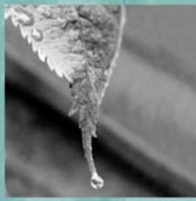
water for life



knowledge and research

Potential for Gas Migration Due to Coalbed Methane Development

Alberta Environment
Authors: James Armstrong, Carl Mendoza and Anthony Gorody
July 2009

Alberta

ISBN: 978-0-7785-8544-2 (Printed version)

ISBN: 978-0-7785-8545-9 (Online version)

Disclaimer
This document is an independent report requested by, and prepared for, Alberta Environment. The authors are solely responsible for the interpretations of data and statements made within this report. The report does not necessarily reflect endorsement by, or the policies of Alberta Environment.

Reproduction and Availability

This report and its contents may be reproduced in whole, or in part, provided that this title page is included with such reproduction and/or appropriate acknowledgements are provided to the authors and sponsors of this project.

Any comments, questions or suggestions on the content of this document may be directed to:

Water Policy Branch
Alberta Environment
10th Floor, Oxbridge Place
9820 – 106th Street
Edmonton, Alberta T5K 2J6
Phone: (780) 427-6210
Fax: (780) 422-4192
Website: www.gov.ab.ca/env

Additional Copies
Additional print copies of this document are available from:

Alberta Environment
Information Centre
Main Floor, Oxbridge Place
9820-106 Street
Edmonton, AB T5K 2J6
Tel: 780.427.2700 (outside of Edmonton dial 310.0000 for toll-free connection)
Fax: 780. 422.4086
E-mail: env.infocent@gov.ab.ca
Website: www.gov.ab.ca/env

WorleyParsons
resources & energy

ALBERTA ENVIRONMENT

Potential For Gas Migration Due To Coalbed Methane Development

C67020000

30 March 2009

Environment & Water Resources

Suite 100, 4500 – 16 Avenue NW
Calgary, AB   T3B 0M6 Canada
Telephone: +1 403 247 0200
Toll-Free: 1 800 668 6772
Facsimile: +1 403 247 4811
worleyparsons.com

PROJECT C67020000 - POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

FILE LOC.: CALGARY

REV	DESCRIPTION	ORIG	REVIEW	WORLEY-PARSONS APPROVAL	DATE	CLIENT APPROVAL	DATE
A	Issued for internal review	C. Mendoza/A. Gorody	J. Armstrong		15-Feb-08		
B	Issued for client review	C. Mendoza/A. Gorody	J. Armstrong		18-Mar-08		
C	Re-issued for client review	C. Mendoza/A. Gorody	J. Armstrong		14-Oct-08		
D	Final with edits		J. Armstrong		25-Mar-09		
0	Issued as Final	C. Mendoza/A. Gorody	J. Armstrong	J. Armstrong	30-Mar-09		

Disclaimer

The information presented in this document was compiled and interpreted exclusively for the purposes stated in Section 1 of the document. WorleyParsons provided this report for Alberta Environment solely for the purpose noted above.

WorleyParsons has exercised reasonable skill, care, and diligence to assess the information acquired during the preparation of this report, but makes no guarantees or warranties as to the accuracy or completeness of this information. The information contained in this report is based upon, and limited by, the circumstances and conditions acknowledged herein, and upon information available at the time of its preparation. The information provided by others is believed to be accurate but cannot be guaranteed.

WorleyParsons does not accept any responsibility for the use of this report for any purpose other than that stated in Section 1 and does not accept responsibility to any third party for the use in whole or in part of the contents of this report. Any alternative use, including that by a third party, or any reliance on, or decisions based on this document, is the responsibility of the alternative user or third party.

Any questions concerning the information or its interpretation should be directed to C. Mendoza/A. Gorody or J. Armstrong.

EXECUTIVE SUMMARY

Coalbed gas (CBG) effectively consists of methane with minor amounts of ethane and propane, but no hydrogen sulphide (H_2S). Recognition of CBG as an increasingly important energy resource has led to rapid expansion of exploration activity. Rapid development started in the 1980s in the western United States of America (USA), and has spread over the last six years to the Western Canadian Sedimentary Basin (WCSB). Increased production activities have brought increased awareness of environmental issues surrounding CBG development. In particular, reports of negative experiences associated with early CBG development in the USA have raised stakeholder concerns in Canada.

Alberta CBG development has largely avoided the water resources issues experienced in the USA from CBG exploitation for two reasons. The major CBG resource plays in Canada to date have been in ‘dry’ coals, while ‘wet’ CBG coals developed in the USA required dewatering in order to recover the gas. Secondly, the rapid increase in Alberta CBG development occurred after Alberta regulators had already implemented protective legislation to address environmental concerns associated with protection of groundwater resources. Further regulations have been added, requiring a baseline water well testing program (May 2006), monitoring of groundwater production above the base of groundwater protection (October 2006), and prescriptive approaches to drilling and installing CBG production wells.

Gas migration behaviour in the subsurface was considered from a scientific perspective. Three principal pathways for gas migration to surface were identified in relation to CBG development. The first pathway is along older or abandoned boreholes with inadequate or decaying seals across shallow coal beds. A second pathway is within water wells completed across water-bearing coal zones and/or adjacent sandstone units. The third pathway is in areas where coal zones approach ground surface.

Perspectives on environmental issues for gas migration from CBG development vary between stakeholders. Risk summarizes the combination of the probability of an event and its resulting negative consequences. A sample risk review related to gas migration was used to illustrate this point. A comprehensive assessment would require much more input from all affected stakeholders. Further development of a risk model with broader stakeholder input and all risks (not just gas migration) may also help raise awareness of the technical details, different perspectives, and mitigation alternatives.

