Hydrogeologic Risk Assessment of Hydraulic Fracturing for Gas Recovery in the Taranaki Region

Taranaki Regional Council
Private Bag 713
Stratford

28 May 2012

Disclaimer: The hydraulic fracturing and geologic information in this report has largely been supplied by oil and gas companies in the region and is believed to be accurate and reliable. However, no liability is accepted for any opinions expressed or for any errors or omissions in the information supplied.

Executive summary

An assessment of the hydrogeologic risks associated with the practice of hydraulic fracturing of hydrocarbon reservoirs in Taranaki up to mid-2011 has been undertaken by the Council. The report was originally released in November 2011, with data from the period 2000 to mid-2011, but updated in February and May 2012 (see Table 5 footnote) to include an assessment of all hydraulic fracturing data. The assessment has been peer reviewed by a Senior Hydrogeologist with the Institute of Geological and Nuclear Sciences Ltd (GNS Science). This GNS Science peer review supports the assessment and conclusions of the Council.

The key findings of the Council's assessment are as follows:

- Oil and gas companies or their successors operating in the Taranaki Region that have undertaken hydraulic fracturing operations up to mid-2011 provided data for this investigation and assessment. The first hydraulic fracture operation was in 1989.

- The data provided shows that during the period 1989 to mid-2011 a total of 65 hydraulic fracturing events were undertaken in 39 wells accessing oil and gas reservoirs that are up to 4 km underground, with the majority deeper than 2.4 km. The shallowest fracturing that has occurred is at 1.15 km at the Manutahi well sites, at 1.36 km at the Kaimiro well sites, at 1.56 km at the Ngatoro well sites, and at 1.75 km at the Cheal well sites. These relatively shallow activities are assessed in more detail in this report.

- Most of the ingredients used in fracture fluids are found within products that are widely used in society, including in products used in homes. While most of the additives used in fracturing in their concentrated (pure) product form are toxic, as shown by the MSDS sheets attached to this report, they are diluted before use by the water carrier and, therefore, are present when injected into the environment in only relatively low concentrations. However, care is needed for some of these products even in low concentrations to avoid any potential for impacts on human health. Therefore, regulation of their use and disposal is appropriate. The typical percentage of additives in the fracture fluid is 2 % with the water carrier drawn from municipal supplies or consented river sources.

- If hydraulic fracturing operations are carried out properly, it is unlikely that contaminants will reach overlying freshwater aquifers in the Taranaki region. However, although unlikely it is not impossible. There are four potential routes for that to occur: (1) leakage from the hydraulic fracturing well casing due to defective installation or cementing; (2) leakage through the geology overlying the hydrocarbon reservoir; (3) leakage from improper handling of chemicals used in the process and from hydraulic fracturing wastewaters (i.e., flow back or produced water from the formation) brought back to the surface at the well site; or (4) a well blowout resulting in underground leakage into aquifers or surface recharge via spillage. The probability of a well blowout is very small, but cannot be completely discounted and has occurred during hydraulic fracturing operations in other countries.

- This review of the hydraulic fracturing operations which have been conducted in the Taranaki Region from 1989 to mid-2011 has not found any evidence of related environmental problems. Figures 8 (page 14) and 11 (page 29 and below) summarize the likely reasons for this by showing the general case of substantial thicknesses of low permeability geologic seals separating the petroleum hydrocarbon reservoirs from freshwater aquifers.

- The report concludes that there is little risk to freshwater aquifers from properly conducted hydraulic fracturing operations in the Taranaki Region. This assumes a combination of natural geologic factors, the use of good practices by industry, and regulation by the Council as follows:

  (i) Satisfactory methods for well design, installation, and operation are used by the petroleum hydrocarbon industry as well as quality control checks to ensure well installation integrity;

  (ii) Hydraulic fracturing occurs at relatively deep depths below freshwater aquifers (i.e., at thousands of metres below ground level, in comparison to freshwater depths which are in the order of hundreds of metres in many cases and less than approximately 1,000 m below ground level in all cases);

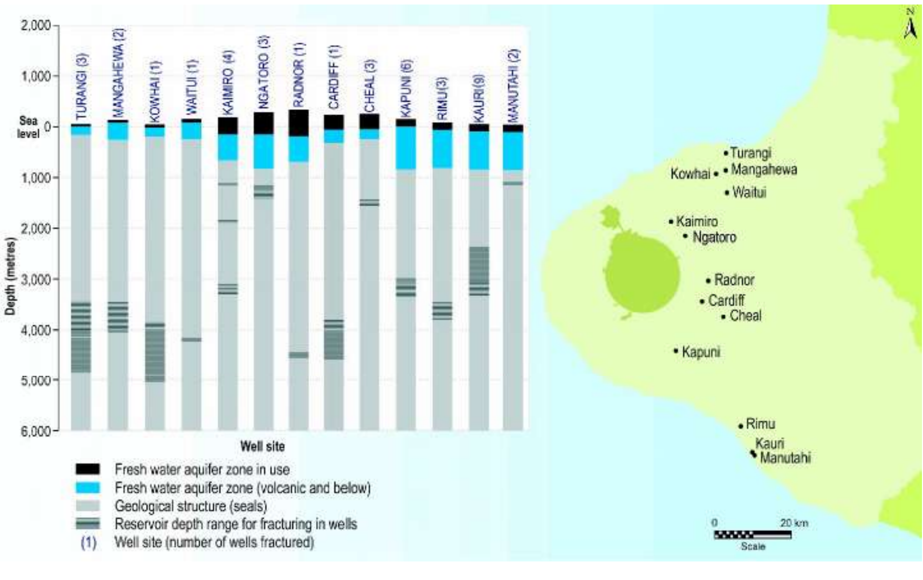
  (iii) The existence of natural petroleum hydrocarbon reservoir seals that trap the hydrocarbons in place;

  (iv) Substantial thicknesses and multiple layers of relatively low permeability geologic seals between the petroleum hydrocarbon reservoir and any freshwater aquifers; and

  (v) Operational management and monitoring by the petroleum hydrocarbon industry and regulation and monitoring (including sampling and auditing operational data) by the Council.

- Although the risk that properly conducted hydraulic fracturing operations could adversely affect freshwater aquifers is very low, the level of risk is greater when hydraulic fracturing is carried out at relatively shallow depths below freshwater aquifers. In such case, a more stringent regulatory oversight is called for.

- The Council has decided to require resource consents, from July 2011, for all subsurface fracturing discharges to land beneath the region and will process these in accordance with the requirements of the Resource Management Act 1991. Compliance monitoring of the discharges will be undertaken and reported to the community.



Hydrogeological summary of hydraulic fracture activities described in this report

Table of contents

List of tables

List of figures

1. Introduction

The purpose of this report is to provide a hydrogeologic risk assessment of the practice of hydraulic fracturing as performed in the Taranaki Region up to mid-2011. The report was originally released in November 2011, with data from the period 2000 to mid-2011, but updated in February and May to include an assessment of all hydraulic fracturing data. The first hydraulic fracture operation occurred in 1989.

Hydraulic fracturing is commonly referred to as fraccing, fracking, or hydrofraccing. The practice is used to enhance petroleum hydrocarbon (i.e., oil and/or natural gas) recovery from subsurface geologic formations (i.e., petroleum reservoirs). As currently practiced in the Taranaki Region and many other parts of the world, hydraulic fracturing is used for the purpose of facilitating natural gas recovery from relatively low permeability formations. It has attracted media attention because adverse environmental impacts on groundwater aquifers have occurred in some limited cases and concern over the potential for those impacts to occur in the Taranaki Region. This report seeks to present an objective view of the risks associated with the hydraulic fracturing in the Taranaki Region by looking at past and proposed hydraulic fracturing activities specific to the Taranaki Region.
The organization of this assessment after a brief introduction is as follows:

1. Section 2 of this report describes the practice of hydraulic fracturing and how it is used to enhance recovery of natural gas from reservoirs, including examples of relatively shallow fractured reservoir formations.
2. Section 3 of this report provides an overview of hydrogeology in the Taranaki Region with specific attention to the depths involved for both groundwater aquifers used for drinking water supplies and petroleum hydrocarbon reservoirs.
3. Section 4 of this report describes all historical hydraulic fracturing operations undertaken in the Taranaki Region (1989 to mid-2011).
4. Section 5 of this report undertakes an assessment of the hydrogeologic risk posed by the practice based on the above information.
5. Section 6 of this report discusses the regulation of hydraulic fracturing under the Resource Management Act 1991.

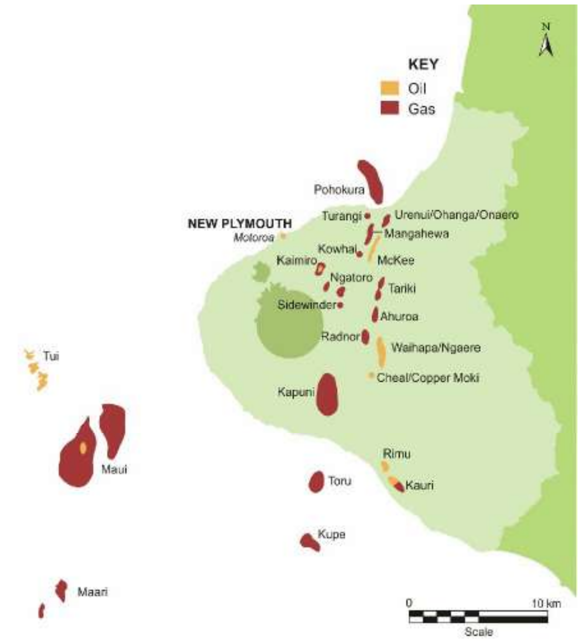


Figure 1 Map illustrating the location of the oil and gas fields, and production facilities in Taranaki.

6. Section 7 of this report provides a conclusion on the hydrogeologic risk posed by hydraulic fracturing to enhance natural gas recovery in the Taranaki Region and includes a statement from the Institute of Geological and Nuclear Sciences Ltd (GNS Science). A Senior Hydrogeologist from GNS Science performed a peer review of this risk assessment.

The major producing oil and gas reservoirs in Taranaki are shown in Figure 1.

2. Description of hydraulic fracturing

The practice of hydraulic fracturing has occurred in oil and gas reservoirs for more than 50 years worldwide, and in Taranaki since May 1989 with increased activity since 2007. Petrocorp Exploration Ltd first used the technique in the Kaimiro-2 well on 11 May 1989 (MED, 2012).

Hydraulic fracturing is increasingly being used to extract gas from shale deposits overseas and is being evaluated for use in New Zealand (L &M Energy, 2011). The gas in such deposits overseas is described as 'unconventional' gas and its successful extraction has caused a revolution in world energy industries, promising to transform not only the supply and productivity prospects of the gas industry, but of world energy trade, geopolitics and climate change (Ridley, 2011). Hydraulic fracturing is also being used to extract methane from coal beds. A useful introduction to hydraulic fracturing and its environmental effects and regulation in the USA for shale gas is provided by U.S. Department of Energy (2009) and for coal bed methane by EPA (2004). There are no similar publications specific to New Zealand. Concerns regarding the potential impacts of hydraulic fracturing on drinking water resources are the subject of current research undertaken by the U.S. Environmental Protection Agency (USEPA). Initial results from this research are not expected until 2012, with the full study not scheduled for completion until 2014 (Swackhammer and Dzombak, 2011).

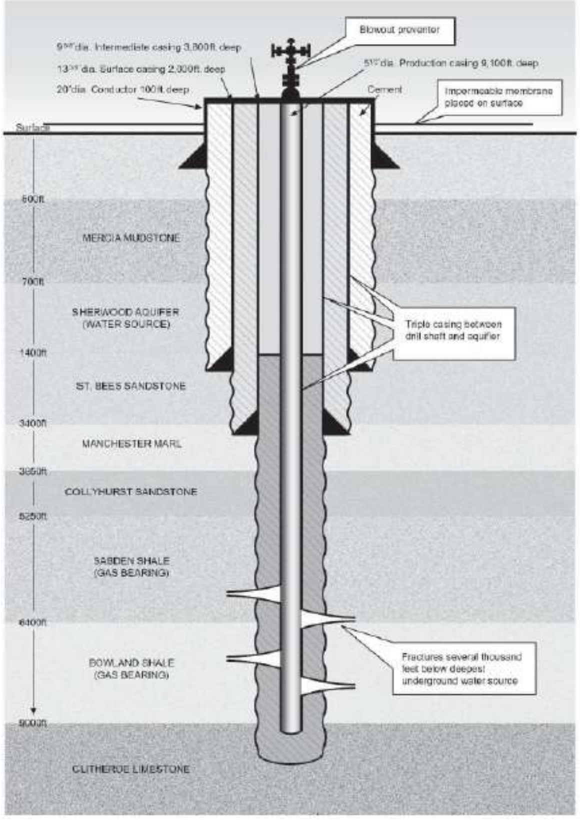


Figure 2 Bowland Shale Well Schematic (Cuadrilla Resources Holdings Ltd, 2011)

Hydraulic fracturing is a process that results in the creation of very small fractures in reservoir rocks to enhance hydrocarbon recovery. Access to subsurface zones for hydraulic fracturing is via a well (Figure 2). A well is drilled and lined with steel casing. The steel casing is held in place with cement and is installed as a succession of tubular sections, each section screwed into the next. The steel casing is secured to the hole walls with cement sealing the entire outer annulus (API, 2009). Production tubing is located in the innermost casing.

