Summary of Hydrogeology Investigations in the Mamm Creek Field Area, Garfield County

Prepared for Garfield County by Science Based Solutions LLC

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Executive Summary

This report briefly summarizes the reports of various consultants and agencies related to the 2004 West Divide Creek seep and the East Mamm Creek gasfield. The seep generated a decade-long series of studies related to the cause of the seep, impacts to water resources and how the State of Colorado could improve the drilling and completion practices for gas wells in the Mamm Creek field area. The aim of this report is to summarize the data and results from those studies and integrate the results to focus on what knowledge we have gained about the interactions of petroleum activities and groundwater quality.

The work began in 2004 after the West Divide Creek (WDC) seep was discovered. Subsequent investigation by the Colorado Oil and Gas Conservation Commission (COGCC) staff indentified the source of the gas as being from the Schwartz 2-15B well operated by Encana Oil and Gas (EOG). The COGCC hearing in fall of 2004 found EnCana was responsible for the seep (COGCC Order 1V-276). The Commission found that the loss of cement at the Schwartz 2-15B well caused an uncontrolled release of gas from the Williams Fork Formation and fined EnCana $371,200. The COGCC required EOG to monitor and remediate the WDC seep beginning in spring of 2004. The results of quarterly monitoring have been posted on the COGCC website and COGCC staff has provided several public presentations. EnCana performed extensive testing of surrounding water wells, surface water and a soil gas survey during 2004.

Garfield County applied for recovery of the fine from the State to be used on a study of the hydrogeology of the Mamm Creek field. This Phase I Hydrogeology study was performed by URS Corporation and completed in 2006. Several other studies followed including the Phase II Study performed by S.S. Papadopulus and Associates in 2008, a review of Phase I and II studies by Science Based Solutions in 2008, review of the 2008 Science Based Solutions study by S.S. Papadopulos in 2010, and the Phase III study performed by TetraTek completed in 2013. Concurrent with these studies the COGCC and Encana Oil and Gas completed the Divide Creek Area Joint Study by Walter Environmental Group in 2011, the East Mann Creek Project Drilling and Cementing Study by Crescent Consulting in 2011. In addition, the USGS produced an area specific publication in 2010.

The original conceptual model for the seep was the uncontrolled release of hydrocarbons moved up the well annulus (behind the casing) until encountering a fault. The leaking hydrocarbons moved up the fault until they reached the surface contaminating the creek bed sediments. Remedial cementation of the Schwartz well stopped further discharge. Based on estimates of volume lost from the well it appeared that some of the hydrocarbons filled sandstone intervals along the fault path. These remaining hydrocarbons have been discharging into the creek with the rate declining over time. Currently the seep discharge continues to decline with levels of methane, higher hydrocarbon gases and benzene dropping. Benzene levels in the monitoring wells have dropped below regulatory limits. The original conceptual model appears to be validated by the behavior of the seep. The area of the seep is shrinking and the impacts declining with time.

West Divide Creek Seep History

On April 1, 2004 a citizen observed bubbles rising from the creek bottom. On March 23, 2004 EnCana had emailed a Sundry Notice, Form 4 to COGCC requesting approval to remedially cement the Schwartz 2-15B well. The well was about ½ mile from the creek. The well was remedially cemented on April 5. 2004 and within eight days the bubbling in the creek was observed to decrease. Figure 1 shows the location of the seep.