Gas migration problems related to CBG development in the ‘dry’ Horseshoe Canyon Formation coals are unlikely to occur, given the hydrogeological conditions coupled with present regulatory requirements. Anticipated CBG development in shallower, ‘wet’ Ardley coal zones will require dewatering, and will benefit from risk management experiences learned from CBG development in the USA. The deeper, ‘wet’ Mannville coals require removing saline water, a strictly regulated activity.

The potential for CBG leakage associated with historical oilfield wells(i.e., drilled prior to the mid-1970’s) needs further assessment, by looking at surveyed locations relative to existing water wells and by using geochemical and stable isotopic gas analyses.

Water well owners need to be educated about their responsibility for well installation and maintenance, including proper abandonment of old and unused water wells.

Common Technical Acronyms and Abbreviations

AAFRD	Alberta Agriculture, Food and Rural Development
AE	Alberta Energy
AENV	Alberta Environment
AGS	Alberta Geological Survey
BGWP	Base of Groundwater Protection
CBG	Coalbed gas (equivalent to coalbed methane, CBM and natural gas in coal, NGC)
FID	flame-ionization detector
ERCB	Energy Resources Conservation Board (previously EUB)
GC	gas chromatograph
OVA	organic vapour analyzer
PID	photo-ionization detector
ppm	parts per million
WCSB	Western Canadian Sedimentary Basin
USEPA	United States Environmental Protection Agency

CONTENTS

Figures

Appendices

1. INTRODUCTION

This report reviews environmental issues related to the potential for gas migration in association with coalbed gas (CBG) resource development. The report uses CBG as a collective acronym to describe the natural gas resource variably termed coalbed methane (CBM) and natural gas in coal (NGC). The term CBG was selected to reinforce the fact that methane is not the only gas present in coal beds.

The report was prepared for Alberta Environment to address public concerns regarding a lack of Alberta-based information about potential impacts associated with CBG development. The concerns were highlighted in a report from the Multi-Stakeholder Advisory Committee (MAC 2006), as per:

Recommendation 3.6.1: AENV and ERCB (formerly EUB) should work with industry to investigate the potential for methane migration or release to water wells as a result of CBM/NGC depressurization.

The report is intended to summarize information in four areas, including: how gas moves within natural systems, potential impacts related to CBG development, differences in gas migration potential associated with CBG production intervals (e.g. Ardley and Horseshoe Canyon coal zones), and experience from other jurisdictions.

The report is developed as follows. A broad overview of CBG development in Alberta is provided in Section 2, including background information on CBG geology and resource potential. The regulatory framework for CBG development in Alberta is summarized in Section 3. General health and safety concerns of landowners related to CBG development projects are examined in Section 4. As a first step to help in addressing these concerns, current understanding of CBG behaviour in the subsurface is examined in Section 5, with specific relation to CBG development. An overview of gas sampling methods and analytical techniques is provided in Section 6. This section has a particular focus on methane (CH_4), the dominant component of CBG.

A risk-based framework is presented to examine the main concerns from different perspectives in Section 7, with some insight provided by a summary of Alberta landowner complaints. A risk assessment approach was used to examine CBG migration potential from different perspectives in Sections 8 and 9 (risk ranking/mitigation). This hypothetical example used assumed perspectives for Industry and Regulators to show how the approach could help compare and communicate stakeholder viewpoints. For the example, generalized perspectives were based on WorleyParsons corporate experience. Extensive interviews with industry, regulators and the public would be necessary to complete a comprehensive risk assessment and/or mitigation plan.

Experiences from longer-term CBG development of ‘wet’ coals in the USA are summarized in Section 10, with additional details regarding experiences in several USA basins provided in Appendices 1, 2 and 3. These experiences are informative, given anticipated future development of ‘wet’ coals (e.g. Ardley, Mannville) in Alberta. Although most current Alberta CBG projects are in ‘dry’ coals, and have different hydrogeological considerations, experience from the USA has relevance for risk management issues.

The last two sections provide a summary of the current understanding related to gas migration and CBG development (Section 11), and an overview of data and knowledge gaps (Section 12).

2. COALBED GAS RESOURCE

- Coalbed gas (CBG) is natural gas (mostly methane, minor ethane/propane) derived from organic matter degradation
- Most current Alberta CBG targets are shallow-dipping coal layers across central Alberta
- Production is mainly from ‘dry’ coals in the Horseshoe Canyon Formation through central Alberta
- Production may increase from ‘wet’ Ardley (nonsaline water) and Mannville (saline water) coals

2.1 Geologic Setting - Alberta

Much of Alberta is located in the Western Canadian Sedimentary Basin (WCSB), which consists of a thick package of sedimentary rocks overlain by a thin veneer of unconsolidated deposits. To the west, the sedimentary rocks are exposed as the Rocky Mountains. This exposure is a result of tectonic activity about 60 million years ago. The package of sedimentary rocks consists of numerous layers that are close to being horizontal, but dipping slightly to the west. The resulting wedge thins to the east with older rocks being exposed as subcrop edges further to the east. The more permeable rocks (e.g. sandstones and some carbonates) form aquifers or reservoirs. The less permeable rocks (e.g. shales) form aquitards or reservoir caprocks. Fluids tend to flow along aquifers and, extremely slowly, across aquitards.

2.1.1 Quaternary Geology

Quaternary deposits in the Alberta basin range in thickness from less than a metre to over 100 m. Repeated glaciation events throughout the area are responsible for depositing sediments via a variety of geological processes. Quaternary geology in the Alberta basin is described in detail in Fenton et al. (1994).

2.1.2 Bedrock Geology

This section provides a brief overview of bedrock units related to the main CBG-bearing units shown in map view (Figure 1), in stratigraphic section (Figure 2) and in a representative cross-section (Figure 3), with a focus on the central Alberta plains area. The geological history comprises numerous events and basin-scale processes such as tectonic compression and uplift, variations in relative sea level, erosion and continental deposition. As a result lateral and vertical heterogeneity (variations) in geologic composition and stratigraphic correlation are to be expected. Selected comments also highlight points that are relevant from an environmental assessment perspective.

