Deep Groundwater Characterisation and Monitoring of a UCG Pilot Plant

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Abstract

Underground Coal Gasification (UCG) is an emerging mining technology that has the potential to allow low cost access to energy from coal that is currently not technically or economically accessible by existing mining methods. As such it offers significant potential to dramatically increase the world's recoverable coal resource.

Between 2005 and 2012 Solid Energy investigated the potential of UCG to complement existing mining methods while facilitating access to un-minable coal resource. Pattle Delamore Partners (PDP) provided consenting, hydrogeological and environmental monitoring support to Solid Energy throughout the project.

In order to manage the technical and commercial risks of applying UCG in the New Zealand geological and environmental setting, a staged gate project development approach was implemented. The first stage involving scoping and feasibility studies was completed between 2005 and 2008. This was followed by the second stage, a pilot plant, designed, constructed, operated, shutdown and rehabilitated near Huntly between 2009 and 2013.

A key project objective was the demonstration of acceptable lifecycle environmental effects of a UCG plant operating in the local geological environment. This paper presents an overview of the water related environmental challenges and resulting strategies surrounding the development, operation and monitoring of the Huntly UCG pilot plant. In particular it focusses on the unique deep groundwater characterization and monitoring that was undertaken. The construction of a conceptual regional hydrology model allowed an effective monitoring plan to be developed. A stacked array of multiple aquifer pressure and water quality measurements in a single monitoring well was designed and implemented to maximize data collection at least cost to the project. Key aspects of the data quality assurance programme are described followed by key results and authors' conclusions. This rigorous approach and execution allowed the less than minor environmental effects of the pilot plant operation to be demonstrated.

Keywords: UCG, monitoring, groundwater, piezometer.

Introduction

Underground Coal Gasification (UCG) is a method of extracting the energy from deep coal that is not mineable by conventional methods. It involves constructing an array of wells or channels within a coal seam and then injecting air or oxygen and igniting the coal. The operation is carried out below local hydrostatic pressure with the oxygen and water influx from the coal seam reacting at temperature with the coal to form methane, carbon dioxide, hydrogen and other minor gases. These are brought to the surface for treatment and then used as a chemical feedstock, for energy, or a combination of these.

UCG has been under development internationally since the 1930s without delivering on its potential, however advances in drilling techniques and changes in the predicted price and availability of oil and gas led to a renewed interest in the technology from the early 1990s. After an in-depth evaluation with a view to providing future energy options, Solid Energy made the decision to undertake a UCG pilot trial and chose the Huntly coalfield as the preferred site. The key technical aims of the pilot plant were:

- To investigate the suitability of the technology in New Zealand's complex geological setting
- To provide data for technical and commercial models to evaluate full scale operation

Understanding the issues around the hydrogeology was key to achieving both of these aims. It is imperative that the process can be conducted without harm to the environment at all points in the operations life-cycle. Of particular importance is protecting the overlying, widely used Tauranga Group aquifer from any harm whether that be by depletion or by contamination. As water plays a crucial role in the reactions and heat balances within the gasifier it is also critical to understand water influx rates and how these will change with time as this can affect gas quality and yields, the percentage of coal accessed and gas and water treatment costs.

Project Hydrogeological Environment

One of the key advantages of operating in the Huntly coalfield, and an important factor in its selection, was the large amount of knowledge that the company had accumulated regarding the geology and hydrogeology of the region. This came from:

- Coal exploration
- Huntly East underground mine
- Rotowaro open cast mine
- A small, previous CSG pilot operation to the north of the UCG plant
- Historical data on the Huntly West underground mine.

The Hydrogeological Units are shown in Figure 1 and Figure 7 below:

Aquifer/Aquitard	Nature of Aquifer	Thickness Range (m)	Aquifer Hydraulic Conductivity (m/day)	Aquifer Transmissivity (m^2/day)	Aquifer Storativity	Confined/ Unconfined	As shown on Hydrogeology Sections
Tauranga Group Aquifer	**Sand and gravel sediment – lensed and channelised. Inter-fingered with silt and clay sediment.**	**<5 - 60**	**0.43 – 17.3**	**10 – 300**	**0.001 – 0.2**	**Semi-confined to Unconfined**	**Tauranga Group Aquifer**
Whaingaroa Siltstone Aquitard		0 - 200					Aquitard
Ahirau Sandstone Aquifer	**Fractured Sandstone**	~30 – 50 (total)	**0.001**	**0.01**	**0.0001**	**Confined**	**Glen Massey Aquifer**
Dunphail Siltstone Aquitard							
Elgood Limestone Aquifer	**Fractured Limestone**						
Rotowaro Siltstone Aquitard		50 – 80					Aquitard
Pukemiro Sandstone Aquifer	**Fractured Sandstone**	**5 - 25**	**0.01**	**0.1**	**0.0001**	**Confined**	**Pukemiro Aquifer**
Glen Afton/WCM Claystone Aquitard		25 - 60					Aquitard
Coal Seams Aquifer	**Fractured coal seams**	**10 -20**	**0.012**	**0.19**	**0.0001**	**Confined**	**Coal Seams Aquifer**
WCM Fire Clay/Weathered Greywacke Aquitard		~0.5 - 10					
Basement Greywacke Aquifer	**Fractured siltstone and sandstone**	**>1000**	**0.01 – 0.001**	**>5**	**nd**	**Confined**	**Greywacke Aquifer**

Figure 1. Huntly coalfield hydrogeological units.

