High-precision depth-sequential groundwater quality sampling in the deeper subsurface

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ABSTRACT

Uncemented annuli of oil and gas wells have potential to promote contamination of aquifers. In Alberta, the base of groundwater protection is a depth where mineralization exceeds 4,000 mg/L TDS. If data are absent, 600 m is a common arbitrary choice. Surface casings of oil and gas wells must be placed to the base of groundwater protection, but older wells may not comply. Faced with these exact circumstances, an owner had two options: either implement costly and technically challenging repairs, or redefine the local protection base by obtaining actual mineralization data. Opting for the latter, a special program was devised for depth-sequential sampling to 600 m. Two objectives were thus: redefine the protection base by getting depth-sequential mineralization data and sample for possible contaminants.

RÉSUMÉ

Les espaces annulaires non-cimentés des puits pétrolifères représentent un potentiel de contamination des aquifères. En Alberta, la profondeur de protection des eaux souterraines correspond à la profondeur à laquelle la minéralisation excède 4000 mg/L (MTD). Dans l’absence de telles données, une profondeur de 600 m est communément utilisée. Les tubes-guides des puits pétrolifères doivent être installé à la profondeur de protection des eaux souterraines. Par contre, il est possible que les puits installés antérieurement soient non-conformes. Devant de telles circonstances, le propriétaire d’un puits se trouvait devant deux options; la mise en œuvre de travaux de réfection coûteux et techniquement difficiles ou la redéfinition de la profondeur locale de protection des eaux souterraines. Favorisant la seconde option, un programme a été développé pour permettre l’échantillonnage séquentiel jusqu’à 600 m sous terre. Les principaux objectifs étaient la redéfinition de la profondeur de protection des eaux souterraines basée sur des données de minéralisation ainsi que l’échantillonnage pour la détection de contaminants potentiels.

1 INTRODUCTION

1.1 Background

An oil and gas company was experiencing surface casing vent flows from several wells in one of its wellfields. Alberta’s ERCB (Energy Resources Conservation Board) required that the oil and gas company rectify the problem. In the absence of hydrochemical data collected in the field, the base of groundwater protection had been placed at an arbitrary depth of 600 mbgl (below ground level). The base of groundwater protection is defined in Alberta as the depth at which ambient groundwater has a mineralization of 4,000 mg/L TDS (total dissolved solids). One of the specific concerns attending the presence of surface casing vent flows was the possibility that potential groundwater resources between the bottom of the surface casing and the base of groundwater protection were being impacted by petroleum hydrocarbon fluids.

To investigate these circumstances, an evaluation well was drilled to 682 m below Kelly Bushing (KB) to:

- facilitate appraisal of groundwater resource prospects in vertical profile;
- try to constrain the depth at which groundwater mineralization exceeds 4,000 mg / L TDS; and
- assess the possibility that groundwater-bearing zones could be impacted by the surface casing vent flow from a selected problem well.

WorleyParsons Komex of Calgary was retained to conduct the evaluation program. Groundwater resources adjacent to the selected problem well were investigated. Depth-sequential samples were collected and prospective groundwater-bearing intervals tested within the various geologic layers penetrated to a depth of 682 m KB. This task was accomplished by the application of carefully chosen drilling techniques, complemented with specialized formation sampling mechanisms, some of which are more commonly used in oilfield exploration than in groundwater applications.

1.2 Objectives

The objectives of the groundwater evaluation program were as follows:

- observe and document geologic conditions in depth profile from ground surface to the arbitrarily-designated base of groundwater protection;
- identify aquifers in the interval from ground surface to the arbitrarily-designated base;
- test possible water-bearing horizons or layers for yield prospects and for groundwater quality; and

- confirm or redefine the base of groundwater protection on the basis of groundwater quality in conjunction with ERCB and AENV (Alberta Environment) representatives.

Prior to initiation of the evaluation program, the following available datasets were reviewed:

- regional geology;
- regional groundwater supply prospects;
- existing water well records; and
- geophysical borehole logs of nearby existing oilfield wells.

An existing problem-well site was selected because it would:

- provide the investigation with a close replication of actual geologic conditions at a problem well site;
- provide the best prospects for encountering and characterizing possible contamination;
- eliminate or minimize the need for land lease acquisition and ground leveling preparation; and
- be most representative of other oilfield wells located along geologic strike .