The Tertiary Paskapoo Formation comprises interbedded sequences of non-marine sandstone, siltstone and mudstone with some thin coalbeds throughout. This formation is a major aquifer, and represents an important source of groundwater for domestic use through southern and central Alberta.

The Scollard Formation consists of interbedded sandstone and siltstone with mudstone and coal layers. The most notable coal is the Ardley Coal zone within the upper member of the Scollard Formation. The Tertiary-Upper Cretaceous boundary is located near the base of the Ardley Coal. The eastern part of the Scollard Formation may also represent a domestic use aquifer.

The Upper Cretaceous Battle Formation contains fine-grained silt and bentonite-rich lacustrine shale, including the bentonitic shales and tuffaceous beds of the Kneehills Tuff. This relatively thin unit represents a laterally-extensive, low permeability barrier between the overlying Scollard (commonly water-saturated) and Horseshoe Canyon (generally 'dry').

The Whitemud Formation comprises kaolinitic sandstone to sandy siltstone.

The Upper Cretaceous Horseshoe Canyon Formation is distinctively heterogeneous, comprised of continental sandstone, siltstone, shale and mudstone with multiple coal layers. Coaly shale and isolated bentonite beds are also encountered. The Horseshoe Canyon Formation represents a wedge of mainly non-marine sediments thinning to the east. To the east, the interfingered transition zone from the Horseshoe Canyon Formation to marine Bearpaw strata likely has significant influence on the general lack of water saturation of Horseshoe Canyon coalbeds.

The Belly River Group comprises a series of clay, siltstone and sandstone units, mainly of non-marine origin, with three main coal-bearing zones.

The Lea Park Formation (deeper geologic strata are shown in Figure 3) is composed of marine, fine grained siltstone and mudstone, and represents the base of the Upper Cretaceous interval.

The Colorado Group represents a series of thick marine shales and some thin, interbedded sandstone layers deposited during the transition from Lower to Upper Cretaceous. The finer-grained layers in the Colorado Group generally act as aquitards between the sandstone aquifers.

Mannville Group strata (Lower Cretaceous) are generally continental in nature. The upper Mannville Group is rich in coal, and likely represents the largest potential CBG resource in the Alberta Basin. The Mannville coals are typically saturated with saline formation water (total dissolved solids (TDS) > 4,000 mg/L).

2.2 Formation of Coalbed Gas (CBG)

Coal is formed through physical and chemical alteration of organic matter (peat), following long-term burial by natural geological processes. CBG (mostly methane) is a by-product of coal formation, and may include minor percentages of ethane, propane, carbon dioxide and nitrogen. The main component, methane, is formed by the natural decomposition of organic matter in the absence of oxygen, and can be produced by three processes. In order of decreasing importance, they are (Clark and Fritz 1997):

- biogenic (bacterial decomposition);
- thermogenic (decomposition by heat); and,
- abiogenic and mantle processes (occurs only in very deep deposits).

There may be a general compositional gradation in CBG with depth (i.e. increasing pressure and temperature) from biogenic (almost all methane) to thermogenic (increasing ethane and propane). The classification as to gas formation process (i.e. origin) and subsequent migration characteristics may have consequences for overall gas composition, stable isotopic signature, and source location or characteristics.

Biogenic methane production is the most common of the three processes in shallow groundwater systems. Biogenic methane is produced by bacterial decomposition of organic matter in the absence of oxygen. Different bacterial populations contribute to methane production through reductive or fermentative processes. These processes can occur under conditions found both near ground surface, such as in muskeg, organic-rich soils, landfills, manure/sewage storage systems, as well as at depths to several hundred metres below ground surface. Research has indicated that methane and other light hydrocarbons (e.g. ethane or propane) can also be produced as a result of low-temperature organic decomposition (Davis and Squires 1954; Rice and Claypool 1981; Rowe and Muehlenbachs 1999).

Gas reservoirs (i.e. sources) derived from such shallow sources have likely only had a short time to develop, and may have limited resources (e.g. carbon pools). Thus, although the accumulation rate might have been rapid, the accumulated volume in potential reservoirs might be relatively small and localized, especially in the absence of an upper low permeability cap. Furthermore, the slow transport mechanisms and the short time for migration after such recent gas production mean that the location of these gas deposits is usually coincident with the source, in the absence of pumping.

Thermogenic methane is formed by the thermal breakdown of complex hydrocarbons resulting from decomposition of organic material largely originating in ancient shales. This process generally occurred after organic matter was buried under a sufficient thickness of sediments to generate the high temperatures and pressures required for gas generation. Thermogenic gases typically originated at great (1000+ m) depths; however, over geologic time these gases may have migrated far from the original source area and subsequently accumulated at shallower depths.

Thermogenic methane may be associated with a wide range of heavier hydrocarbons, as either gases or crude oil liquids, and hydrogen sulphide (H_2S). However, Rowe and Muehlenbachs (1999) suggest that non-methane hydrocarbons can be generated thermally under low-temperature conditions. Thus, care must be taken when using the presence (or absence) of non-methane hydrocarbons to differentiate between biogenic and thermogenic methane.

Abiogenic methane is produced under strongly reducing conditions found deep within the earth's crust. This process is not significant to the current discussion.

2.3 CBG Occurrence

CBG is typically formed, and found, at shallow to intermediate depths. Methane dominates the composition of CBG, although small fractions of ethane, propane, carbon dioxide and nitrogen may be present. CBG does not contain any hydrogen sulphide, thus is regarded as "sweet" gas (AE 2008). In Alberta, natural gas containing H_2S (sour gas) is primarily found in the (deeper) Mississippian and Devonian strata, due to the mineralogical characteristics of these carbonate-dominated formations.