The data from existing and historical mining enabled comprehensive mapping of the regional groundwater pressure gradients and this was one of the key inputs into design of the monitoring system. Two further elements were apparent from this study:

1. The shallow Tauranga Group aquifer was characterised by a flow from east to west, generally towards the natural drainage channels following the topography.

2. The coal seam and deeper aquifers were characterised by a flow towards the east where Huntly East mine provided a sink as shown in Figure 2.

The second key element affecting the hydrology in this region is the effect of local faulting. A high resolution 3D seismic survey was carried out over an area of approximately one square kilometre to indicate any faults with greater than 2m of vertical throw. This provided an indication where faults could provide a barrier to flow across or a conduit for flow parallel to the fault. Local faults identified from an interpretation of the 3D seismic data are shown in Figure 3.

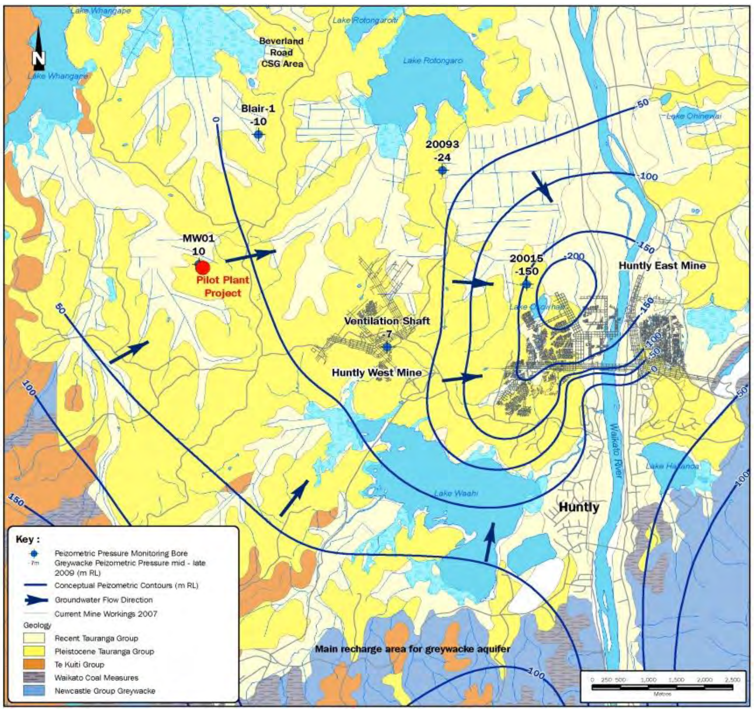


Figure 2. Local coal groundwater piezometric contours

Monitoring System Design

The groundwater monitoring system was designed to not only detect any contamination occurring, but also rigorously prove that the pilot had been conducted with no detrimental effects particularly to the shallow Tauranga Group aquifer. To this end it was decided to sample from aquifers above and below the coal seam in addition to the coal seam itself and the Tauranga Group. It was also critical to ensure that the process of taking the measurement did not affect the measurement; this is very difficult in low permeability and storativity aquifers where the flow induced by the sampling creates pressure differences and flows that are significantly different from the natural environment.

The deep monitoring wells were designed to maximise the information gained from a single well due to the large hole depths of up to 400m below ground. Immediately after drilling the well was geophysically logged to accurately detect the position of the lithological boundaries down the hole. A string, consisting of four low-flow bladder pumps and seven vibrating wire piezometers or piezometer geophone combined units, was attached to a weighted stainless steel wire at precisely measured locations corresponding to the boundaries determined from the logs. This was lowered into the well, grouted to the lowest point where a water sample was required, and left to set. A 1.5m long gravel pack was then installed followed by a small amount of blinding sand followed by grout up to the next sampling level. This was repeated until the final instrumentation set that included a pump was installed after which the well was fully grouted to surface. As the coal aquifer was considered the most important to monitor, two pumps were installed in this aquifer to allow for some redundancy. Single pumps were installed in a fractured basement zone and in the Pukemiro aquifer. As installation progressed the Pukemiro aquifer was found to have very low storativity and it was not possible to get samples from some of the wells. Additional sampling was installed in the Glen Massey aquifer to compensate for this. These were simple cased wells employing a bladder pump and pressure transmitter below a packer. All piezometers were connected to solar-powered wellhead dataloggers which connected wirelessly to the main control and monitoring system.

