The Potential Effects of Hydraulic Fracture Stimulation in Island and Coastal Environments:
A Review of the Literature

Revision: 1

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Document No.: 16-206_Anticosti_Literature_Review_R1.docx

5 March 2016

Title:	The Potential Effects of Hydraulic Fracture Stimulation in Island and Coastal Environments: A Review of the Literature	
Client:	MDDELCC, Québec City, Québec	
Document ID:	16-206_Anticosti_Literature_Review_R1	
Revision Number:	1	Date: 5 March 2016
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Reviewed by:	Ken Raven, Ian Clark and Maurice Dusseault	

EXECUTIVE SUMMARY

This literature review considers the issues arising – environmental and industrial – that will need consideration should oil and gas production proceed on Anticosti Island, Québec. For that eventuality, we make a number of recommendations.

The hydrogeological conditions that exist beneath coasts and islands adjacent to or surrounded by sea water differ from continental regions. There is currently minimal use of groundwater for domestic or industrial purposes on Anticosti Island, although in this karstic terrain, groundwater provides essential baseflow for the major and minor rivers. Groundwater salinity is variable, but largely potable and quite low in dissolved solids (<1,200 mg/L). Well established principles indicate that the depth to the freshwater/saltwater interface will be well below sea level although such estimates may be affected by karst conditions, such as those that exist on Anticosti Island. This interface is unlikely to be affected by hydraulic fracturing at depth although upconing or karst-induced penetration of seawater into shallow aquifers could occur if groundwaters are extensively used as fracturing fluid make-up water rather than as a supplement to a program of continuing storage in surface lagoons.

The basic practice of hydraulic fracture stimulation – fracking – is presented together with a description of the industrial footprint that accompanies such oil and gas production. Hydrocarbon extraction will impose a substantial footprint on the island involving (i) an expanded or dedicated terminal for ferry operations from the mainland, (ii) vehicle transportation routes, (iii) clearing the drilling pads for well sites, (iv) any associated hydrocarbon, water and waste-water storage facilities, (v) pipelines to conduct the extracted hydrocarbons to tidewater port facilities, (vi) hydrocarbon handling facilities at tidewater (gas pipeline header or liquefaction plant, oil loading to tankers) for shipment to markets, (vii) local bedrock quarrying of aggregate for infrastructure construction, and (viii) blasting bedrock for pipeline trenches and other infrastructure, given that surficial deposits in some central island regions may be thin. In global examples of gas development on islands, the impacts of infrastructure construction are shown to be accommodated and minimized by standard practices.

Potential unanticipated impacts of infrastructure development on Anticosti Island include (i) leakage of fuel from storage sites and transfer stations, (ii) sediment runoff into local watersheds from landscape cleared for drill pads, (iii) leakage of wastewater at drill sites, (iv) fuel spillage from truck transportation of fuel (winter or summer), (v) management (removal by pipeline or re-injection) of produced and flowback saline waters, (vi) disposal of oil-impregnated drill cuttings in a secure landfill, and (vii) coastal contamination by a maritime oil spill.

Geomechanical stress patterns are taken into consideration during routine fracking operations to optimize the induced fracture pattern. Industry experience suggests that maximum fracture growth height above the Macasty Formation (1500 to 1800 m depth) would be much less than 500 m. The potential for induced vertical fracturing migrating much above the target formation is dismissed as being remote. The Macasty Formation lies beneath a substantial thickness of low-permeability materials. The potential for an uncontrolled blowout of oil or gas or brine from the Macasty, given the lack of significantly overpressured conditions and the low permeability of the Formation itself, is also remote.

Natural gas of deep biogenic origin has been found to be discharging from saline springs on the Island. The source horizons have not been identified but it is found in proximity to the deep Jupiter

fault. Hydraulic fracturing in the vicinity of this fault should be strongly discouraged. The greatest potential for migration of natural gas into shallow aquifers or the atmosphere is along poorly completed well bores. This can be mitigated by proper well sealing, careful post-completion testing and good decommissioning practices.

Our assessment is that surface impacts of infrastructure development on Anticosti Island are largely predictable and must be considered in the context of a greenfield energy exploitation play. Unanticipated impacts of leaks and spills differ little from other, non-island sites. Impacts from leakage from depth of fracking fluids and/or oil and gas on Anticosti are considered to be minimal.

Recommendations for further study include:

(i) a regional hydrogeological investigation to assess groundwater quality, methane concentrations, depth of the salt-water interface, and groundwater flow directions,

(ii) regional characterization of stable isotopes and radiocarbon of methane in groundwater. This will provide baseline data in advance of any fracking activities.

(iii) further investigation of the saline springs and gas discharges on the island, together with characterization of the interstitial fluids from cores taken from the target horizons

(iv) further geomechanical studies to define in-situ stress patterns and values, as well as the general geomechanical properties of the strata so as to better constrain hydraulic fracture modeling results.

(v) whole-rock geochemical data from the 2014-15 stratigraphic drill cores would provide a chemostratigraphic framework to understand spatial and temporal variations in mineralogy, organic content, naturally occurring heavy and radioactive metals and rock mechanics of the Macasty shale.

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LIST OF ACRONYMS

Alk:	Alkalinity (mg $CaCO_3$/L)
BGWP	Base of Ground Water Protection – the lowest occurrence of useable water, defined consistently by an accepted standard (e.g. 4000 parts per million total dissolved solids in Alberta)
amsl:	above mean sea level, elevation
bgs:	below ground surface
DO	Dissolved Oxygen (mg/L)
DOC	Dissolved Organic Carbon (mg/L)
Eh:	Redox potential relative to the hydrogen electrode (mV)
Fm.	Formation
FW	Fresh Water
GMWL:	Global Meteoric Water Line, relationship of $\delta^{18}O$ to δD in rainfall
GWQ:	Groundwater Quality
K:	Hydraulic conductivity (m/s)
MW:	Monitoring Well
ORP:	Oxidation-Reduction Potential (mV)
ppm	parts per million, in fresh groundwater this is equivalent to mg/L
ppb	parts per billion, in fresh groundwater this is equivalent to µg/L
SEC:	Specific Electrical Conductance (µS/cm)
SW	Salt Water
TDS:	Total Dissolved Solids (in mg/L)
USGS:	US Geological Survey
‰	per mil, or parts per thousand
$\delta^{18}O$	delta Oxygen 18, measurement of oxygen isotopes (‰)
δD	delta Deuterium, measurement of hydrogen isotopes (‰)

1 INTRODUCTION

The technical literature concerning the development of hydrocarbon (oil and/or gas) resources in island environments is reviewed to allow consideration of how such development might affect conditions on Anticosti Island, Québec, where reconnaissance and delineation exploration drilling has begun. There is virtual certainty that if the resource is found to be of commercial interest now or in the future that modern energy wells will be drilled and completed by hydraulic fracture stimulation. The use of hydraulic fracturing is deemed necessary for any commercialization of the Macasty Formation source rock reservoir in Anticosti Island. In order to anticipate geoenvironmental issues that might arise during such development, the authors have prepared this literature review based on their experience of similar such work in North America, Europe and Asia.

Island environments where surrounded by salt water pose several unique problems that require careful planning and long-term management:

- the freshwater supplies are isolated by the adjacent seawater and saline formation water that both surround the island and underlie it;
- hydrocarbon extraction is an industrial activity that must be sustained by ferry operations from the mainland and the level of activity may need its own marine terminal – or an expansion of an existing terminal – if sufficiently large drilling and production operations are planned; and
- hydrocarbon extraction will impose a substantial footprint on the island involving transportation routes, the well sites and any associated hydrocarbon, water and waste-water storage facilities as well as pipelines to conduct the extracted hydrocarbons to tidewater port facilities, and beyond to markets.

This review begins with a discussion of the dynamics of fresh groundwater in a marine environment, which is the case for fresh-water aquifers in coastal and island environments, e.g., Gaspé and Anticosti Island (section 2). The potential effects of hydraulic fracture stimulation, commonly known as "fracking", are then discussed (section 3), followed by reviews of the technical literature on infrastructure development (section 4), in particular greenfield developments such as on Barrow Island off north-western Australia and the Shetland Islands off Scotland (section 5). Finally, the issues raised by this general literature review are discussed in section 6 in the context of Anticosti Island, with recommendations to address issues that have not yet been resolved.

2 HYDROGEOLOGY OF ISLAND AND COASTAL AQUIFERS

2.1 The Nature of the Freshwater/Saltwater Interface

Fresh groundwater typically discharges along coastlines with a chloride concentration of ≤20 mg/L. However in coastal aquifers a salt-water interface exists, seaward of which is salt water with a chloride concentration of 19,000 mg/L (Total Dissolved Solids or TDS=35,000 mg/L). The depth and geometry of this interface between freshwater and saltwater – referred to herein by *FW/SW interface* – is of critical importance to managing the groundwater resources of any island or coastal aquifer. In oil and gas development it is clear that the depth of this freshwater-saltwater interface must be established.

Figure 1 shows a conceptual model of this interface associated with the early estimation from the 19th century based on the Ghyben-Herzberg principle, i.e., (Reilly and Goodman, 1985):

$$z = \frac{\rho_f}{\rho_{s-}\rho_f} h$$

where z is the depth below sea level of the interface, ρ_f is the density of fresh water, ρ_s is the density of salt water and h is water-table elevation above sea level. However, real FW/SW interfaces are more complex.

Figure 2 shows an actual interface beneath Miami, Florida where the Biscayne Aquifer is contaminated by sea-water intrusion. The FW/SW interface as defined by the Ghyben-Herzberg principle follows the 400 mg/L contour and therefore is only a first approximation of the interface. A better approximation was developed by M.K. Hubbert (1940).

Hubbert (1940) showed that above some datum, e.g., the base of the Biscayne Aquifer, the fresh-water (h_f) and salt-water (h_s) heads could be defined by:

$$h_f = p/(\rho_f\, g) + Z$$

and

$$h_s = p/(\rho_s\, g) + Z$$

where p is the pore pressure at that point of measurement and Z is the vertical location above the datum on the interface. Hubbert noted that the interface between fresh- and salt-water would be dictated by the continuity of fluid pressure. Therefore these two heads must be equal at the interface and thus the elevation of the interface, Z, is given by (Reilly and Goodman, 1985):

$$\mathrm{Z} = \frac{\rho_f}{(\rho_f - \rho_s)} h_f - \frac{\rho_s}{(\rho_f - \rho_s)} h_s$$

Figure 2 indicates that in reality there is not a sharp interface between salt water and fresh groundwater because groundwater discharge and tidal fluctuations create a dynamic situation. Rather, a zone of transition occurs reflecting a number of factors including fresh-water over extraction by pumping, decrease in surface-water infiltration due to channelization, artificial recharge and Pleistocene sea-level variations.

To obtain high-resolution FW/SW interface information, the US Geological Survey has installed multi-level monitoring wells in southern California (e.g., Hanson *et al*., 2009; Anders *et al.,* 2014). Hanson et al.(2009) concluded that seawater intrusion in the coastal aquifers of southern California is associated with advancement of the salt-water plume through coarse-grained units at the base of fining-upward sequences of marine sediments, a finding similar to that on Lulu Island in the Fraser estuary of British Columbia near Vancouver (Neilson-Welch and Smith, 2001). Edwards *et al.* (2009) describe how the structural geology of the Los Angeles-Long Beach area created pathways by which salt water intruded into the Dominguez Gap area caused by over pumping after the 1920s.

Similarly in coastal and island carbonate aquifers the advancement of the salt-water plume may occur through fissures and into vertical solution cavities in karstic zones of the aquifer (Stringfield and LeGrand, 1969, 1971) that they associate with karst development during the Pleistocene era when sea levels were much lower. These authors also note the existence of intermittent brackish springs inland and heterogeneous head and groundwater quality patterns.

In northwestern Europe the Chalk aquifer of England, Sweden and France requires sophisticated groundwater-extraction management so that intrusion is minimized, especially given the extensive network of fissures in the Chalk aquifer that allows inland seepage of seawater. In southern England seawater intrusion into the Chalk is managed by seasonally adjusting pumping rates so that the high winter groundwater flow is captured near the coast while peak summer demands are met by inland wells (Downing, 1998).