Wells may be drilled entirely vertically, or with a horizontal end section penetrating hydrocarbon reservoirs. Horizontal wells improve production performance for certain types of formations (API, 2009). Examples of a horizontal and vertical well are shown in Figure 3.

Stated simply, the hydraulic fracturing process involves perforating the steel casing at the target depth (i.e., within the reservoir at depth) (Figures 3 and 4) and then pumping fluids consisting of freshwater, fracture chemicals and a medium, called proppant (usually some kind of medium-grained sand or small ceramic pellets that are wedged into the fractures under pressure and prevent the fractures from closing when the injection is stopped) at high pressure down the well through the perforated casing and into the reservoir to exceed the fracture strength of the reservoir rock and cause an artificial hydraulic fracture to form only in the receiving formation, but without penetrating the overlaying geological seals that define the hydrocarbon reservoir. The fracture fluid is maintained under pressure for a short period of time determined by the fracture design engineer (Todd Taranaki, 2011).

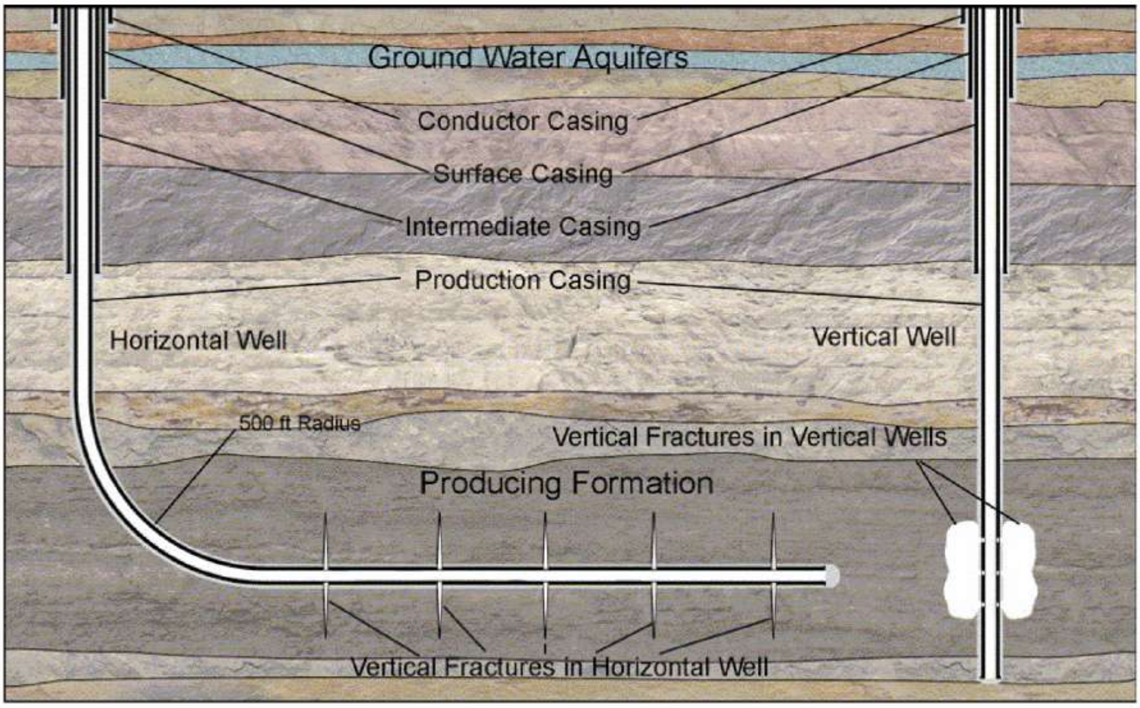


Figure 3 Example of a horizontal and vertical well (API, 2009).

Once a fracture has been initiated, fracture fluid and proppant are carried into the fracture. The types of fractures produced depend on the formation but are generally in the order of millimetres wide and metres to tens of metres long. The proppant is used to keep the fracture open when pumping is stopped and the fracture fluid withdrawn. The placement of proppant in the fractures is assisted by the use of cross-linked gels. These are solutions, which are liquid at the surface but, when mixed, form long-chain polymer bonds and thus become like gels that transport the proppant into the formation. Once in the formation these gels 'break' back to a liquid state so that they can be flowed back to the surface in return fluids without disturbing the proppant trapped in the hydraulic fracture. With continued flow, formation hydrocarbon fluids and residual fracture fluids are drawn into the fracture, through the perforations into the wellbore and thence to the surface (Todd Taranaki, 2011).

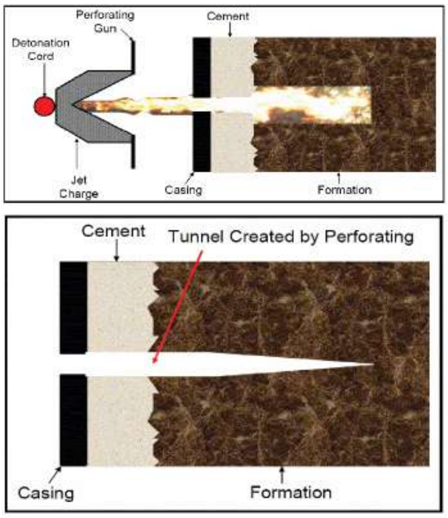


Figure 4 Well perforation process (API, 2009).

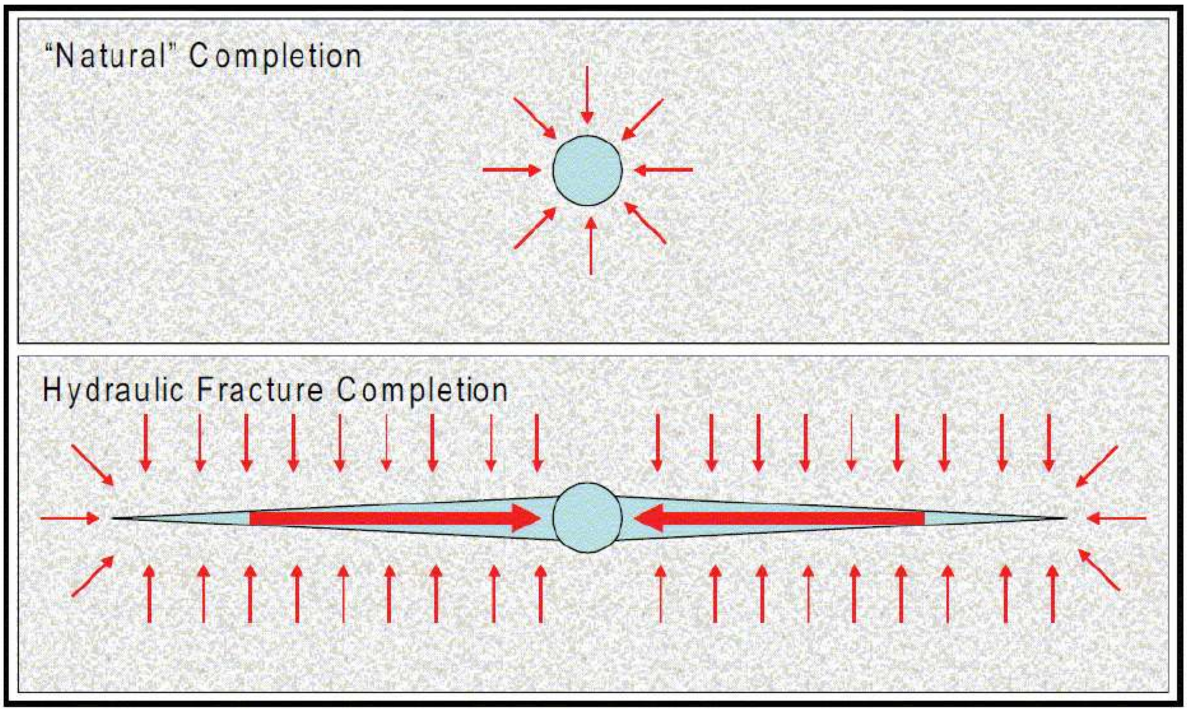


Figure 5 Illustration of a fractured and non-fractured well completion (API, 2009).

Figure 5 shows a non-fractured wellbore and a hydraulic fracture completion and the flow paths towards the well (API, 2009).

When the pressure is released some of the residual fracture fluid is driven by high pressure in the reservoir up the well and is collected at the surface for disposal. The returned fluids (also known as flow back fluids) constitute about 30-80 % of what was injected, depending on formation properties. The remaining fluids stay in the reservoir but some of these are gradually "leached" out with the hydrocarbon flow.

Water and oil based fracture techniques are available, with the former the most common in Taranaki (Tables 1- 5). Oil based fracturing uses petroleum based medium such as diesel oil or condensate. Diesel oil has been used by Swift Energy in the past (Table 3). Diesel oil, which, contains a mixture of organic compounds including benzene, ethylbenzene, toluene, and xylenes (BTEX), within the specifications provided for New Zealand by regulations, poses a greater potential environmental hazard than water-based fracture fluids if not managed correctly. Benzene, for example, is considered carcinogenic and is found in household products such as adhesives, asphalts, lighters, and gasoline.

Details of a hydraulic fracturing operation by Todd Energy Ltd in 2010 using water with chemicals/additives are presented below as an example. Todd Energy Ltd supplied the following data on a volume weighted average basis for the four formation zones fractured (refer section 4, Table 1). There were minor variations between the four treatments:

<u>Mangahewa-6 well in North Taranaki at the Mangahewa-C well site</u>
- Injection interval 3887- 4190 m total vertical depth
- Maximum surface pressure used 10,400 psi
- 1500 cubic metres water used sourced from a municipal supply

- Ceramic proppant- 117 tonnes
- 600 cubic metres return fluids (estimate)
- 35 cubic metres of chemicals/additives, including the following (2.5 % of total by volume) :
    - Xcide 102 – this is a biocide to prevent bacterial action underground interfering with the gel management system (0.1 %)
    - Claytrol – this is a clay stabiliser to prevent any clay minerals in the reservoir rock expanding on contact with water and plugging the reservoir (0.16 %)
    - GS-1 – sodium thiosulfate which is a gel stabiliser (0.02 %)
    - GLFC-1b – this is a gelling agent to hold the sand in suspension: natural guar gum (0.86 %)
    - Inflo-150 – contains ethylene glycol (antifreeze), methanol, and other compounds which serve as a friction reducer to ease pumping and evacuation of fluid (0.14 %)
    - BF-7LD – this is a buffer fluid (potassium carbonate) (0.53 %)
    - XLW-56 – this is a crosslinking agent (0.43 %)
    - GBW-41L – this is a gel breaker (hydrogen peroxide) (0.16 %)
    - GBW-12cd – this is an enzyme (hemicellulase enzyme) (0.11 %)
    - GBW-5 – this is a gel breaker (ammonium persulphate) (0.001 %).

It is important to note that the information presented in the MSDS sheets is for pure product. Each of the products is significantly diluted prior to injection. For the above fracture fluid 97.5% and 2.5% by volume were water and chemicals/additives, respectively. This is a typical ratio for Taranaki fracture fluids.

The gel management system allows the proppant to be moved into fissures. The gel is weakened later to allow the fluid to come back out followed by the hydrocarbons. Appendix I contain the MSDS (Material Safety Data Sheets) for a number of commonly used additives in hydraulic fracturing in Taranaki, including those used in the above fracture operation.

Most of the ingredients used in fracture fluids are found within products that are commonly used in homes and are listed and compared in Appendix II. The role of each ingredient in the fracture process is also explained in layman's terms. While most of the additives used in fracturing in their concentrated (pure) product form are extremely toxic, as shown by the MSDS sheets (Appendix I), they are diluted by the water carrier and, therefore, are present in relatively low concentrations. However, even in low concentrations care is needed for the use of some products in the environment to avoid any potential for impacts on human health. When used properly in hydraulic fracturing operations and not introduced into overlying groundwater or other sensitive environments, these additives are unlikely to be harmful.

The additives that are needed for the fracturing process to work are required to be named and explained to, and approved by the Environmental Protection Agency (EPA). Information on the additives used by Origin Energy in coal seam gas extraction in Australia is available on the PEPANZ website[1] as examples of the type of products used in hydraulic fracturing in New Zealand.