In plan view the monitoring layout included two rings of monitoring points:

- An inner ring that would be close enough to the gasifier to register pressure events and any movement of gasification products in the immediate vicinity during operation and then show these reducing after operation.
- An outer ring that would prove any effects did not extend beyond a halo around the gasifier.

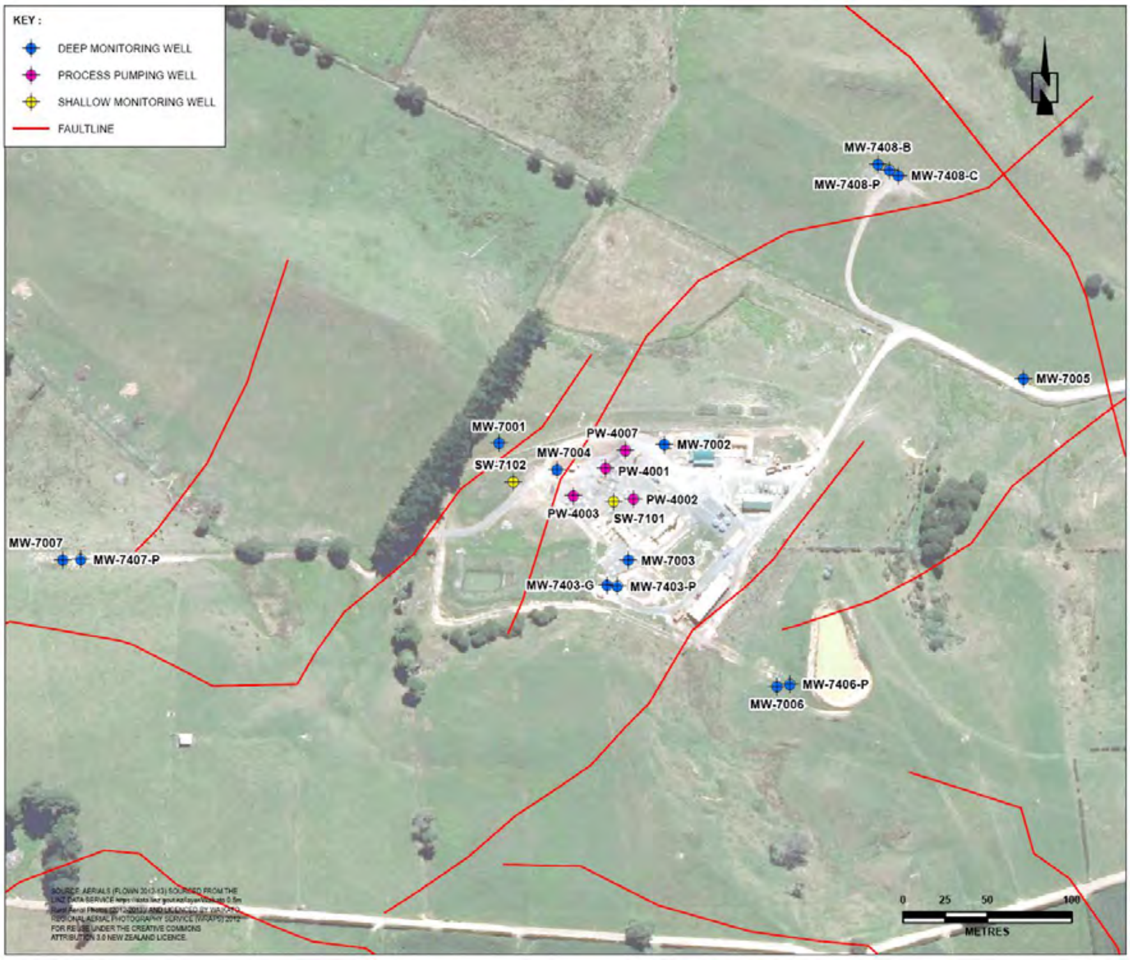


Figure 3. Position of monitoring wells and faults

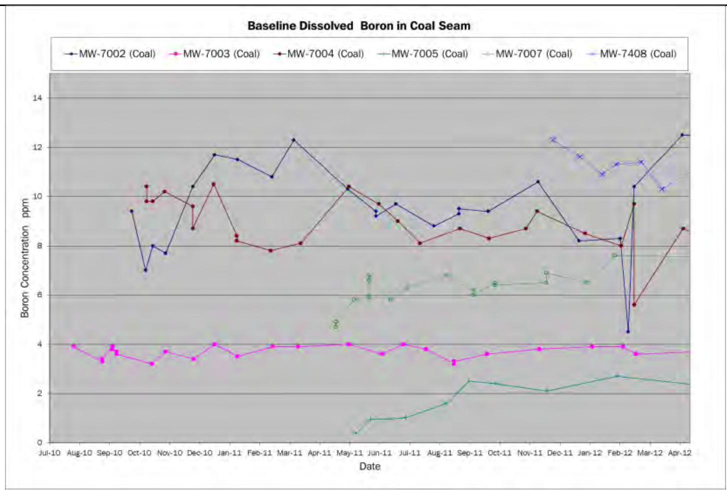
In addition a survey of all the surrounding farm water bores (location and the depth) and location of springs was undertaken and a set of bores was identified for routine sampling. This was an excellent investment in relationships with the local landowners as it provided an opportunity to discuss with them the results and offer insight into the performance of their wells.

Figure 4. Farm bore monitoring positions

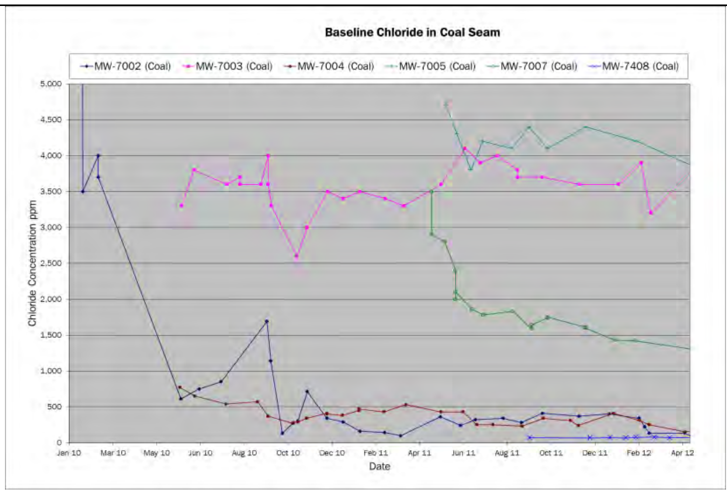
Baseline Monitoring

To meet the aim of demonstrating no environmental effects it was critical to establish definitive baseline water quality data. It was thought that a single value with relatively narrow bounds for variation could be quickly established for each of the aquifers. However, because the deeper aquifers are not contiguous, it was found that some of the key constituents varied considerably from location to location and also over time. This is illustrated in Figure 5.