The management of sea-water intrusion into U.S. aquifers involves not only the use of multi-level monitoring wells but also variable-density numerical simulation software developed by the US Geological Survey (e.g., Nishikawa *et al.,* 2009 in southern California and Hughes *et al.,* 2009, in Florida). Todd and Mays (2005) summarize the simple analytical tools that may be used to manage sea-water intrusion into coastal and island aquifers during groundwater extraction. The reader is referred to the review by Barlow and Reichard (2010) of sea-water intrusion studies along the North American coastline.

2.2 Potential Modifications of the Interface by Fluid Extraction

There are no known published accounts of shallow hydrogeologic effects caused by hydraulic fracturing beneath islands. Hydraulic fracturing has been reported by news media beneath Barrow Island, off northwestern Australia, and the island of Tierra del Fuego, Chile, and it is likely to have been conducted beneath other islands, such as the barrier islands along the Texas Gulf coast. However, where such hydraulic fracture stimulations do occur, the results are not published because fracking is a routine oil-field practice and the stimulated formations are likely so deep that the effect on the FW/SW interface would not be detectable.

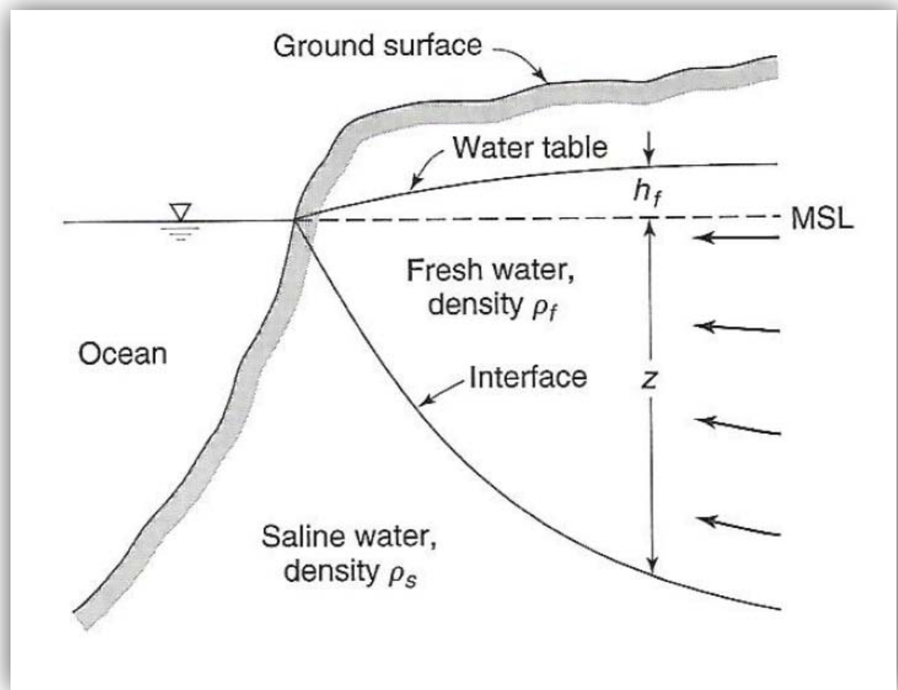

Figure 1 A simple conceptual model of a FW/SW interface in a coastal aquifer in which z is the depth to the interface from mean sea level (MSL) and h_f is the height of the water table above MSL (from Todd and Mays, 2005)

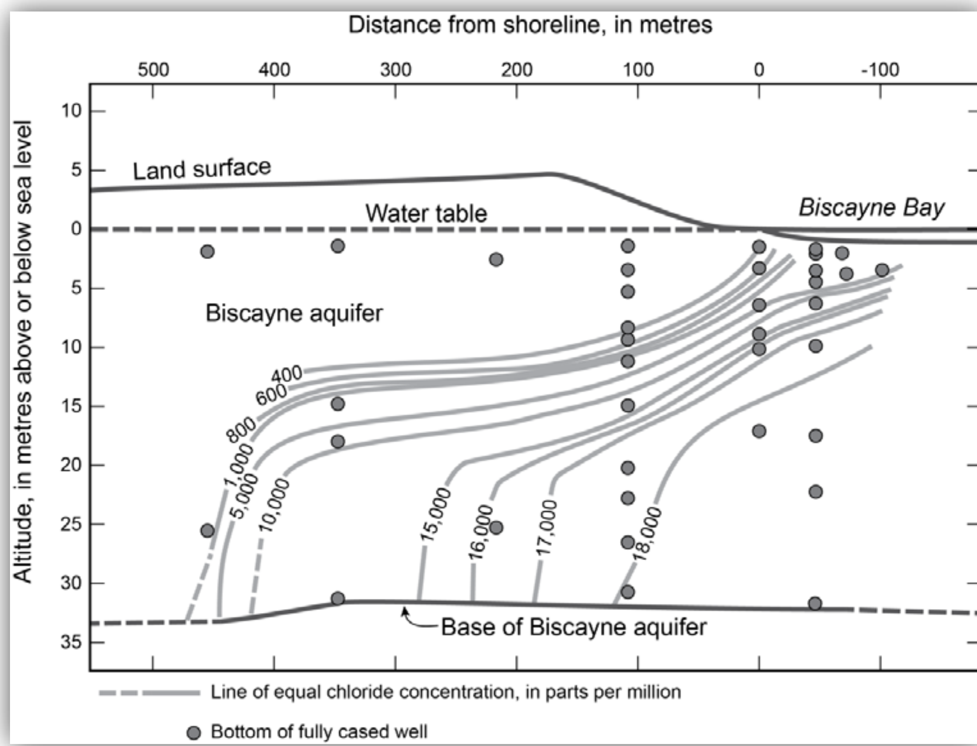

Figure 2 Profile of the chloride concentrations in the Biscayne Aquifer, Miami, Florida (from Reilly and Goodman, 1985).

3 POTENTIAL EFFECTS FROM HYDRAULIC FRACTURE STIMULATION

3.1 Drilling and Completing an Energy Well

Oil and gas wells – *energy* wells as opposed to *water* wells – are now usually drilled to allow a 1-3 km long horizontal leg of the well to be installed in order to more efficiently drain the target formation. This approach permits the drilling of multiple wells from a single pad, and greatly reduces the surface impact of oil and gas development, compared to the traditional approach of one vertical well – one pad. The following applies to oil or gas wells in a *play*, which is the jargon used to identify development of a particular geological horizon in a region, such as the Marcellus play or the play that occurred on the south shore of the St Lawrence River in Québec five years ago. King (2010) provides an overview of this topic. A play involves a set of energy development operations, in which seismic exploration work is done and wells are drilled into a particular formation in a particular region, usually (but not always) leading to commercial development at some scale.

Figure 3 illustrates the main features of an energy well's construction and completion. A vertical well is drilled to a depth of several hundred metres to install a surface casing that protects the shallow potable water and surficial sediments. The well is extended vertically and eventually turned to adopt a horizontal attitude. One or two additional steel casings will be installed in this operation. The energy well is considered *completed* when the horizontal leg of the well has been *perforated, stimulated* or *fracked* to allow the formation fluids to flow into the wellbore. The full technical term for the fracturing is *hydraulic fracture stimulation*, following which the well is ready for production. It is cost effective to undertake numerous fracking operations along the length of the horizontal leg, which is referred to as a *multi-stage hydraulic fracturing* or MSHF (Dusseault et al., 2011).

Figure 4 illustrates how MSHF stimulation operations are conducted within a horizontal well. The critical aspect of this approach is to maximize the extent to which each single well can access the formation containing the hydrocarbon resource. The horizontal leg nowadays is typically from 1.5 to 3 km in length, and the tendency is toward longer horizontal sections (3 km) as drilling and completion technology improves.

The formation behind the cased horizontal section is usually accessed by a method referred to as *plug-and-perf*. An interval in the closed steel casing is isolated by two packers so that the casing may be perforated and therefore allow HF fluids and proppant to be injected into only one zone. In other configurations, several perforated intervals may be isolated together by packers and simultaneously subjected to fracking. However, because this reduces somewhat the ability to control the outcomes in each of the stages, this approach is becoming less popular.

Stimulation through hydraulic fracturing, in the configuration of Figure 4, takes place sequentially, with one perforated interval after another being isolated and fractured. The injected fluid usually includes (i) gelling agents that allow the generation of a fluid with viscosity to carry proppant, (ii) biocides to prevent fouling of the well through biodegradation of the organic gelling agent, (iii) sand or ceramic proppants to hold the fractures open so that oil and/or gas may later escape, and (iv) other chemicals to facilitate the process (e.g., cross-linking agents to enhance the viscosity effect of the gel, corrosion inhibitors and oxygen scavenging agents, scale inhibitors, potassium chloride to reduce shale swelling, viscous breakers to aid in de-polymerizing once the pumping ceases, fluid loss control agents such as finely ground $CaCO_3$).

Another approach to well stimulation that has developed in the last 20 years is the use of friction reducers such as polyacrylamide polymers to allow water to be injected more rapidly and flow a greater distance; these new technques are referred to as “slickwater” fracturing. The small amount of polymer creates a “boundary effect” on the walls of narrow-aperture induced and opened natural fractures, reducing the energy required for pumping, and allowing more “slickwater” to be injected more rapidly for the power applied. A broad review of hydraulic fracturing technology may be found in King (2012).

As an example, in the Horn River play in northeastern British Columbia, a large reservoir thickness means that large volumes of fracture fluid are used in each stage, perhaps as much as 3500 m^3, and probably the largest per-fracture treatment volumes in the world at the time. In the Marcellus Formation in Pennsylvania, however, injection volumes per stage are much smaller, a few hundred m^3, because the formation is thin (40-50 m) and because there appears to be no strong barrier to upward HF propagation at the top of the shale gas interval. It is desirable to keep fractures from propagating excessively above the top of the productive horizon simply because it is a waste of money to inject fluids that do not aid production. In a case such as the Marcellus, the spacing of the treatment sites along the wellbore will be different than in Horn River because of this thickness effects, and this may also affect the lateral spacing between wellbores.

The depths shown in Figure 4 are representative of the range for a typical play where there will be a range of depths because of the geology of the region. The Marcellus is close to 3 km deep in the southeastern part of the play in central Pennsylvania, but only a kilometre deep in the northwestern part of the play in Ohio. In a few cases, the depth to the horizontal wellbore could potentially be as shallow as 300 m, as occurred in the coal bed methane play in Alberta ten years ago, or as much 4500 m in the deeper shale gas wells in British Columbia, but it is unlikely that shallow development using HF would be advisable or be allowed, and in any case it may not be economically desirable because shallow strata simply may not have enough gas per cubic metre to warrant commercialization attempts. In Anticosti Island, the maximum depth to the prospective Macasty Formation is on the order of 2200 m, which this represents approximately the maximum depth at which fracturing would take place. Some limits are placed on the minimum depth required for HF (e.g., no fracturing at less than 400 m below the base of an aquifer according to RPEP, which would mean not less than 600 m below ground surface), and perhaps limits on the volumes used until HF behavior is better understood locally. Development decisions will depend not only on depth, but also on richness, thickness, gas/oil ratio and other factors. The regulatory agency would be involved in this process, acquiring useful data to be used to help evolve guidelines that protect the environment yet allow the stakeholders (the people of Québec, the oil companies, the local population) to benefit from development.

Vertical hydraulically-induced fractures will propagate a significant distance above the target formation (Warpinski and Teufel, 1987; Davies et al., 2012; Fisher and Warpinski, 2012) but apparently never more than 600 m above the target horizon and usually terminating far below the lowest elevation of potable groundwater. In fact, the value of 600 m above the target formation that is reported in some of these articles is not based on measurements of fluid migration or fracture propagation; it is an estimate based on microseismic measurements, and it is well known that microseismicity is triggered by pressure increases, which can occur great distances in advance of actual bulk fluid transport. Some limited vertical propagation of fractures above the top of the target stratum is often necessary to ensure the vertical carrying of proppant high enough into the target formation. During early stages of any development or play, until there is common knowledge about the potential of the target formation, companies will collect information about the strata and carry out monitoring during HF trials to assess fracture behavior so as to guide further development. The optimum placement of the wellbore within the formation depends on factors such as the horizontal and vertical stresses, the nature of the HF fluids to be used (density, viscosity), and the injection pressure and rate to be used in stimulation. The stimulation size (volume) at each perforated stage along the axis of the well, and the spacing between stages, are optimized during the early development stages when pilot hydraulic fracturing in horizontal wells is conducted (Mayerhoff *et al*., 2010).