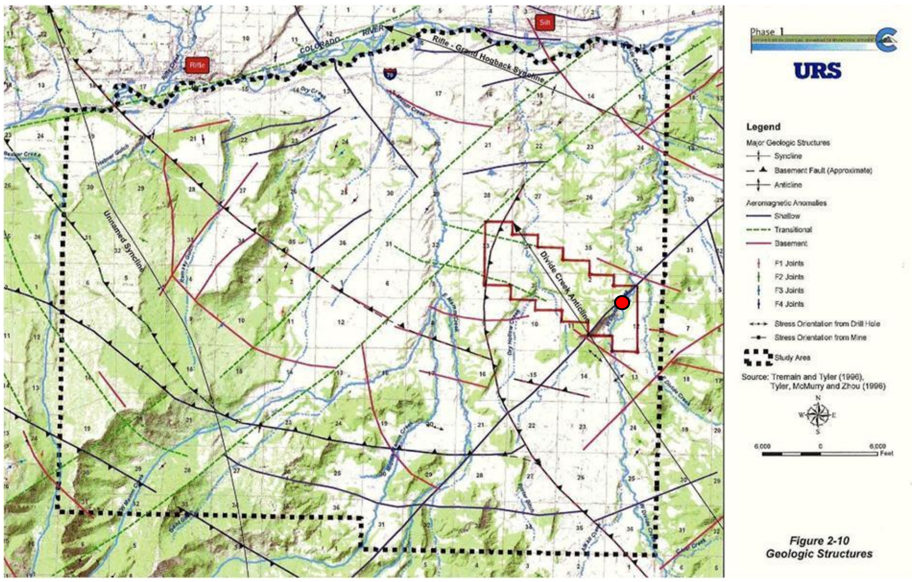

Figure 1 – Map of a portion of southern Garfield County outlining the Phase I study area, the major structural features including faults. The Divide Creek Anticline, an upward bowing structure, is shown by the black arrow on the right side of the map. The eastern Mamm Creek field area is outlined in red. The West Divide Creek seep is shown by the red circle.

COGCC secured gas and water samples on April 2 that showed elevated levels of benzene. A nearby pond on the Langegger property was also contaminated. Subsequent investigations identified the gas as coming from the Schwartz 2-15B well operated by EOG.

The well, completed on February 6, 2004, lost cement from the production zone allowing gas to vent for 55 days upwards along the back of the casing into the well bore and through a fault until the remedial cement job secured the well. The venting hydrocarbons charged the Wasatch Formation sandstone bodies along the fault with gas, contaminated the creek bottom, and finally the stream. The methodology used by the COGCC to determine if gas well activity was impacting water resources involved analysis of dissolved gas in water. The methodology used the presence of methane and of the higher carbon homologues, ethane, propane, n-butane, iso-butane, n-pentane and hexanes, together with methane stable isotopic data to conclusively identify the origin of the gas.

Figure 2 shows a conceptual diagram of the process. Since the concentration of benzene exceeded regulatory limits COGCC required EnCana to remediate the creek. A drilling moratorium was placed on the area surrounding the Schwartz well (2 mile radius) while investigations were continued. Remedial activities included installing and sampling monitoring wells (Figure 3), installing and then improving the air sparge system, studies of benthic macrofauna, sampling of surrounding domestic wells, and a soil gas survey.

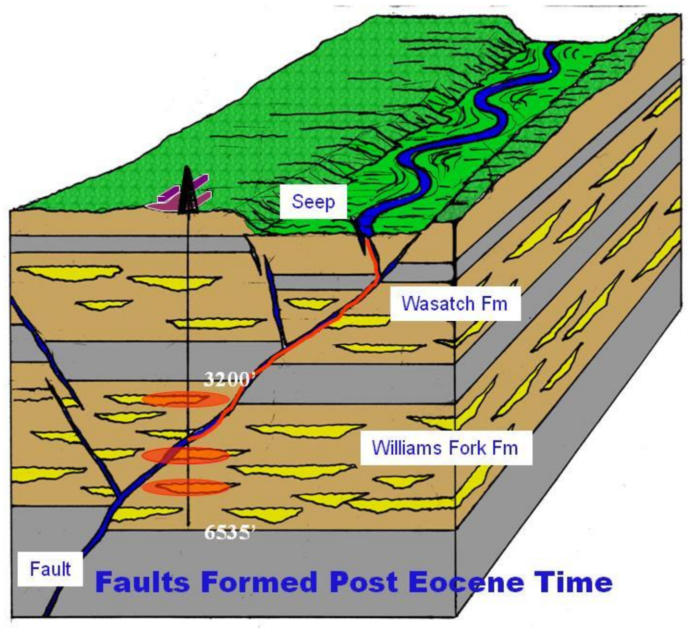

Figure 2. Conceptual diagram of the process that caused the seep, from EnCana 2005.