In the absence of definitive technical information for a given locality, it is common for AENV to place the base of groundwater protection at a conservative depth. The depth chosen by AENV is typically 600 m.

1.3 Site Location and Acknowledgements

Given that this paper is about a problem site, permission to publish was granted with a proviso that client anonymity be preserved. For that reason, the site's location is not identified, other than its general geologic setting (Rocky Mountain Foothills).

We would like to take this opportunity to express our gratitude to Schlumberger for its permission to explicitly refer to its MDT* (Modular Formation Dynamics Tester, with (*) representing Schlumberger's mark).

2 HYDROGEOLOGICAL SETTING

2.1 Regional Geology

Consistent with a Rocky Mountains Foothills setting, an imbricate structure prevails, reflecting relatively intensive structural deformation. Indeed, intensive thrust faulting resulted in the stratigraphic succession being repeated locally. In general, dips were relatively steep.

The stratigraphic succession that provides context and sufficient perspective to the evaluation program, in descending order, is as follows:

Stratigraphic Unit	Comments
Brazeau Fm Wapiabi Fm Cardium Fm Blackstone Fm	Expected main target succession (upper succession), Cretaceous
Mill Creek Fm Beaver Mines Fm	Deeper succession (lower succession), Cretaceous

A review of published geologic suggested that the proposed 600 m test interval would be entirely within the upper succession (i.e., Blackstone to Brazeau interval). Drilling confirmed the interval to be within the Brazeau Formation to Wapiabi Formation interval.

The Wapiabi Formation consists of dark grey to black marine shales (Glass, 1990). Minor siltstone, sandstone and limestone are also present. Throughout most of the foothills, a fine-grained sandstone is present near the top (Chungo Member). Formation thicknesses ranges from over 300 m to about 640 m.

The succession continues with gradation to the overlying Brazeau Formation. The Brazeau Formation correlates with the Belly River Formation. It is a sequence of interbedded mudstone, siltstone and fine-grained sandstone (Glass, 1990). Subordinate, but prominent, coarser-grained sandstones are also present. Thin coal beds, coaly shale and numerous thin bentonite layers occur in the upper part of the sequence, while chert-pebble conglomerate occurs in the lower part. Fluvial fining upward cycles are most common, but a variety of lacustrine facies, including offshore rhythmites are also present.

2.2 Regional Hydrogeology

2.2.1 Aquifers

Regional groundwater yield probability had been assessed by the Alberta Research Council (ARC, Ozoray and Barnes, 1978). From this information, regional water supply prospects are generally in a range of 0.4 to 2L/s. This is an excellent yield prospect in comparison to common domestic (i.e., residential) requirements. Hence, groundwater resources were confirmed to be a viable water supply option for the region in general.

2.1.1 Groundwater Quality

Hydrochemically, the study area vicinity is in an interesting location. Westward across Foothills terrain, the groundwater is generally a hard, calcium-bicarbonate type. With overall west-to-east groundwater flow, natural softening produces a softer, sodium-bicarbonate type water to the east towards the plains.

Groundwater in shallow bedrock has a natural mineralization of approximately 500 mg/L TDS near the study area. Therefore, within the study area, overall mineral content compares favourably with drinking water guidelines. The ARC information confirmed that mineralization increases significantly with increasing depth, as would classically be expected.

3 FIELD PROGRAM

3.1 Field Operations

A top drive Ingersoll Rand TH-100A air /water mud rotary conventional water well rig was used. After setting a 20 m conductor casing, a 200 mm diameter hole was advanced. The drilling method used for this segment of the hole (20 to 150 m) was conventional rotary drilling, with the application of a 200 mm downhole hammer, using air as the drilling medium. The TH-100A's 750 CFM 250 psi air compressor was boosted by two slave 900 cubic feet per minute (CFM) 350 psi compressors. A scrubber filter was placed in line prior to air drilling to inhibit possible entrained compressor oil or lubricants from entering the borehole. The hole was advanced to 150 m KB. The Kelly Bushing was 2.8 m above ground level.

Water interceptions at three intervals (at 55 m, 98 m and 125 m) in the upper 150 m were observed in the air discharge. It was thus necessary to case off this entire interval to make it possible readily to observe any subsequent (deeper) groundwater flow.

To accommodate the 219 mm diameter casing, the hole was then switched over to mud drilling and was reamed to 311 mm. Prior to setting 219 mm surface casing, the hole was geophysically logged.