---

[1] NZ resource sector position paper: Fraccing on www.pepanz.org

Water used in fracture operations is generally sourced from municipal supplies in Taranaki. Even though this is high quality water, biocides are added to prevent the possibility of bacterial action interfering with the gel management system discussed above.

During the process of fracturing, some of the chemicals are sorbed by the geologic media (e.g., clay stabilisers). Process design provides for some chemical degradation due to pressure, temperature, and physical-chemical reactions (e.g., biocide and gel breakers) (Bay, 2011).

Generally, much of the fracturing fluid remaining behind from the initial clean-up period is due to gas breakthrough (i.e., enough fracture fluid has been produced that gas production commences). Additional fracture fluid is then entrained as part of the mixed well stream over time until as much as can be recovered has been removed. This is evidenced by the chemical composition of the produced fluid slowly changing from that of primarily fracturing fluid to primarily in situ formation fluid (e.g., hydrocarbons and some salty water). How long it takes to essentially recover the fracture fluids depends on several factors, primarily the overall production flow rate (higher is better), the producing gas/fluid ratio, and nature of the geologic materials.

The volume of fracture fluid that is recovered in initial return flow, and then subsequently over time in the well bore flow, depends on the fracture operation itself and the properties of the formation being fractured. For example, in the Managahewa-6 hydraulic fracturing described above an estimated 40 % of fracture fluids were initially recovered in return fluids. It is possible that most of the fracturing fluid injected will be recovered and that only a relatively minor fraction remaining within the hydrocarbon reservoir is totally unrecoverable, mainly the amount that is retained on the proppant due to capillary action. Fracturing fluids that are returned to the surface in return flow may contain naturally occurring hydrocarbon (e.g., BTEX). These contaminants are usually present in low concentrations (less than 8 ppm for Waitui-1 well return fluids) but still require careful management to avoid adverse environmental effects. An analysis of drilling fluids that also contain some return fluids is presented in Appendix III for the Todd Taranaki Ltd Waitui-1 well. An analysis of fracturing fluids from a Greymouth Petroleum Ltd deepwell injection consent application is also shown in Appendix III.

Hence there is a subsurface discharge of contaminants (energy, chemicals, water and sand/ small ceramic pellets) to land at considerable depth which produces relatively minor changes to the physical and chemical condition of the land (i.e., the reservoir) in a way that does not affect other foreseeable users of the land resource.

The fluids returned to the surface also need to be properly managed and regulated to avoid potential for adverse environmental effects. Fluids may be deepwell injected or land farmed with appropriate environmental standards in place.

3. Taranaki hydrogeology

Freshwater aquifers suitable for water supply purposes are found within various relatively shallow Quaternary and Tertiary formations. As indicated below in this section, 85% of groundwater use comes from wells drilled into the Quaternary volcanic materials that unconformably overlie most of the area to depths of 100 to 200 m below ground level (BGL). The remaining wells are scattered throughout shallow Quaternary marine terrace deposits or the deeper Whenuakura and Matemateonga Tertiary formations. The deeper Tertiary formations utilized are generally less than 500 m BGL while groundwater in the Taranaki Region generally becomes too saline for use by the 600 to 850 m depth BGL range (if not shallower). Unless otherwise noted, technical information on the hydrogeology of the Taranaki region presented in this section is from TRC (1996) and/or Stevens (2001).

3.1 General overview

Knowledge of the climate, landforms, and geology is required to understand a region's hydrogeology.

Taranaki's rainfall patterns are closely related to elevation and exposure to the main rain-bearing northerly to westerly winds. Rainfalls averaging less than 1,600 mm/year occur only in the southern part of the region and on a narrow coastal strip of north Taranaki. Most of North Taranaki has in excess of 2,000 mm/year (Thompson 1981). There is a strong gradient on Mt Taranaki/Egmont where rainfall at the summit is about 8,000 mm/year. The high regular rainfalls on the mountain provide water for the numerous waterways that radiate from it and are an important source of groundwater recharge.

The dominant features of the Taranaki landscape are the andesitic cone of Mt Taranaki/Egmont (2,518 m) and its surrounding volcanic ring plain. The region extends into the dissected hill country to the east, and to the marine terrace formations to the south and, to a lesser extent, the north.

Quaternary Taranaki volcanic sediments cover most of the Taranaki Peninsula while Quaternary marine terraces cover the remaining coastal fringe to the north and south. They lay uncomformably over a thick Tertiary sedimentary succession (sands, silt and mudstones, shell bells) which comprises about 5% of the total area of the Taranaki Basin at its north-eastern edge (Kings and Thrasher, 1996). Most of the freshwater aquifers used in the Region are found within the volcanic and marine terrace formations. Tertiary freshwater aquifers underlie the volcanic and marine terrace aquifers. In order of increasing depth, these are the Whenuakura and Matemateaonga formations. The deeper Mount Messenger Tertiary formation, while out cropping in the far north of the region, generally is too deep under much of the region to be of any practical use as a groundwater supply.

Figure 6 (page 11) shows a schematic geological map and stratigraphic cross-sections of the Taranaki region.

The north-south trending Taranaki Boundary Fault Zone essentially marks the boundary between the Taranaki basin to the west and the up-thrown Tertiary sedimentary formations (the dissected hill country) to the east. To the west the down-thrown Tertiary formations are of wide extent and stratigraphically similar to the sequences of the eastern hill country. They are unconformably overlain by Quaternary volcanic deposits of the Taranaki/Egmont Volcano, the preceding volcanic centres and the surrounding ring plain.

A number of geologic formations are recognised within the Tertiary sediments, principally in order of increasing depth (from youngest and shallowest to oldest and deepest) are the Whenuakura, Tangahoe, Matamateaonga, and the Urenui formations. The Urenui and Tangahoe formations are dominantly impermeable siltstones and mudstones and form extensive aquitards.

Water wells up to 100 m deep drilled into the Matemateaonga formation have yields of between 0.8 – 15 litres per second. Matemateaonga formation aquifers approach as deep as 800 m below mean sea level (MSL) in South Taranaki and 500 m below MSL near New Plymouth (Townsend et al, 2008).

3.2 Taranaki Volcanics aquifers

Approximately 80% of all groundwater used within Taranaki is extracted from aquifers on the ring plain contained in volcanic deposits. Most of this is used for agricultural purposes (Taylor & Evans, 1999). The Taranaki Volcanics Formation includes the present ring plain surrounding Mt Taranaki and that of the earlier volcanic centres. It comprises significant lava, pyroclastic (air fall material including ash) and lahar deposits. Thicknesses of up to 170 m have been encountered near Stratford. However, in general the formation thins concentrically away from the volcanic source (Mount Taranaki/Egmont). The formation extends to the coast in the west of the region. To the east, the volcanic deposits thin and give way to the older Tertiary deposits of the Taranaki Basin. To the north and south they are disrupted by the Quaternary Marine Terrace Formations.

The Volcanics Formation comprises both coarse material (sands, breccia, agglomerates) and fine material (clay, tuff and ash), resulting in irregular lithologies and anisotropic hydrogeologic conditions (Taylor & Evans, 1999). This produces a complex groundwater system of multiple perched and partially confined aquifers. Typically the unconfined groundwater level (water table) on the ring plain is encountered at depths of 1 to 10 m below ground level; these are the aquifers that are most used in Taranaki for domestic and farm purposes. Taranaki Ring Plain Survey (TCC, 1984) found that shallow wells are generally low-yielding, with flow rates up to 4 litres per second being typical, although yields of 13 litres per second have been recorded.

Flow rates for the shallowest wells (about 20m) typically range from 0.2 to 0.7 litres per second whereas deeper bores typically have flows of 0.8 to 4.0 litres per second. Flow rates of up to 13 litres/second have been obtained but are rare. The deeper aquifers in the volcanics are usually confined, whereas the shallower aquifers are usually unconfined. In addition, perched water tables are found above various impermeable layers throughout the volcanic deposits. These are caused by localised iron pans and mudstones, and have been found at almost any depth from a few metres down to about 230 m. Groundwater levels in wells drilled in volcanic deposits on the ring plain are generally close to the surface (Taylor and Evans, 1999).

Recharge of the Volcanics Formation aquifers is primarily from rainfall infiltration.

3.3 Marine Terrace aquifers

Uplifted marine terraces extend 90 km through South Taranaki and 80 km along the North Taranaki coastline (Taylor & Evans, 1999). The cutting of marine terraces and the deposition of Plio-Pleistocene shelf sediments are attributed to eustatic fluctuations in sea level, progressive uplift of south Taranaki, and subsidence of the south Wanganui Basin. In South Taranaki the Marine Terrace Formation overlies the Whenuakura Formation on an erosional unconformity (wave cut platform). Basal units are typically marine sands, often with conglomerate or shell layers. The basal marine sediments grade up to non-marine (terrestrial) sediments. The marine terrace sediments range up to about 40 m in thickness and include multiple unconfined aquifers.

Productive aquifers have been found in the sand layers that occur between 9 and 23 m in depth from the available survey data. The water table and the permeability of the marine deposits are sufficiently high for groundwater supplies.

The average observed bore yield is 1.3 litres per second. Wells in the south more typically yield up to 2 litres/second, but yields up to 3.8 litres per second have been recorded (Allis, et al., 1997). The highest yields occur from the coarser grained units such as the basal sands and conglomerates. It should be noted that the observed yield depends on the size, construction and individual conditions of a bore, and does not necessarily reflect the theoretical yield from the aquifer itself.

The water table in the marine terraces is generally encountered at depths of 1 to 15 m below ground level. The water table typically follows the topography, though much more subdued.

Recharge of the Marine Terrace aquifers is primarily from rainfall infiltration.

3.4 Whenuakura aquifers

The Whenuakura Formation is the sequence of Tertiary marine sediments in the Rotokare group that occurs on-shore in South Taranaki underneath Quaternary Marine Terraces and the Taranaki Volcanics (Evans & Murray, 1998). The Whenuakura Formation comprises Tertiary concretionary shelly blue-grey siltstone/mudstone/sandstone. It includes bedded pebbly sands, siltstone, mudstone, limestone and shellbeds. It is overlain by the Volcanics Formation north of Hawera and the Marine Terraces Formation to the south. It is underlain by impermeable layers of the Tangahoe Formation. The Whenuakura Formation is not exposed at the surface except in some incised river valleys in the south (Taylor & Evans, 1999).

The Whenuakura Formation consists of a series of numerous marine mudstones (papa), fine loose sands, sandstone, shellbeds and occasional hard concretionary bands. Regionally significant aquifers occur in some of the sand and shell layers, while other similar layers, although water-bearing, do no seem to be useful for water supply purposes.

Groundwater is abstracted from the sandstone and shelly limestone layers and several relatively extensive aquifers have been identified within the formation. Bores abstracting from the Whenuakura Formation typically display yields of up to 9.5 litres per second. Hydraulic conductivities have been measured at 1.3×10^{-5} to 5.8×10^{-5} ms^{-1}. Bores abstracting from Whenuakura aquifers are about 150m deep.

Recharge to these aquifers is not well understood. Some recharge may occur via the overlying Volcanics Formation in the north and in the far south where the overlying marine terraces are relatively thin. Some recharge may also occur where the formation is exposed in incised river valleys to the eastern hill country. Up to 40 metre thick sequence of Quaternary Marine Terraces unconformably overlie the Whenuakura Formation. The Tangahoe Formation lies under the Whenuakura Formation and is made up of a massive marine blue-grey mudstones. Despite occasional shellbeds and fine water-bearing sand layers, the Tangahoe Formation is considered an aquitard that separates aquifers in the Whenuakura Formation and underlying Matemateaonga Formation.

3.5 Matemateaonga aquifers

The Matemateaonga Formation comprises alternating Tertiary sandstone, conglomeratic shell and mudstone beds. The formation extends across almost the entire region, except north of Urenui (Taylor & Evans, 1999). In a hydrocarbon exploration bore near Stratford the formation was encountered from 170 to 1,086 m below ground level. It is exposed throughout large areas of the eastern hill country in central and south Taranaki (Figure 6). The formation contains a greater proportion of sands towards south Taranaki, and is more fine-grained in the north.

The upper Matemateaonga aquifers in North Taranaki are largely unconfined. Elsewhere in the region, the aquifers are either confined or partially confined. Flowing artesian conditions exist at a number of localities, particularly in a band of incised hill country bordering the ring plain from Toko south to Ohangai. The Tertiary sediments that make up the inland hill country in the east of the region also underlie the volcanics deposits of the ring plain. The principal Tertiary water bearing formation is the Matemateaonga, where generally extensive aquifers are developed within sand and shellbeds between relatively impermeable mudstone layers (Allis et al, 1997).