The plan view shown in Figure 5 is a possible MSHF approach with horizontal wells spaced 100 m apart laterally. In this figure, the concepts of a stimulated region directly affected by the HF operation and a drained region that is much larger are shown. When the formation permeability is low, HF stimulation will generate small perturbations beyond the region of the induced fracture network and the zone within which there is actually fracture propping. Over the life of the well, the volume within the drainage radius beyond the actual fractured zone will contribute to production.

In Figure 5 it is assumed that the stimulated zone limit is about 50 m on either side of the wellbore, which is a realistic scenario for the Macasty Formation on Anticosti Island that is 35-75 m thick. The fractured zones themselves do not overlap, but the drainage regions overlap somewhat. Quantification of these aspects for optimization can only be achieved by monitoring production trials that are subsequently modeled using geomechanical simulators (e.g., Pettitt et al., 2011; Nassir et al., 2014).

At depth, adjacent wells might be configured as shown in Figure 6. In this representation, only six fracture stages along the axis of the horizontal well section are shown for artistic purposes, and only the fracture stimulated zone is represented by the ellipsoids; the more extended drainage volume explained in Figure 5 is not shown in Figure 6.

The two wells shown in Figure 6 will be drilled from the same pad, and many other wells can also be drilled from the same pad because of advances made in the directional drilling of wells in the 1990's, the use of downhole drilling motors (mud motors), data transmission to the surface while drilling to allow bit steering, and so on. It should be emphasized again that although the drilling and fracturing industry appears roughly the same in 2015 as it did in 2005, major changes have taken place that have resulted in increases in horizontal well length, more fracture stages along the well, larger treatment volumes, cheaper drilling costs and improved HF stimulation results.

After fracture stimulation, part of the fracturing fluid (30-50%) will flow back to the producing well when the pressure is dropped to foster oil and gas production. This is known as *flowback,* and because this wastewater will contain many of the components injected into the target formation, it may be hazardous. As well, if there is mobile water in the producing formation, some of this water will be co-produced along with the oil and gas, and this is called *produced water*. It will be primarily natural formation brine with very high total dissolved solid (TDS) concentrations and in some circumstances it could have substantial concentrations of toxic metals such as barium and radium.

The geochemical composition of flowback fluids from the Marcellus shale-gas play in Pennsylvania has been described by Ferrar *et al*. (2013), Haluszczak *et al*. (2013), Engle and Rowan (2014) and Warner *et al.* (2014). Bibby *et al*. (2013) developed a list of recommended basic reporting parameters for flowback fluids. Maloney and Yoxtheimer (2012) have summarized the production of waste materials from the Marcellus Shale play and noted how it was necessary for much waste to leave the

State for final disposal. Waste treatment and disposal thus represents a challenge for an island environment that lacks existing infrastructure, and there are risks associated with the transshipment of waste materials off the Island, as handling and re-handling substantially increase the chances of a spill or other release to the environment.

It is conceivable that hydraulic fracture stimulation, when conducted in structurally-deformed regions or areas where in-situ stresses are close to a critical slip condition (see Zoback, 2010, chapter 11), could result in lateral pore-pressure transmission to nearby stressed faults, with subsequent seismic slip causing minor earthquakes (e.g., Ellsworth, 2013; Frohlich and Potter, 2013; and Skoumal et al., 2015). The process of HF stimulation has occasionally led to felt earthquakes in the Western Canada Sedimentary Basin of British Columbia and Alberta, usually less than magnitude M4 (Farahbod *et al*., 2015), however one was measured at M4.4 at Fox Creek, Alberta in January 2015 (Edmonton Journal, 2015), another at M4.8 in January of 2016 (Globe and Mail, Jan 12, 2016), and several in British Columbia somewhat larger than M4.0 in the last few years (Atkinson *et al*. 2015).

It is unlikely that earthquakes of this size could be generated in the Macasty play because (i) the formation thickness is small and therefore small HF volumes are involved, (ii) there is no evidence that the stress conditions in Anticosti Island are close to a critical condition for induced seismicity and (iii) the depths are less than 2.2 km. In an island environment, any events that might be large enough to be felt at surface in the vicinity of the HF activity will not be felt off-island.

3.2 Potential Contamination by Surface Activities

As examples of island development, we note developments on Tierra del Fuego in Chile and Argentina and Barrow Island, Australia, where hydraulic fracturing has been employed beneath both islands. Barrow Island is presently newsworthy because it is where Chevron and partners have been constructing a massive gas gathering and handling facility for off-shore gas and the Shetland Islands, Scotland, where a similar but smaller facility is under construction for off-shore gas. In such cases, the effects of construction are accommodated and minimized by standard practices, as the case of the development on the Shetland Islands shows. A similar development involving Shell, Exxon and other partners has been occurring on Sakhalin Island, Russia, however this project is also associated with off-shore gas and, like the Shetland Islands, there is no drilling and hydrocarbon extraction occurring on-shore.

Any development on Anticosti would be different from Sakahalin and the Shetlands in that it would be dominated by hydrocarbon production as well as oil and gas gathering and handling onshore. In that sense, Sakhalin Island may be a somewhat better example, but there, the development is limited to the shore line to access the gas and oil fields that are 5-15 km offshore. Such a scenario could develop along the south west shore of Anticosti Island, with wells drilled from near-shore drill pads, and extending out under the sea, a process referred to as onshore-to-offshore development. However, given the sensitivity of the shoreline, the increased cost of extended reach drilling, and the modest size of the resource base in the Macasty Formation, development of this type might never take place, and certainly would not occur until much of the pure onshore drilling was finished.

Any such possible future onshore-to-offshore development may be inappropriate at the present time because of the points mentioned above. Furthermore such development would only be permitted once knowledge of the Macasty play is far more sophisticated than today and once the proponents execute an environmental assessment addressing the unique characteristics of such a development.

The surface activities of importance to potential contamination of land and water supplies are:

1) **At the well pad**:

   - Drilling and production will require water and waste-water storage and management. Such facilities (water impoundments, flowback tanks, carefully designed lagoons, flow lines) are subject to leakage. Such events are of relatively low probability but, should they occur with water-based fluids that have chemical traces or high dissolved salt contents,,are of considerable consequence because of the nature of the hydrogeological environment on Anticosti Island.
   - It will be necessary to store significant quantities of diesel fuel on each well pad for drilling and production purposes, thus storage tanks of several thousand liters of diesel will be on each multi-well site during the active development phase.
   - At each well pad, the surface activities will require clearance of vegetation and excavation for production and handling activities. This will likely cause erosion and sediment runoff, particularly where surficial materials such as till or outwash sand are present and exposed. Until the site is re-vegetated the sediment runoff will create small debris lobes in topographically low areas as shown by Williams *et al*. (2008).

2) **Transportation of Fuels on Anticosti Island:**

   - Truck transportation of diesel fuel from the ferry terminal to the various well pads will be necessary and may represent the highest hazard for spillage of fuel. The consequence of such releases in any Island environment is dependent on the nature of the overburden and the underlying bedrock. The consequences of such spills are well understood by regulatory agencies and their remediation is well practiced.

3) **Produced Water**:

   - The produced waters, including *flowback* fluids, from any hydrocarbon reservoir will be saline, i.e., there will be high concentrations of chloride and related ions (Br, Na, K, etc.) that will require careful handling and disposal, whether in the surrounding sea or somewhere on land. The total dissolved solids (TDS) content of this produced water may be as high as 180,000 mg/L (Capo, 2014), which is typical for brines from producing formations such as the Marcellus Shale. It may also contain harzardous compounts such as barium and radium (Rowan *et al*., 2011) in concentrations exceeding aquatic toxicity guidelines or drinking water limits. Poor handling and disposal practices of produced waters were implicated in the deterioration of stream-water quality in several streams in Pennsylvania draining the Marcellus play (Olmstead et al., 2013; Wilson and Vanbriesen, 2013; Brantley et al., 2014).

4) **Solid Wastes:**

   - Drilling cuttings (Leonard and Stegemann, 2010) are the drilling chips and pulverized rock particles produced by the drilling operation in the form of a mud-like waste that may contain oily materials. Cuttings are typically disposed in a special landfill, but if oil-base drilling muds are found to be desirable to avoid formation damage and are permitted, special drill-cuttings treatment will be required and recycling of oil-base drilling fluid implemented. To avoid off-island transport risks, such treatment facilities would have to be constructed on Anticosti Island. At present, we believe the possibility that expensive oil-base drilling fluids would be used to be remote..

- o Flowback solids will include proppants and other materials recovered during hydrocarbon extraction that will be captured during filtration of the produced water. These materials, such as filter cake from treating hydrocarbon wastewaters, may be radioactive with potentially hazardous concentrations of radium (Perma-Fix, 2015).
- o Other sources of solid waste may include pipe scale (usually classified as NORMS – naturally occurring radioactive materials), soil contaminated by spills or leakages, tank bottoms, calcium-rich sludges from water treatment plants, and so on.

3.3 Potential Contamination by Hydraulic Fracturing Fluids

Hydraulic fracturing has been criticized by environmentalists as a technology that is environmentally dangerous to shallow groundwater. However, there are no reliable published accounts in refereed journals as to why this might be the case; in other words, this claim remains in the realm of conjecture. Myers (2012) attempted to discredit deep hydraulic fracturing through unconstrained modeling results, but his article was strongly criticized (Cohen *et al*., 2013) for its inaccurate numerical modeling that guaranteed that negative effects would occur from such badly constructed model conditions and extreme assumptions. As yet, there have been no known incidents of HF-related contamination incidents of the kind postulated by Myers from significant depths except for migration along legacy wellbores in the vicinity of an HF treatment, which would not be an issue on Anticosti Island.

Practice in Canada has shown that the environmental impacts related to HF operations are reasonably well understood. The critical review of hydraulic fracturing by Dusseault and Jackson (2014) indicated that several factors would prevent or, at least, inhibit uncontrolled upward migration of induced fractures and, therefore, of hydraulic-fracturing fluids:

1) **The Construction of the Production Well** (see API, 2009)**:** Hydraulic fracture stimulation is done through the production tubing that is sealed from the production casing (see Figure 3), not through the production casing itself, and the annular pressure on the production casing is monitored. If there is a breach in the production casing, it is detected immediately. The bottom part of the production casing is almost always well-cemented because the cement set under a high hydrostatic head, making it very dense, and producing an optimum seal.

2) **Orientation of induced fractures**: Hydraulic fracturing in zones where the minimum principal stress is horizontal will lead to induced fractures that will rise preferentially, rather than be vertically symmetric around the fracture point (Figure 7). This is because the rock mass fracture gradient (the minimum stress gradient) is on the order of 18-23 kPa/m depending on rock density, but the density of the fracturing fluid is perhaps 1,000 to 1,300 kg/m^3 (i.e., a specific gravity of 1.0-1.3, depending on the amount of suspended proppant), producing a vertical pressure gradient in the fracture of about 10 to 13 kPa/m. As shown in Figure 7, this leads to a greater driving pressure at the top of the fracture than at the bottom, leading to preferred fracture rise. The maximum fracture growth height appears to be of the order of several hundred metres as deduced from studies in various US shales including the Marcellus and Barnett shales, and around one incident of 1100 m offshore (Davies *et al*., 2012; Fisher and Warpinski, 2012), although we believe this offshore incident was most

probably because of HF fluids rising to surface along a wellbore, rather than a fracture rise through the otherwise intact formations.

3) **Imbibition of injected fluids and associated strain**: Some of the volume of fluid injected either flows back at the end of each hydraulic fracture stage, or is accommodated within open or partially open fractures in the shale gas reservoir, or is absorbed by the shale itself (Engelder, 2012). Therefore, irrespective of any potential gradient, the availability of brine for migration from the Marcellus to shallower horizons – as suggested by Warner *et al.* (2012) – is limited because the brine is trapped by capillary forces and low permeability.