The casing was set and cemented to a depth of 147.66 m below KB. A (natural gas) blowout prevention (BOP) system was then installed at surface, as per ERCB specifications. The hole was then advanced to 682 m KB total depth using a 200 mm diameter tricone bit. Air was used as the circulation medium throughout the deeper drilling operation to directly facilitate observation of any water interceptions that could be of practical importance. To maintain cutting returns and dust control, water was injected at approximately 1 m^3 per hour. The water was obtained from a nearby municipal supply. Routine groundwater chemistry was run on this water to establish baseline readings and to provide quality control. The maximum hole deviation measured in the well was 5°.

Throughout advancement of the evaluation hole, when a potential water bearing interval was encountered, field parameters of temperature, pH and electrical conductivity were measured. Also, water samples were collected for laboratory analysis. Select results (i.e., those for major ions) are summarized in Table 1. Field parameters were also measured when intercepting sandstone layers without apparent increases in return flow to try to monitor for possible small-yield layer contributions.

Table 1: Major Ion Results

Sample Identity	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Bicarbonate (mg/L)	Carbonate (mg/L)	Chloride (mg/L)	Sulphate (mg/L)	TDS (mg/L)
Module 1 (Canister 1 of 6)	0.6	<0.2	<0.3	3.4	8.0	<0.5	<0.5	0.8	9
Module 2 (Canister 1 of 6)	1.1	<0.2	<0.3	11.0	18.0	<0.5	1.6	2.6	25.3
Composite Routine #1	5.4	0.7	3.9	222	130	104	102	86.3	588
Composite Routine #2	2.3	0.2	0.9	43.0	39.4	15.9	0.8	15.3	98.1
Comp 1	0.4	0.3	<0.3	143	144	74.0	8.8	47.9	346
Comp 2	0.4	<0.2	<0.3	9.5	15.4	2.6	0.5	2.6	23.3
Municipal 0600	39.4	12.9	<0.3	2.6	138	<0.5	2.7	39.8	166
Municipal 0800	39.3	12.7	<0.3	7.8	140	<0.5	8.8	40.4	178
Municipal 1100	39.1	12.7	<0.3	2.4	137	<0.5	2.7	39.7	165
55M	1.6	<0.2	<0.3	172	100	83.1	24.8	74.7	407
98M	2.0	0.3	1.0	200	289	81.1	11.3	23.0	462
125M	4.8	1.7	2.8	224	183	150	9.6	13.5	497
150M	3.0	1.1	<0.3	221	534	16.4	8.0	16.8	530
Epsilon 1 (176.5M)	13.7	18.1	10.8	565	378	24.6	418	188	1,470
Epsilon 2 (176.5M)	10.3	1.4	1.8	636	378	22.7	450	177	1,470
Epsilon 3 (176.5M)	8.0	2.0	1.8	589	384	8.6	467	355	1,630
Epsilon Gamma	28.5	48.0	<0.3	793	642	<0.5	194	287	1,730
200,230,247M	3.9	0.9	4.2	657	456	56.7	631	19.3	1,600
400,455M	1.9	0.3	3.1	273	322	40.4	196	23.0	697

Upon completion of drilling the test hole, the hole was conditioned with mud prior to conducting a second downhole geophysical run. Schlumberger then collected a detailed suite of borehole geophysical logs to identify potential water bearing units. The geophysical logs were a crucial element in the evaluation program. The logs were interpreted onsite and sampling intervals were jointly selected by a geophysicist and hydrogeologist from WorleyParsons Komex in consultation with a pre-assigned representative from Alberta Environment.

To obtain water samples for analysis, Schlumberger supplied a downhole Modular Dynamics Formation Tester (MDT*) sampling system (Schlumberger, 1992). A total of 19 side-wall seals were attempted with the MDT* probe-configuration, of which only three were successful (Table 2). A total of nine seals were then attempted with the MDT* packer-configuration. Eight seals were successful (Table 2). A key finding of this side-wall testing program was that only one of the selected intervals was sufficiently permeable to yield water. This interval was at a depth of 176.5 m KB.

