Data will be stored internally on data loggers and picked up at decommissioning. Should multiple stimulations take place over a short period of time, the recording stations will likely be maintained and be operational for multiple weeks or months. Data will be transferred to the central office via radio network or retrieved on internal storage devices after the operations are complete for analysis.

2.4.4. Outputs / Reporting

The outputs from post processing will include a report comparing microseismic activity during HFS operations to microseismic activity before and after operations.