4) **Effect of uplift and surface erosion**: In most parts of the world where sedimentary basins have been uplifted and subsequently eroded (all shale gas basins identified to date are in uplifted, eroded basins, for example by glaciation in Canada), the stresses in the earth become redistributed in such a way as to create a zone from 100 m (300 ft) below ground surface to perhaps as much as 1000 m (3,000 ft) thick where fractures will not tend to rise vertically, but will turn and propagate horizontally, parallel to bedding (Han *et al*. 2009), because the vertical stress has become the smallest of the principal stresses.

5) **The nature of the overlying strata:** There generally exist significant thicknesses of low-permeability strata overlying shale-gas reservoirs. These strata are generally low-porosity carbonates and shales (Séjourné 2015a, b), and are usually somewhat naturally fractured,as has been observed above the Marcellus and the Utica Shale in Pennsylvania. In the Macasty play, the rock mass has not been significantly distorted by folding or extensive faulting, and it is expected that the natural fractures are largely closed by the high compressive stresses at depth.

6) **Design of hydraulic fracture stimulation:** The companies that undertake hydraulic fracturing use mathematical models and monitoring data to design their injection operation in such a way that the actual fracturing zone, including the region within which there is a beneficial perturbation of the natural fractures (the stimulated rock volume or SRV), does not extend significantly beyond the top of the shale-gas target zone. These models become better predictive models over time in a play because data are collected to calibrate the models. Furthermore, there is no economic incentive to induce fracturing above the target horizon because it would not add to the productive capacity of the well, so fracture fluid volumes are limited to avoid such waste.

7) **Production from shale-gas reservoirs**: Production of the shale-gas reservoir is the goal of drilling and hydraulic fracture stimulation. It is expected that from 15% to 35% of the total gas in place will be produced from the shale gas zone over a 10-25-year well life (King, 2010). This production leads to pressure depletion, which means that the target becomes a pressure sink from which fluids cannot flow.

For these reasons the migration of vertical fractures more than a few hundred metres is remote. However, industrial accidents do occur and two associated with hydraulic fracturing have been documented in Canada by the Alberta Energy Regulator (formerly ERCB). These include:

a) **InterWellbore (IWB) communication**: A recent case near Innisfail, Alberta (ERCB, 2012a) determined that a horizontal well had been drilled to within 129 m of an offset well that subsequently discharged ~ 500 barrels (80 m^3) of hydraulic fracturing and formation fluids at the surface when the new well was fractured (see Figure 8).

b) **Premature Fracking**: An accidental hydraulic fracturing incident occurred in northern Alberta that caused HF fluids to penetrate a shallow aquifer. The rig crew believed that they were fracturing at the target depth (1.5 km below ground surface or bgs). However, they accidently perforated the casing at 136 m and injected HF fluids into a shallow sandstone aquifer (ERCB, 2012b).

The vast majority of cases of IWB communication involve pore-pressure pulses, not breakthroughs as at Innisfail, Alberta. Experience in the Barnett Shale of Texas indicates that a distance of ~200 m is sufficient to allow such IWB communication (M.D. Zoback, Stanford University, personal communication, 30 November 2012). Kim (2012) indicates that the distances measured in Alberta are larger with a median value of ~250 m. A maximum IWB pressure pulse of 2400 m has been reported in Alberta (Kim, 2012), while in British Columbia evidence of pressure pulses to 4100 m have been noted (K. Parsonage, BC O&GC, personal communication, 24 January 2014).

New regulatory guidelines have been published in Alberta to reduce the probability and impact of this type of pressure transmission (AER 2013). We note that because of the low compressibility of water, a pressure impulse can easily be transmitted great distances, but actual physical flow of HF fluids is limited to the region proximal to the HF treatment. In addition, flow over longer distances involves dispersion, dilution and adsorbing of agents within the water, attenuating the potential environmental impact.

Dusseault and Jackson (2014) concluded that deep hydraulic fracture stimulation was not a significant environmental risk, except when abandoned or suspended (i.e., 'idle') well casings are intersected within the zone contacted by fracturing fluids during the high pressure stage of fracture injection. Similarly, producing wells in the same target formation as new horizontal wells undergoing hydraulic fracture stimulation may be affected by fracture fluids when the inter-wellbore distance is within perhaps 250 m, depending on the size of the hydraulic fracture stimulation. This distance may increase if faults are intersected, particularly if they are at a critically stressed state.

3.4 Potential Contamination by Fugitive Natural Gas

The contamination of domestic and/or farm water wells by natural gas has been a subject of great public concern since 2009 when evidence of fugitive natural gas entering homes and water-well vaults causing explosions (see Figure 9) came to public attention. This *fugitive natural gas* was associated with the Marcellus Shale gas play (see Wilber, 2012) and public media tended to associate the problems with hydraulic fracturing. The two *Gasland* motion pictures released in 2010 and 2013 greatly contributed to this misinformation.

However the probable cause of the particular case shown in Figure 9 – and perhaps other cases like this – was the displacement of natural gas naturally present in shallow fractured bedrock by high-pressure air used in rotary drilling operations during shale-gas development. The concept is presented in Figure 10, which emphasizes the presence of naturally occurring methane in the shallow bedrock. In some jurisdictions, air drilling or aerated fluid drilling can take place to depths of 1000 m if the formations are strong and if there are no hydrocarbons present in shallow layers that could lead to drilling risks.

The association of natural gas and local water-well contamination became established in the public mind with fracking although the areas in which shale-gas development was occurring already were well known for the presence of shallow natural gas in the bedrock. This conflation of naturally-occurring methane with gas-well drilling and production in areas of natural gas development was the cause of enormous confusion in the public's mind. However deep-sourced methane is naturally present in shallow bedrock in many areas of Canada, including the St Lawrence Lowlands in Québec, even where natural-gas extraction has not occurred.

Part of the confusion arose because of one of the earlier studies by the Duke University research team in the Marcellus play area. The title of their early paper (Osborn *et al*., 2011) appeared to suggest that the methane that they sampled in domestic/farm wells was caused by hydraulic fracturing. A careful reading of the article indicated that no hydraulic fracturing fluids had been detected by them and that they thought the elevated methane concentrations might be due to leaky gas wells, in which the leakage was due to the poor quality of the cement annuli of the gas well.

Subsequent work by the Duke team (Darrah *et al*., 2014; Jackson, 2014) and others (Hammond, 2016) confirmed this hypothesis, although as Professor Robert Jackson of Duke University pointed out, the gas wells themselves may have been fracked but it was the poor *well integrity* that caused the escape of fugitive methane (Scientific American, 2013). The cement that forms the annular seal between outer casing and the wall of the borehole was not tight and the fugitive gas escaped up the wellbore annulus (see Dusseault and Jackson, 2014). The potential seepage pathways for natural gas to the ground surface are summarized in Figure 11.

Hammond (2016) shows that the fugitive gas in the Dimmock area of Pennsylvania is actually from thermogenic gas from intermediate-zone bedrock and not from the hydraulically fractured Marcellus Shale. Consequently better wellbore integrity is required particularly after approximately 11 of 28 gas wells in the St Lawrence Lowlands of Québec were found to be leaking gas at measureable rates (Lamontagne, spreadsheet of surface casing vent flow data, personal communication, 2014).

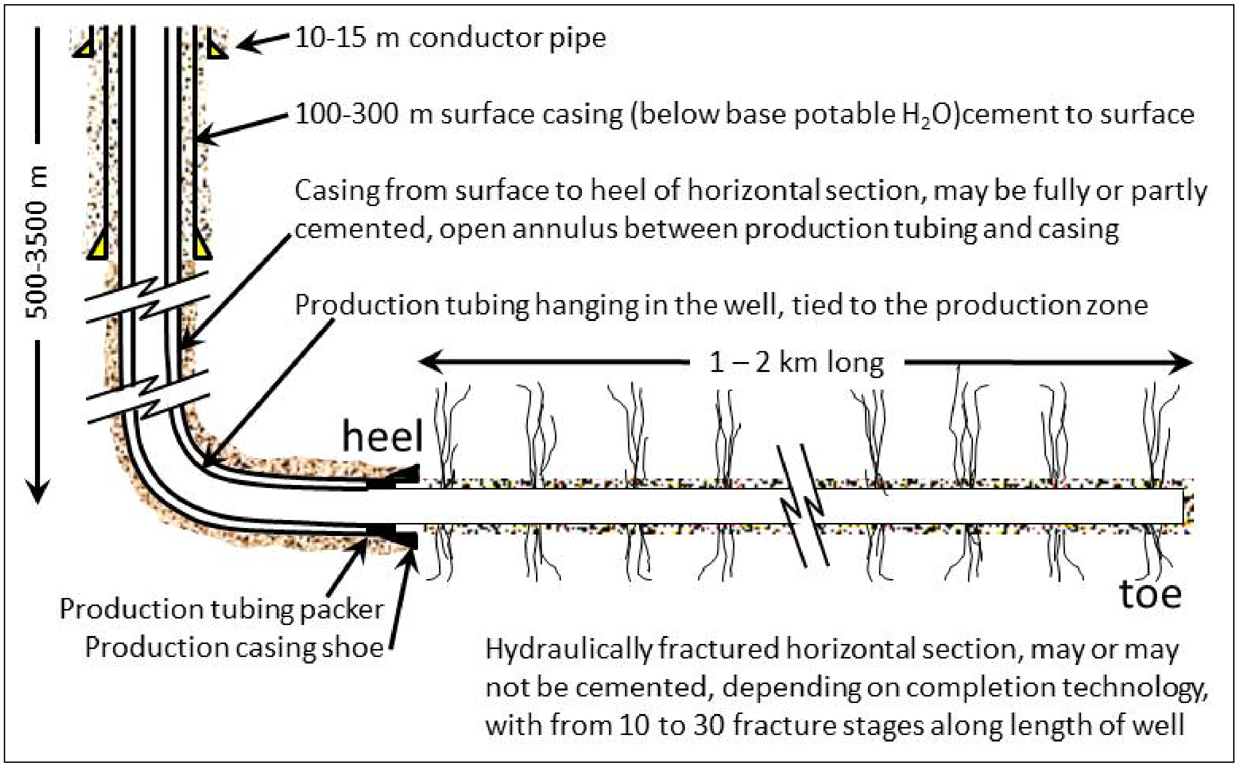

Figure 3 Construction of a horizontal energy well within the target producing formation (from Dusseault and Jackson, 2014)

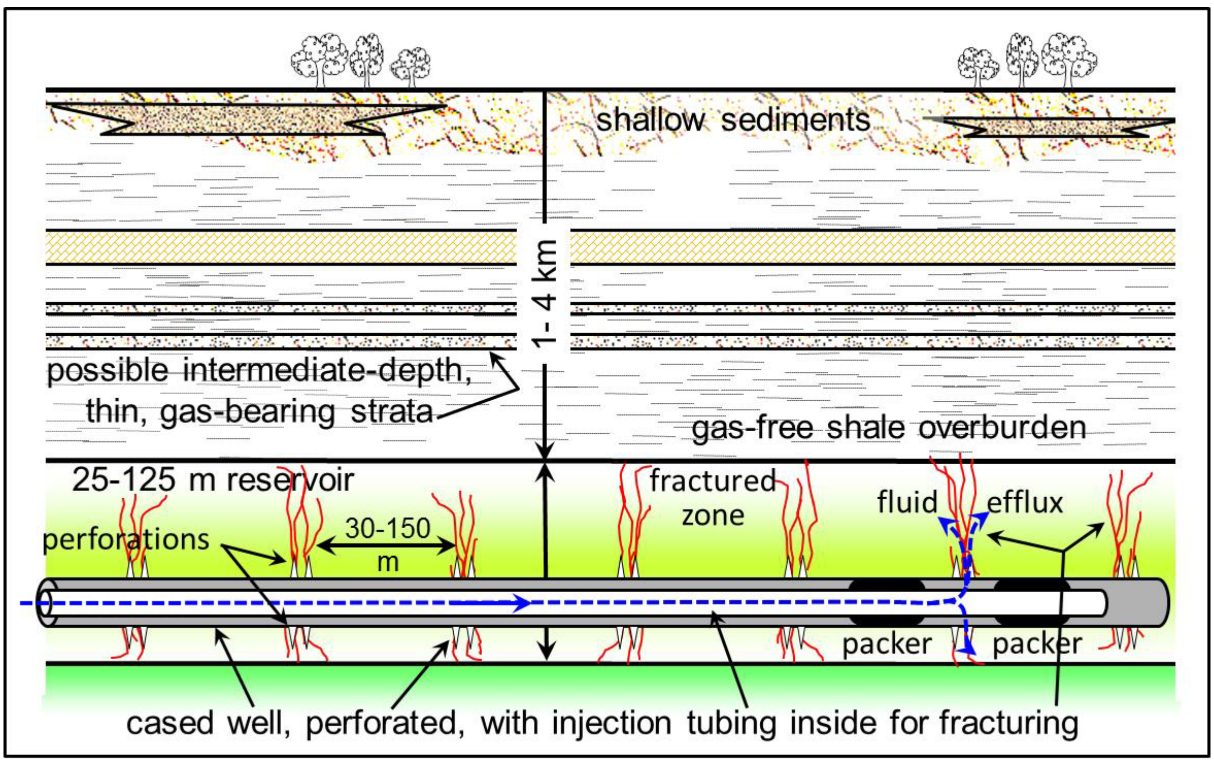

Figure 4 Multi-stage hydraulic fracturing within a horizontal well (Dusseault and Jackson, 2014)