The Boron in the coal seam varied widely from well to well. As Boron is sourced from deep geothermal waters this is likely to be due to variations in the thickness and properties of the lower coal measures between the base of coal and the top of basement. The Boron concentration in the basement was consistent at approximately 10 ppm.



Chloride concentrations show not only a variation in the natural level from position to position but also considerable difference due to the legacy effects from drilling. Chloride based drilling muds were used to drill the wells and although extensive flushing was carried out in most cases some legacy remained.



Toluene concentrations in the basement were very low and are a good example of the problems associated with monitoring very low concentrations particularly if the allowable limits are very low. Prior to operation there were traces of Toluene in the basement and the coal. It appears that some of this could come from well drilling but there is also some small residual and variable concentration.

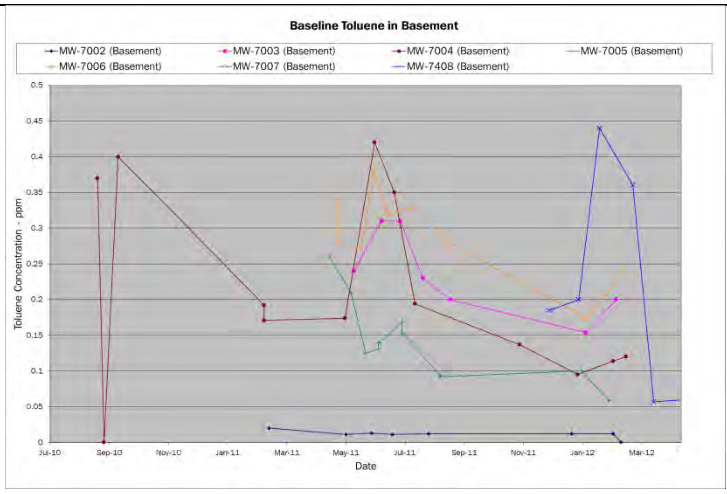


Figure 5. Baseline concentration examples prior to ignition

The Tauranga Group water from the dedicated sampling bores was less variable once the effects of drilling had dissipated. Only minor differences between wells sampling the lower units of the Tauranga Group and the upper units of the Tauranga Group were observed.

The farm bores showed unique signatures that persisted throughout the trial, interestingly these did not appear to be a function of bore depth or of location. All components from all Tauranga Group bores were well within drinking water guidelines.