Small amounts of H_2S may be produced in shallow aquifers due to microbial activity at low temperatures. This H_2S is usually associated with the reduction of sulphate, a naturally occurring ion that is commonly found in the (geologically) young glacial tills of Alberta. Although H_2S is not associated with CBG production, complaints may develop because of other sources of sour gas that influence water well quality. For this reason only, health and safety concerns with H_2S are mentioned in Sections 4.2 and 10.0 (and detailed in Appendix 2).

In Alberta, economic quantities of methane occur in the subsurface in one of two primary scenarios: biogenic methane, or mixtures of thermogenic and biogenic methane (found in low-pressure CBG reservoirs and adjacent permeable sandstone layers); and, mainly thermogenic methane (found in medium to high-pressure conventional reservoirs). Methane can also occur in the shallow subsurface, but is not an economical resource compared to the first two scenarios. This work focuses on CBG reservoirs and their possible influences on the shallow environment, and water wells in particular. As noted below, other sources of methane and dissolved gases may complicate any given scenario.

2.3.1 Quaternary Sediments

Methane is found within Quaternary deposits in Alberta, but typically not in sufficient volumes to represent an economic resource. Methane occurrences are usually localized in Quaternary deposits because of their heterogeneous and discontinuous nature, and their shallow depositional environment and history. Natural shallow sources of methane include biodegradation of organic carbon (e.g. vegetation) deposited along with the sediments such as in shallow peat bogs or coal zones. Other common localized sources of methane include fugitive emissions from nearby landfills, septic and sewage systems, animal waste lagoons and similar sites where organic carbon wastes have been disposed. Methane presence can also be linked to anaerobic biodegradation of hydrocarbon contaminants released to the subsurface.

A third source of methane gas presence in Quaternary sediments is emissions originating from upward vertical leakage from much deeper conventional oil and gas reservoirs (e.g. Smith 1978; Harrison 1985; Chafin 1994). Typical vertical pathways for these fugitive gas migration include improperly sealed or abandoned wells, seismic shotholes and exploration testholes associated with oil and gas activity. Such pathways could also connect deeper CBG reservoirs to Quaternary sediments. Methane gas presence due to upward leakage is discussed in greater detail in Section 5, while methods used to differentiate methane sources from CBG exploration or conventional gas exploration are discussed in Section 6. Both subjects are also discussed in the context of the USA experience in Appendices 1 to 3.

2.3.2 Coal-Bearing Bedrock

This section provides a broad overview based on publications by the authors referenced below. Prominent CBG-bearing coal beds in Alberta are reviewed in detail in Dawson et al. (2000), Lemay (2003) and Gatens (2005). The depositional history and evolution of prominent coal-bearing units in Alberta has been described by Bachu (1997), Beaton et al. (2002), and Bachu and Michael (2002). The net distribution of coal in bedrock units in the Alberta plain is shown in Figure 1. The main coal zones include the Ardley (Scollard Formation), Drumheller and Horseshoe Canyon (Horseshoe Canyon Formation) and Mannville

(Mannville Group). Figure 2 shows the stratigraphic relationships between these formations, as well as other coals zones in Alberta (Lethbridge, Taber, McKay, Luscar and Kootenay).

A cross-section through central Alberta's significant coal-bearing formations is presented in Figure 3. The following summary of the geologic setting proceeds downward from ground surface (contrary to geologic convention) to highlight the focus on environmental concerns associated with CBG production and groundwater users.

The main CBG-containing units are summarized in downward order (youngest to oldest) to maintain focus on shallow environmental impacts. More detail regarding coalbed nomenclature, equivalences and geographic distribution is summarized in Lemay (2003).

Exploration of CBG potential in Alberta's coal-bearing formations has been dictated by the geologic history, which has divided the resource occurrence into two main areas: the deformed and undeformed parts of the Alberta basin (Figure 3). Within the deformed part, there has been a substantial degree of tectonically-related structural folding and faulting associated with uplift of the Rocky Mountains and Foothills. As a result, these units show variable continuity and vertical and/or lateral offset. Given this geologic complexity, combined with varying methane content found in the limited exploration work to date, most of the CBG development has occurred in the undeformed part of the Alberta basin.

Tertiary (Paskapoo/Scollard)

Coal deposits, typically with low CBG economic potential, can be found across Alberta in shallow, low-rank coal zones (Bachu and Michael 2002). As noted above, the youngest (Tertiary) Paskapoo Formation represents a major aquifer. Thin layers of coal within this aquifer likely account for some portion of methane presence reported throughout much of Alberta (Lemay 2003).

Within the Tertiary Scollard Formation, the Ardley coal zone represents the shallowest significant resource, although it may contain less total CBG compared to deeper coal beds. These coals are reported to exhibit varying water saturation (from 'dry' to 'wet'), with both saline and non-saline water reported. In a recent summary, Gatens (2005) noted that there have been relatively few production tests in the Ardley coal zone, and most wells are not actively being produced or tested. Approximately 1% of CBM production wells are completed in the Ardley coal zone (ERCB 2007c).

Late Upper Cretaceous (Horseshoe Canyon)

The Alberta Geological Survey (AGS) and Alberta Energy (AE 2008) reported that more than 90% of CBM/NGC development in Alberta to date has occurred in south Central Alberta involving the multiple coal layers (1-30) in the Late Cretaceous Horseshoe Canyon Formation. This preferential development is based on reasonably high bulk permeability, a high percentage of methane (relative to other hydrocarbon gases), and a tendency for these coals to be 'dry'. Main coal seam groups in the Horseshoe Canyon Formation include the Carbon-Thompson and Drumheller coals. Note that sandstone layers adjacent to coal zones can act as a secondary reservoir for CBG.