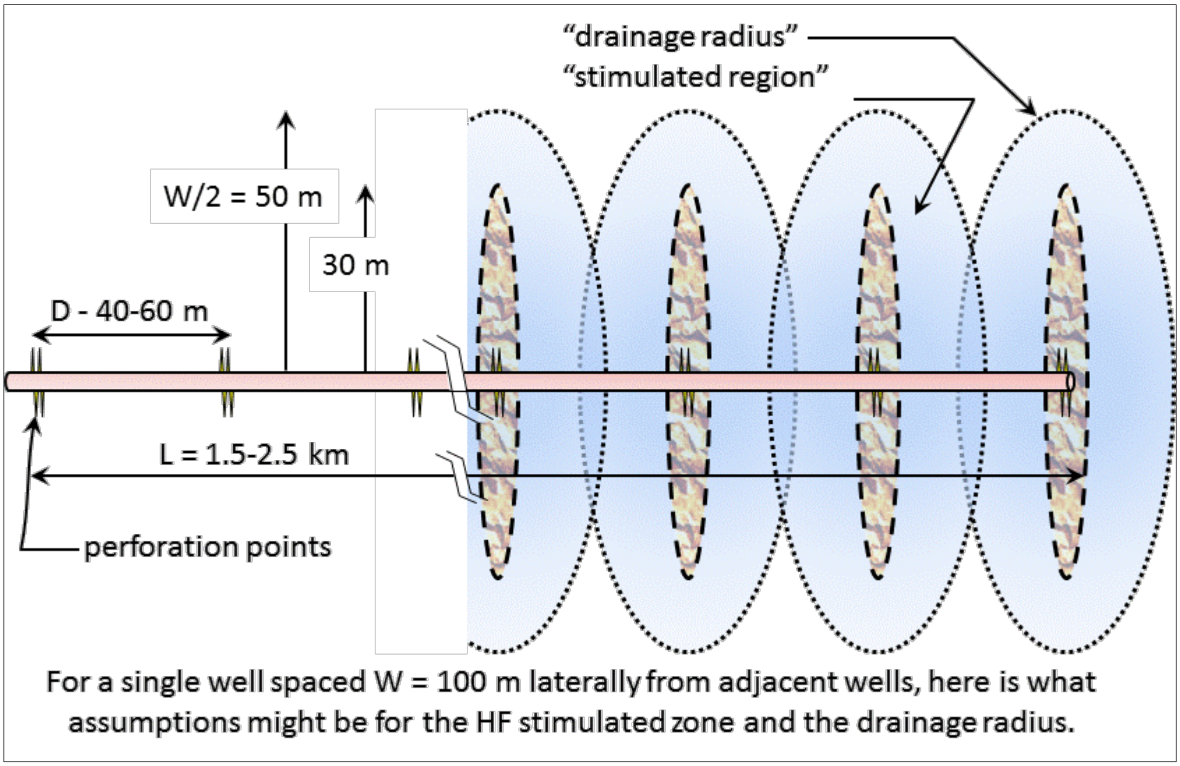

Figure 5 Plan view showing the concepts of a stimulated region and a drained volume

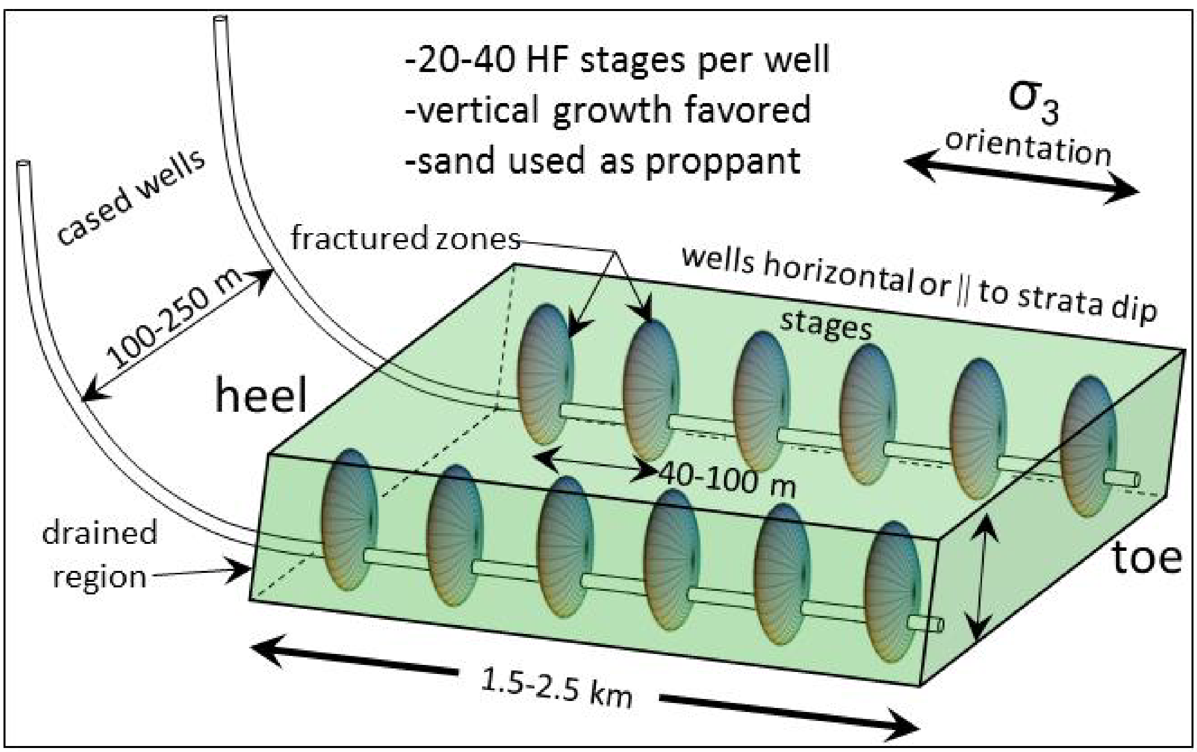

Figure 6 Configuration of MSHF wells within the target formation (Dusseault, 2015)

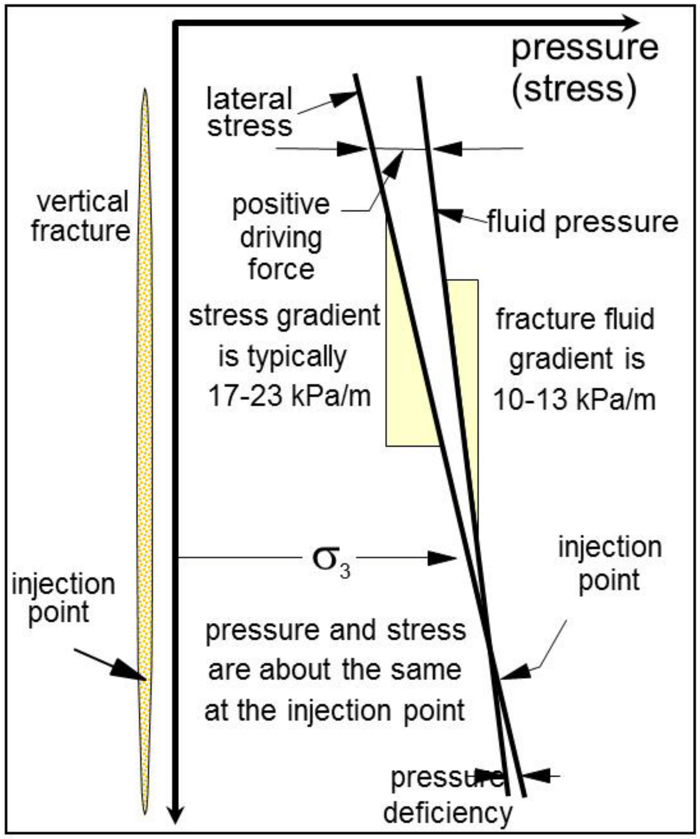

Figure 7 Hydraulic fractures rise because of differential pressure gradients (Dusseault and Jackson, 2014)

Figure 8 Interwellbore communication event, Innisfail, Alberta, January 2012 (photo by Calgary Herald).

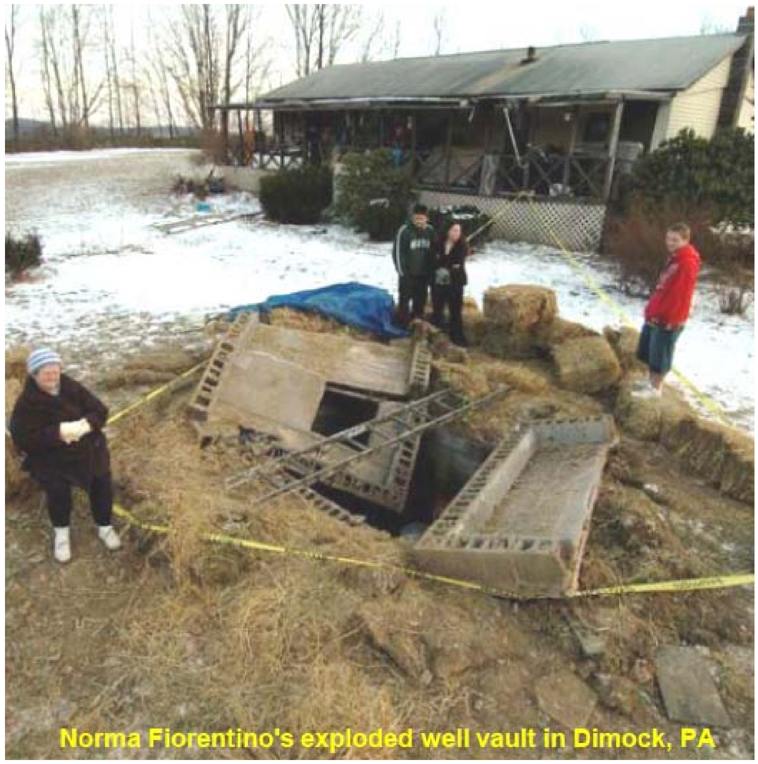

Figure 9 An exploded water-well vault near drilling operations in the Marcellus Shale gas play, January 2009 (Soeder, 2012)