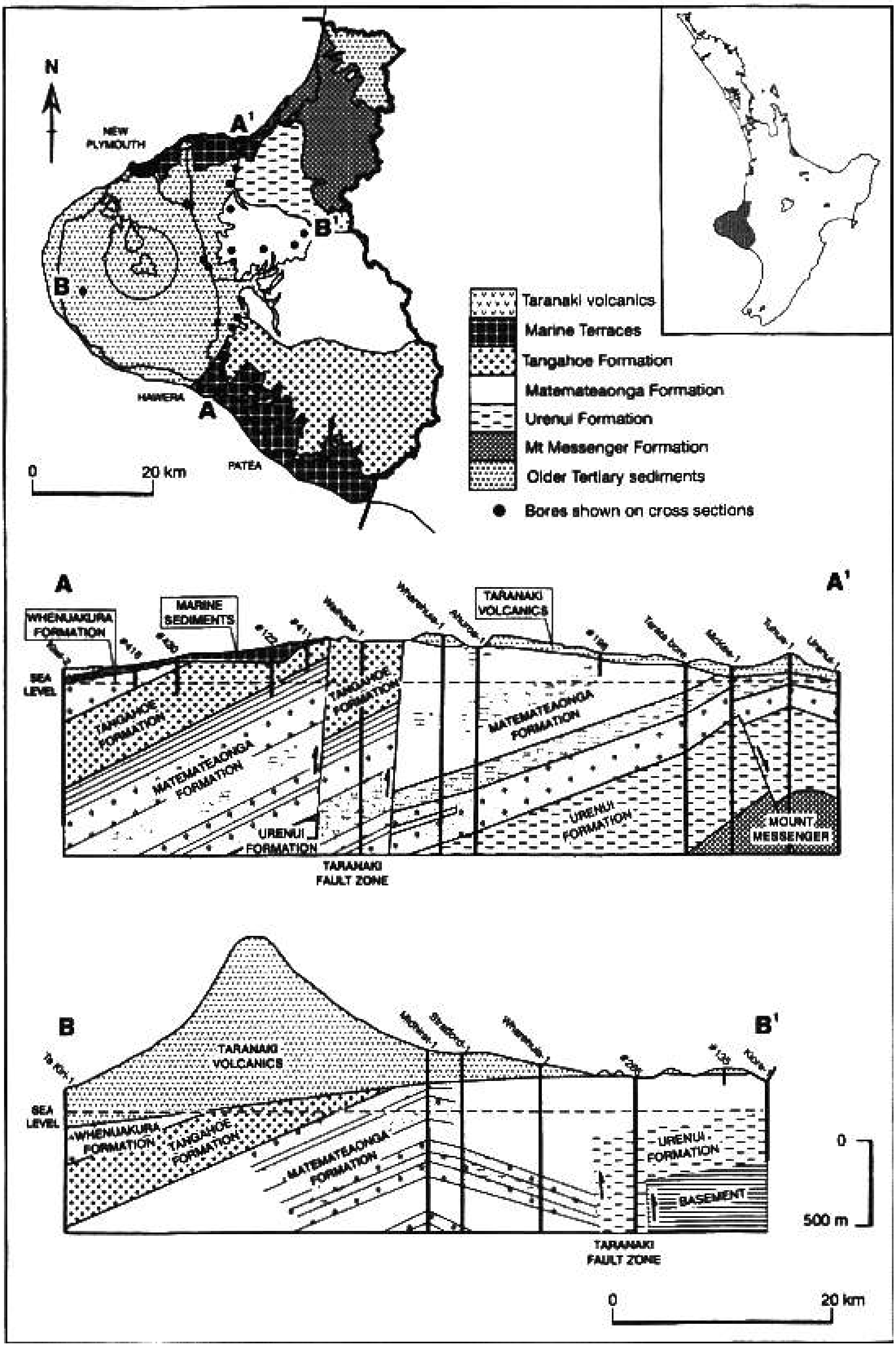


Figure 6 Schematic of the geological formations that contain freshwater aquifers in Taranaki (Stevens, 2001)

Observed yields of up to 15 litres per second have been encountered from aquifers within the Matemateaonga Formation. Hydraulic conductivities of $1.4\text{x}10^{-5}$ to $3.0\text{x}10^{-4}$ ms^{-1}, and storativities of $1.1\text{x}10^{-5}$ to $2.3\text{x}10^{-4}$, have been measured.

Potentiometric contours for the upper Matemateaonga Formation aquifers are shown in Figure 7. The contours show radial groundwater flow away from Mt Taranaki and south-westerly flow from the eastern hill country, where the formation is exposed at the surface. The potentiometric contours indicate that there is probably significant recharge to the aquifer from surface infiltration in the unconfined areas of the east and north and leakage from the overlying volcanic deposits of Mt Taranaki/Egmont and the surrounding ring plain.

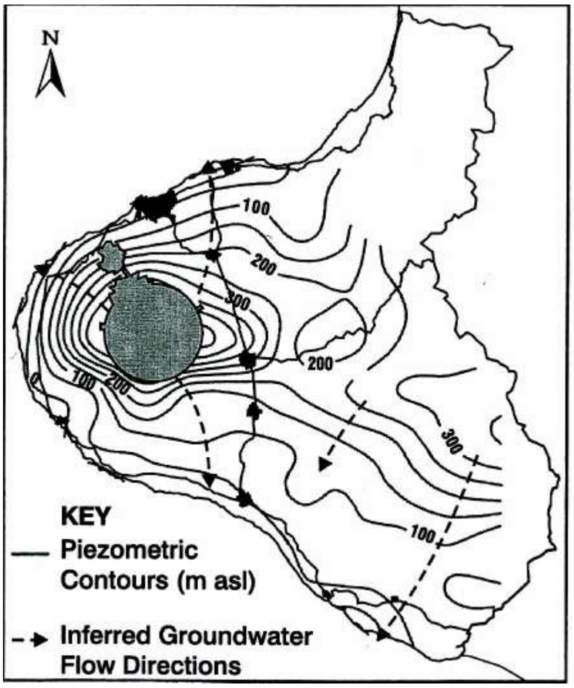


Figure 7 Matemateaonga aquifer potentiometric map showing groundwater flow direction (TRC, 1996).

Freshwater-bearing formations in the Matemateaoanga Formation occur as deep as 800 m in coastal South Taranaki, 600 m in central Taranaki, and up to 500 m in North Taranaki near New Plymouth. The same author has reported salty geothermal water down to 900 m below sea level in New Plymouth (Taylor & Evans, 1999).

The Matemateonga Formation and its aquifers dip to the south and west in the region so aquifers in this formation will not be found at consistent depths across the region.

The upper section of the formation contains freshwater while the lower section and below contains saline water. The interface between the two sections is called the Freshwater/Saltwater Interface (FW/SW I). A transition from fresh to salt water occurs over several hundred metres so the FW/SW I is not a single depth and references are approximate and location/elevation dependent. Resistivity logs that are run on all wells drilled in the region and held in open file by the Ministry of Economic Development - Crown Minerals show this trend.

3.6 Groundwater quality

3.6.1 General groundwater quality indicators

The lithology of the aquifer and its geochemistry as well as the residence time of the groundwater in contact with subsurface zone geologic media contribute to the quality of a particular groundwater. This is reflected in the groundwater quality of the principal aquifers in Taranaki, where in general an increase in total dissolved solids is observed with increasing depth through the Volcanics, Whenuakura and Matemateaonga aquifers.

Regional Council data indicates that fresh groundwater typically grades to saline (up to 22,000 gm^{-3} as NaCl) at depths between 600 and 850 m. There may also be zones, based on interpretation of resistivity borehole logs, where saline groundwater may be as shallow as 300 m. Such depths, however, are generally only encountered during hydrocarbon exploration activities. Drilling for water via deep bores, rarely extends below the 400-500 metres depth range where confined artesian aquifers are targeted in the upper part of the Matemateaonga Formation.

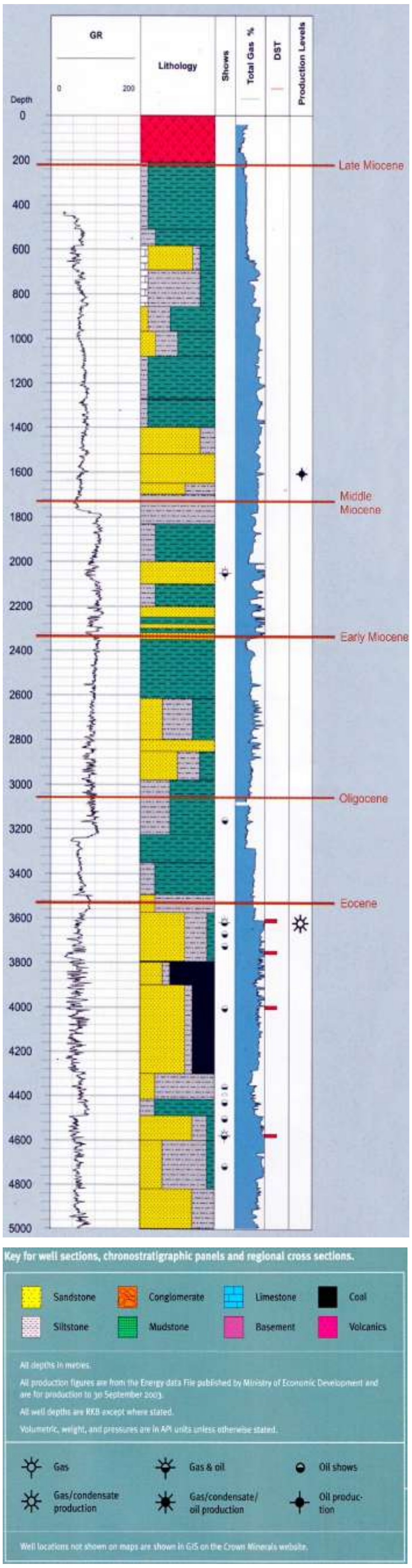
Groundwater from the Volcanics aquifers typically has elevated free carbon dioxide and substantial concentrations of iron and manganese. The free carbon dioxide occurs from the decomposition of organic matter, particularly as a result of frequent overwhelming of existing vegetation by eruptive events (TCC, 1984). This has resulted in the formation of relatively aggressive groundwaters and can cause corrosion of pipe work and metallic fittings.

The groundwater quality of the underlying Tertiary aquifers is considered to be generally of better quality than the overlying volcanic aquifers, although it has a higher hardness and can have elevated ammonia levels.

3.6.2 Methane in groundwater

Methane gas in water bores has been found across the region for many years and predates any hydraulic fracturing in the region. The source of the gas is from water wells either penetrating a gas-rich organic formation (e.g., old swamps) at shallow depths (known as biogenic methane) or from the gas percolating upwards from the decomposition of buried organic material at depth (known as thermogenic methane). A possible example of both is shown in the Kaimiro-1 well log where the presence of gas is noted in all strata above the reservoir and increases close to the 50 m depth below ground level in the Volcanics (Figure 8). The well was drilled in July 1982 and is in the Kaimiro Field (MED, 2004).

An example of thermogenic methane is possibly shown in the McKee Field where gas is also within 50 m of the surface (MED, 2004). In North Taranaki gas has been accessed from water bores and used for domestic and cowshed use.



Key for well sections, chronostratigraphic panels and regional cross sections.

All depths in metres.

All production figures are from the Energy data File published by Ministry of Economic Development and are for production to 30 September 2003.

All well depths are RKB except where stated.

Volumetric, weight, and pressures are in API units unless otherwise stated.

Well locations not shown on maps are shown in GIS on the Crown Minerals website.

Figure 8 Kaimiro-1 well lithological, production levels, gas levels and other data. Well drilled in July 1982 (MED, 2004).

3.7 Groundwater use and management in Taranaki

Although yields from the aquifers in the Taranaki region are relatively low, groundwater is still a valuable resource for the region. Groundwater is abstracted predominately for domestic and farm water supplies throughout the region. It is also utilised for community water supplies by several settlements in the south of the region.

The groundwater resources of the ring plain were first described in the Taranaki Ring Plain Water Resources Survey (TCC, 1984). This survey found that approximately 13% of all water used was sourced from groundwater and used mostly for stock and domestic supplies. The majority of the groundwater (85%) was abstracted from shallow wells and bores in the Taranaki Volcanics Formation. This water use data has not varied much to date (July 2011). Often these wells were hand dug and unlined.

The remaining groundwater is drawn from Whenuakura and Matemateonga aquifers, with the municipal water supplies of the Patea and Waverley townships as examples of the former.

The greater proportion of bores drilled are on the ring plain to the east of Mt Taranaki (in areas not covered by rural water schemes sourced from surface water supplies) and on the Marine Terraces in the south of the region, as shown in Figure 9.

In more recent times there has been an increasing trend to utilise the deeper Tertiary aquifers (i.e. the Whenuakura and Matemateaonga aquifers) for stock and domestic water supplies. This is mainly due to the better security of supply and improved water quality that is obtainable. Bores to depths in excess of 180 m are not uncommon. Often bores abstracting from the Tertiary aquifers were completed by grouting a well casing through the overlying volcanic or marine terrace strata and leaving an open hole in the underlying Tertiary formation. However, the installation of well screens is becoming increasingly more common.