The thin, discontinuous coals of the Horseshoe Canyon Formation are typically classified as sub-highly volatile bituminous coal. Recognition of their CBG potential has increased over the past decade, compared to a previous interpretation of too low a rank (Dawson 1995). Exploration has identified the main CBG intervals as being relatively shallow (200-800 m depth). Most of the Horseshoe Canyon coal layers tend to be ‘dry’ except near the northern end (McWilliams *et al*. 2005). Drill logs have generally encountered 10-20 coal seams (individual thickness of 1-2 m) with a total thickness up to 25 m. These coals outcrop to the east, where near-surface deposits have been mined.

Horseshoe Canyon coalbeds are underpressured (gas pressure is less than the equivalent hydrostatic pressure), and are generally reported to contain minimal water in the cleats. Furthermore the Horseshoe Canyon Formation contains bentonite-rich sandstones that could create permeability barriers, if water contact caused them to swell. The mechanism(s) by which the coals became ‘dry’ after having originally been deposited in a water-saturated environment are not yet clear. What is clear, however, is the presence of a vertical permeability barrier (e.g. the bentonite-rich shale of the Battle Formation) that prevented (and still does) downward vertical water influx. The overlying Scollard (with Ardley coals) and Paskapoo Formations tend to be water-saturated. The absence of downward water movement into the Horseshoe Canyon Formation is a strong indicator that upward methane migration is unlikely.

There are wet zones within the Horseshoe Canyon Formation, as explained by McWilliams *et al*. (2005). The up-dip (eastward) presence of impermeable shale (Bearpaw Formation) in the transition zone acted as a seal that formed a stratigraphic trap for the gas, and prevented water entry into the system. These authors commented that “Coal zones that shale out are dry, whereas ones that outcrop are commonly wet, suggesting that coals are the conduit by which fluid enters the system”. Wet areas of the Horseshoe Canyon are likely to be encountered at the northern and eastern parts, due to absence of the Bearpaw shale, leading to direct recharge of the coals from meteoric waters. In these areas, the Horseshoe Canyon coals may represent a local aquifer. Water wells penetrating these coals may be susceptible to gas presence and production, depending on the extent of pumping.

Early Cretaceous (Mannville and Other Units)

The Early Cretaceous Mannville coals are generally characterized as being bituminous. These coals are typically saturated with saline water, and are generally seen in 2 to 3 relatively thick deposits, typically 5 to 10 m, but up to 20 m thick. The Mannville coals are estimated to have the greatest volume of CBG potential, but have not yet been proven to be an economic resource. The saline water presence makes this CBG target relatively expensive, requiring extraction, handling and responsible disposal of the saline water. Finding economic water-handling techniques will strongly control successful development of CBG from this formation (Gatens 2005). Mannville coals are typically low to normal-pressured.

Closer to the Foothills and Rocky Mountains, the Kootenay coals in the Mist Mountain Formation are commonly ‘wet’, but are extensively fractured as a result of tectonic processes that formed the Foothills. Further exploration and production research is required to prove the viability of CBG projects in the Kootenay coals.

2.4 Resource Development

The presence of CBG has been known for centuries, due to the explosion hazard caused by methane gas during coal mining. More recently, degassing of coalbeds to address these safety concerns led to the realization that methane removal from coal mines could be economical (Van Voast 2003).

Development of CBG as a resource has a history encompassing less than three decades. 1980 marked the first commercial production of CBG in the United States of America (USA). Rising gas prices drove subsequent increased exploration activity. In contrast, CBG development in Alberta did not rapidly increase until commercial production began in 2002.

CBG reserves "many times greater than the collective reserves of all the known conventional gas fields" have been identified worldwide on most continents (North America, Asia, Europe and Australia (GSL 1996)). In Alberta, the total estimated volume of gas-in-place CBG (not all methane is recoverable) was 14 trillion cubic metres ($14x10^{12}$ m^3) (Beaton 2003, Beaton et al. 2006). The recoverable reserves of CBG established in 2007 for areas currently undergoing production was estimated at 24.3 billion cubic metres (10^9 m^3). In comparison, estimated conventional natural gas reserves are 1,069 10^9 m^3 (ERCB 2008).

Coal units are both the source and the reservoir for CBG (i.e. the gas originally formed during the coalification process). This statement has several implications for CBG-containing units (GSL 1996). Methane will form to some degree if there is coal, but will represent an economically valuable resource only if a sufficient volume of gas is stored and can be produced. Therefore, the coal beds must have formed in an environment with sufficient overlying pressure to prevent gas loss during coalification. At the same time, in order for the coal layer to act as a gas reservoir, it must have a sufficiently high gas permeability (either natural or induced) to enable gas movement toward recovery wells (Dawson et al. 2000). Depending on the permeability of adjacent rock layers, CBG may also migrate locally and be present in those formations.

CBG recovery is related to the three forms in which it is stored in coal: sorbed in micropores within the coal matrix, as free or dissolved gas (if the gas is saturated) in cleats (natural fractures within the coal), and in larger-scale macrofractures (Figure 4). The amount and composition of gas stored depends on a number of factors including: degree of fracturing, cleating, micropore structure, coalbed thickness and lateral continuity, ash content, maceral composition (loosely defined as residual coalified plant matter), water presence, and coal rank and maturation (GSL 1996; Bachu 1997). Other relevant factors that affect CBG storage and recovery include the surrounding sedimentary stratigraphic setting (e.g. tectonic stress, depositional setting, structural continuity, silt and clay content, interbedding, and thickness of confining layers) and hydrogeologic conditions (presence of formation fluids and permeability) (Bachu, 1997).