The surface seep was initially approximately circular and about 400 feet in diameter (Figure 3). The impacted area has gotten smaller with time. The seep continues to discharge gas and associated hydrocarbons, but the depletion of the source has lowered the benzene concentrations below the regulatory standard in a sustained manner (Figure 4). The isotopic and compositional data show the source has remained unchanged (Figure 5). The data is consistent with the hydrocarbons from the gas well charging Wasatch sandstones along the fault and then gradually depleting after gas well remediation.

Drilling and Completion Modifications

In July, 2004 the COGCC issued a notice of operators (NTO) drilling Mesa Verde wells in the Mamm Creek field area that established a drilling moratorium in a two-mile radius around the Schwartz 2-15B well (Order 1V-276). This notice instructed operators to follow certain cementing and reporting procedures in response to the West Divide Creek (WDC) seep and the problems in the nearby Amos/Walker and Dietrich wells and the P3 well pad site. The moratorium was lifted in 2005 and drilling in the area began following the new rules established. The new procedures provided much improved and timely information transfer to the State concerning problems encountered during drilling and completions. The notice was updated in April 2006 after operators had drilled more than 300 wells in the area and further modified in November 2006. In 2007 the cementing Notice to Operators (NTO) was further revised.

The Phase I study noted that there were elevated pressures (see below) in some Mamm Creek Field wells that could indicate problems with well integrity and lead to leaks into water wells. This led to the bradenhead NTO in 2010. Since that time the COGCC has required sundry notices and selected gas sampling for bradenhead venting. The operating procedures have continued to be updated as more information has been collected. It appears that the Wasatch Formation contains variable amounts of gas that can enter the well bore and move upwards (COGCC, 2011). Control of this gas is important to prevent the discharge into the shallow portions of the aquifer.

The COGCC had Crescent Consulting review the effects of changes in drilling and cementing procedures focused on EnCana wells (Crescent, 2011, COGCC, 2011). The report concluded that the new practices had been effective in improving cementation and produced better recognition and mitigation of gas control problems. The report also noted that identification of shallow gas zones and prompt isolation is necessary. The geologic nature of the shallow Wasatch means unpredictable losses of circulation and cement occur, but cement squeeze jobs can be an effective remediation for gas control in problem wells.