A second key task was determining applicable testing suites and implementing a comprehensive quality control system covering the total process from the taking and transport of the samples through to the laboratory testing. Each laboratory result was checked by PDP before being released to Solid Energy or the Regional Council. It was also critical that the regulatory authority understood this procedure and the resulting time delay. The open and strong relationship that had been formed with Waikato Regional Council was important in obtaining their approval to this approach. To give a perspective of the scale of the sampling and measurements undertaken, over the course of the program 728 samples were taken from shallow wells, deep wells, local bores and production wells. These were analysed for multiple components resulting in excess of 50,000 individual results. The PDP quality control checking identified 80 of the 50,000 results which required rechecking; of these 22 required results amendment, an error rate of less than 0.05 percent. The reasons varied and included sample swaps, field contamination, dilution errors and sediment interference with no single error predominating.

Operational Results

Prior to operation a range of tests were conducted to more accurately determine the hydrogeological parameters of the coal seam and the way the surrounding lithologies responded to changes in pressure in the coal seam.

After the initial monitoring wells were installed a water injection test was carried out by injecting water into the coal seam at process well PW4001 in order to define the aquifer parameters at the UCG site. Prior to ignition two wells, PW4001 and PW4007 were connected hydraulically and the link was then dewatered. These two tests provided the limits for the possible responses throughout the strata to a wide envelope of possible operational pressures in the gasifier. The response of the inner ring of monitoring wells to both tests is shown in Figure 7 and Figure 7 below. Key conclusions that can be drawn are:

1. There is negligible response at the -185m RL level to either an overpressure or underpressure in the coal seam indicating that the Tauranga Group is unlikely to be affected by this range of operating conditions within the gasifier.
2. MW-7002 shows markedly higher connectivity to the gasifier than other wells. This was expected due to the coal cleat (jointing) orientation being close to the orientation between PW4001 and MW7002. Analysis of data from the water injection test showed a horizontal anisotropy factor of 5, between along and across cleat.
3. There appears to be increased connectivity to MW7002 in the injection as opposed to the drawdown test. This is caused by the opening of the cleats under pressure; detailed analysis indicated that this occurred at pressures over 150m excess water head.

These observations gave confidence that even during operational overpressure events such as Reverse Combustion Linking, there should be no effect on the upper strata particularly the Tauranga Group. It also indicated that MW7002 would be an extremely good sampling point to detect conditions around the fringe of the gasifer.