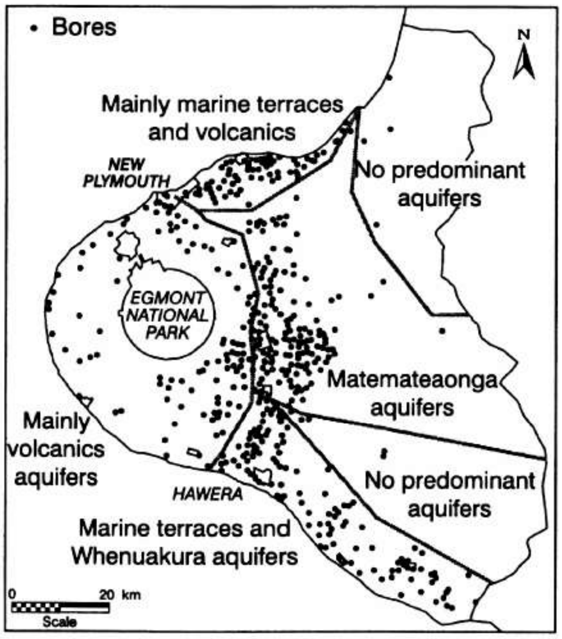


Figure 9 Bore locations in the Taranaki region (TRC, 1996)

New Plymouth District Council has completed some exploratory drilling in the north of the region to assess the potential for municipal water supply, but with the exception of a 250 m deep bore near Oakura, did not find aquifers of sufficient yield.

4. Hydraulic fracturing undertaken in the region

In Taranaki two service companies undertake all the hydraulic fracturing: BJ Services and Halliburton. Both have offices and personnel located in New Plymouth and work under contract for the oil and gas industry.

A survey of hydraulic fracturing practices up to mid-2011, in the region was undertaken using information supplied by all the oil and gas companies. The information was supplied without reservation by all the companies with the exception of those owned by Greymouth Petroleum Ltd (Table 5), which was supplied on a without prejudice basis. The Ngatoro well (1, 7, & 9) and the Kaimiro well (1, 2, & 3) data was provided without reservation by Greymouth Petroleum Ltd. The fracture fluid used, depth (mTVD- metres true vertical depth), geological formation, and groundwater information from this survey are summarised in Tables 1-5 below.

Table 1 Todd Energy Ltd supplied hydraulic fracturing data for North Taranaki well sites (Figure 11)

Date	Well	Type fracture fluid medium	Geologic formation	Depth mTVD	Freshwater/ Saltwater Interface (m TVD)
5 May 1997 21 May 1997 31 May 1997	Mangahewa-2	Water	Mangahewa	4103-4124 3696-3714 3590-3608	400
29 January 2010 5 March 2010 10 March 2010 18 March 2010	Mangahewa-6	Water	Mangahewa	4186 - 4190 4092 - 4096 3933 - 3936 3887 – 3890	400
28 April 2011	Waitui-1	Water	Mangahewa	4341 - 4352	400

Table 2 Shell Todd Oil Services Ltd supplied hydraulic fracturing data for Kapuni well sites (Figure 11)

Date	Well	Type fracture Fluid medium	Geologic formation	Depth mTVD	Freshwater/ Saltwater Interface (m TVD)
23 July 1993	KA15	Water	Kapuni	3328-3347	1000
8 March 1995	KA8	Water	Kapuni	3144-3161	1000
7 October 1995	KA6	Water	Kapuni	3377-3383 3387-3402	1000
17 July 2003	KA05	Water	Kapuni	3414 – 3418	1000
2 February 2005 2 March 2005 26 March 2005	KA04	Water	Kapuni	3577 – 3584 3446 -- 3454 3349 – 3357	1000
13 May 2010 24 May 2010 27 May 2010 11 December 2010 8 February 2011 13 February 2011	KA18	Water	Kapuni	3828 – 3833 3767 –3790 3709 –3742 3678 – 3681 3605 – 3624 3566 -- 3571	1000

Table 3 Swift Energy hydraulic fracturing data for South Taranaki well sites (Figure 11) supplied by Origin Energy NZ Ltd who purchased Swift in 2008

Date	Well	Type fracture fluid medium	Geologic formation	Depth mTVD	Freshwater/ Saltwater Interface (m TVD)
17 December 2001	Rimu A3	Diesel	Tariki sands	3555 - 3592	900
28 November 2001	Rimu A2	Diesel	Tariki sands	3820 - 3877	900
30 July 2002	Rimu A2A	Water	Tariki sands	3570 - 3580	900
17 March 2003	Kauri A1	Diesel	Upper Tariki sands	3380 - 3383	900
15 March 2003	Kauri A4	Diesel	Kauri sands	2480 - 2489	900
29 August 2003	Kauri E1	Diesel	Kauri sands	2429 - 2456	900
28 August 2003	Kauri E2	Diesel	Kauri sands	2476 - 2484	900
10 September 2003	Rimu A1	Diesel	Tariki sands	3595 - 3646	900
28 October 2004	Kauri E3	Diesel	Kauri sands	2511 - 2519	900
10 October 2004	Kauri E4A	Diesel	Kauri sands	2462 - 2473	900
28 October 2004	Kauri E5	Diesel	Kauri sands	2473 - 2485	900
27 June 2005	Kauri E1	Diesel	Kauri sands	2429 - 2456	900
29 June 2005	Kauri E7	Diesel	Kauri sands	2471 - 2479	900
16 October 2005	Kauri E2	Diesel	Kauri sands	2476 - 2484	900
2 July 2005	Kauri A4	Diesel	Kauri sands	2480 - 2489	900
29 June 2005	Kauri E9	Diesel	Kauri sands	2450 - 2467	900
12 October 2005	Manutahi A1	Diesel	Manutahi	1157 - 1179	900
14 October 2005	Manutahi B1	Diesel	Manutahi	1160 - 1175	900

Note: Origin initially submitted the freshwater/salt water interface was at 1000m, based on an estimate derived from data at the Kupe Production site in South Taranaki some 25 km north west of the Rimu, Kauri and Manutahi wells. However, later more detailed analysis of resistivity logs from wells in the area indicated the interface was at 900 m and this level was used in the above table.

Table 4 TAG Oil Ltd supplied hydraulic fracturing data for Central Taranaki well sites (Figure 11)

Date	Well	Type fracture fluid medium	Geologic formation	Depth mTVD	Freshwater/ Saltwater Interface (m TVD)
26 April 2010	Cheal A7	Water	Mt Messenger	1750	200-500
29 September 2010	Cheal B3	Water	Mt Messenger	1750	200-500
14 November 2010	Cheal BH1	Water	Mt Messenger	1750	200-500

Note: The BH1 well contains the horizontal section referred to below and was subject to a multi stage fracture programme with five zones subject to a separate fracture treatment.

Table 4(a) Austral Pacific fracturing data for the Cardiff Central Taranaki well site (Figure 11)

Date	Well	Type fracture fluid medium	Geologic formation	Depth mTVD	Freshwater/ Saltwater Interface (m TVD)
2005	Cardiff-2A-ST1	Water	Mangahewa	4057-4067	400-600
2005				4139-4159	
2005				4791-4820	

Note: This suspended well sits in the TAG Cheal permit area but was not part of the TAG acquisition from the receiver of Austral Pacific. However, TAG has taken over the wellsite (Cheal C) and was able to supply some data on the well and past hydraulic fracturing. Assumed hydraulic fracturing occurred on three separate occasions in 2005.

Table 5 Greymouth Petroleum and subsidiary company supplied fracturing data for Central and North Taranaki well sites (Figure 11)

Date	Well	Type fracture fluid medium	Geologic formation	Depth mTVD	Freshwater/ Saltwater Interface (m TVD)
11 May 1989	Kaimiro 2	Water	Mt Messenger	1361- 1378	945
August 1989	Kaimiro 3	Water	Moki	2036 - 2055	655
November 1993	Kaimiro 1	Water	Mangahewa	3607 - 3622	725
16 June 2000	Ngatoro 9	Water	Mt Messenger	1561 - 1586	795
24 May 2001	Ngatoro 7	Water	Mt Messenger	1602 - 1637	795
7 February 2002	Ngatoro 1	Water	Mt Messenger	1600 - 1657	775
20 February 2006	Turangi 1	Water	Mangahewa	4000 – 4100	214
2 March 2006	Turangi 1	Water	Mangahewa	3700 – 3800	214
12 March 2006	Turangi 1	Water	Mangahewa	3500 – 3600	214
19 August 2008	Turangi 2	Water	Mangahewa	4100 – 4200	214
20 August 2008	Turangi 3	Water	Kaimiro	4800 – 4900	214
25 August 2008	Turangi 2	Water	Mangahewa	3600 – 3700	214
29 August 2008	Turangi 3	Water	Kaimiro	4400 - 4500	214
4 September 2008	Turangi 2	Water	Mangahewa	3500 – 3600	214
26 January 2009	Kowhai A1	Water	Kaimiro	5000 – 5100	249
2 February 2009	Kowhai A1	Water	Mangahewa	4100 – 4200	249
5 February 2009	Kowhai A1	Water	Mangahewa	4000 – 4100	249
8 February 2009	Kowhai A1	Water	Mangahewa	3900 – 4000	249
30 May 2010	Radnor 1B	Water	Mangahewa	4800 – 4900	1037
15 June 2011	Kaimiro 2 ST1	Water	Mangahewa	3300 – 3400	850

Notes:

1) Fracturing depth data from 20 February 2006 onward has been rounded to the nearest 100m for commercial sensitivity reasons. The earlier data is open file and not subject to the same classification by MED.

2) Freshwater / saltwater interface depths are based on the depth to a resistivity value that is calculated for rock saturated with 1,000 ppm total dissolved solids water. Depths come from log data from the well site named in each row, or are extrapolated from the nearest well with available resistivity log data.

3) Petrocorp Exploration Ltd Kaimiro 1, 2 & 3 wells and NZOG Ngatoro 1, 7 & 9 wells hydraulic fracturing data availability was notified to the TRC by the MED in April 2012 and obtained in May. Kaimiro 1 and 3 wells are at the Kaimiro Production Station site, while the Kaimiro 3 well is at the Kaimiro B site. The Ngatoro I & 2 wells are at the Ngatoro A site and Ngatoro 9 is at the Ngatoro B site.

The number of onshore wells fractured over the period in Taranaki is summarised in Figure 10. This shows there was a total of 65 hydraulic fracturing events in 39 wells. An average of almost three wells were hydraulically fractured per year during the period 1989 to mid-2011, with most activity from 2003 onward.

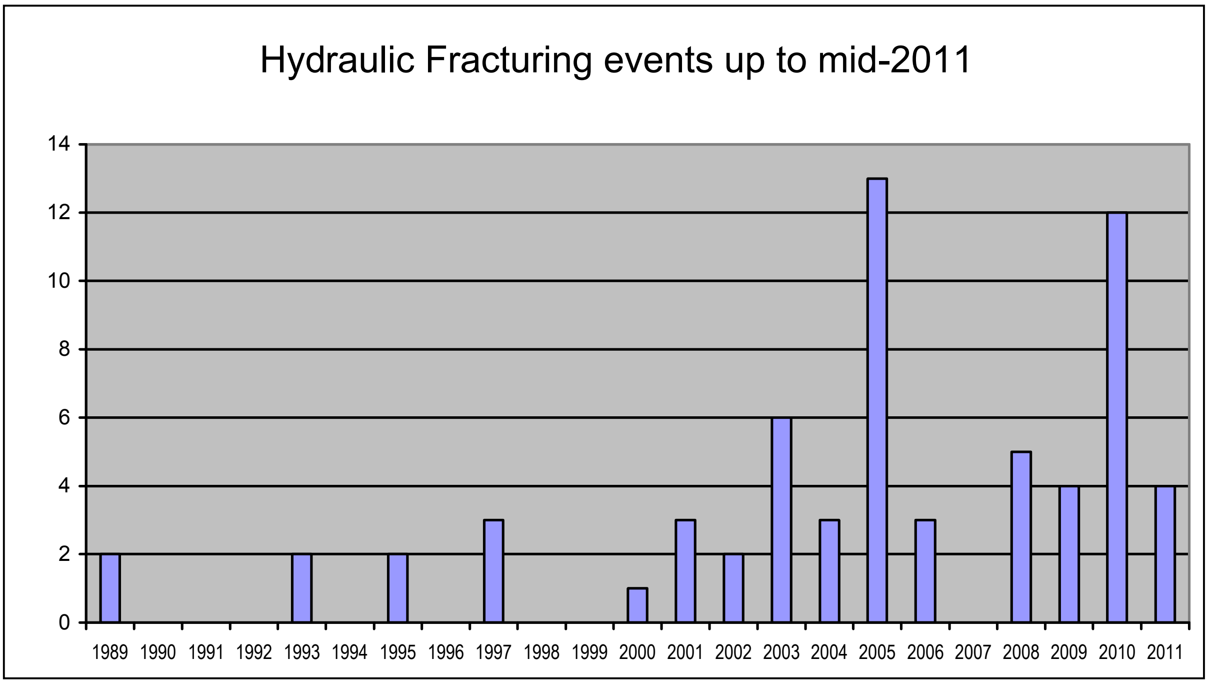


Figure 10 Well hydraulic fracture events per year 1989 to mid-2011

The data in Tables 1 to 5 shows that fracturing occurs in oil and gas reservoirs that are up to 4 km underground with most deeper than 2.4 km (Figure 11). The shallowest fracturing that has occurred is at about 1.15 km (Table 3) at the Manutahi well site. This is discussed further below. Adverse media publicity has focused on fracturing undertaken by Tag Oil Ltd at the Cheal well site. Fracturing at this site is also discussed further below and provides an example of the monitoring and reporting that is undertaken as a part of modern hydraulic fracturing activities (BJ Services Ltd, 2010).

