Whetstone Associates

Technical Memorandum

To:	Margaret Ash, Peter Gintautas (COGCC)	**4143B**
From:	Susan Wyman, P.E., P.G.	
Date:	May 23, 2008	
Subject:	Technical Review of Norwest Applied Hydrology Report on Monitor Well POCI55 (Petroglyph Energy, Inc.)	

Monitoring well POCI55 is a 5-inch to 5½-inch well cased to a depth of 1,074.8 feet with multiple completions (screened and filter-packed intervals) separated by cement and/or bentonite annular seals. The well was drilled for Petroglyph Energy, Inc. by Layne Christenson Drilling under the supervision of Norwest Applied Hydrology (Norwest) in February 2008. Whetstone Associates has reviewed the well completion report "Monitor Well POCI 55 Drilling, Logging, Completion, And Testing Summary Report" (Norwest, 2008) and have prepared the following comments.

Overall Completeness

The report is substantially complete, and provides source data (drillers logs, geophysical logs, gas charts, and laboratory analytical data sheets) that were used in selecting well completion intervals and interpreting test results. However, some of the field data collected by Norwest is omitted. Field measurements during well development were not presented, and neither paper nor digital records of packer pumping test data were provided.

Section 3.9 Geophysical Logs Evaluation

The report provides all logs and provides good justification for the selection of aquifer completion intervals, based on gamma ray (GR), deep induction resistivity (DIR), short normal (SN), neutron porosity (NPOR,) and density porosity (DPOR) logs.

Section 4.1 Casing Placement

The screen and blank casing were successfully placed at the target locations, identified based on geophysical logging.

The report does not discuss the number, size, and location of centralizers on the well casing, although the driller's log (page 10) indicates that centralizers were used.

Section 4.2 Annular Completion

A. Grout Level in Bottom Interval

The first batch of cement grout placed at the bottom of the hole did not account for slough in the hole. This error resulted in cementing up approximately 9 feet of well screen in the lower interval.

B. Bentonite Placement

Although the contractor used several good methods for placing annular materials (such as tremiing materials into the annular space and tagging materials with the tremie pipe), these practices were not always followed. The coated bentonite pellets used to form plugs between the sand and cement were poured from the surface rather than placed by tremie pipe, as stated by Norwest:

> "When applying Bentonite between sand and grout approximately nine feet of bentonite was placed by pouring from ground surface down the annular space." (Norwest, 2008, pg 4-3)

The driller's log concurs; for example, the log indicates 'Pour 7 ea 50# buckets 3/8 bentonite tablets down annulus' (Layne, drilling log, page 11).

Bentonite plugs were intended to be placed from 981- 990 ft below ground surface (bgs), 871-880 ft bgs, and 411- 420 ft bgs. Pouring bentonite pellets down the annulus to a depth of 990 feet is poor practice and violates Colorado well construction rules. Rule 10.5.3.4 states that:

> Bentonite grout may be used in required grout intervals only pursuant to a variance from the Board and if its use is consistent with the requirements of this Rule and Table 3. Bentonite shall not be used to seal the outermost casing of a well within 40 feet below ground surface. **Bentonite shall not be poured from the surface, but shall be placed directly into the appropriate interval**. (2 CCR 402-2, Section 10.5.3.4, emphasis added).

C. Filter Pack Size and Settlement

The silica sand filter pack is a suitable inert material, and meets the standards for environmental monitoring well construction. However, no justification was provided for the selection of filter pack grain size. The Raton Formation is logged as a fine-grained to very fine-grained sandstone with calcareous cement, noted as friable in some intervals (Norwest, 2008, Appendix B). No discussion of formation grain size or cementation was provided in the text. The 6-9 sand may not be sized to formation, and could be too coarse.

Coarser filter pack materials tend to have more settlement than finer materials. In most intervals, the filter pack was extended 9 – 18 feet above the top of the screen. In the uppermost interval, the filter pack was extended approximately 110 feet above the top of the screen. Given the long intervals of filter pack sand (51 ft, 101 ft, 119 ft, and 208 ft), the settlement could be excessive, possibly lowering the sand below the top of the screen. To prevent excessive settlement from such long screened intervals, the filter pack for the lower intervals should have been surged during placement, or extended farther above the screen, or placed in shorter intervals.