Table 2. Summary of MDT* Targets

Depth (m)	Lithology	CMR Permeability	MDT Configuration	Result
130.2	Casing test	N/A	Probe	Casing Check
176.0	Sand/Coal contact	<1 mD	Packer	Lost Seal
176.5	Thin Coal	3 mD *	Packer	Sampled, SC
193.5	Thin Coal	2 D**	Packer	Dry Test
224.0	Sandstone	<1 mD	N/A	Not tested
252.0	Siltstone	<.1 mD	N/A	Not tested
261.5	Sandstone/Coal contact	10 mD**	Packer	Dry Test
351.5	Sandstone	10 mD***	Probe	Dry Test
359.5	Sandstone	<.1 mD	Probe	Lost Seal
392.0	Sandstone	<.1 mD	Probe	Lost Seal
406.0	Thin Sandstone	<.1 mD	Probe	Lost Seal
406.0	Thin Sandstone	<.1 mD	Packer	Tight Zone, SC
449.5	Thick Sandstone	<.1 mD	Probe	Dry Test
451.5	Thick Sandstone	< 1 mD	Packer	Dry Test, SC
459.5	Thick Sandstone/Siltstone contact	<.1 mD	Probe	Lost Seal
459.5	Thick Sandstone/Siltstone contact	<.1 mD	Packer	Dry Test
474.0	Thin Sandstone	N/A	Probe	Lost Seal
483.0	Thin Sandstone	N/A	Probe	Lost Seal
518.0	Sandstone	N/A	Packer	Dry Test
532.0	Sandstone	<.1 mD	Probe	Lost Seal
536.5	Sandstone/Coal contact	1 Darcy**	Packer	Dry Test

* No caliper log excursion
** Caliper log excursion suggests this is due to a washout
*** No increase in water-entrained discharge observed
SC, Supercharging due to low mobility

3.2 Equipment Decontamination

Measures that were implemented to ensure that petroleum hydrocarbons or other contaminants were not introduced to the borehole during drilling operations were:

- All drilling steel, casing and equipment introduced to the borehole was pre-cleaned;
- All lubricants used for drilling were screened to be of environmental specifications. This included pipe thread lubricant, hammer oil, Hydril and Grant rotating head (i.e., BOP wellhead assembly) lubricants; and
- MDT* tool and equipment were cleaned according to a project-specific protocol that was developed during project preparation. Analyses of rinsate samples from all 12 sample canisters (each MDT* sample module carries six canisters) were conducted. Nevertheless, as could be predicted because the MDT* is an oilfield tool, elevated levels of benzene, toluene and ethylbenzene were observed in nine of the 12 sample canisters. Composite samples analyzed for routine potability also indicated elevated levels of mineralization. The levels of lingering organic and inorganic residuum were determined to be unacceptable for the purposes of the investigation. That being the case, the decontamination protocol was modified, a second wash regime implemented, and 12 samples taken again.

A very encouraging decrease in the presence of residual hydrocarbon levels was observed in all canisters. Inorganic levels also generally decreased to an acceptable level. Two canisters were rinsed a third time and sampled.

4 GROUNDWATER TARGET-INTERVAL SELECTION

4.1 Geophysical Borehole Logging

Once the borehole was drilled to TD at 682 m KB, Schlumberger collected a detailed suite of logs between 150 mbgl (surface casing) and 682 m KB, including:

- natural gamma;
- induction (20, 30, and 60 inch investigation);
- neutron porosity;
- spontaneous potential (SP);
- caliper and long axis caliper; and
- density (formation density, porosity, photoelectric factor and density correction).

As well, in an effort to help identify zones with unbound water (capillary and primary porosity), and to have an estimate of formation permeability, a Combinable Magnetic Resonance (CMR) log was also collected over selected intervals of interest.

Zones of interest, as candidate target intervals, primarily included sandstone and coal layers identified by natural gamma, porosity, resistivity and SP logs in conjunction with cuttings vials and litho-logs. Permeability estimates from the CMR logs were used to help focus sampling efforts with the MDT* on depth intervals with optimum yield prospects.

The actual downhole sample acquisition trips with the MDT* were correlated in real time by visual inspection with simulations multi-screen displays of MDT* position versus select previously run geophysical logs.

4.2 Selection of Sampling Horizons

Once Schlumberger completed its logging run, the various complementary datasets for the interval below 150 m were examined for optimal side-wall sampling targets. Conceptually, targets with yield potential included thin and thick sandstone layers, coal seams and bedding planes between coal and sandstone and between sandstone and siltstone.

A list of selected targets is presented in Table 2. This table lists target depth and lithology, CMR permeability of the interval, MDT* configurations used (i.e. sampling using the MDT* probe module only or with packers deployed from packer modules) and the result of the test.