Tag Oil Ltd has supplied information on hydraulic fracturing to the Council. The fracturing at the Cheal well sites (Table 4) in 2010 comprised:

- Wells A7 and B3 were drilled vertically to 1750 mTVD. Well BH1 was deviated and had a horizontal 548m section at 1758 mTVD.
- A water based fracture fluid system.
- Total volume of water/fracture chemicals and sand in brackets for A7 well 77.2 cubic metres (17.5 tons sand proppant), 183 cubic metres for the B3 well (34.4 tons sand proppant), and 511 cubic metres for the BH1 well (115 tons sand proppant). Note the BH1 well comprised five fracture stages with five zones subject to a separate fracture treatment.
- XLFC-1B, X-CIDE 162, Wax-Chek 5222,US-4D, sodium bicarbonate, Saraline 185V, PSA-2L, PSA-1, GW-3, GBW-12CD, Clay Master-5C, and BF-7L were used as additives with the fracture fluids. MSDS sheets for these additives are provided in Appendix I.
- The fracture chemicals comprised 0.85 % of the fracture fluid in each fracture.
- Maximum surface pressure used for the A7 well 3,700 psi, 2,200 psi for B3 well, and 2,268 psi for the BH1 well.
- Volume of return fluids for each well was difficult to determine as they flowed back to a group separator and were reused in power fluids.

- Reservoirs are in the Mt Messenger geological formation (lies below the Matemateonga formation the upper part of which has the freshwater/salt water interface).
- Modelled maximum fracture fissures extent at 1750 m was less than 50 m within the reservoir.
- Freshwater/salt water interface for the wells is 200-500 m below the surface in the Matemateonga Formation. (Council data from an old exploration well close by Stratford notes it is about 600 m in the Matemateonga Formation which is consistent with the maximum depth estimate by Tag Oil Ltd).
- In view of the above data, the distance from the top of fracture fissures in the reservoir to the freshwater/saltwater interface is about 1100 m (1700-600=1100 m). Within this zone are numerous "geologic seals" (interbedded claystone and sandstone layers) to provide protective separation between fracturing and freshwater aquifers in the Matemateonga Formation above and, therefore, minimize any potential impact from hydraulic fracturing operations.
- Return fluids were reused or taken off site and deep well injected at depth into saline zones under a resource consent. Water produced with the hydrocarbons (termed 'produced water') contains some fracture fluids that are "leached" out of the formation. It is used with other produced water from the reservoir and imported water in power fluid which is heated and circulated through the reservoir to enhance oil recovery. Any excess power fluids are deepwell injected under a resource consent.

Origin Energy NZ Ltd has supplied information on hydraulic fracturing undertaken by Swift Energy Ltd to the Council. Origin Energy Ltd purchased Swift Energy Ltd in 2008. The fracturing undertaken at the Manutahi well site (Table 3) in 2005 comprised:

- A diesel based fracture fluid system. The Frac/Pac design was used whereby resin coated sands are pumped into the formation via well perforations and act as a filter to control production of formation sand.
- The fracture fluids for both wells comprised 99 % diesel and 1 % additives (GO-64, XLO-5, NE-110W, GBO-9L, SuperSetP). MSDS sheets for additives in Appendix I.
- 3919 kg 16/30 PolarProp used for Manutahi A1 and 5,300 kg PolarProp used for Manutahi B1.
- Maximum surface pressure used 1666 psi during treatment and 2749 psi at screen- out (the packing of the sand) for A1 well and 2165 psi during treatment and 2338 psi at screen-out for the B1 well.
- Volume of diesel/fracture fluids 56 cubic metres for A1 well and 74 cubic metres for the B1 well.
- Volume of produced back fluids 56 cubic metres for the A1 well and 74 cubic metres for the B1 well.
- Fracture fluids were reused or produced back through the processing plant during production testing.
- Manutahi A1 well casing was perforated at 1157-1179 mTVD. A fracture length of about 8.5 m and a fracture height of about 9 m were achieved.
- Manutahi B1 well casing was perforated in the 1160 - 1175 mTVD range. A fracture length of about 14 m and a fracture height of about 12 m were achieved.
- Both wells had cement bond logs run after cementing the final casing string which indicated that the cement over the formations was of good quality. In addition,

the tubing pressure and the A annulus pressure (tubing to casing annulus) were and are monitored during regular well testing to ensure well integrity.
- Petroleum hydrocarbon reservoirs in the Manutahi Formation (lies below the Matemateonga and Tangahoe Formations) and a coal measure above the reservoir in the Manutahi Formation in the 1116-1118 mTVD range.
- Resistivity logs indicate freshwater to 590 m followed by a transition to salt water in the 590- 900 m depth range. Hence the freshwater/salt water interface for the wells is considered to be about 900 m in the Matemateonga Formation with the Tangahoe Formation (a mudstone considered an aquitard) between this zone and the Whenuakura Formation (where aquifers are used for water supply purposes).
- Produced water levels and quality did not change pre- and post-fracturing. This indicates that reservoir integrity was maintained.
- Directly above the reservoir is a coal layer. During production and subsequent workover activities, there was no evidence of coal being observed. This indicates that the fractures did not extend beyond the reservoir.
- In view of the above data, the distance from the top of the fraccing fissures in the reservoir to the freshwater/saltwater interface is about 257 m (1157- 900= 257 m). Within this zone are numerous geological seals in the Manutahi and Matemateonga Formations to provide protective separation between fracturing and freshwater aquifers in the upper Matemateonga and Whenuakura Formations above and therefore minimize any potential impact from hydraulic fracturing operations.
- Both wells had cement bond logs run after cementing the final casing string which indicate that the cement over the formations is of good quality. In addition, the tubing pressure and the A annulus pressure (tubing to casing annulus) are monitored during regular well testing to ensure well integrity.

Hydraulic fracturing undertaken by Swift Energy, from 2001 to 2005, is described in a paper presented to a Society of Petroleum Engineers International conference. The paper concluded fracture treatments using oil-based fluids produced better hydrocarbon flows than treatments using water-based fluids. Preventing possible water damage to the formation is probably a major factor in this accomplishment (Green et al, 2006). Table 3 confirms that, with one exception, the fracture fluids were oil-based (diesel).

Greymouth Petroleum Ltd (GPL) took over the Ngatoro and Kaimiro fields from other operators (see footnote for Table 5) who had undertaken hydraulic fracturing in 6 wells. GPL was able to supply the following data about each hydraulic fracture from paper records held in storage. All of the wells had hydraulic fracture stimulations that could reasonably be classified as a fracpak. These are relatively small treatments designed to both increase well deliverability and reduce fine sand production from the wellbore.

The shallow fracturing undertaken at the Ngatoro and Kaimiro wells (Table 5) between 1989 and 2002 involved:

Ngatoro 1 Well

- Well drilled to a vertical depth of 4119m TVD.
- A water based frac fluid was used.

- Total volume water and fracture chemicals were about 68 cubic metres plus 11600 kilograms of sand proppant.
- KCL, Clayfix II, WG-19,HYG-3, Be-5,Lo Surf 357 were used as a additives with the fracture fluids.
- Fracture chemicals comprised less than 1% of the fracture fluid.
- Maximum surface pressure used was 2200 psi.
- Reservoirs are in the Mt Messenger Formation which is below both the Matemateonga Formation and the Tangahoe Formation (a significant sealing mudstone aquitard).
- Modelled maximum fissure propagation height was less than 15m in the formation at the depth of 1600-1657m TVD.
- Fresh water/saltwater transition zone base is shown on logs to be at 795m TVD.
- Distance from the top of fracture fissures in the reservoir to the fresh water/ saltwater is about 800m. Within this 800m there are multiple geologic aquitards providing physical barriers to migration increasing the improbability of contamination of fresh water by fracking fluids.

Ngatoro 7 Well

- Well drilled to a vertical depth of 2115m TVD.
- A water based frac fluid was used.
- Total volume water and fracture chemicals were about 76 cubic metres plus 11600 kilograms of sand proppant.
- KCL,Be-5, Clayfix,K-34,NF-5, WG-11,HYG-3,Lo Surf 357,GBW-30,WG-19,BC-140,SP-breaker,CAT-3 were used as a additives with the fracture fluids.
- Fracture chemicals comprised less than 1% of the fracture fluid.
- Maximum surface pressure used was 2500 psi.
- Reservoirs are in the Mt Messenger Formation which is below both the Matemateonga Formation and the Tangahoe Formation (a significant sealing mudstone aquitard).
- Modelled maximum fissure propagation height was less than 18m with in the formation with completions at the depth between 1602-1637m TVD.
- Fresh water/saltwater transition zone base is shown on logs to be at 775m.
- Distance from the top of fracture fissures in the reservoir to the fresh water/ saltwater is about 800m. Within this 800m there are multiple geologic aquitards providing physical barriers to migration increasing the improbability of contamination of fresh water by fracking fluids.

Ngatoro 9 Well

- Well drilled to a vertical depth of 1753m TVD.
- A water based frac fluid was used.
- Total volume water and fracture chemicals were about 50 cubic metres plus 88400 kilograms of sand proppant.
- KCL,Be-5, Clayfix II,K-34,FE-1A, WG-11,Lo Surf 357,GBW-30,BC-140,SP-breaker,CAT-3 were used as a additives with the fracture fluids.
- Fracture chemicals comprised less than 1% of the fracture fluid.
- Maximum surface pressure used was 2750 psi.
- Reservoirs are in the Mt Messenger Formation which is below both the Matemateonga Formation and the Tangahoe Formation (a significant sealing mudstone aquitard).

- Modelled maximum fissure propagation height was less than 18m with in the formation with completions at the depth between 1561-1586m TVD.
- Fresh water/saltwater transition zone base is shown on logs to be at 795m TVD by correlation to the Ngatoro-1 well.
- Distance from the top of fracture fissures in the reservoir to the fresh water/ saltwater is about 700m. Within this interval there are multiple geologic aquitards providing physical barriers to migration increasing the improbability of contamination of fresh water by drilling fluids.

Kaimiro 2 Well

- Well was drilled to a vertical depth of 2113m TVD.
- A water based frac fluid was used.
- Total volume water and fracture chemicals were about 50 cubic metres plus 9700 of sand proppant.
- Loser 300,Fe-1A,FR-20,KCL,Clay Stat XP,WG-11,BE-4,HYG-3,WG-11,K-34,Cl-11,SP-Breaker,Matriseal 2,WAC 12L were used as a additives with the fracture fluids.
- Fracture chemicals comprised less than 1% of the fracture fluid.
- Maximum surface pressure used to pump frac was 2450 psi.
- Reservoirs are in the Mt Messenger Formation which is below both the Matemateonga Formation and the Tangahoe Formation (a significant sealing mudstone aquitard).
- The formation of completions is at a depth between 1361-1378m TVD.
- Fresh water/saltwater transition zone base is shown on logs to be at 945m TVD.
- Distance from the reservoir completed to the fresh water/ saltwater is about 400m. Within this 400m interval there are multiple geologic aquitards providing physical barriers to migration increasing the improbability of contamination of fresh water by drilling fluids.

The MSDS sheets for the products used in the hydraulic fracturing described above are shown at the end of Appendix I.

In deeper hydrocarbon reservoirs (e.g., Mangahewa and Kapuni), fracturing has occurred at depths of 2- 5 km. These zones are separated from freshwater aquifers by even more extensive geological seals on the order of about 1.5—4 km thick depending on the exact location.

All the fracturing that has occurred in the region has occurred below sea level in saline geological formations (Figure 11).