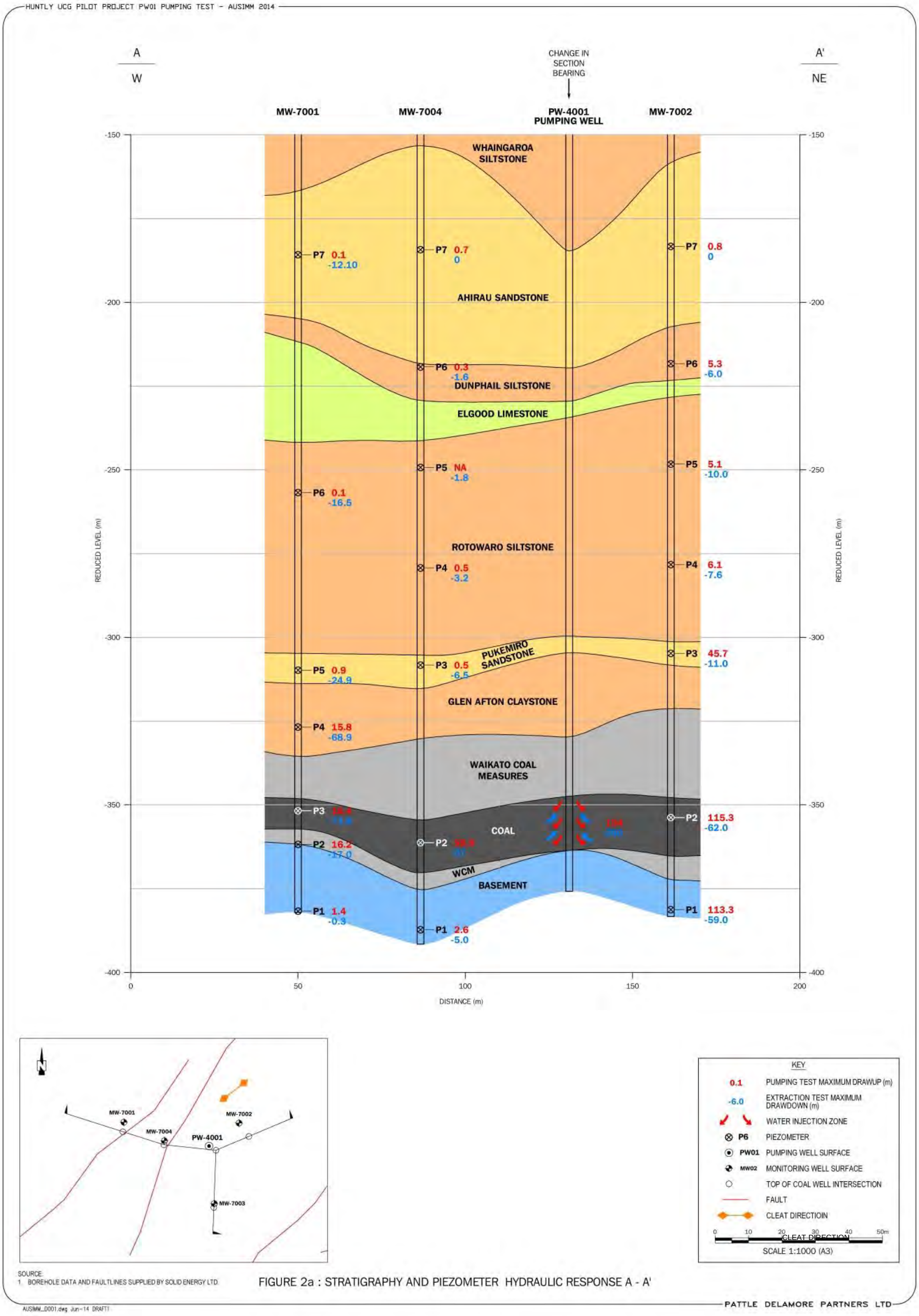


Figure 6. Piezometer response to preliminary testing - along cleat

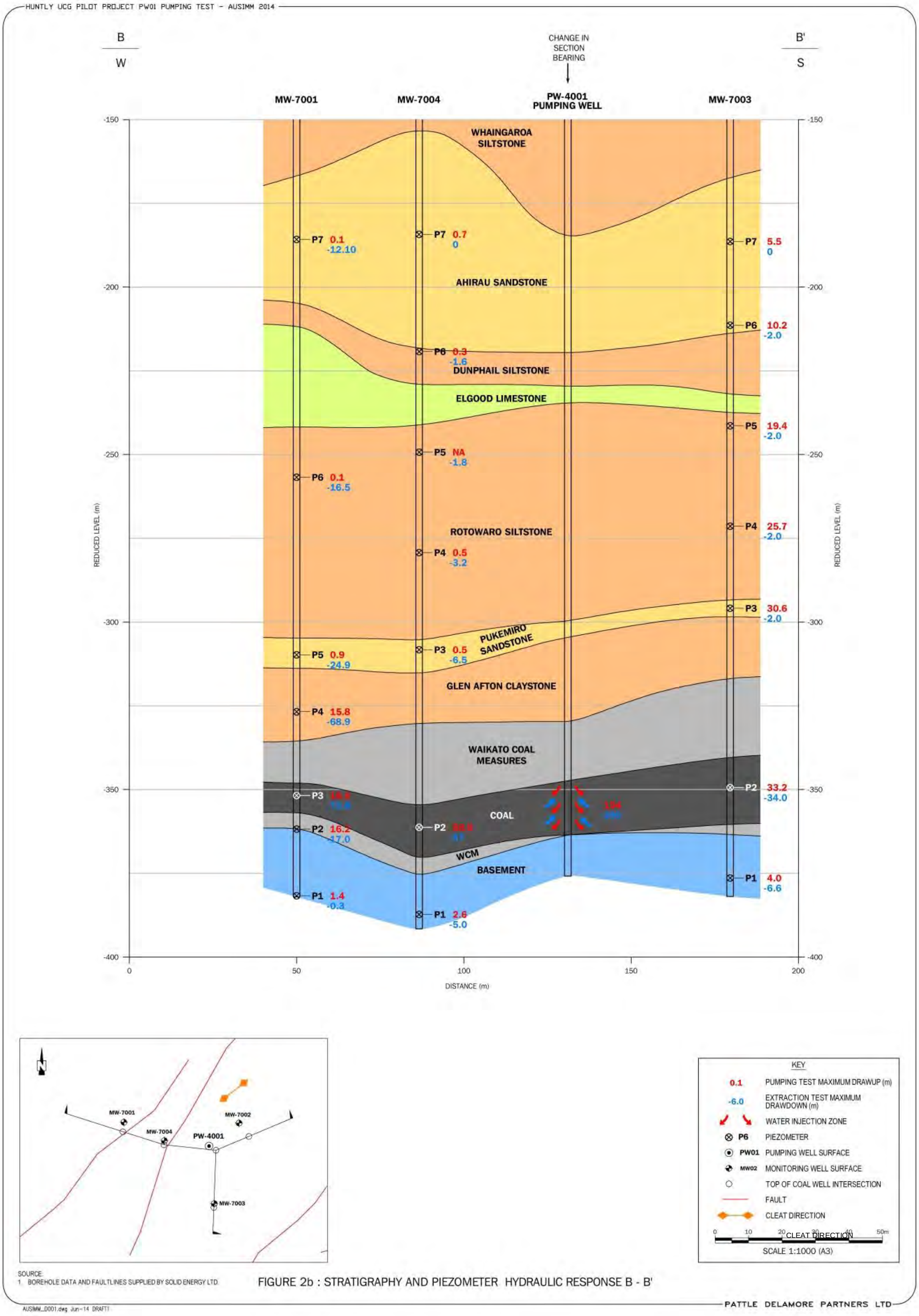


Figure 7. Piezometer response to preliminary testing – cross cleat.

Ignition at the base of PW4001 occurred on 12 April 2012. After a period of initial development between PW4001 and PW4007, PW4003 was linked in by Reverse Combustion Linking. This involved injecting high pressure air into PW4003 and encouraging the fire to follow the air supply and burn back towards PW4003. This was followed by a period of consolidation after which the more difficult cross cleat linking of PW4002 was attempted. Progress on this was slow therefore, as the pilot plant had met its major operational objectives, the plant was shut down on the 18th September 2012. This allowed the remaining issue of legacy effects to be proven.

After operations ceased and the underground cavity filled, water was abstracted initially by air lift and after the water had cooled sufficiently, by downhole electric submersible pumps. This water was analysed until the concentration of indicators of the effects of gasification had returned to near background levels at which point the site was abandoned.

Conclusions

The first and most important conclusion is that there were no detrimental effects on the groundwater in the Tauranga Group aquifer by either contamination or depletion. A spike in Dissolved Organic Carbon (DOC) was observed at the coal seam at MW7002 during a period of high pressure whilst linking PW4002, however, this quickly reverted to background levels once the pressure was reduced (Figure 8). Monitoring wells further away showed no response in any of the aquifers. Although a wide range of components were monitored, changes in DOC proved to be the most responsive indicator to the effects of gasification.