Targets were initially chosen and classified on the basis of their log response and lithologic observations during drilling. The targets were then further classified by similar log response to attempt to extrapolate the result from tested targets. The absence of observed significant water-entrained discharge in the air circulation below approximately 200 m during drilling formed part of the rationale for this extrapolation.

5 GROUNDWATER SAMPLING

5.1 Groundwater Samples from Observed Interceptions

Groundwater samples were collected at each of the water interceptions observed. Recognition of water interceptions was readily facilitated by observing the amount of water entrained in the discharge of the air circulation. The water samples were sent to a commercial laboratory for analysis of routine potability.

Water interceptions were observed at depths of approximately 55 m, 98 m, 125 m and 150 m KB. Composite samples were made from circulation-entrained water collected at 200, 230 and 247 m KB and from 400 and 455 m KB. Combining these samples was a necessary compromise because the individual samples were insufficient to enable meaningful analyses. The lithology at the depths from which these samples were collected was observed in cuttings and correlated with geophysical logs as corresponding to sandstone intervals.

Sandstone layers of similar thickness below 200 m did not yield observable increased water discharge increments. In light of this important visual observation, the section was provisionally interpreted to be tight below that depth.

5.2 MDT* Sample Acquisition and Downhole Testing

Although the program was developed to contain several complementary lines of evidence, the entire test program was nevertheless designed around Schlumberger's MDT*. The MDT* is a highly versatile downhole sampling and testing tool. It can acquire multiple formation water samples from selected sidewall intervals in a single run. Among various other attributes, the tool can also be used to estimate hydraulic conductivity.

Targets were selected over the depth range of most interest for this investigation to attain representative sampling of zones with the highest potential to have producible groundwater. As sampling proceeded, it became obvious that the entire section was tight. Hence, the focus of sampling shifted to documenting the testing of a representative number of well-spaced and different lithologies in which groundwater resources might typically be expected.

The MDT* tool configuration initially consisted of a single side-wall probe module, optical fluid analyzer module, two sampling modules having a total of twelve 450 mL sample canisters, a pumpout module, and electrical and hydraulic power modules. At each target depth, the probe was extended against the borehole wall to provide a sealed fluid path from the prospect reservoir to the flowline. Of 19 attempts with the probe configuration, the probe only sealed to the borehole wall at two depth intervals (351.5 m and 449.5 m KB) and at a casing check conducted at 130.2 m KB.

Because of the low success rate with the single probe, it was decided to change the configuration of the MDT* tool to add packer modules in the module chain. A dual packer module replaced the single probe sample-acquisition module. Of the nine zones targeted with the packers, only one did not seal satisfactorily. However, moving the tool down by 0.5 m enabled a good seal to be achieved even in this instance, and resulted in the only groundwater sample collected during the program. A summary of targeted intervals, their lithology, CMR permeability, MDT* module configuration and result of each sampling attempt are listed in Table 2.

6 OBSERVATIONS

6.1 Geological Observations

Consistent with published information, site geology comprised predominantly siltstones and fine-grained sandstones, with a number of thin (less than 1 m thick) coal beds irregularly distributed over the depth of the hole. It was found from simple application of acid to cuttings that the majority of sandstones had calcareous cement, which explained the very low observed hydraulic conductivity of these layers.

The most substantial sandstone interval (18 m thick) was observed at a depth of 442 m KB. Other sandstone layers are observed at depths of 516.0-519.5m, 530.0-536.5 m, 545.0-557.0 m and 564.0-571 m KB.

The top of the Wapiabi Formation was interpreted at a depth of 571.8 m KB (or 569 mbgs) compared with 640 m KB in problem well. This reflects the significant structure in the area, and suggests there is faulting between the wells. The magnitude of offset between corresponding events on the logs from the two wells decreases upward. This interpretation was based on a comparison of natural gamma and neutron porosity logs from the problem well and the groundwater evaluation well. The surface location of the two wells was separated by approximately 70 m.

6.2 MDT* Sampling Results

6.2.1 Overview

A summary of the selected targets, their lithology, CMR permeability, MDT* configuration and results of the sampling attempt is presented in Table 2. As is evident from Table 2, all but one of the tested intervals tested dry because of very low mobility values of less than 1 milliDarcy per centipoise (mD/cp). Water at 15°C and 16°C has viscosity values of 1.139 and 1.109 cp, respectively (CRC, 1978), resulting in permeability values of less than 1 mD. In this regard, supporting consultations were provided by Schlumberger personnel.