D. Likely Cement Encroachment into Filter Pack

At 640 feet, cement was placed directly on 6-9 sand, with no bentonite seal or transition sand. (A transition sand is a fine-grained or very fine-grained sand that impedes the movement of grout into the underlying coarser filter pack sand.) Without these materials in place, the cement may migrate into the filter pack, clogging the filter pack and affecting the chemistry of the monitored groundwater. According to Nielsen (1991):

> "Neat cement, because of it's chemical nature…is a highly alkaline substance (pH from 10 to 12), and thus introduces the potential for altering the pH of water which it contacts. The alteration of pH, in turn, can affect other chemical constituents in the water. In addition, because the emplaced mixture is a slurry…it may tend to infiltrate into the coarse materials that comprise the primary filter pack around the monitoring well screen if it is placed directly on top of the primary filter pack." (Nielsen, 1991, pg 319)

Although the cement was ordered at the correct mix ratio (6 gallons per sack) according to the drillers log, an undiluted cement could have still penetrated into the sand pack. Any dilution from water added before pumping the cement down the tremie pipe, or any fall through groundwater from the bottom of the tremie pipe to the placed location, could contribute to an even less viscous cement that could further penetrate a coarse (6-9) sand.

Section 4.3 Well Development

The well was developed by airlifting (15 minutes on, 5 minutes off) for a total of 10 hours, with a reported flow rate of 35 – 40 gpm. At 40 gpm for 450 minutes out of 10 hours, a total of 18,000 gallons would have been removed. At the end of 7 hours of airlifting (approximately 12,600 gallons), the water remained "very murky" with high pH values (9.7 s.u.).

A. Limited Reporting

Norwest does not provide tables of field measurements or observations during development. Changes in electrical conductivity and pH during development could provide insight as to whether the well was cleaning up, whether breakthrough of a cement of bentonite plug occurred, or whether the observed turbidity was derived from the formation, bentonite, or cement grout. The color of the the "very murky" airlift discharge is not reported. Grain size or Imhoff cone sediment volumes are not provided.

B. Inadequate Development or Incorrect Completion Indicated by High Turbidity and pH

The high turbidity and pH could indicate that either (1) the well was inadequately developed, (2) the well was incorrectly sealed, or (3) the filter pack grain size was too coarse.

The duration of well development (10 hours, ¾ time, at 35 – 45 gpm) should have been adequate to remove drilling fluids from within the screened intervals. The annular volume of an 11-inch hole with 6-inch OD casing is 37.6 gallons per foot, or 9.4 gallons per foot assuming 25% porosity. Given the 479 linear feet of sand pack, airlifting 18,000 gallons removed approximately 43 times the filter pack purge volume of 415 gallons. Although the number of purge volumes required to adequately develop a well varies based on annular thickness, drilling fluid, casing slot size, and other factors, 6 to 20 volumes are typically adequate to properly develop a well. The excessive purge volumes required for POCI55 may indicated that the well was improperly completed and, if so, it is possible that the well may never be adequately developed.

Improper completion could be attributed to either cement grout penetrating the filter pack or an excessively long filter pack that is not in contact with the well screen. It can be very difficult to develop "dead" filter pack that is tens or hundreds of feet from the screen and filled with drilling mud. Inadequate information is provided in the report to determine whether the turbidity and high pH result from cement (pH 10 -12) or drilling mud (typically pH 8.5 – 9.5).

Section 4.4 Total Depth Drill Out

The lower 37 feet of the well (including approximately 9 feet of screen) was mistakenly cemented. The text in section 4.4 states that the cement plug started at 1,035 feet, while Table 4.2.1 indicates that the cement in the annulus starts at 1041 feet. There is a 6-foot discrepancy between these two values.

The cement plug inside the casing was drilled out after 7 hours of well development. However, drilling the plug did not remove cement from the filter pack. Since the filter pack is likely plugged with cement, hydraulic calculations should not include the length of the drilled out section of screen.

Section 5 Cased Hole Geophysical Logging

After well completion, a cement bond log, collar locater log, gamma log, and neutron log were run in the cased hole. The cement bond log was unable to indicate whether or not cement had penetrated the filter pack.

Section 6 Aquifer Packer Testing

Aquifer pumping tests were conducted in four screened intervals (1,010–1,049 ft, 896–976 ft, 687–788 ft, and 527–542 ft) by isolating the screens using inflatable packers. The report interprets the results qualitatively. No quantitative analyses are presented for pumping test drawdown and recovery tests.

The text refers to Figure 6-1 as a diagram showing the packer and transducer assembly. However, Figure 6-1 shows the transducer pressure response while testing the first interval. The equipment configuration is provided in an un-numbered figure at the end of Section 6.

Although lengthy written descriptions of testing are provided for each interval, no summary sections or summary tables of tested intervals, pumping rates, or aquifer hydraulic conductivities are provided.