5. Hydrogeologic risk assessment

If hydraulic fracturing operations are carried out properly, it is unlikely that contaminants will reach overlying freshwater aquifers in the Taranaki region. However, although unlikely it is not impossible. There are four potential routes for that to occur: (1) leakage from the hydraulic fracturing well casing due to defective installation or cementing; (2) leakage through the geology overlying the hydrocarbon reservoir; (3) leakage from improper handling of chemicals used in the process and from hydraulic fracturing wastewaters (i.e., flow back or produced water from the formation) brought back to the surface at the well site; or (4) a well blowout resulting in underground leakage into aquifers or surface recharge via spillage.

5.1 Leakage due to defective well installation/operation

Section 2 of this report described the installation of wells composed of steel casing cemented in place. Well construction involves the installation of a series of protective steel casings inside each other and cemented in place. They are specifically designed and installed to protect freshwater aquifers and to ensure the production zone is isolated from overlying formations as well as to avoid losing product and for the safety of wellhead facilities. Once the casing strings are run and cemented there are multiple barriers between the inside of the production tubing and water bearing formations (fresh or salt). The production tubing in the well provides access to the reservoir for fracturing and is designed to be able to withstand the pressures associated with the process. Figure 2 shows a typical well schematic and the conductor, surface, intermediate, and production casing.

Before a fracture job is undertaken a series of integrity tests are performed. The tests are designed to ensure that the well, well equipment and fracturing equipment are in proper working order and will safely withstand the application of fracturing treatment pressures and pump flow rates. The tests start with the testing of the well casings and cements during the drilling and well construction process. Testing continues with pressure testing of fracture equipment prior to fracturing (Todd Taranaki Ltd, 2011).

The fracture process is overseen continuously by operators and service companies to evaluate and document the events of the fracturing process. Every aspect of the fracturing process is carefully monitored, from the wellhead and down-hole pressures to the pumping rates and the density of fracture fluids. The monitors also track the volumes of each additive and the water used, and ensure the equipment is functioning properly. Tag Oil Ltd provided a post fracture treatment report, prepared by the fracturing contractor BJ Services Ltd, for the Council’s information to show the scope and results of monitoring and modelling that take place to ensure there are no unexpected or undesirable outcomes (BJ Services Ltd, 2010).

The potential for groundwater to be impacted by leakage from a hydraulic fracturing well that is properly constructed and operated is very small.

5.2 Leakage Through Geologic Media

Leakage of hydraulic fracturing contaminants through the geologic media overlying the petroleum hydrocarbon reservoir (i.e., the "geological seals") would require the migration of fluids (i.e., including hydraulic fracturing fluids with introduced and natural contaminants and petroleum hydrocarbon gasses) upwards through substantial thicknesses (as indicated in Tables 1-5, hundreds to thousands of metres in most cases) of naturally occurring low permeability geologic formations.

These "geological seals" act as natural barriers in the subsurface formations that hold the hydrocarbons in the reservoir. Without such seals, hydrocarbons would naturally escape to the earth's surface and deplete the petroleum hydrocarbon reservoir. These "geologic seals" also act as barriers to any potential vertical migration of fracture fluids upwards towards overlying relatively shallow freshwater aquifers. Fractures and faults within these "geologic seals" could provide pathways for upward movement. Some faults are known to exist in the region. However, these do not generally extend directly to the surface or from relatively deep petroleum hydrocarbon reservoirs into the relatively freshwater aquifers. Additionally, faults do not necessarily connect to or provide a pathway for the migration of fluids. The thicker these "geologic seals" are, the less likely they may be breached and allow upward migration of fluids from hydraulic fracturing operations.

Hydraulic fracturing involves the pumping of a fluid into a reservoir at a calculated predetermined rate and pressure to generate very small fractures or cracks. The process of designing fracturing treatments involves identifying properties of the reservoir including fracture pressure and the desired length of the fractures. Operators have strong economic incentives to ensure that the fractures they generate do not propagate beyond the reservoir and into adjacent rock strata. Allowing the fractures to extend beyond the reservoir would result in financial loss and could also result in the loss of the well and associated petroleum hydrocarbon resource. The length of the small fractures fissures can be modelled by fracturing contractors from fracturing data based on the physical properties of the reservoir. An example of this was provided by Tag Oil Ltd to the Council for inspection as discussed above (BJ Services Ltd, 2010).

As shown in Tables 1-5 and illustrated in Figure 11, hydraulic fracturing in Taranaki for the most part has occurred at depths deeper than 2,400 metres. Occasionally, fracturing stimulation of less deep reservoirs has occurred and the Council has looked at these more closely, as shown above, given the greater potential risk.

There have been five cases where hydraulic fracturing operations occurred at relatively shallow depths less than 2,400 m at the following wells: Manutahi (Table 3); Cheal (Table 4); Ngatoro (Table 5); and Kaimiro (Table 5). In the Ngatoro case there was still in excess of 700 m of "geologic seals" between the hydraulic fracturing zone and the freshwater aquifer. In the Kaimiro case there was in excess of 400 m of "geological seals" between the fracture zone the freshwater aquifer. In the Cheal case there was in excess of 1,100 m of "geological seals" between the hydraulic fracture zone and the freshwater aquifer. The Urenui Formation mudstones vary in thickness and form the regional seal for the Mount Messenger Formation. Where present the Tangahoe Formation lies between the Whenuakura and Koira and Matemateonga formations (Figure 6). The well log for the Kaimiro 1 well (Figure 8) shows the local geology for the Kaimiro and Ngatoro wells and the presence of the mudstone and siltstone “geological seals” above the limited fracture zones.

In the Manutahi case, the estimated separation between the hydraulic fracturing zone and the freshwater aquifer was 257 m. This is the least of any of the known operations listed in Tables 1 through 5. Immediately above the reservoir is 18 m of the Manutahi Formation. This includes a 2 m thickness of coal, and then the lower section of the Matemateonga Formation. The lower section of the Matemateonga Formation contains saline water. It is believed that these formations provide sufficient protection against transport of any fracture fluids through them into the freshwater aquifer. A variety of data supplied by Origin Energy NZ Ltd (referred to in Section 4) indicates that the “geologic seals” overlying this petroleum hydrocarbon reservoir have remained intact, validating this interpretation.

The available information indicates that for the hydraulic fracturing that has been undertaken in the Taranaki region to date there is no evidence that the natural “geological seals” above the petroleum hydrocarbon reservoir have been breached and even if they had been there would still be substantial thicknesses of low permeability geologic media protecting the overlying freshwater aquifers. However, from a risk perspective, the closer the hydraulic fracturing operations zone comes to freshwater aquifers, the greater the risk and the need for appropriate regulation. There are large separation distances between most past hydraulic fracturing activities and freshwater aquifers (Figure 11). There are geological seals that define the reservoir and multiple geological seals above to stop any contaminants from fracturing activities reaching freshwater aquifers. As an example, the well log for the Kaimiro-1 well shows multiple mudstones, siltstones and sandstone layers are present underground (Figure 8). The five relatively shallow fractures, by Petrocorp Exploration Ltd, New Zealand Oil and Gas Ltd (with both companies well sites now operated by Greymouth Petroleum Ltd), Tag Oil Ltd and Swift Energy Ltd (now Origin Energy Ltd) were investigated in more depth (see Section 4) and considered not to pose a risk to freshwater aquifers above.

In order for hydraulic fracturing to result in an impact on freshwater aquifers in the Taranaki Region, it would be necessary for a combination of independent events to occur simultaneously and go undetected. These include multiple leaks in the various casings and production tubing (Figure 2) coupled with the unlikely occurrence of fluids moving long distances upward out of the salt water zone to reach a freshwater aquifer. Such a combination of adverse events is considered extremely unlikely.

Water quality testing of groundwater and streams closeby the Cheal well has been undertaken in response to some local concerns and no contaminants associated with the hydraulic fracturing process found. Similar sampling at Manutahi has been undertaken as a precautionary measure. Sampling is planned for the Ngatoro and Kaimiro well sites, where shallow hydraulic fracturing also occurred, again as a precautionary measure, and all the sampling results will be presented to the community on the Council’s website

In view of the following factors specific to Taranaki Region geology, the risk of upward leakage from petroleum reservoirs through geologic media as a result of hydraulic fracturing operations is considered very small:

1. The depth of hydraulic fracturing is generally relatively deep compared to the depth of freshwater aquifers;
2. The technology to properly design and install wells exists and there are methods that allow checking of the integrity of the well installation;
3. Petroleum hydrocarbon reservoirs have natural overlying "geologic seals" that trap the gas in place; and
4. There are substantial thicknesses of low permeability geologic materials separating petroleum reservoirs from overlying freshwater aquifers.

5.3 Leakage or Improper Handling of Chemicals and Wastewaters

It is standard procedure at well sites to have some type of containment for holding drilling fluids and wastes. Originally, containment consisted of unlined pits dug into the ground. More recently, if pits are used, they are lined to prevent leakage and, depending on the wastes involved, steel tanks for an improved level of containment may also be required.

The chemicals used in the hydraulic fracturing process are stored on site and must meet EPA requirements (e.g., concerning bunding, separation and safety). The monitoring of EPA requirements in the workplace is the responsibility of the Department of Labour. Improper storage and use of chemicals could result in contaminants reaching freshwater.

The wastewaters involved in the case of hydraulic fracturing operations include flowback of hydraulic fracturing fluids and produced formation water. As noted by Ground Water Protection Council and Interstate Oil and Gas Compact Commission (2011) "The containment of fluids within a pit is the most critical element in the prevention of contamination of shallow ground water. The failure of a tank, pit liner, or the line carrying fluid ("flowline") can result in a release of contaminated materials directly into surface water and shallow ground water."

Contained wastewaters ultimately require treatment to appropriate standards and discharge, deep-well injection, or re-use in hydraulic fracturing or other well field operations. Proper disposal "is critically important to the protection of both surface and ground water" (Ground Water Protection Council and Interstate Oil and gas Compact Commission, 2011).

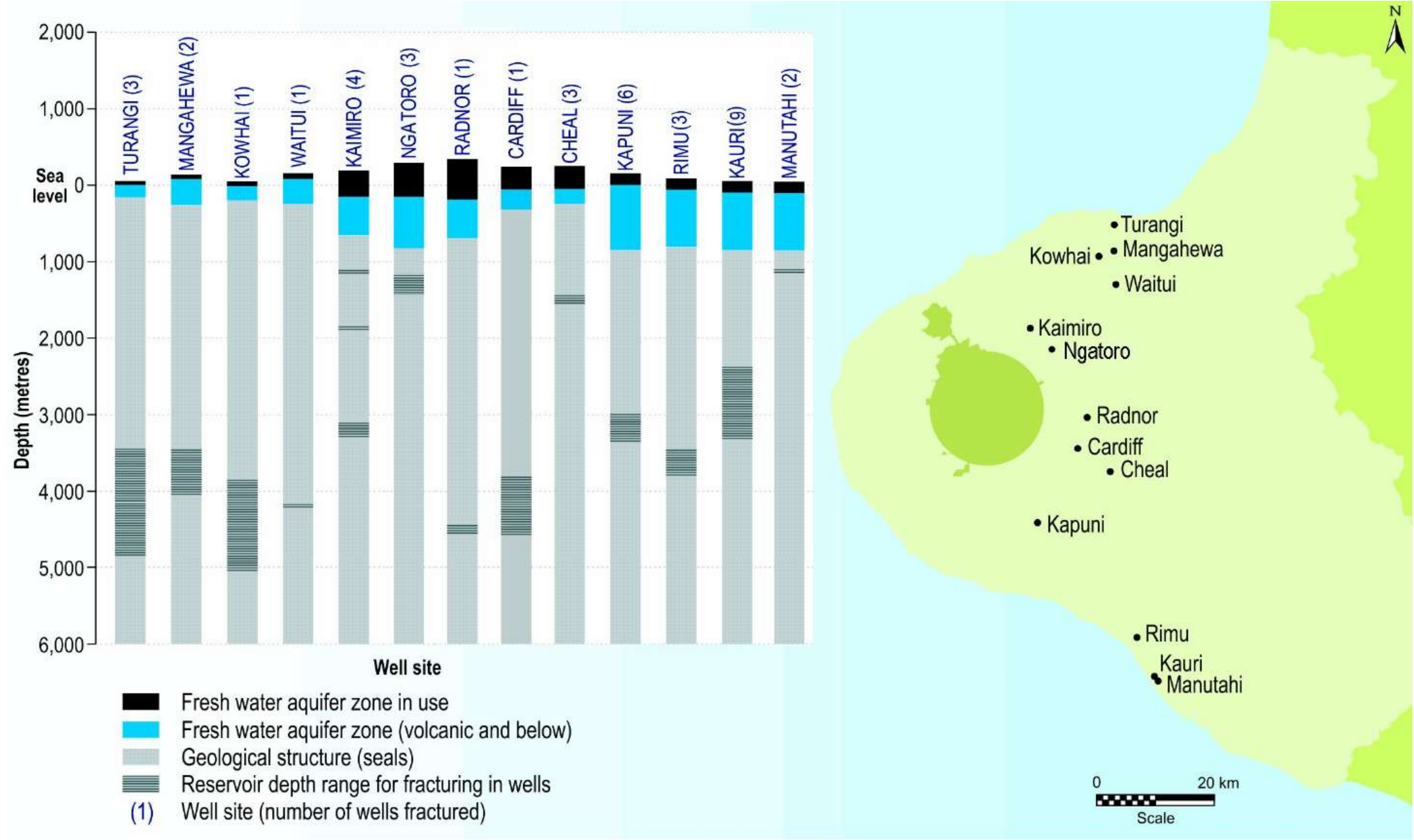


Figure 11 Hydrogeological summary of hydraulic fracture activities described in Tables 1-5.