Supercharging was observed in three of the tests (those conducted at 176.5 m, 406 m and at 451.5 m KB). Supercharging results when measured pressures are increased by the excess pressure of mud filtrate invasion that has not had sufficient time to re-stabilize due to low permeability. This usually happens when permeability values are near 1 mD, and as such is diagnostic of low permeability zones.

6.2.2 Test of a Thin Coal at 176.5 m KB

Since this was the only interval from which a sample could be extracted, it is described in some detail. All other test intervals were too tight to yield a sample. Optical Fluid Analyser (OFA) plots were generated to obtain an indication of the fluid type in the flowline. These plots provide a set of numbered tracks that represent OFA fluid density, and different bands represent different fluid types. For example, tracks 0 through 4 represent fluid turbidity, tracks 7 and 9 represent water content in the flowline, and track 8 responds to the presence of oil. A combined interpretation of flowline fluid is represented in tracks that are designated as Gas Detect and Fluid Fraction.

The pressure curves started at hydrostatic pressure (1740 kPa at 176.5 m). When the packers were inflated with borehole fluid, the fluid in the flowline was compressed, resulting in an increase in pressure to almost 2000 kPa. The pump in the pumpout module was then started, resulting in an observed decrease in pressure to 730 kPa at an elapsed time of 650 seconds. The pump was turned off, resulting in an observed gradual increase in pressure to about 1360 kPa. This was followed by a spike to almost 1500 kPa at 3400 seconds when the pump was turned back on. The pressure reduced to 125 kPa at 4375 seconds.

The OFA Fluid Density curves were found to show a decrease in width on all tracks, except tracks 6 and 9, suggesting the presence of water. The OFA also showed that the Fluid Fraction was primarily water, and that there was gas in the flowline. When the pump was turned off this time, pressure returned to hydrostatic pressure, indicating a lost seal. The width of the OFA Fluid Density tracks was observed to increase, suggesting that mud had entered the flow line. The pump was turned on again, and the seal was regained. A minimum pressure of less than 100 kPa was reached at 6425 seconds, and the pump was turned off. The OFA Fluid Density curve widths decreased as pressure declined.

At this time, the first sample bottle was opened and a formation water sample collected. The process was repeated, until six formation water samples were collected (plus one unknown (i.e., while downhole) misfire). After the "seventh" sample was collected, the packers were deflated, and the pressure was observed to return to hydrostatic pressure, and borehole fluid was seen entering the flowline, as evident from an increase in width of all tracks of the OFA Fluid Density curves. One further sample, a borehole fluid sample, was collected to enable comparison with formation fluid samples.

A notable observation in the pressure time-history recorded at a depth of 176.5 m KB was the difference in minimum drawdown pressure and apparent formation pressure (inferred from the asymptote of pressure recovery) between the first and subsequent drawdown cycles. Much higher minimum and apparent formation pressures on the first cycle suggested supercharging, or elevated pressures at the borehole wall due to the mudcake. This is indicative of a low permeability formation. The elevated pressures were apparently overcome in later cycles (after the lost seal event).

A temperature time-history was also generated on a normalized pressure curve. Fluid temperature was 16°C at the beginning of the time series. As fluid was pumped through the flowline, the temperature dropped. The rate of temperature change, or gradient, was reduced when pumping stopped at about 3400 seconds. When the pump was started, temperature dropped to 15.3 °C. When the seal was lost at about 4480 seconds, temperature increased to 15.5°C. The temperature versus time gradient increased while pumping, reaching a minimum temperature of just under 15.2°C after the pump was turned off, during collection of the first sample. From here on, small oscillations were observed, with temperature gradient increasing while pumping, reaching minima during the early part of sample collection, when flow into each sample canister was highest. As the pressure gradient decreased, the flow decreased, and temperature tended to increase slightly.

The decrease in temperature is further supportive information that the fluid collected in the sample bottles was genuinely formation fluid.

The municipal water is a hard calcium-magnesium-bicarbonate-sulphate type, with a low mineralization of about 170 mg/L TDS. Sulphate is quite subordinate to bicarbonate, being at about 25% of the anions versus 70% bicarbonate in meq/L. Chloride content is low (less than 10 mg/L, as shown in Table 1).