Section 6.1 Aquifer Test Interval 1

It is confusing to refer to the flow rate adjustments during the initial pumping tests as "step tests" because the tests were not conducted like a typical step test. In a formal step test, the pump is not shut off between steps. Typically, step-drawdown tests involve pumping the well at a fixed flow rate until water levels stabilize (typically 20 – 60 minutes) at a given drawdown (Step #1), then increasing the flow rate to a new fixed flow and drawdown (Step #2), and repeating at a new, higher flow rate (Step #3). These test results are often analyzed to determine the non-linear well loss coefficient and aquifer loss term. Since the initial tests in POCI 55 were not conducted using this method, the term "step tests" is probably not applicable.

The report also incorrectly states that "after the rate test the formation was allowed to recover to its approximate original starting pressure." Figure 6-1 shows that, at the end of the second step test, the pressure was about 26 psi (60.7 feet) below the original starting pressure. It would be more accurate to say that the aquifer was allowed to recover for X minutes, or X%. Failing to allow the aquifer to recover before starting the longer duration constant-discharge test can make test analysis difficult, because it violates the mathematical assumptions underlying most solution methods. However, since the test results were not analyzed quantitatively (or at least a quantitative analysis was not presented), the dynamic pre-test conditions are less problematic.

The gas measurements collected from the isolated (packed off) zone and from the upper zone above the packer provide very useful information for identifying the source of gas entering the well. The report text and chart recorder in Appendix E clearly indicate that the lower screened zone did not produce measurable quantities of gas during the pumping test, while methane was produced from the zone above the packed interval.

Section 6.2 Aquifer Test Interval 2

The discussion of transducer pressure readings in the second paragraph on page 6-6 is incorrect. Although the three transducers were attached at the same location on the pipe string (ie, on the first joint above the packer assembly) the middle and lower transducers were equipped with ¼-inch nylon drop tubes such that their measuring points were not the same as their location. Since the three transducers are measuring pressure at different points, they would not be expected to read the same pressure. Rather than question why the three pressure readings were not identical, the author should question why the readings were not farther apart, given the vertical separation between the measuring points. If the middle transducer drop tube extended to the center of the packed interval, the difference in measuring point elevation would have been 75 feet and the transducer should have recorded a 32.5 psi difference. Similarly, if the vertical separation on the lower transducer was 150 feet, the transducer should have recorded a 65 psi difference. If properly connected, the nylon drop tube has no effect on the transducer readings other than to change the measuring point.

The static water level prior to the test (provided on page 6-6) was 482 ft bgs, which is 15 feet lower than the pre-test static water level measured for aquifer test Interval 1. This is inconsistent with observations from the first packer pumping test, which indicated downward flow and downward vertical gradients. If the first observations were correct, the water level should have been higher at isolated intervals higher in the hole.

As the report states, the lower packer was not seated during the aquifer test on this interval. The packer may have leaked, but no mention is made of pressures at the surface tank to confirm the leakage. Since nitrogen gas is typically used for inflating packers, if the gas flow to the lower packer was not turned off during the test, the escaping nitrogen could have influenced water chemistry. (The laboratory data sheets do not provide nitrate or nitrite results for the sample collected from aquifer test Interval 2, although they are provided for Interval 1.)

The term "significant well bore damage" (in the first paragraph at the top of page 6-7) is unclear.

Two longer duration pumping tests were conducted, with stable pre-test water levels and constant pumping rates. The measurements collected should provide good information for quantitative analysis of aquifer hydraulic conductivity. This analysis was not provided.

Gas measurements indicated 2-3 mcf/day for the first 15 – 20 minutes of the Interval 2 aquifer test. While the report appears to thoroughly and accurately document the measured gas flow rate and composition, it also editorializes the quantities of flow as “insignificant when compared to … that found venting from domestic wells in the near vicinity”. While it is correct that the chemical signature is different from the signature in some local domestic wells (i.e., no hydrogen sulfide in POCI 55), and the quantities of gas are significantly lower than in the upper interval, the report should not trivialize a gas flow rate of 2-3 mcf/day. The effect of 2-3 mcf/day on a domestic well can be significant. The conclusion, however, that “this aquifer zone is not capable of sustaining a significant volume of gas and is not expected to be included in the mitigation efforts” may be valid at this location. More data or analysis may be required to extrapolate this conclusion over a broader area.