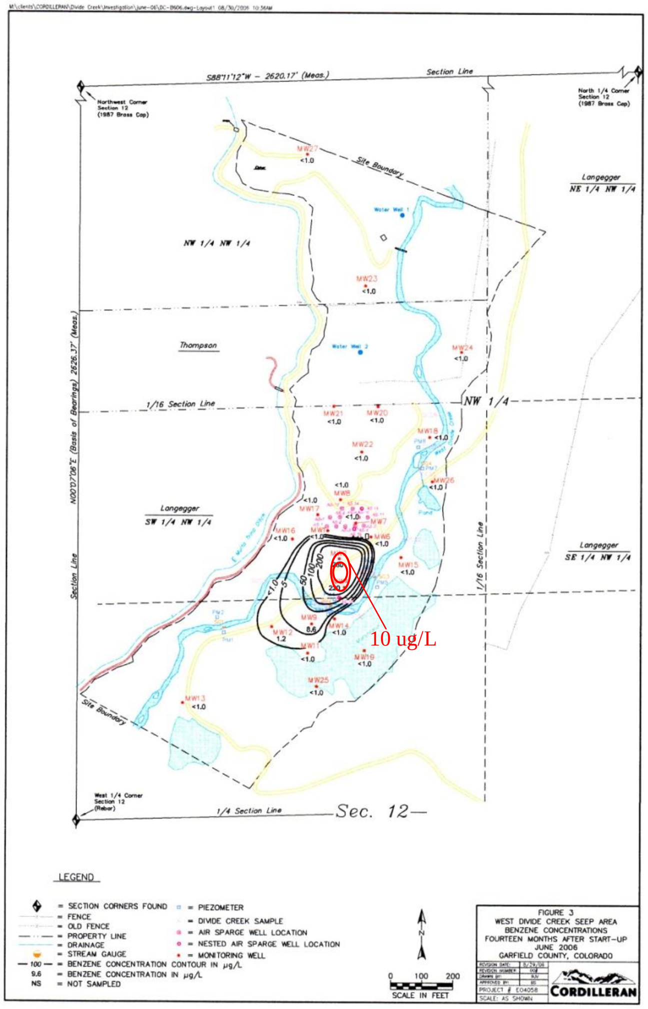

Figure 3 – Isopachs of benzene concentrations from monitoring well data outlines the center of the seep. Black isopachs are data are from 2006 with highest values of 200µg/L. Red isopachs are from 2014 data with highest values of 10µg/L.

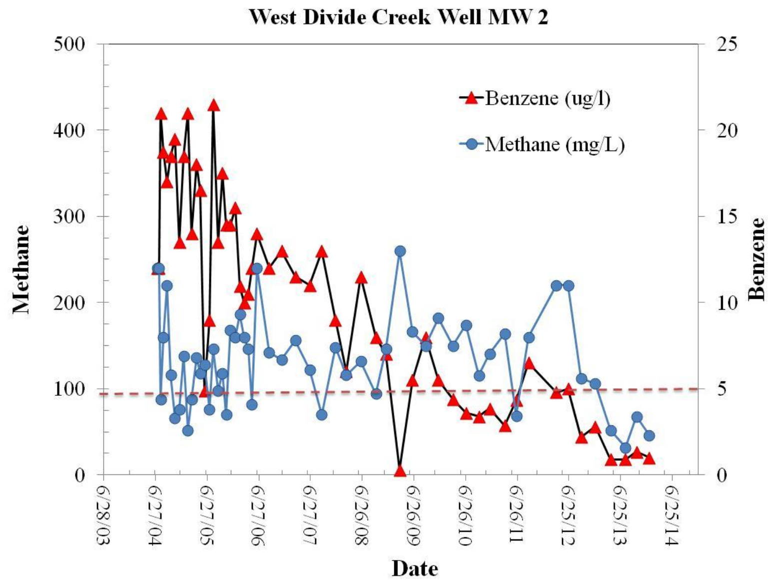

Figure 4 - Concentrations of methane and benzene from monitoring well MW 2 installed in the center of the seep (see Figure 2).

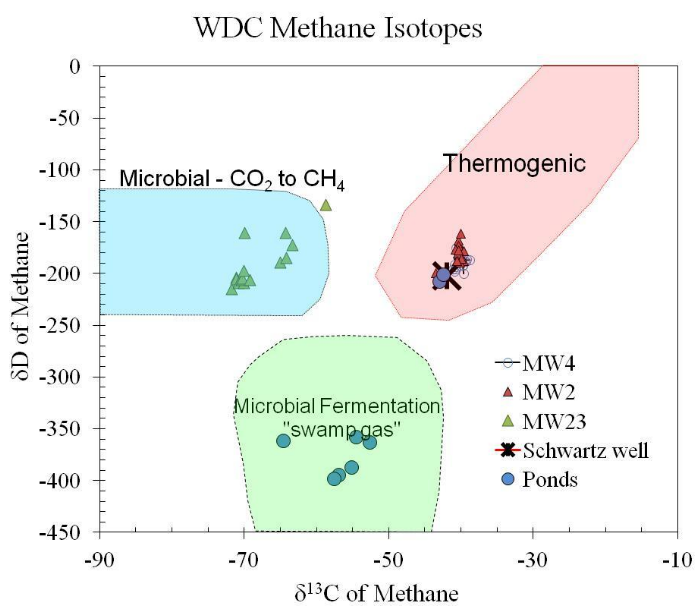

Figure 5 – Carbon and hydrogen isotopic values of methane monitoring wells and local ponds at the WDC seep (see Figure 2).