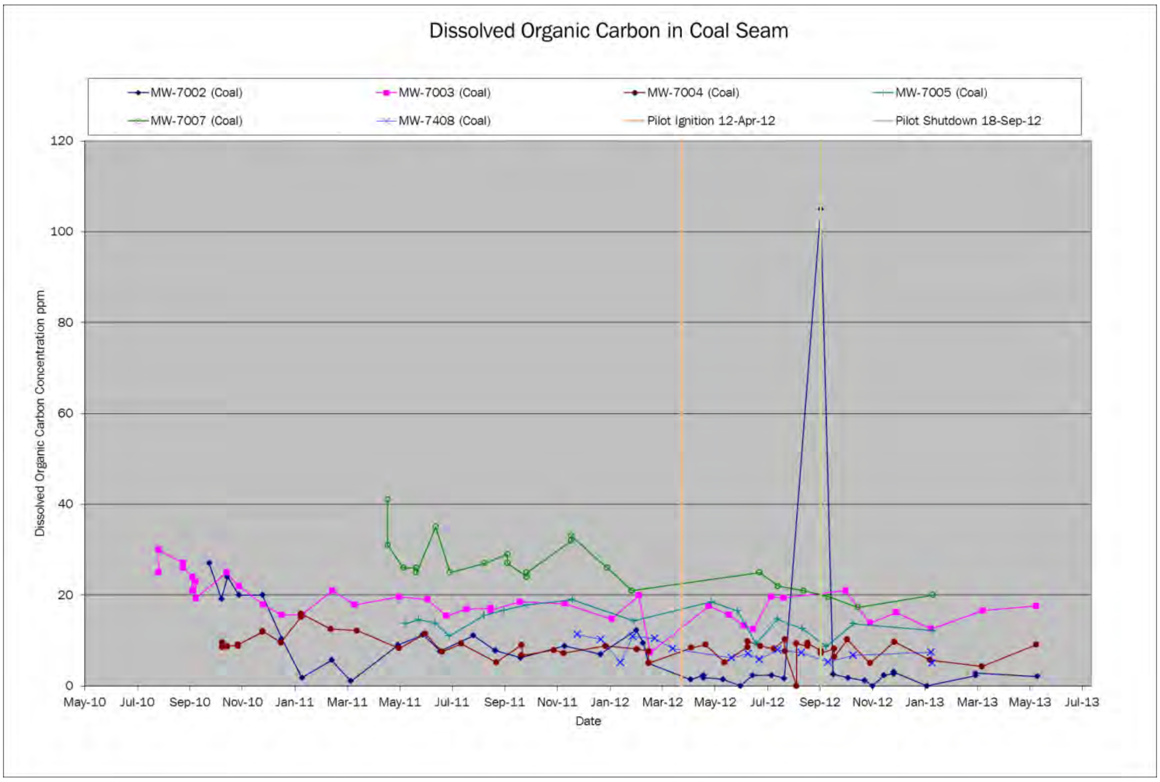
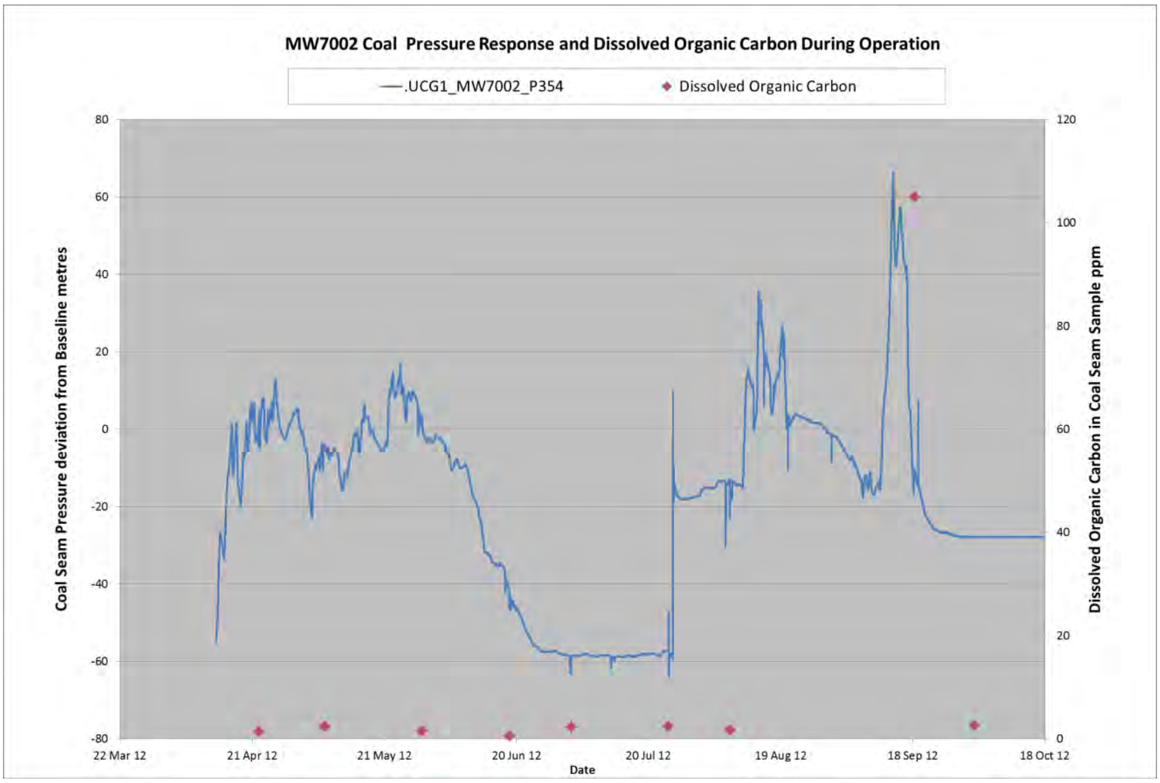


Figure 8. Changes in DOC in coal seam during operation.

The monitoring system also showed the benefits and potential of multiple string piezometers for detailed understanding and control of deep groundwater flows. They can be successfully coupled with low flow sampling apparatus and allow a more targeted and cost-effective sampling programme. In addition to the ability to accurately characterise the hydrogeology as detailed above, the operational benefits are clearly illustrated in `Figure 9 where the groundwater pressure spike causing the movement of liquids and thus an increase in DOC can be seen. This online pressure monitoring allowed corrective action to be taken immediately, rather than waiting two to three weeks for the results of the groundwater quality testing to identify the issue.



`**Figure 9.** MW7002 coal pressure response and DOC.

Finally, the piezometer array allowed the characterisation of the lithology response to pressure increase and decrease. Although the response in the Tauranga Group was very limited it became obvious that operations involving high pressure, such as Reverse Combustion Linking, are best avoided where possible. Although products of gasification were not transmitted to the Tauranga Group; the pressure gradient caused by extended operation at higher pressures could push liquid from the lower aquifers such as the Glen Massey into the base of the Tauranga Group. This would have a detrimental effect as the Glen Massey water is more saline than that in the Tauranga Group. If the programme had been continued, techniques such as horizontal drilling would have been utilised to remove the necessity for high pressure operation and allow more precise positioning of the channels within the coal both along and cross cleat.

Acknowledgements

This paper would not have been possible without the contributions of many other colleagues and associated sub-contractors. It was a very enjoyable site to work on because of a great team of dedicated people who cared about producing quality work, whatever their role. Thanks to all of you for assistance, encouragement and friendship.