In Alberta, most CBG exploited since commercial production started in 2002 comes from 'dry' coals in the Horseshoe Canyon Formation and is of biogenic origin. While shallower CBG targets (e.g. Ardley coal may be 'wet' or 'dry') have similar gas signatures, deeper targets (e.g. Mannville coal is likely water saturated) should have an increasingly thermogenic gas signature. As an aside, these latter coalbeds may have different water extraction issues: CBG production from water-saturated parts of the Ardley coal may require the extraction of large volumes of non-saline water; while, the Mannville coals will require saline water removal.

According to Gatens (2005) and presentations at the Coalbed Methane Symposium (2005), CBG zones in all of the units listed in Section 2.3.2 have been considered as potential CBG targets, and will likely get increasing attention as local experience develops. After the Horseshoe Canyon Formation and Belly River Group, the next likely targets for exploitation include the shallower Ardley Coal Zone in the Scollard Formation and deeper coal zones in the Mannville Group (Figures 1 to 3).

As of December 31, 2007, there were 9339 producing CBM wells in Alberta, with the large majority completed in the Horseshoe Canyon/Belly River formations (ERCB 2007b; 2008). Minor production derives from the Mannville coal zones, with test wells having been drilled into the Ardley and Kootenay coal zones.

‘Dry’ Coals

More than 90% of current CBG development in Alberta has occurred in the ‘dry’ coals of the Horseshoe Canyon Formation/Belly River Group. Being essentially ‘dry’, there is no need to dewater the coals to allow gas exsolution. Thus, gas production can begin immediately following completion of coal stimulation. This situation differs notably from USA experience where dewatering has typically been required (‘wet’ coals).

Experience has shown that stimulation of ‘dry’ coals is best achieved using nitrogen gas, and that any water introduction can lead to a loss of producible methane. Produced water volumes are commonly less than the established cut-off limit of 5 m^3/month (ERCB 2006c).

‘Wet’ Coals

The shallow Ardley coals in the Scollard Formation have been found to be variably saturated with non-saline water (defined by Alberta Environment as water with total dissolved solids ≤ 4,000 mg/L). Dewatering of saturated zones would likely be required for CBG production. These coals may also represent an aquifer in some areas of Alberta; thus, USA experiences may be more relevant in assessing gas migration potential related to CBG development.

The deep Mannville coals are expected to be saturated with saline water (TDS > 4,000 mg/L); thus, dewatering of these units will require pumping and disposing of water that is not presently considered usable. Accordingly, residents are unlikely to use these ‘wet’ coals as a water source due to their depth and salinity.

A special case of ‘wet’ coals is where these units are used as a groundwater source. This situation may arise anywhere that the coal beds are present within 150 m of ground surface (no special permit required for a private water well). The potential for water wells completed within coal layers to have a natural occurrence of gas (including methane) has been identified in government documents (e.g. AAFRD 2006a). Two common causes for this scenario include areas where coalbeds are not thick enough to represent an economic resource, and in areas where recognized CBG targets subcrop (typically along their eastern edges).

3. REGULATORY FRAMEWORK – ALBERTA

- AENV regulations focus on environmental protection, including aquifers and water wells
- ERCB regulations focus on safe and responsible development of CBG resources
- Both groups work together to regulate CBG development and water well concerns
- Specific water well complaints are handled through AENV, who may request help from ERCB

3.1 Overview

The Alberta regulatory framework for CBG development involves several governmental agencies, as outlined below. Websites detailing the regulations are available and provided by these agencies. Regulatory requirements may be reviewed and modified by AENV or ERCB as they see fit. A Scientific Advisory Panel (SAP) was established to review results of the first year of water well baseline testing data collected under Directive 035 (ERCB, 2006b). This report is due in fall 2008, and may include recommended changes to parameters and/or monitoring methods.

All resource development issues related to CBG are regulated directly by the Alberta Energy Resources Conservation Board (ERCB, formerly Energy and Utilities Board or EUB) through a series of Guides, Directives and Standards (www.ercb.ca see INDUSTRY tab). These regulations control the drilling, completion, stimulation and operation of CBG projects, where regulatory requirements differentiate between CBG wells completed above or below the Base of Groundwater Protection (BGWP). The BGWP defines the depth below which saline water is expected. Saline water is defined by Alberta Environment in the Water Act as water having mineralization greater than 4,000 mg/L expressed as total dissolved solids (TDS). The depth to BGWP across Alberta was developed by Alberta Geological Survey (AGS) in partnership with AENV using a geostatistical mapping process based on stratigraphic information. A provincial summary map and a location-specific query tool (based on legal land description) are available through the ERCB website (https://www3.eub.gov.ab.ca/Eub/Dds). Completion requirements for CBG exploration and production wells vary depending on whether the specified target is above or below the BGWP.

Alberta Environment (AENV) directs all environmental standards, including handling water well complaints and approving diversion of non-saline water (AENV 2004). Complaints regarding water well issues related to CBM activity can be logged through AENV's toll-free Central Complaint Line (1-800-222-6514). A staff member will respond by telephone as soon as possible, often within 24 hours of receiving the telephone complaint. The first step is to try to identify the problem over the phone and recommend a solution if possible. Further detailed investigation may subsequently begin if resolution is not reached in the initial conversations.

Both AENV and ERCB authorization is required if CBG production will require dewatering of non-saline groundwater in the target 'wet' coalbeds (Alberta Regulation 205/98 2000). Recovery and disposal of saline water (>4,000 mg/L TDS) is regulated by ERCB via several documents (Oil and Gas Conservation Act (Chapter 0-6, RSA 2000); Oil and Gas Conservation Regulations (AR 151/1071) and Directive 065 (ERCB 2007b).

Government revenue related to royalties is handled through Alberta Energy.