Section 6.3 Aquifer Test Interval 3

The leaking lower packer was evident again in test Interval 3. (No attempt was made to pull the packer string, identify to source of the leak, check fittings, or replace the lower packer.) The statement that “The inflation of the packers did not influence the pressure monitored in the lower zone” should be followed with “because the lower packer was not fully seated”.

The report refers to transducers pressures indicating a separation of aquifers, but does not provide head in feet or pressure in psi at the measuring points for the upper and middle transducers. A complete table or figure showing head or pressure measurements and the intervals represented may be useful for understanding the hydrogeologic system and for further decision making.

While the pumping rate (17 gpm) provides some useful information, it does not necessarily indicate that this aquifer zone is more productive than test Interval 2, which yield 14 gpm. The pumping rate is a function of the pump curve (which would allow higher yields from *isolated* intervals higher in the well, due to the downward vertical gradients), the hydraulic conductivity, and the length of the producing interval. Because the lower packer was not seated correctly, the length of the test interval is greater for aquifer test Interval 3 than for Interval 2. If the test results were analyzed, they might indicate a lower hydraulic conductivity in Interval 3 although the pumping rate was higher than in Interval 2.

The text states that “this amount of gas is insignificant” but does not report the flow rates in the text or in Table 6.3.2. The chart recorder (Appendix E) indicates higher and more consistent flows than in the previous test interval. The rates should be reported in the text.

Section 6.4 Aquifer Test Interval 4

Problems with the pump and with gas production in this interval made it impossible to pack off Interval 4 and conduct a pumping test.

As previously noted, the statement that “the lower transducer is reading a pressure significantly higher than the middle and upper transducer indicating an inaccurate but precise value due to the use of the ¼-inch nylon tubing” is false. If properly installed, the drop tubing does not affect the transducer reading. The lower transducer <u>should</u> measure a higher pressure because the measuring point is lower in the hole and submerged under a greater water column. The fact that the middle and upper transducers produced the same pressure reading should be a cause for concern, unless they are located close together on the pipe string.

The depth to water of 493 feet bgs measured by the upper transducer indicates upward vertical gradients in the well, compared to water levels calculated from transducer data for the previous test intervals. However, this water level is higher than the water level physically measured in the open hole (530 ft) which would indicate downward vertical gradients. Complications due to gas production from this zone could have made the transducer readings inaccurate.

The build up of gas pressure in Interval 4 was significant when both packers were inflated. The gas flow rate was measured at 30 to 50 mcf/day and was composed of 100% combustible gas v/v measured using a hand-held RKI 4-gas meter. The report did not analyze the shut-in test data quantitatively, and no water quality samples were collected from this zone.

Section 6.5 Aquifer Water Quality Testing

The report correctly states that the water quality results are not considered representative of background water quality due to high pH values indicating the presence of mud or grout. It should be noted that the pH values up to 11.2 are clearly indicative of cement grout (pH 10-12) rather than drilling mud (typically pH 8.5 – 9.5). It is also noteworthy that the pH was highest in test Interval 3, which produced the most water and may have pulled in the most cement. The high pH values could affect the concentrations of metals, TDS, and other constituents in the water samples, a point that is not made clear in the text. The effects of pH on organic chemistry are not discussed.

Similarly, Table 6.5.1 shows the lowest water temperature measured in water from the deepest perforated interval (Aquifer Test Interval 1), with higher temperatures in overlying Interval 2 and Interval 3. The temperature pattern of the coldest water coming from the deepest interval may be anomalous, and may be the result of the exothermic reaction of curing cement in the upper zones. If the higher temperatures measured in the discharge water from Interval 2 and 3 are the result of heat generated by exothermic reactions that take place when cement cures, then the results may indicate that testing and sampling of the well occurred prematurely, before the cement had fully cured.

No summary table of water quality results is provided. The reader is left to search through the laboratory data sheets in Appendix F. The data sheets appear to be complete, although nitrate and nitrate analyses for Interval 2 and Interval 3 are not presented. Similarly, water quality results for Interval 4, which produced the most gas, are not provided because a sample was not collected.

The presence of carbon dioxide (CO_2) and other gasses should not be interpreted as evidence that "biogenic processes [are] involved in the oxidation of methane" when (a) the affects of cement and high pH on the carbonate geochemistry in the system are not explained and (b) the affects of sample preservation are not considered. The CO_2 was most likely an artifact of sample collection and preservation, rather than a result of subsurface biological processes. The CO_2 was reported as a Tentatively Identified Compound (TIC) in a sample submitted for volatile organic compound (VOC) analysis. Standard environmental protocols require that VOC samples be preserved to pH 2 or less. Because the carbonate alkalinity of the submitted samples ranged from 72 – 180 mg/l as $CaCO_3$ and the bicarbonate alkalinity ranged from 8.25 to 129 mg/l as $CaCO_3$, acidification of the samples to pH ≤ 2 would have converted the dissolved inorganic carbon to $H2CO_{3(s)}$ or $CO_2(g)$. The gaseous CO_2 is likely the result of sample acidification, rather than biological processes.