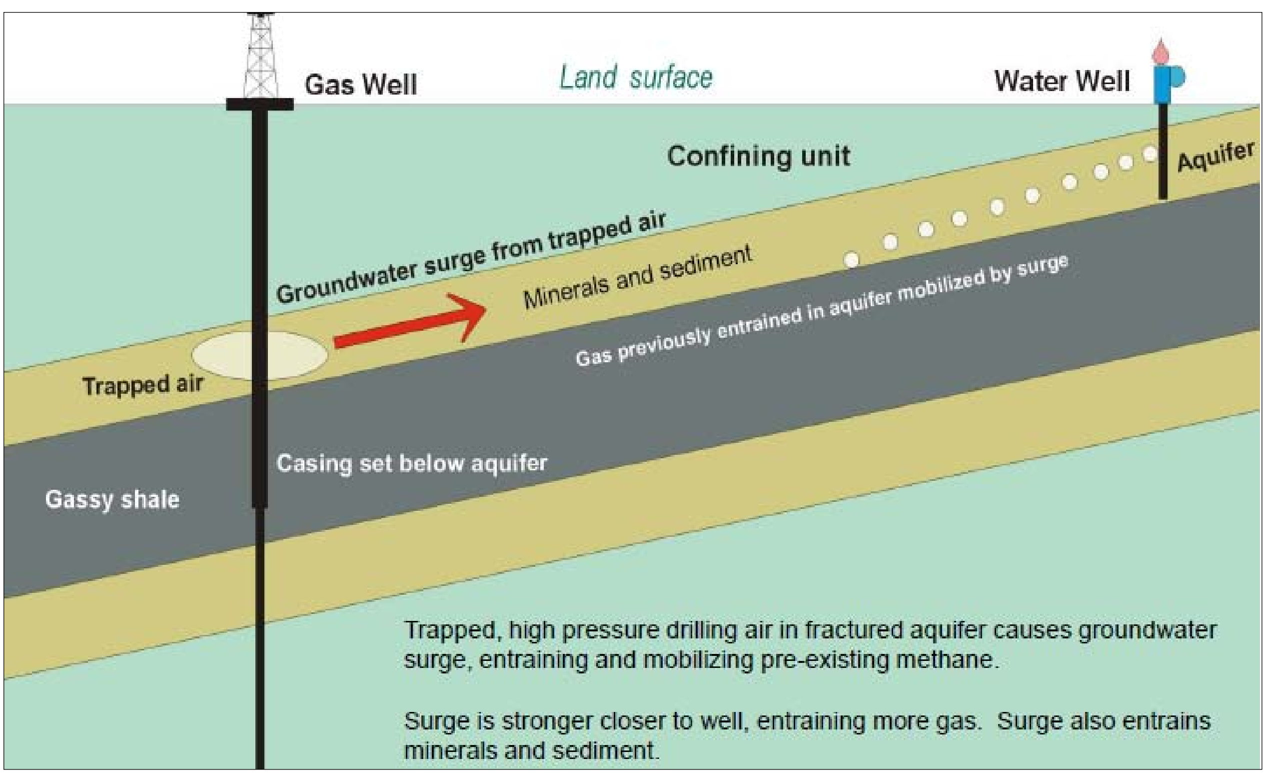

Figure 10 The probable cause of the exploded well vault shown in Figure 9 (Soeder, 2012)

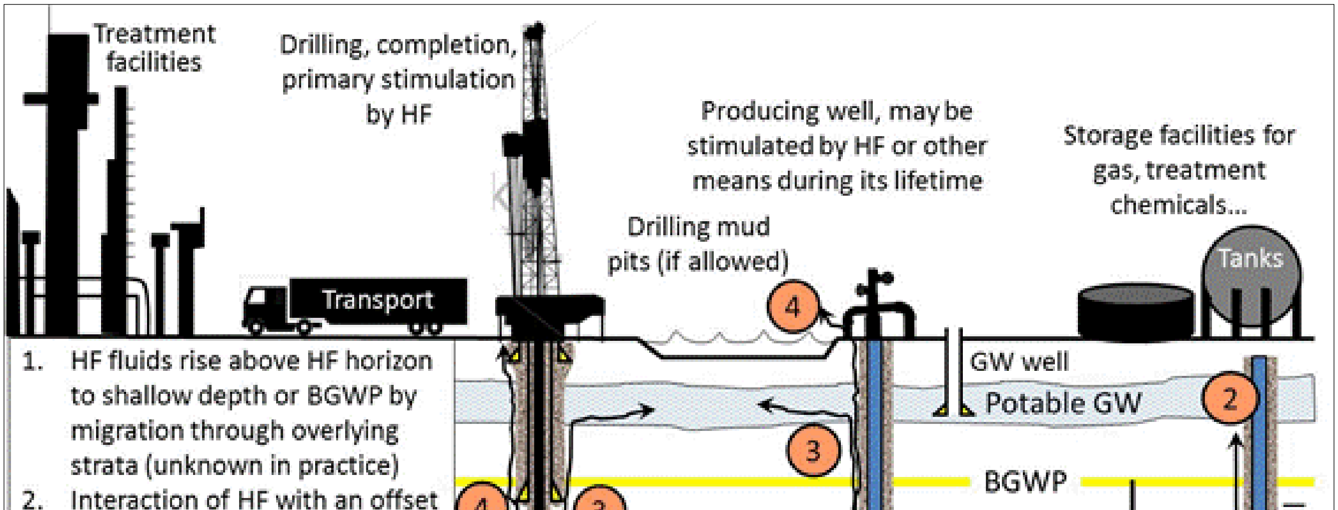

Figure 11 Pathways by which natural gas might migrate to the ground surface

4 POTENTIAL EFFECTS OF INFRASTRUCTURE DEVELOPMENT

4.1 Establishing Road and Port Infrastructure

Drilling, completion and production operations require an extensive road network on islands that may not exist prior to energy development.

If exploratory drilling and preliminary seismic exploration has already occurred, then it is likely that a road network exists although it may be very limited in its extent and ability to convey large transport trucks carrying equipment. Therefore, it must be assumed that a road network with associated drainage, culvert and bridge facilities will need to be established if development of the resource is to proceed. This is quite standard practice and experience in the forestry industry is applicable so that these structures can be constructed readily. At present, on Anticosti Island, there is a sparse network of roads that decreases in quality and density from the western edge of the Island to the east.

Similarly, the necessity of ferrying equipment to any island may strain the existing port facilities. This will almost certainly require the development of a local quarry to produce crushed rock for breakwaters or expansion of port facilities, and perhaps to manufacture high quality aggregate for roads or concrete structures such as tank foundations or port facilities.

4.2 Drilling and Production

Exploratory drilling (Figure 12) requires a relatively modest clearance of land, however if it is decided to proceed with production then the footprint of the well will necessarily increase. Figure 13 shows a well pad in northwestern Alberta indicating that drilling and completion activities create a small-scale industrial plant site. This will likely also include a lagoon for storage of non-hazardous HF fluid or water (Figure 14). In Figure 13, it is notable that over 60% of the tanks are to contain fracture fluid flowback, keeping it from being stored, even temporarily, in lagoons or lined ponds.

The completed well pad has a very limited footprint. Figure 15 shows two of the gas wells at the McCully field near Sussex, New Brunswick, which produces from 32 gas wells. Production is fed into a gas processing plant that is linked to an international pipeline by 50 km of transmission line.

4.3 Gas Collection and Storage

Gas collection will require transmission lines from individual well pads to the central processing station. The largest single footprint for a hydrocarbon development would be a gas collection plant that would need to incorporate either liquefaction facilities or the capability to pump gas from the island to the mainland.

4.4 Discussion of Potential Effects

Wilkinson *et al*. (2014) identified the following environmental impacts throughout the project life cycle:

- Preventing contamination of water systems, particularly groundwater and surface water, as well as land and air;
- Avoiding negative impacts on habitats and biodiversity;

- Managing carbon intensity and controlling fugitive emissions;
- Dealing with the flow and other produced water and securing access to related water-treatment facilities; and
- Avoiding induced seismicity as a consequence of hydraulic fracturing and/or the reinjection of produced water.

The production of sediment and its transport into nearby wetlands and streams is an obvious problem considered by Williams *et al.* (2008) and Entrekin *et al*. (2011), while Kruse (2013) discusses how wetlands and streams can be protected during shale-gas plays.

Entrekin *et al.* (2011) reviewed the geomorphic distribution of channels in the Fayetteville and Marcellus shale-gas plays and noted to the proximity of many unconventional gas wells to streams. They concluded that elevated sediment runoff from pipelines, roads, and well pads could seriously damage stream and pond ecosystems.

This finding was confirmed by Williams *et al*. (2008), who instrumented field sites in Texas, adjacent to Barnett shale gas wells. Although they recorded an exponential decline in sediment runoff over time due to a 'site stabilization' effect, they noted that when compared with adjacent rangeland, the sediment yield was approximately 50 times higher due to high sediment yield from the disturbed area around the well pad rather than from the pad itself.

Discussing the Marcellus shale gas play, Vidic *et al*. (2013) has pointed out that:

> *"It is difficult to determine whether shale gas extraction in the Appalachian region since 2006 has affected water quality regionally, because baseline conditions are often unknown or have already been affected by other activities, such as coal mining. Although high concentrations of Na, Ca, and Cl will be the most likely ions detected if flowback or produced waters leaked into waterways, these salts can also originate from many other sources. In contrast, Sr, Ba, and Br are highly specific signatures of flowback and produced waters. Ba is of particular interest in Pennsylvania waters in that it can be high in sulfate-poor flowback/produced waters but low in sulfate-containing coal-mine drainage. Likewise, the ratio of $^{87}Sr/^{86}Sr$ may be an isotopic fingerprint of Marcellus shale waters."*

Increases in suspended solids are equally noted due to the development on and around well pads resulting in an increased sediment runoff yield (Williams *et al*., 2008). Entrekin *et al.* (2011) studied streamflow turbidity in areas of Arkansas that are undergoing development of the underlying Fayetteville shale. They noted that during the high flows measured in April 2009 there was a strong correlation between shale-well density and stream turbidity in seven drainage basins.

The development of stream-gas reconnaissance sampling to estimate methane releases has been described by Heilweil *et al*. (2013) and appears to be a viable means of evaluating groundwater impacts from unconventional gas development. The method involves measurement of in-stream methane concentrations and groundwater discharge to the stream as well as modelling of in-stream mass transfer of methane. A study was conducted along a 2300 m reach of a creek in Utah, where methane was found to be persistent in the stream over distances of 2000 m with a release rate to the stream of 190 g/d.

Figure 12 Well pad in New Brunswick during exploratory drilling

Figure 13 Well pad for hydraulic fracturing in Northwestern Alberta (Trican Industries)

Figure 14 A geotextile-lined storage lagoon for storage of HF fluids, Marcellus Shale gas play (from Saiers, 2011).

Figure 15 Two gas wells at the McCully field, New Brunswick

5 EXAMPLES OF NATURAL GAS DEVELOPMENT IN ISLAND ENVIRONMENTS

There are no cases known to the authors of this report in which hydraulic fracturing is being conducted beneath an island. There are several examples of gas processing facilities being built on islands near to off-shore oil and gas fields where hydraulic fracturing may be occurring, e.g., Sakahlin Island on the Pacific coast of Russia, Barrow Island off the northwest coast of Australia and Shetland Island off the northern coast of Scotland UK.

Of these three examples, the one that is probably the most similar to any future development of Anticosti would be the Shetland example in terms of regulatory oversight, terrain, climate and prospective size. The figures on the following pages indicate the kinds of permanent and temporary infrastructure that will be required including:

- The gas processing plant, Figure 16, on which construction began in 2010, is 25 hectares in area. The plant is capable of processing 14 million m^3/day of natural gas, which is transmitted by pipeline to mainland Scotland. Construction materials included 39,000 tonnes of concrete, 3,900 tonnes of steel and 15,000 m of underground glass reinforced epoxy pipe, all of which had to be shipped to the Island. Total cost of plant ~ C$1.5 billion, included in a total cost of gas-field development of ~ C$6.6 billion.
- Annual precipitation in the Shetland Islands is 1000-1700 mm with frequent storms. The terrain is glaciated and therefore uneven, which required extensive surface-water drainage as shown in Figure 17. The water is channelled into a separator and tested for contaminants before being discharged to the sea.
- Pipeline construction (Figure 18) is required to transfer gas to the processing plant and from there to the marine pipeline to mainland Scotland. The unconsolidated glacial sediments found on Anticosti Island vary in thickness from a few meters in places to 50-60 m along the northern coastline (St-Pierre et al., 1987), consequently it would appear that any pipelines could be constructed in the surficial till of the Island.
- Port infrastructure of various sizes would be required as shown in Figures 19 and 20.
- Temporary housing will have to be provided (Figure 21) for transient workers.

Figure 16 Shetland Gas Project, Scotland, UK (photo: Hauraton)

Figure 17 Surface drainage system being installed (photo: Hauraton)

Figure 18 Pipeline construction, Shetland Gas Project (photo: Total)

Figure 19 Small jetty for deepwater vessels servicing off-shore fields but which might suffice to supplement a ferry terminal during development of Anticosti oil and gas field (photo: Financial Post, 8 February 2016)

Figure 20 Port infrastructure built to service the Shetland Gas Project (photo: http://www.shetlanddecommissioning.com/decommissioning-services)

Figure 21 Temporary construction camp (photo: http://www.geograph.org.uk/photo/2466872)

6 EVALUATION OF POTENTIAL EFFECTS ON ANTICOSTI ISLAND

This final section begins with a review of the hydrogeology and petroleum geology of the sedimentary sequence beneath Anticosti Island. It then proceeds to identify data gaps that we recommend be remedied.