Public land stewardship issues are handled by Alberta Sustainable Resources Development (SRD), while settlement of issues for landowners related to right-of-access, compensation, and damage are handled by the Surface Rights Board (SRB), an arbitration board under SRD.

In contrast to the Alberta regulatory situation, evolution of CBG-related regulations in various basins within the USA is reviewed in Appendices 1, 2 and 3.

3.2 Protection of Groundwater Resources

A number of regulations and directives have been published to address risks to groundwater resources posed by CBG development. CBG activities that have potential to affect groundwater resources include: well stimulation, dewatering of ‘wet’ coals (pumping saline water), installation/cementation of surface casing, and others. AENV and ERCB both are involved in protecting groundwater resources during CBG exploration.

Ardley coals in the Scollard Formation may also represent usable aquifers; thus, these situations may be similar to experiences encountered in the USA. Regulations have been developed in Alberta to protect usable groundwater, as discussed below. In contrast the ‘dry’ Horseshoe Canyon/Belly River coals and ‘wet’ saline Mannville coals do not represent usable aquifers.

3.2.1 AENV Role

The primary role of AENV in relation to CBG development is to protect groundwater resources. From a monitoring perspective, AENV developed the water well testing protocol referenced in ERCB Directive 035 (ERCB 2006b) and Directive 056 (ERCB 2007a) that requires establishing pre-drilling (baseline) conditions prior to drilling a CBG well that will be completed above the BGWP. The resulting dataset must be submitted to AENV within two months of testing. AENV may also become involved if a resident has a complaint regarding changes in groundwater quality or quantity due to CBG development activities. The complaint needs to be registered through AENV, who then directs the energy company to conduct or contract out a confirmatory water well testing program.

Aquifer protection is also achieved by requiring AENV authorization if CBG production involves dewatering of non-saline groundwater (<4,000 mg/L TDS) in the target ‘wet’ coalbeds (Alberta Regulation 205/98 2000). If the water is considered saline (>4,000 mg/L TDS), then ERCB involvement is triggered.

3.2.2 ERCB Role

The ERCB regulates all drilling, completions and stimulation activities associated with CBG development, as well as water handling issues associated with saline water extraction (produced water). ERCB approval is required to contain, treat, or re-inject the produced water into the subsurface. Depending on the volume of water produced, additional regulations may apply (ERCB 2006c). A summary of the regulatory instruments used to control CBG development is provided below.

CBG Well Drilling Requirements

The ERCB has regulations and guidance pertaining to surface casing requirements (Directive 8, ERCB 1997), cementing of the casing for drill hole stability and environmental considerations (Directive 9, ERCB 1990), shallow well operations (Bulletin 2005-04 ERCB 2005), shallow fracturing (Directive 27, ERCB 2006a) and water extraction in conjunction with hydrocarbon recovery above the BGWP (Directive 044, ERCB 2006c).

Typically a surface casing is installed to a pre-determined depth. Cement is injected inside the casing, and then pressure is applied to squeeze the cement out of the bottom of the casing and back to the surface via the annular space between the casing and the perimeter of the drilled hole. Once the cement sets, a smaller diameter drill bit is used to drill through the cement. Prior to telescoping the hole beneath the depth of the surface casing, cement integrity is assessed by downhole geophysical logs.

Cementing of surface or intermediate casing to a minimum of 180 m (600 ft) has been required since at least 1971.

The hole is then advanced past the bottom of the surface casing to the target depth, whereupon production casing is installed and cemented. Various logging tools are then lowered down the production casing to determine specific depth intervals that are thought to be capable of producing gas.

CBG Well Completion Requirements

The well is completed by perforating the production casing, to allow CBG to flow into the well. The preferred production intervals are identified using a set of petrophysical logs taken down the production casing. Explosive charges are then placed against the casing wall at a specific depth, and set off to "shoot" a series of holes to perforate the casing. This procedure may be repeated a number of times.

This process has several purposes: to clean out the perforation pore throats, to reduce skin damage at the coal-drill hole interface due to drilling and cementing activities, and to increase the permeability of the coal layer. This process is illustrated in Figure 5, which shows a typical CBG well in Horseshoe Canyon coals.

CBG Well Stimulation

Following perforation of the casing, each producing interval is typically stimulated to enhance permeability of the coal layer. According to Rieb and Leshchyshyn (2005) and Hoch (2005), the most common methods used to stimulate Horseshoe Canyon coals involve the injection of high rates of nitrogen (either alone, or with proppant and a low percentage of CO_2). Nitrogen gas is considered an inert gas that will not react with other media.

The stimulation process is completed from the bottom of the well to the top, similar to the perforation program. Prior to stimulating each interval, the targeted perforation zone is isolated. Nitrogen is then injected into the isolated interval to stimulate (fracture) the coal layer outside the well. During this process, applied pressure is monitored in both the isolated zone and within the casing above the isolated zone. In this way, the presence or creation of a vertical pathway connecting two vertically-separate coal layers (naturally occurring or induced during fracturing) can be immediately recognized. Experiences has shown that this cross-connection rarely occurs (<1% of cases), and then only between coal layers that are 1-2 m apart (i.e. within the same coal group). If there is no pressure response in the casing pressure monitor, there is no pressure cross-connection with the layer being stimulated.

Induced fractures tend to spread apart (open) in the direction of minimum principal stress, and propagate (extend) along a direction perpendicular to the minimum principal stress. Relatively shallow coal layers (<300 metres depth) generally have the smallest component of stress tending to be vertical, associated with the weight of the overlying rock (USEPA 2004). Therefore, fractures tend to propagate horizontally. In deeper coals, the minimum principal stress tends to be horizontal, implying vertical fractures could be expected. However, coal layers tend to have natural fractures (cleats) as a result of the coalification process. These fractures act as planes of weakness leading to preferential development of induced fractures. As a result, fractures started within a coal layer tend to propagate within the coal layer (Taylor 2005), rather than extend into overlying capping rock units such as mudstone, shale and limestone.