Phase I Report Summary

URS Corporation completed the Phase I study in 2006. Figure 1 shows the study area and several structural features. The Mamm Creek field covers roughly the northern portion of the study area. The report serves as a baseline study of the hydrogeology of the Mamm Creek Field area and identified several important conditions that effect water quality in the area. The major findings include:

1 The Wasatch Formation is thinner in the Moratorium area – Figure 2-7 in the report,

2 The eastern portion of the study area has a fairly continuous sandstone layer allowing greater lateral mobility from any point source contamination,

3 The area has a major structural feature (Divide Creek Anticline) that produces greater vertical numbers of vertical fractures providing enhanced vertical permeability – Figure 2-10 in the report,

4 The area has more shallow, intermediate and deep linear features indicating more faults and fractures in general – Figure 2-12 in the report,

5 The area has water wells with elevated specific capacity indicating greater vertical and horizontal permeability – Figure 3-5 in the report,

6 The area has a number of wells with elevated bradenhead pressures – Figure 4.5 in the report,

7 The area has many wells with elevated solutes (TDS) and chemical characteristics (elevated F, Se, SO_4, greater NO_2/NO_3, Na and Cl) that may indicate greater vertical connection with the underlying Williams Fork Formation – Figure 5-14, 5-16 in the report,

8 The area has many water wells that have elevated methane, much of which is thermogenic in origin (Figure 5-31) indicating greater vertical connections between the Williams Fork Formation and the surface – Figure 5-23in the report.

This report concluded that there may be a connection between the water quality issues and petroleum activity. Alternatively, the poorer water quality may be controlled by geological features including greater natural vertical fracturing and lithology of the Wasatch in the impacted area (see Figure 1).

Phase II Report Summary

The Phase II investigation continued the Phase I work with several key goals including to confirm the analytical results at water wells that had concentrations for specific parameters which were health concerns or had elevated Na and Cl, and collect water samples from domestic wells and gas samples from nearby gas wells to determine if the water wells had been impacted by gas from deeper formations. The major findings include:

1 - Some water wells showed levels of nitrate, fluoride and selenium that are greater than drinking water standards. Those homeowners were notified.

2 – There are two distinct types of groundwater, sodium bicarbonate and sodium sulfate that are found in the water wells.

3 – Most Williams Fork produced water has somewhat saline sodium chloride chemistry with total dissolved solids between 7,390 and 21,700 ppm.

4 - Water chemistry, gas composition and methane isotopic data in domestic wells along the Divide Creek Anticline show the aquifer may be impacted by produced water and natural from deeper sources.

Phase III Report Summary

The objective of the Phase III Hydrogeologic Characterization for the Mamm Creek Study Area was to install three shallow (400') and deep (600') monitoring wells near the seep site, determine the vertical structure, flow patterns and chemical and isotopic composition of groundwater in the Wasatch aquifer. In addition, the Currie domestic well was sampled to provide a control on Wasatch aquifer water. The amounts of chloride, methane and benzene in these wells provide important constraints when using these parameters to determine impact of petroleum activity on water wells. The major findings include:

1 – The conceptual model of the hydrogeology associated with the investigation is low-permeability siltstones and sandstones which contain intermittent fracture patterns that may be laterally or vertically continuous over short distances. The vertical gradient is usually downward.

2 - Up to four samples per well over a period of 2 years established the chemistry of local Wasatch groundwater. These analyses, including the domestic well, all had low, but detectable concentrations of methane and benzene. Groundwater present in the shallow wells generally show reducing conditions.

3 – Based on isotopic data, the dissolved methane in all shallow wells (< 400 feet deep) appears to have either biogenic or mixed biogenic-thermogenic (MW-1A) origins rather than the purely thermogenic methane found in the Williams Fork Formation. This data is supported by the wet-gas analysis.

4 - The deeper wells (MW-1B and MW-2B) have methane with thermogenic isotopic signatures. The wet-gas analysis supports this interpretation. The highest dissolved thermogenic methane was 8.7 mg/L in MW-1B and the lowest concentration was 0.53 mg/L in MW-3B.

5 - Methane in MW-3B shifted between thermogenic, biogenic and mixed isotopic signatures over the sampling period (2011-2013).

6 - Low concentrations of benzene are likely present throughout the area due to some combination of natural migration from the deeper Williams Fork Formation and naturally-occurring benzene in the Wasatch Formation. Below 400 feet, concentrations of benzene may be observed to be higher with increasing depth due to naturally higher benzene at depth.