6.1 Hydrogeology

There is a veneer of unconsolidated glacial sediments on Anticosti Island, in some coastal areas exceeding a few tens of meters in thickness (St-Pierre *et al*., 1987), but the majority of groundwater flow likely occurs in the underlying bedrock and it is important to note that karstic features are common on the Island and play an important hydrogeological role (Séjourné *et al*.., 2015). The karst features were considered immature by Roberge and Ford (1983).

In a study of groundwaters in the vicinity of three exploration wells drilled in 2012/13 (SNC-Lavalin 2016, Lefebvre, 2016) groundwater monitoring wells were constructed at the sites Canard, La Loutre and Jupiter. Aquifer tests showed groundwater was found be restricted to the fractured bedrock with no significant aquifer potential in the thin surficial sediments. Hydraulic conductivity was moderate to low at the three sites with only slow groundwater circulation.

Côté *et al*. (2006) identified three types of karst lakes on Anticosti Island that were categorized by the variability in annual lake level change including 1) relatively stable lakes, 2) lakes with a variable level and 3) lakes that completely or almost completely drain. Snowmelt and the spring rainfall events fill the lakes and recharge the aquifer including the underground fracture and solution channel network. The lakes are known to drain later as ice blockages thaw and drainage pathways open to cause discharge. The surface water also recharges the underlying groundwater flow system through fractures or karst pathways. The recharge supplies freshwater to the shallow groundwater system but the presence of karst makes it difficult to determine the vertical or horizontal extent the groundwater travels.

The lakes undergo partial or complete emptying between June and September through surface water and groundwater (including karst) pathways. The lake levels and groundwater levels increase again in the fall with the increased autumn rainfall and reduction of transpiration by the forest cover. Frozen ground and snow covers the island between December and May. Annual precipitation is approximately1050 mm.

Peel *et al*. (2013) created a north-south monitoring network of 10 monitoring wells in the western part of Anticosti Island with each well less than 100 m deep near the western part of Anticosti Island. Geophysical logs were used to examine the subsurface natural fracture network examined in this region, which is dominated by sub-horizontal fractures parallel to bedding planes, whose abundance decreases rapidly with depth to disappear at ~70 m depth. Borehole testing of these sub-horizontal fractures indicated a hydraulic conductivity on the order of $5x10^{-7}$ m/s with a range between $2x10^{-8}$ and $5x10^{-6}$ m/s. Based on these results Peel et al. (2013) identified bedrock fractures as the important pathways for groundwater flow.

Vertical fractures may also be a significant factor for groundwater flow in the central part of the island, where a network of expanded joints controls the orientation of the karst (Séjourné *et al*.., 2015). Roberge and Ford (1983) reported that the major joint set, which is karstified, has an orientation of

110°N along the main axis of the Island, and parallel to the strike of the strata. This orientation corresponds to one of two main sets of fractures in outcrop recognized by Pinet et al. (2015). The Roberge and Ford work was confirmed by Peel et al. (2013), who documented vertical fractures in outcrops and identified the potential for vertical fracture networks to be an important control on groundwater flow.

The karst environment and the vertical distribution of fractures described by Peel et al. (2013) create a complex hydrogeological environment. When groundwater levels are high, groundwater flow through the shallow bedrock is likely rapid as water moves through numerous fractures and karst features. As groundwater levels decline. Tthere are fewer narrower fractures available for flow and the number of fully saturated karst features also likely declines, leading to slower groundwater flow.

Groundwater samples were collected along the north-south transect developed by Peel et al. (2013) from the Vauréal, the Ellis Bay and the Bescie Formations at depths less than 100 m below ground surface (BGS). The groundwater was fresh water (i.e., TDS < 1,200 mg/L) with calcium and bicarbonate the predominant ions in the groundwater indicating carbonate-mineral dissolution processes that would be expected, given the numerous observations of karst features on the Island. Sodium bicarbonate groundwaters were also identified, which suggests there is ion exchange between sodium and calcium that increases the sodium concentrations and lowers the calcium concentrations. This monitoring transect and baseline sampling will enable an on-going examination of potential effects of oil and gas operations In the region. These results were consistent with the freshwater springs sampled by D'Aoust (2015) and discussed by Clark et al. (2015).

Groundwater quality at the three drill sites (Lefebvre 2016) was found to be marginal. Only one of the three sites (La Loutre) had acceptable groundwater quality, while at Canard the groundwater exceeded norms for hardness and at Jupiter for salinity. Most groundwaters had dissolved methane, and one well was leaking shallow methane along the well bore outside the casing.

The data in the borehole database for the Island were reviewed to estimate the depth of the freshwater-saline water (FW/SW) contact (Table 8 in Séjourné *et al*.., 2015). It is worth noting that saline groundwater occurred at the same depths as petroleum hydrocarbons in the boreholes. Groundwater salinity results showed freshwater was present in borehole D005 down to a depth of 1307 m BGS and saline water was identified near 1630 m BGS. The results for D005 are not considered reliable since it is difficult to identify hydrogeological processes that would allow freshwater to continue to >1300 m BGS, therefore this report is of dubious veracity. Freshwater was noted down to 199 m BGS in borehole D006, with "slightly" saline water detected at ~240 m BGS and saline water at 246 m BGS.

The maximum depth to the FW/SW interface is uncertain and cannot reliably be estimated by a simple Ghyben-Herzberg calculation because the salinity at depth will likely be greater than sea water. Furthermore, sea-water penetration inland is well documented in coastal karst systems (Stringfield and LeGrand, 1969, 1971) and simple estimates, such as provided by the Ghyben-Herzberg principle, would not be reliable in such situations.

6.2 Saline Springs and Gas Seeps

The brine spring identified as Source-de-la-Chaloupe is located near the southeast end of the island at about 50 m above sea level, and is situated over the Jupiter Fault, which does not outcrop on the

Island. D'Aoust (2015) and Clark *et al*. (2015) have sampled and interpreted the water chemistry from the Source-de-la-Chaloupe. The preliminary results indicate that the water chemistry is primarily sodium and chloride and the total dissolved solids of the brine are near 95,000 mg/L (D'Aoust, 2015) which is almost three times greater than the total dissolved solids concentration of sea water (approximately 34,500 mg/L).

The saline water has no tritium and is therefore not modern groundwater. Stable-water isotopes suggest the water is a mixing of Holocene-age groundwater and evaporated seawater (Clark *et al*., 2015). The spring water is likely a mixture of relatively young groundwater (of Holocene age) with mixing with deep basin brine that may have been activated during deglaciation of the Island (Clark *et al*., 2015).

D'Aoust (2015) reported the Source-de-la-Chaloupe mineral-spring brine to have a chloride concentration near 53,500 mg/L, a bromide concentration ~250 mg/L and a sodium concentration ~ 25,000 mg/L. The molar ratio of chloride:bromide is ~480, which is less than the ratio in seawater (655), and in the range of brines from sedimentary basin formations. The lower chloride:bromide ration for the brine indicates that evaporation of sea water must have been accompanied by other geochemical reactions beyond the condition of halite precipitation (Alcala and Custudio, 2008). The molar ratio of sodium:chloride in sea water is ~0.85, but the molar ratio of sodium:chloride in the brine is ~0.72. The lower ratio for the brine may be due to the relatively higher concentration of calcium in the brine compared to sea water and is also indicative of geochemical reactions affecting the brine in addition to evaporation of sea water.

Isotopic analysis of the methane in the brine indicates the gas has a biogenic origin and methanogenesis could be induced from circulation of groundwater through rocks rich in organic matter, such as the Jupiter, Merrimack or Macasty formations (Clark et al., 2015).

The chemistry of the Source-de-la-Chaloupe brine is an indication of the complex hydrogeological setting of the island and that there are areas where fresh water and saline formation water are in contact. Further work is required to determine the source of the saline water and the distribution of saline groundwater on the island as saline groundwater flux throughout the Island may play an important role in understanding the hydrogeology of the Island.

The location of this gas and brine spring in relatively close proximity to the Jupiter fault suggests that this subcropping feature has extension fractures to surface (faults have displacement, whereas fractures are permeable features without significant planar displacement). Further, the extensive carbonate travertine that has accumulated at the spring vent suggests that this feature has been functioning for centuries to millennia. Careful mapping of the region for other saline and gas discharges, including groundwater surveys, would provide additional insights as to whether this feature indicates a breach in the low-permeability formations overlying the Macasty, and therefore leaking from depth to surface.

6.3 Hydrogeological Issues Affecting Development

Additional hydrogeological investigations are required to address three major issues that will be of importance to any hydrocarbon-extraction developments on Anticosti Island:

1) The depth of the *fresh water-saline water (FW/SW) interface* across the Island is not known

with any confidence; in fact is poorly understood according to those who have worked on the Island. Because fresh water will be the principal component with which hydraulic fracturing fluids are created, it will be necessary to develop a more complete understanding of the groundwater flow system on the Island. The groundwater must be managed in such a manner during hydrocarbon extraction to avoid up-coning of the FW/SW interface as the groundwater is produced to create HF fluids. It will be difficult for hydrocarbon operators to satisfy the requirements of Articles 38 and 40 of Québec RPEP (2016, Ch.5) if the FW/SW interface is not known.

2) A potential for contamination of the shallow bedrock aquifer through careless industrial practices exists because of the *karst environment*. Karst freatures appear to be observed mainly in the National Park (Karst de la haute Saumon) away from the oil and gas permitted areas, and in a small region called Karst de la Jupiter west of the Park (Séjourné et al., 2015), but it is likely that karst features are far more common, partially or entirely hidden under the thin Holocene cover, and need to be carefully mapped. Nevertheless, guidelines for oil and gas industrial practices have been published and adherence to these guidelines should prevent significant groundwater contamination (Québec RPEP, 2016, Ch.5), even in the presence of karst conditions.

3) The nature of the groundwater flow system and the process by which natural gas is incorporated in the groundwater, as demonstrated by Clark *et al.* (2015), requires much better understanding. Multilevel monitoring wells installed in critical locations would help resolve this issue.

These issues should not impede careful hydrocarbon exploration and extraction on Anticosti Island; rather, they need to be investigated, resolved and regulated in the manner that has been practiced elsewhere in Québec for many years. Recommendations and actions to establish baseline groundwater data have precedents in Québec (e.g. Lavoie et al., 2014).

6.4 Oil and Gas in Groundwater

Oil shows and gas odours have been reported on Anticosti Island (Petryk, 1981) but it is not possible to determine whether the shows or odours are from the shallow bedrock or if they indicate upward migration of deeper hydrocarbons along preferential pathways (minor faults, joint sets, bedding planes). At shallow depths (< 200 m BGS), some oil and gas wells also show the presence of liquid and gaseous hydrocarbons. For example, oil shows were noted at 133 m and 144 m in wells D002 and D001 respectively, as well as natural gas shows associated with fractures to a depth of 190 m in the D015 and D016 wells (Séjourné *et al*., 2015).

All groundwater monitoring wells completed near the Canard, La Loutre and Jupiter energy test wells have dissolved methane at concentrations up to levels of free-gas saturation (Lefebvre, 2016). Indications in this work suggest that these are a mixture of biogenic and thermogenic methane although the basis for this observation is not given.

Such slow upward seepages are common in sedimentary basins containing oil and gas at depth because these fluids are buoyant with respect to water, and the buoyancy eventually leads to surface seepages, perhaps over periods of millions of years. The entire Paleozoic Basin extending along the northwest front of the Appalachian Mountains from the Carolinas to the western shores of

Newfoundland is rife with gas seepages and occasional oil seepages, especially where the rocks have been fractured by diagenetic processes (e.g. Dietrich *et al*. 2011; Hinchey *et al.* 2015 – Fig 8).