5.4 Well blowouts

"Well blowouts are variously defined as 'uncontrolled flow of well fluids and/or formation fluids from the wellbore' or 'uncontrolled flow of reservoir fluids into the wellbore'" (Jordan and Benson 2009). A well blowout may occur during any phase of oil and gas well operations, but the risk of a blowout is highest during tripping and drilling activities (Grottheim 2005). There are several types of blowouts that may occur. With respect to onshore sites, the two types of concern are surface and underground. With regard to potential impact on shallow freshwater aquifers, in the former case formation fluids reach the surface and may result in contamination through surface recharge while in an underground blowout formation fluids generally flow from lower high pressure stratum to shallower low pressure ones (Valleyo-Arrieta 2002).

Reliable statistics on well blowouts and particularly with regard to gas wells undergoing hydraulic fracturing appear to be elusive. What data are available indicate that the probability of a blowout has decreased as oil and gas industry operational methods have improved over the years (Jordan and Benson 2009). Nevertheless, they still occur. Data also indicate that the probability of kicks and, therefore blowouts if kicks are not controlled increases with an increase in drilling depth (Grottheim 2005). General statistics for oil and gas production in the central valley of California, indicate that the rate of blowouts for the period 2001-2008 in which 16,400 wells were drilling was very low both in terms of either the number of well years (i.e., 1 per 5,200 wells) or drilling distances (1 per 13 million feet) (Jordan and Benson, 2009). The applicability of these statistics to the circumstances of the drilling, hydraulic fracturing, and production of gas wells in the Taranaki Region is uncertain. If they are illustrative, given the relatively small number of wells involved they indicate a very low probability of a blowout. Although the probability of a blowout may be very low, it cannot be completely discounted. Blowouts have occurred during hydraulic fracturing operations in other countries.

6. Regulation of fracturing under the Resource Management Act

Whether or not a consent should be required for the discharge of hydraulic fracturing fluids to deep petroleum hydrocarbon reservoirs in the Taranaki region is a matter of varied opinion. The Council has recently obtained a legal opinion specifically on this matter.

In summary, the legal opinion notes that the situation is complex, but the Council could require a resource consent for the activity of fracturing on the grounds that it is a discharge of contaminants (energy, chemicals, water, proppant) to land , albeit at depth, from an industrial or trade premise as per section 15 1 (d) of the RMA. While the Council's Regional Fresh Water Plan (2001) does not specifically address the activity, a catch all rule (Rule 44) allows the Council to process hydraulic fracturing discharge applications as a discretionary activity under the RMA if deemed necessary.

To avoid any doubt, the Council has adopted a conservative approach and informed the industry in late-July 2011 that a resource consent would henceforth be required for hydraulic fracturing (i.e., the discharge of fracturing fluids to land). Each application will be assessed on its merits. Given an application for hydraulic fracturing at considerable depth would likely meet the "no more than minor adverse environmental effects" and the "no affected party" tests in the RMA, the application could legally and properly be non-notified. There is public interest in hydraulic fracturing from some limited quarters but this does not mean that these interest groups are affected parties to a resource consent application as recognised pursuant to the RMA.

An information sheet on the assessment of environmental effects information requirements for those making fracturing discharge applications will be prepared. As well as meeting the fourth schedule requirements of the RMA for an assessment of environmental effects, applicants will provide material that demonstrates the integrity of the well (i.e., that it has been designed and constructed in accordance with good practices and found through appropriate checks to meet applicable standards), the existence of "geologic seals" above and below the hydraulic fracturing interval, and that the appropriate safeguards are in place. The monitoring that is to be undertaken by the applicant should also be outlined. The Council will also conduct its own monitoring and auditing programme in each case.

Under the Council's Regional Fresh Water Plan (2001) the drilling and construction of a hydrocarbon exploration or production well is a permitted activity under Rule 46. The key standard that must be met requires all wells to be cased and sealed to prevent the potential for aquifer cross-contamination. This essentially requires appropriate casing and cementing programmes to be in place to ensure protection of freshwater aquifers.

To ensure the integrity of the well and avoid contamination of groundwater, including aquifer cross-contamination , there are generally a number of safety measures in place including: (1) using reservoir knowledge and staff expertise (pressure testing and a qualified/experienced well team); (2) well design (casing and cementing programmes), ensuring well integrity (pressure testing and corrosion management); and (3) the application of industry standards (e.g., American Petroleum Institute Standards).

Compliance monitoring programmes for the subsurface discharge of fracture fluids will be developed and could include groundwater monitoring of nearby wells/bores to document conditions prior to fracturing (i.e., establishment of baseline water quality), and afterward. This will allow assessment of potential water quality impacts based on site-specific data. Monitoring will include dissolved methane, major ions, and other specific chemical constituents likely to be present in hydraulic fracturing or formation fluids.

The regulation of the activity will be further specifically considered in the review of the Regional Fresh Water Plan (2001) that is currently being undertaken by the Council.

7. Conclusions

The oil and gas companies that have undertaken hydraulic fracturing operations in Taranaki have provided data for the above investigation and assessment. The operations have occurred between 1989 and mid-2011. All but Greymouth Petroleum Ltd provided the data without reservation, with the latter data provided on a without prejudice basis. The Ngatoro well (1, 7, & 9) and the Kaimiro well (1, 2, & 3) data was provided without reservation by Greymouth Petroleum Ltd.

Considering the depths involved (of both hydraulic fracturing operations and freshwater aquifers), the limited scale of hydraulic fracturing currently occurring, the integrity of the well casing, the integrity of the natural reservoir geologic seals, and the nature of the multiple natural geological seals between the petroleum hydrocarbon reservoir and any freshwater aquifer, there is no evidence that hydraulic fracturing operations for gas production conducted in the Taranaki Region between 1989 and mid-2011 have involved any substantial adverse impact on groundwater quality. Assuming hydraulic fracturing operations are properly designed and conducted in the future, there is little potential for any in the future. The situation with regard to historical hydraulic fracturing operations is summarized in Figures 10 and 11, which generally show large thicknesses of low permeability natural materials between past hydraulic fracturing activities and freshwater aquifers.

Although it is not possible to eliminate all risk, the risk that properly conducted hydraulic fracturing operations could adversely affect freshwater aquifers in the Region is considered very low. It can be maintained low through adherence to good technical practices by industry and regulatory control by the Council. From a risk perspective, the closer hydraulic fracturing is conducted to freshwater aquifers the greater the potential risk. The Council has decided henceforth to require resource consents for all hydraulic fracturing discharges to land at depth beneath the Region and will process these in accordance with the requirements of the RMA.

The assessment has been peer reviewed by a Senior Hydrogeologist with the Institute of Geological and Nuclear Sciences Ltd (GNS Science). This GNS Science peer review supports the hydrogeological assessment and conclusions of the Council.

References

Allis, R.G; Zhan, X; Evans, C Kroopnick, P 1997. Groundwater flow beneath Mt Taranaki. New Zealand, and implications for oil and gas migration. New Zealand Journal of Geology and Geophysics 40.

API, 2009: Hydraulic fracturing operations- well construction and integrity. American Petroleum Institute Guidance Document HF1, First Edition, October 2009.

Bay J, 2011: Contract Strategies Ltd, pers comm, August/September 2011.

BJ Services Ltd, 2010: Post fracture treatment report Tag Oil Cheal B-HZ-1. A report prepared for Tag Oil by BJ Services Ltd, November 2010.

Cuadrilla Resource Holdings Ltd, 2011: Memorandum submitted by Cuadrilla Resources Holding Ltd (SG 08), May 2011. Internet site, www.publications.parliament.uk , accessed November 2011.

EPA, 2004: Evaluation of Impacts to Underground Sources of Drinking Water by Hydraulic Fracturing of Coal-bed Methane Reservoirs National Study and final report. United States Environmental Protection Agency, June 2004.

Evans C, Murray D., 1998: Extent of Groundwater Aquifers in the Whenuakura Formation of South Taranaki. Taranaki Regional Council & University of Otago, July 1998.

Fleming, C.A 1953: The geology of Wanganui subdivision; Waverley and Wanganui sheet districts (N137 and N138). New Zealand Geological Survey Bulletin 52.

GNS 2008: Geology of the Taranaki area, scale 1:250,000. Compiled by D Townsend, A Vonk and P J J Kamp. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 7. GNS Science, Lower Hutt.

Green D, Seanard K, Martin A N, 2006: Hydraulic fracturing of Miocene and Oligocene sandstones in the Taranaki Basin, New Zealand. Society of Petroleum Engineers International 2006, SPE 101121.

Grottheim, O.E. 2005. Development and assessment of electronic manual for well control and blowout containment. MS Thesis, Texas A&M University, College Station, TX, 146 pages.

Huckerby J, 1998: Mangahewa gas programme. NZ Petroleum Conference Proceedings 30 March- 1 April 1998.

Ground Water Protection Council and Interstate Oil and Gas Compact Commission. 2011. Hydraulic fracturing, how it works. Fracturing fluid management. Frac Focus: Chemical Disclosure Registry internet site, http://fracfocus.org, accessed October 2011.

Jordan, P.D. and S.M. Benson. 2009. Well blowout rates in California Oil and Gas District 4 – update and trends. Exploration and Production Oil & Gas Review, Vol. 7, Issue 2, pages 59-65.

King P.R. and Thrasher, G.P. 1996. Cretaceous-cenozoic geology and petroleum systems of the Taranaki basin, New Zealand. Monograph 13, GNS Science, Lower Hutt, 244 pages.

L & M Energy, 2011: Company announcement to explore South Island shale plays. Company announcement, 24 June 2011.

Ministry of Economic Development 2004: New Zealand's Petroleum Basins. Published by Crown Minerals, Ministry of Economic Development, Wellington.

Ministry of Economic Development 2012: Some limited data from their files for hydraulic fracturing undertaken in the Kaimiro 1,2, & 3 wells, by Petrocorp Exploration Ltd, and Ngatoro 1,7, & 9 wells, by NZOG Ltd.

Ridley M, 2011: The Shale Gas Shock. The Global Warming Policy Foundation Report 2. ISBN: 978-9566875-2-4.

Stevens 2001: Groundwater of New Zealand- Chapter 18. NZ Hydrological Society report edited by M Rosen and P White, 2001, ISBN 0-473-07816-3.

Swackhammer, D.L. and D.A. Dzombak. 2011. SAB review of EPA's draft hydraulic fracturing study plan. Letter dated 4 August to L.P. Jackson (USEPA Administrator). Science Advisory Board, USEPA, Washington, DC, 3 pages.

Taranaki Geological Society, 1993: Field Guide to Taranaki Geology, Taranaki Branch of the Geological Society of New Zealand. Geological Society of New Zealand Inc. Misc Series Publication No. 64.

TRC, 1996: Groundwater Resources of the Taranaki Region. Taranaki Regional Council, 1996.

TRC, 2003: Taranaki- our place, our future; report on the state of environment of the Taranaki Region- 2003. Taranaki Regional Council, 2003.

TCC, 1984: Groundwater Hydrology-Taranaki Ring Plain Water Resources Survey. Taranaki Catchment Commission, 1984.

Taylor C.B. and Evans C.M., 1999: Isotopic indicators for groundwater hydrology in Taranaki, New Zealand. Journal of Hydrology (NZ) 38(2), pp237-270.

Thompson C S, 1981: The Climate and Weather of the Taranaki Region. Ministry of Transport New Zealand Meteorological Service, Wellington, 1981.

Todd Taranaki Ltd, 2011: Resource Consent application to the Taranaki Regional Council for Mangahewa D well site hydraulic fracturing. Application prepared by BTW Company Ltd 23 August 2011.

Townsend, A Vonk and P.J Kamp. GNS, 2008: Geology of the Taranaki Area. GNS, 2008.

U.S. Department of Energy, 2009: Modern shale gas development in the United States: A primer. U.S. Department of Energy, Office of Fossil Energy National Energy Technology Laboratory, April 2009.

Vallejo-Arrieta, V.G. 2002. Analytical model to control off-bottom blowouts utilizing the concept of simultaneous dynamic seal and bullheading. PhD Dissertation, Louisiana State University, Baton Rouge, LA, 202 pages.