7 - Chloride levels in the most of the wells are consistent with other domestic wells in the area. Concentrations of chloride observed in some wells (MW-1B, MW-3A and MW-3B) are somewhat higher than those observed in the surrounding domestic wells.

8 - Concentrations of chloride are also typically higher in the vicinity of the Divide Creek Anticline, ranging from several hundred mg/L to nearly 2,000 mg/L in other wells. Since the Williams Fork Formation underlies the Wasatch Formation, the anticline structure and related fractures may provide the means for transport of fluids from the deeper and higher salinity zones to the surface in the area.

Discussion and Synthesis

The reports all agree that the eastern Mamm Creek area has many faults and fractures, particularly in the area along the Divide Creek Anticline that contribute to the vertical permeability of the Wasatch Formation. This does not mean that the Wasatch Formation is hydraulically connected to the underlying Williams Fork Formation. In fact, the gas-bearing Williams Fork has a low permeability seal separating it from the overlying Wasatch otherwise there would be no accumulations of economic amounts of natural gas. However, the faults and fractures in the Wasatch are responsible for the initial difficulty encountered in drilling and completing gas wells. This led to the West Divide Creek seep and problems in several adjacent domestic wells (Universal Geoscience Consulting, 2010). It appears that some gas wells encounter sections of Wasatch sandstones with gas that flow upwards inside the well casing producing elevated bradenhead pressures and contamination of the shallow aquifer.

This structural condition is also reflected by the variations in aquifer yield and groundwater quality that include higher total dissolved solids (TDS), chloride, methane and benzene concentrations, probably related to the Divide Creek Anticline (McMahon et al, 2010, URS, 2006, Papadopolous, 2008, 2010, TetraTek, 2013). For instance, Figure 6 shows the linear relationship between total dissolved solids and the dissolved chloride and sulfate. As noted in the Phase II report, there is a distinct type of deeper groundwater that has elevated sulfate, while produced water has elevated chloride content. It appears that many groundwater wells have a mixture of shallow groundwater with low chloride and TDS, higher sulfate-rich deeper groundwater and Williams produced water. This implies either a significant degree of vertical hydraulic communication, that the wells may be a more significant pathway for vertical fluid movement than anticipated or that produced water spills and leaks occur at the surface. This data shows the difficulty in fully understanding the hydrogeology of the area and the potential impacts from petroleum activity even after all the research.

Detection of impact to water wells from gas is less problematic given the lessons from the WDC seep. While the WDC seep has created problems only now dissipating, it does offer a methodology to identify future impacts from gas leaks. That identification may be complicated since the Wasatch Formation has some natural background levels of the likely indicators, methane and benzene, particularly in the deeper portions. Figure 7 shows the isotopic values for the WDC seep, natural gas wells and the shallow and deep Phase III monitoring wells. We can see that while the shallow Wasatch appears to have a distinctive isotopic fingerprint, the deeper wells show a thermogenic component. This thermogenic component may be due to upward leaking of relatively small amounts of Williams Fork gas that passes through the seal. Some upward mobility of natural gas over gas fields is expected. This can affect groundwater chemistry and even soil gas and vegetation. Such alterations to normal patterns have been used to identify gas fields during exploration. However, as several reports detail, the wellbores represent significant pathways and can lead to contamination if the well cement integrity fails. In the case of the WDC seep, the COGCC used not only isotopic, but also C2-C6 composition data. This type of data is now standard for samples from gas wells and water wells. By securing pre-drill samples from water wells with this type of data, we can establish the normal conditions and more easily identify the cause of changes.