There have not been any reported issues of significantly over-pressurized intervals in the Macasty Formation (Séjourné *et al*., 2015). The brines coming to the surface at the Saumure-de-la-Chaloupe have a density of approximately 1.1 g/cm^3, which would yield a pressure gradient of about 10.9 kPa/m. If there is mixing with some fresh water near the outflow of the brine springs, one would expect that the source brines at depth would be even more saline, hence a reasonable assumption is that the formation brines a modest distance below the base of fresh water have a density of at least slightly above 1.1 g/cm^3. This means that, realistically, any pore pressure gradient measured accurately at depth that is less than about 11-11.5 kPa/m may be considered to be in the range of hydrostatic pressure. Figure 22 is a pressure-stress-depth plot from well D020, recently published (Séjourné, 2015a, Figure 14).

This depth plot shows no significant departure from a condition of hydrostatic pressure anywhere in this well, although this well encountered the Macasty Formation only at a depth of 1000 m, and elsewhere in the Island it can be found at a depth of about 2200 m. Quoting from Séjourné *et al*. (2015):

> *Dans l'ensemble, les forages réalisés sur l'île n'ont pas rencontré d'intervalles significativement sur-pressurisés dans la couverture de la Formation de Macasty.* (page 60)

One reported incidence of evidence of mild overpressure in the form of a modest blowout in an old well, at a depth of 2111 m, exists. More specifically, there was an overpressure reported in well D007 at 2111 m depth in the Vauréal Formation approximately 300 m above the Macasty Formation. The potential blowout was controlled by increasing the weight of the drilling mud (Séjourné *et al*., 2015).

Recent boreholes, D017, D018, D019, were drilled at least partially with air rather than mud due to the lack of over-pressures in the rocks overlying the Macasty Formation (Séjourné *et al*., 2015) and because there are few zones that produce large rates of fluid in the interval being drilled. However, the lack of drilling mud allowed groundwater inflows into D017 and D018. The lack of general overpressure combined with the relatively low permeability of the overlying strata leads inevitably to the conclusion that the probability of an uncontrolled blowout of oil or gas (or saline water) in the Island of Anticosti during and after stimulation is very low, and completely manageable at the scale that it would entail. Given the sparse population and the lack of infrastructure that could be affected, the consequences of such an event would be very minor. Hence, overall, the risks are extremely low, and no further studies are recommended in this domain of overpressure with depth.

Séjourné *et al*. (2015) report only two gas analyses that have been documented and both samples were collected from the wells D003 at 761 and 1080 m depth in the Vaureal Formation. The first analysis indicated the presence of 0.03% hydrogen sulphide but the analysis report showed the sample analyzed was contaminated and contained 80% air. The second analysis was not contaminated and did not detect hydrogen sulphide in the sample, which suggests there is not a significant component of hydrogen sulphide in the boreholes. For both samples methane gas accounted for more than 98% of the analyzed gas and ethane was 0.04%. Carbon dioxide, which may be a corrosive agent, was only 0.11% of the gas samples.

The Mingan Formation (located below the Macasty Formation) was characterized for conventional oil and gas reserves. The Mingan Fm. is slightly under-pressurized and may limit the risk of water inflow into wellbores and the Macasty Formation. The under-pressurized formation does not represent a risk for oil and gas development.

The borehole trajectory of the recently drilled boreholes has been determined through borehole orientation surveys or deviation surveys. However, orientation surveys were not conducted on the older boreholes in the wells, which had, at best, an inclination reading without indication of the direction of drilling. The lack of detailed borehole orientation surveys increases the risk for future drilling or fracking operations to encounter the older boreholes potentially leading to short circuiting of drilling fluid, fracturing fluid or oil/gas, although the overall risk remains very low because the general location of all wells is adequately defined.

Oil and Gas Issues Affecting Development

At the time of writing the size of the hydrocarbon resource on Anticosti Island is not known with great confidence. This will be a project to be shared by industry, the GSC and agencies of the Government of Québec. It appears that there is sufficient oil to make its extraction economically attractive, however it will be co-produced with large quantities of gas, and without the marketing of the gas, it is not likely that the Anticosti resource would be viable, as the production and re-injection of the gas would be too expensive to allow economic production of the associated liquids.. The additional footprint of oil storage and transmission will have to be addressed but this cannot be investigated until the size of the resource is better understood and the Government of Québec has indicated that development should proceed.

There are a considerable number of geoscientific issues that also need to be resolved, over and above those mentioned in section 6.3. These include:

1) Confirm the conclusions of the regional geomechanical study using new (i.e., 2015) stratigraphic well logs, fracture traces, etc and correlate with new industry data;
2) Place the Séjourné (2015) geomechanical study, which was based on wells, into a larger perspective by incorporating the regional dominant stresses;
3) Complete the identification of geomechanical barriers to the upward migration of induced fractures by identifying existing fractures, if any, and their orientation, versus the orientation of the regional stresses.
4) Define the geometry of the Jupiter fault and that of the associated fracture pattern above the termination of the fault in the Merrimack Formation.
5) Whole-rock geochemical data from the 2014-15 stratigraphic drill cores will provide a chemostratigraphic framework to understand spatial and temporal variations in mineralogy, organic content, naturally occurring heavy and radioactive metals and rock mechanics of the Macasty shale.

In addition, there are ecological issues concerning habitats and biodiversity that deserve continued investigation but are not addressed here.

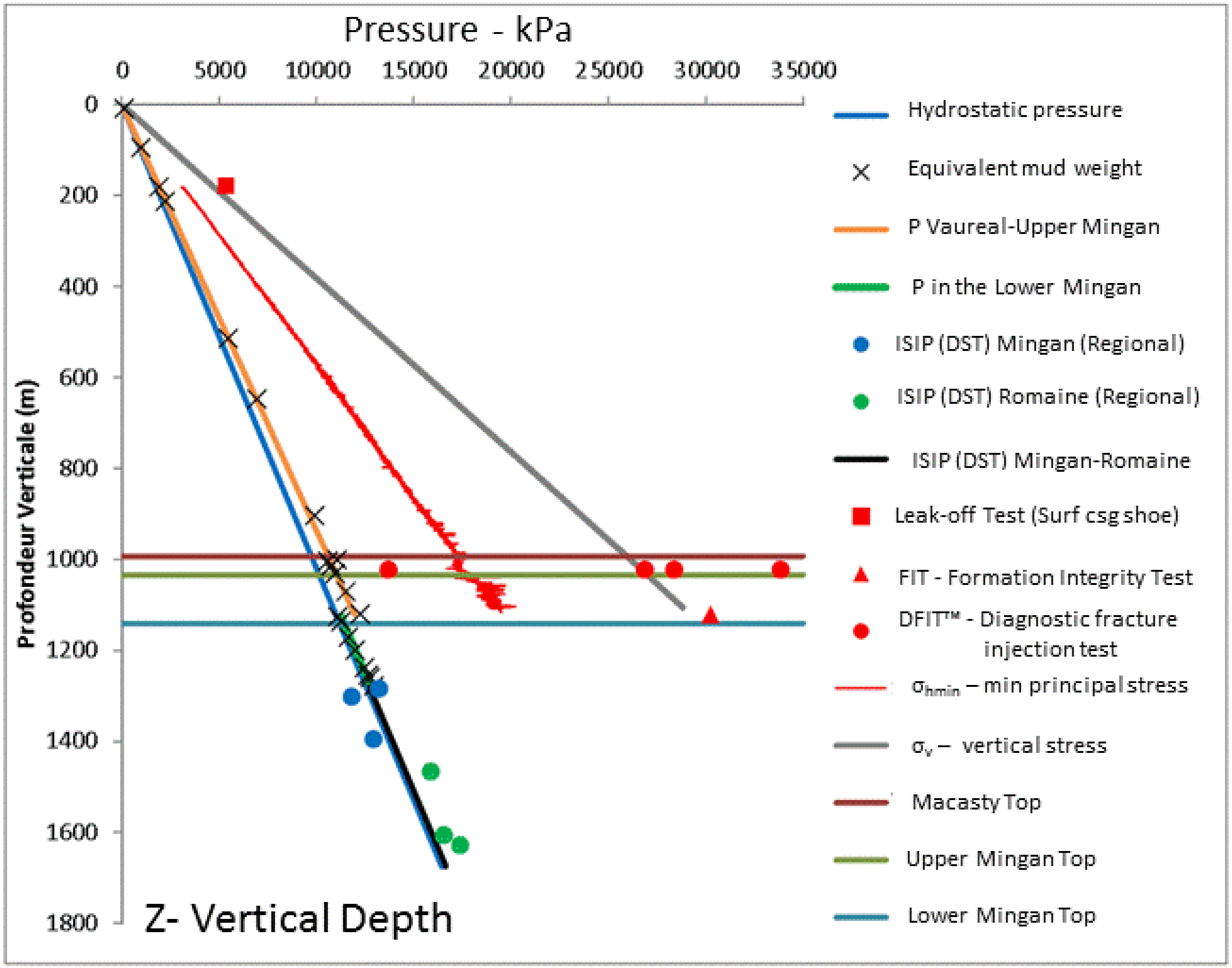

Figure 22 Postulated and measured stresses and pressures from Anticosti Well D020. Translated from the original (ISIP – instantaneous shut-in pressure from a DST – drill stem test; Séjourné, 2015a, Figure 14).

7 CONCLUSIONS

The evolution of a play, such as the Macasty play beneath Anticosti Island, involves a process of adaptive management that goes on from the beginning to the end of the play. Preliminary assumptions that guide engineering practice are subject to change as more is learned, as technologies evolve, as incidents are managed. The oil industry learns by doing, in part, because there always remain uncertainties and because technologies change over time. In particular, it will not be known in the beginning how well contained the hydraulic fractures will be within the target formation, so the lateral spacing of the wells, the size of the treatments and the spacing of the fracturing points along the well axis will not be optimized until more data are collected and fracturing trials executed.

Nevertheless, enough appears to be known about the environmental risks associated with energy wellbores and hydraulic fracturing, courtesy of the tens of thousands of fractured horizontal wells that have been installed, stimulated and produced over the last decade, that progress in the Macasty play on Anticosti Island can be undertaken with very low levels of risk. It appears that there are no special issues related to well installation and hydraulic fracturing associated with the island nature of the Macasty play (other than transportation and availability of materials).

Groundwater resources on Anticosti Island are developed at only a very few sites. The occurrence of groundwater in the shallow bedrock on Anticosti Island represents a potential resource for producing the required fracking fluid, and camp drinking water but is also at potential risk from spillage of diesel fuel and produced oil, drilling fluids, formation fluids and flowback water stored on surface. The presence of karst and the uncertainty of the freshwater/saline water interface require further study of the hydrogeology of the Island.

Hydraulic fracturing itself appears not to be a significant risk within the subsurface because migration of vertical fractures more than a few hundred metres is not a realistic possibility, given the limited thickness of the Macasty Formation and hydraulic fracturing practices.

To assure acceptable outcomes, all concerned should follow the ALARP principle – environmental impacts should be As Low As Reasonably Practicable – meaning that care must be taken in these specific areas (at least):

- Wellbores must be installed, operated and decommissioned according to best practices, with some quality control measures in place to assure good outcomes.
- Materials that have any hazard rating must be transported and stored in approved manners, according to well-known principles in the chemical handling sector. This includes fuels, primary chemicals, or product solids such as water treatment sludges or tank bottoms.
- Proper handling of flowback water and produced water is a necessary environmental requisite for development of such resources.
- Provisions must be in place to rehabilitate drilling sites, storage sites and to respond to spills that may occur.
- Product (oil and gas) transportation, storage and transshipment facilities and related practices must be carried out under clear guidelines related to industry recommended best practices.

The effect of the surface activities in an Island environment will be significant where the Island is a "greenfield" environment. In such cases, the surface and environmental effects of construction and operation of the facilities (e.g. gas treatment plants, liquefaction plants, oil storage areas, loading facilities) are accommodated and minimized by standard practices, This is, of course, commensurate with the magnitude of the resource, which is not yet established for Anticosti Island.

8 CLOSURE

This report has been prepared for the exclusive use of the Government of Québec,

Geofirma Engineering Ltd. have exercised professional judgment in analyzing the information and in formulating recommendations based on the results of the study. The mandate of the company is to perform the given tasks within guidelines prescribed by the client and with the quality and due diligence expected within the profession. No other warranty or representation expressed or implied, as to the accuracy of the information or recommendations is included or intended in this report.

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Respectfully submitted,

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