Section 6.6 Aquifer Testing Summary

The report identifies that a significant flow of combustible gas occurred from the upper zone (sand packed from 420 to 628 ft and screened from 526.6 to 541.6 ft) and lower quantities of gas were derived from the lower zones.

Too much emphasis is placed on the detection of sulfide and CO_2 as being indicative of biological oxidation and removal of methane gas. Sample preservation may have generated gaseous CO_2 in the sample (see comments above) and it may not be possible to determine the oxidative state of groundwater given the high pH (9.7 to 11.2) that resulted from improper well completion. Because the water quality data are suspect, the generalizations about biological oxidation and removal of methane gas may not be warranted. At least, further consideration of the geochemistry may be necessary.

The phrase "the aquifer testing showed a potential connection between aquifer zones as indicated by the lower pressure transducer' could be misinterpreted to imply that the aquifers were interconnected. Clearly, the differences in pressure head measured during the various tests indicate that the aquifers are not distinctly connected, and that the clay units provide vertical separation between aquifers. A more correct phrasing is that "*during testing*, the lower packer allowed connection between the test intervals." The connection between the test interval and the underlying well casing was not "potential", it was actual and was repeatedly measured by the lower transducer.

The statement that "significant amounts of water are available in the lower zones" is not consistent with a pumping rate of 5 gpm with a drawdown of 218 psi (504 ft) in test Interval 1 (the lowest test interval).

The statement that there is limited water available in the upper sands is not justified. A pumping test was not conducted because the pump was inoperable, so yield could not be tested. The low pressure measured by the upper transducer may simply indicate that the transducer was set near the top of the aquifer, not that the aquifer permeability (or yield) was low.

Section 7 Cased Video Logging

The video was not provided for review. However, from the text it is apparent that cement grout was visible in several screened sections. The statement that "grout is not thought to be the plugging agent because during completion sand was placed approximately 10 feet or higher above the slots with nine feet of bentonite above the sand prior to placing the grout" is incorrect, for reasons noted previously: (1) the bentonite was poured from ground surface, and may not have reached the target interval, (2) in some cases, cement grout was placed directly on top of very coarse (6-9) sand without any bentonite or transition sand, and (3) more than 10 feet of settlement of the transition sand is easily conceivable given the coarseness of the sand (which typically settles more than fine sand) and the very long length of sand pack (up to 208 ft).

It is not clear whether the statement that the water column starts at 526.5 feet was derived from the video or from the open hole measurement. In either case, an explanation as to why the water level mentioned in this section differs from the water level calculated from pressure transducer measurements is needed.

Section 8 Conclusions and Recommendations

The conclusions summarize that the upper zone produces the most gas, and that gas is trapped in the upper Poison Canyon Formation. This conclusion is supported by the information and test results provided. However, the statement that "gas migration is not wide spread and is linked with the upper zone possibly by man-made conduit" does not result from the monitoring well data presented in this report. The data presented in this report does not provide a basis for this statement.

The recommendation that subsequent mitigation and monitoring wells should be drilled in the upper zone is probably valid. However, due to problems with well completion and the inherent variability in the subsurface (both stratigraphic variability and fracture variability), it may be premature to completely ignore the lower zones.

The recommendations in the third paragraph for packing off gas and monitoring water level (pressure) changes are excellent.

The fourth paragraph is correct that more representative water quality samples should be collected from other wells that are properly completed.

References

CCR, 2005. Rules and Regulations for Water Well Construction, Pump Installation, Cistern Installation, and Monitoring and Observation Hole/Well Construction (Water Well Construction Rules) 2 CCR 402-2. Effective Date January 1, 2005

Hem, John D., 1985. Study and Interpretation of the Chemical Characteristics of Natural Water, Third Edition, U.S. Geological Survey Water Supply Paper 2254. 263 pp.

Nielsen, David M., 1991. Practical Handbook of Ground-water Monitoring, CRC Press, 717 pp.

Norwest Applied Hydrology, 2008. Monitor Well POCI 55 Drilling, Logging, Completion, And Testing Summary Report, consultants report prepared for Petroglyph Energy, Inc.