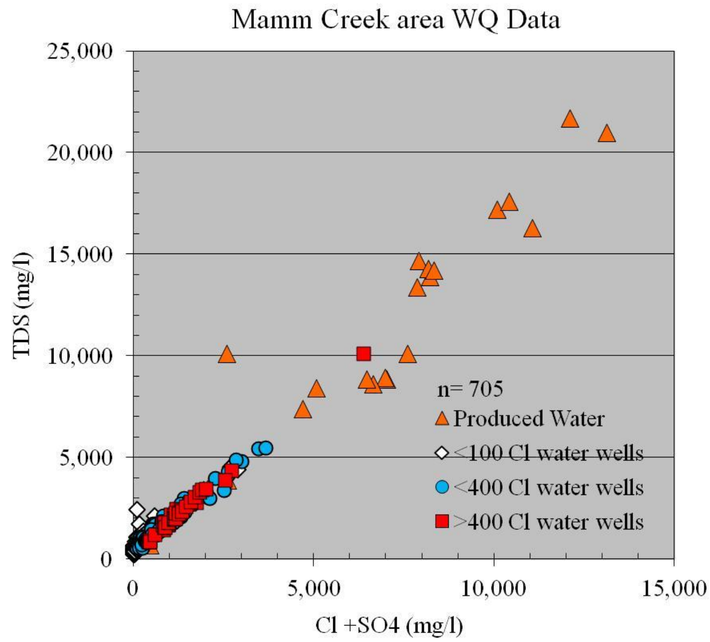

Figure 6 – Plot of chloride+sulfate versus total dissolved solids (TDS) for 689 water well samples in the Mamm Creek Field area. The linear relationship implies that most groundwater is a mixture of shallow low chloride water, deeper sulfate-rich groundwater and Williams Fork produced water.

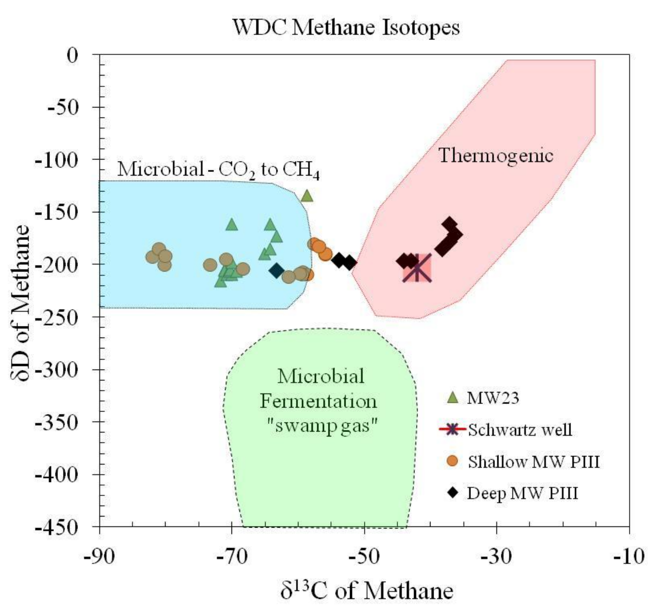

Figure 7 – Carbon and hydrogen isotopic values of methane monitoring wells at the WDC seep and the shallow and deep monitoring wells installed in the Phase III study. Note the some deep monitoring wells show a thermogenic signature.

Conclusions

The West Divide Creek seep is in the process of dissipating. The level of hydrocarbon contamination continues to decline and the benzene levels have fallen below regulatory levels. The complex geology of the area was challenging for standard drilling and completion procedures leading to problems with gas contamination of the local aquifer at some locations. Improved drilling and completion procedures directed by COGCC and improvements by operators in their standard operating procedures have reduced problems. Improved reporting of data to COGCC provides better monitoring and identification of problems and the opportunity for continued modifications in the future as indicated.

The Hydrogeologic studies performed by Garfield County have helped understand the nature of the Wasatch aquifer and the relationship between the Wasatch and underlying William Fork Formation. The complex fault and fracture systems have an impact on the groundwater quality particularly along the axis of the Divide Creek Anticline. Identification of impacts to water wells in this area is complex and will continue to challenge regulators, however the continued gathering of data now required by COGCC will help refine the methodology. Based on the experience of the West Divide Creek seep, pre-drill testing of water wells is essential to establish a baseline water quality and help better detect and define future impacts. The new regulations by the State of Colorado require both pre- and post-drilling testing of water wells near new petroleum wells. Garfield County should support the COGCC in ensuring the new regulations are implemented quickly and efficiently.

Documents Reviewed

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