From discharge collected samples, shallow groundwater at depths up to 150 m is a soft, sodium-bicarbonate type. Its mineralization is low to moderate, with three out of four samples having a mineralization of less than 500 mg/L TDS. Chloride and sulphate contents tend to be quite low (Table 1).

In contrast, the formation water from 176.5 m KB (Epsilon 1, 2 and 3 samples) is a sodium-chloride-bicarbonate type. Chloride is the dominant anion at approximately 50% by meq/L, while bicarbonate content is also appreciable, but subordinate, at about 30% meq/L.

The borehole conditioning fluid (Epsilon Gamma sample) is a sodium-bicarbonate-sulphate-chloride type. Its mineralization is somewhat higher than that of the formation water, while its chloride content is substantially lower (Table 1). These differences clearly distinguish between the conditioning fluid and the formation fluid.

6.3 Results Interpretation

6.3.1 Mineralization

The municipal water appears to be harder than any of the groundwater samples collected, having slightly elevated levels of magnesium and calcium. It also has sulphate levels that are slightly higher than those observed in the samples from depths between 98 and 150 m. This water is quite distinctive, however, by virtue of its very low mineralization (less than 180 mg/L TDS, Table 1).

The groundwater samples collected from observed water interceptions were found to show an almost linear increase in laboratory-calculated TDS values between 55 and 150 m. Calcium, sodium and bicarbonate appear to be the main contributors to this trend. Chloride levels decreased monotonically with depth from 25 to 8 mg/L over the interval. Sulphate concentrations also generally decreased with depth.

The samples between 55 and 150 m have a distinctly different hydrochemical character than the municipal water. Calcium and magnesium concentrations are lower by approximately an order of magnitude in the groundwater samples. Sodium concentrations are higher by almost two orders of magnitude from 2.5 to 220 mg/L. Chloride concentrations are almost an order of magnitude higher and mineralization is higher from 166 mg/L in municipal water to between 407 and 530 mg/L TDS in the groundwater samples between 55 and 150 m.

There again is a distinctly differentiable hydrochemical character between groundwater samples collected between 55 and 150 m and the sample collected with the MDT* at a depth of 176.5 m KB. The most notable changes are observed in the concentrations of sodium, chloride and sulphate. Sodium increases from a range between 172 and 224 to concentrations between 565 and 636 mg/L. Chloride increases from a range between 8 and 24.8 mg/L to between 418 and 467 mg/L. Sulphate increases from a range between 13.5 and 75 mg/L to between 177 and 355 mg/L TDS. Calcium and magnesium concentrations also increase, and the resulting calculated mineralization values increase from between 407 and 530 mg/L TDS above 150 m to between 1470 and 1630 mg/L TDS at 176.5 m. This corresponds to slightly brackish, though still readily usable, water, and is still well below the 4,000 mg/L TDS criterion that defines the base of groundwater protection.

An increasing trend in TDS values was observed, reaching a maximum at a depth of approximately 250 m, below which TDS values generally decrease. The trend below 250 m would be consistent with the absence of groundwater over this depth interval. Elevated TDS values reached near 250 m are essentially diluted by the comparatively low TDS municipal water injected as drilling proceeded.

There is a distinctly different hydrochemical character between the samples collected at 176.5 m KB with the MDT* and a borehole fluid sample collected when the packers were released (the Epsilon Gamma sample). The borehole fluid has higher calcium and magnesium, higher sodium, higher bicarbonate, lower chloride and higher TDS concentrations than the formation water samples. The most compelling difference between the hole conditioning mud (i.e. Epsilon Gamma) and the formation water appears to be the chloride content. A clear contrast seems to prevail between a 418 to 467 mg/L chloride range in formation water and 194 mg/L chloride in the conditioning mud.

The results of analyses of composite samples from the intervals between 200 and 247 m KB and between 400 and 455 m Kb are listed in Table 1 (samples 200,230,247M and 400,455M). Individually, the samples taken at each of the five depths were not large enough for chemical analysis. Hence, although a compromise, they were composited over approximately 50 m intervals and reflect averages over these depth intervals. Mineralization of the upper composite sample most likely reflects closeness to the groundwater source at 176.5 m KB, somewhat changed due to dilution by injection water. Sodium, chloride and mineralization are comparable to levels observed at 176.5 m KB. The chemistry of the deeper sample suggests further dilution with injection water. Sodium, chloride and mineralization (TDS) levels follow the decreasing trend that would be expected from dilution.

6.3.2 BTEX Results

The rinsate tests from the MDT* sample canisters (i.e. bottles 1 through 12) provide a baseline of BTEX residuum. Even after three complete washing regimes, canisters 1 and 7 were not entirely free of BTEX (relative to detection limits).

As could be expected, therefore, the formation fluid samples yielded some positive readings for BTEX. Most informative, however, were the results for Epsilon 3. This sample yielded comparatively low BTEX levels, which were somewhat similar in concentrations to the second rinsate baseline. It was therefore deduced that the formation water obtained by MDT* sampling from the coal seam at 176.5 m probably was not contaminated.

6.3.3 Analysis for Natural Gas

The sample canisters can be pre-pressured to emulate predicted formation fluid pressure to enable sampling of natural gas. Laboratory analyses of natural gas in the (water) sample collected from 176.5 m KB show a significant amount of methane, and comparatively small proportions of ethane, propane and butane. Concentrations of methane, ethane, propane and butane were 299,664, 136, 103 and 109 ppm, respectively. Concentration of C6+ was 895 ppm, possibly reflecting residual tool contamination. Corresponding carbon isotope ratios (d13C) are –55, -33, -29 and –29 ppt. The gases are thermogenic in origin and do not follow the usual order of molecular abundance (methane>ethane>propane>butane). The carbon isotope compositions may be representative of a shallow Belly River Coal.

Published carbon isotope compositions between surface and 4000 m were reviewed. Comparison of these data with the sample results from 176.5 m suggested that the gas was shallow (1100 to 1200 m). This conclusion is based primarily on the isotopic composition of ethane and propane. However, without additional background or baseline information for the actual field, it was difficult to identify a conclusive source. It was not the objective of the study to characterize gas. Nevertheless, analysis of the gas sample makes it possible to exclude the possibility of a deeper source.

7 SUMMARY

1. All intervals directly tested downhole with the MDT* had rather low hydraulic conductivity. More precisely, with the exception of only one horizon (176.5 m KB), the MDT* tests confirmed that the selected otherwise optimum target intervals were all too tight to yield a sample.
2. In contrast, groundwater interceptions were readily evident from air-assisted discharge observations at shallow depths (55, 98, 125 and 150 m KB).
3. Successful acquisition of formation samples from 176.5 m KB was especially important in that it provided field confirmation that the MDT* was functioning properly. In turn, this confirmed that the target intervals were properly tested.
4. Various independent lines of evidence confirm that triplicate samples collected at 176.5 m KB are genuinely representative of formation water, namely:
    i. hydrochemical contrasts between samples of municipal water used during drilling, borehole conditioning fluid, and shallow groundwater discharge,
    ii. MDT* pressure drawdown-buildup curve forms were consistent with successful acquisition of formation water, and
    iii. MDT* fluid temperature and OFA traces were similarly consistent with successful acquisition of formation water samples.
5. Successful formation sampling with an MDT* was best achieved through the use of packers. Sidewall rugosity, which is likely inherent with air drilling, seemed to inhibit attaining successful sidewall seals using the MDT* probe (i.e., without packers deployed). Using mud circulation instead of air could probably reduce such rugosity.
6. In the vicinity, prospects for obtaining viable groundwater resources that are potable at depths below 200 m are remote.
7. No contamination of the Brazeau (Belly River) Formation was noted in relation to the pre-existing surface casing vent-flow from the problem well.
8. On the basis of the results of this investigation, it was proposed that the base of groundwater protection be revised to 200 mbgl

8 CONCLUSIONS

Schlumberger's MDT* system was found to provide a highly sophisticated, versatile and effective customizable module train that is well-suited to enabling accurate groundwater quality sampling in the deeper subsurface. Only one noteworthy groundwater interception was encountered within the target intervals. Although this interception (i.e., at 176.5 m KB) yielded water with a mineralization of <4,000 mg/L TDS, thereby precluding revision of the base of groundwater protection on hydrochemical criteria alone, it enabled the utility of the instrument to be confirmed. In turn, the base of groundwater protection was successfully revised, on a strictly local basis, to a shallower depth on the basis of proven absence of a deeper aquifer (between ~300 m and 682 m KB). In this latter regard, the project was therefore of a partial, but immediately sufficient, success in terms of its prime objective.

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