Although fractures will tend to extend preferentially within coal layers (Hoch 2005; Taylor 2005), fracture breakout into overlying units can occur under some conditions. For the ‘dry’ Horseshoe Canyon coal beds, however, fracture breakout is unlikely to pose a significant environmental risk related to methane release. Given that these coals are typically underpressured, a fracture break out above the uppermost coalbed, would likely result in a minor inflow of water into the coal rather than a gas release.

Water inflow is likely to be minor based on the combination of thin coal zones, local influence of stimulation activities and relatively low coal permeability. Shallower coal layers (e.g. Ardley coals in the Scollard Formation) are unlikely to experience fracture breakout based on considerations of stresses and rock strength. A study of hydraulic fracturing in relation to coalbed methane development in the USA concluded that this process poses “little to no threat” to underground sources of drinking water (USEPA 2004).

The issue of enhanced fracturing of coal layers during stimulation merits further discussion due to the associated increased concern expressed by stakeholders. Early experience during CBG development showed that fluid-based fracturing was generally not beneficial in the ‘dry’ Horseshoe Canyon coals (Hoch 2005). As noted earlier, the extreme sensitivity of the ‘dry’ Horseshoe Canyon coals to water has led to the current practice of stimulation based on nitrogen gas. While experiences are reported to vary, stimulation (with or without fracturing) increases coal permeability (Taylor 2005; Hoch 2005). Guidelines for shallow fracturing operations are provided in ERCB Directive 027 (ERCB 2006a).

Evidence that nitrogen stimulation likely has an insignificant influence on shallower water-bearing intervals was obtained from a field trial in Alberta. A CBG producing company was required to conduct additional field tests of potential influences of fracturing on water wells near a CBG project. A monitoring well was installed near a CBG well (45 m lateral distance, 23.3 m vertical separation), with water levels measured by data logger for several months preceding and following a stimulation program. The results showed that water level changes during the stimulation program were within the previously-measured natural variability, indicating that nitrogen stimulation likely had an insignificant influence on shallower water-bearing intervals.

Cleat movement in hard coals may cause "self-propping" behaviour that maintains the increased permeability. In contrast, soft coals may not maintain long-term stimulation effects as fractures close under compressive stress. In such cases, operators may re-stimulate (re-fracture) and/or introduce a proppant (granular material to keep induced fractures open). Technical developments continue to be made on these aspects, as well as on methods to address permeability decreases due to movement of coal fines within fractures and/or scaling.

3.3 Baseline Water Testing

3.3.1 Basic Water Well Testing Process

To address landowner concerns about potential impacts of CBG exploration on water wells, EUB released Directive 035 (ERCB 2006b). This directive mandates that CBG operators offer to test all active water wells within a 600 m radius of a proposed CBG well when the CBG well is to be drilled above the BGWP. The radius may be extended to 800 m if there are no wells within 600 m. The water well testing must be done before the CBG well is drilled.

The water well testing is to be done to a published AENV standard (AENV 2006a). This standard includes collection of water for routine potability and bacterial (total and fecal coliforms, sulphate-reducing bacteria and iron-related bacteria) analyses, collection of free gas samples where possible, and stable isotopic analysis of a representative number of free gas samples.

3.3.2 Water Well Complaint Process

Any complaints regarding well water quality and/or quantity must be registered with AENV in order to get a formal response. AENV has a toll-free Central Complaint Line (1-800-222-6514) to log a complaint regarding water well issues related to CBM activity. If the ERCB receives the complaint, they refer the complainant to AENV. As soon as possible, often within 24 hours of receiving a complaint by phone, AENV staff return the phone call. ERCB staff may participate in a complaint investigation, as requested by AENV.

The first stage of investigation is for the AENV investigator to try to identify the problem over the phone and recommend a solution if possible. If the problem cannot be resolved at this stage, a more detailed investigation begins. If the company engaged in CBG exploration initiates an investigation, AENV is to be involved in the process to resolve the complaint. As part of the investigation, CBG developers may be required to retest the complainant's well, and/or provide an alternate water source during the investigation period. Subsequent requirements and/or follow-up activities will depend on the findings of the investigation. AENV reserves the right to request an external third-party review of the information.

3.3.3 Complaints Received

Between January 2004 and May 2006, Griffiths (2007) reports AENV investigated 125 water well quality complaints in the Central Region. Seventy-three of these were related to well maintenance, and none were due to gas migration. During the same period in the Southern Region, 230 complaints were investigated. Twenty-three of these were allegedly related to CBG activity. Most were related to well maintenance and as of early 2007 eight of these cases still were not resolved. According to AENV records for 2007, the Central and South regions had 28 and 21 well complaints, respectively.

3.3.4 Unresolved Complaints

By mid-2007 five complaints remained unresolved. Files from these complaints were forwarded to the Alberta Research Council for an independent investigation (ARC 2008). The complaints addressed a combination of free methane gas in the water wells and other symptoms of reduced water quality. ARC compared water analyses from these wells to historical analyses, and water quality analyses for other water wells in the area obtained from the AENV database. Carbon isotopes in methane from water wells and CBG wells were also reviewed, along with other evidence. The overall conclusion of the ARC was that the “energy development projects in the areas most likely have not adversely affected the complainant water wells” (ARC 2008).

The current status of the CBM water well baseline monitoring program in Alberta is that there is no scientific evidence of CBG exploration activity causing coalbed gas to migrate to domestic water wells. Evidence does exist of natural gas negatively affecting the environment in association with conventional oil and gas exploration holes, mainly through leakage along borehole annuli (e.g., CAPP 1996). The expanding population in Alberta brings an increase in the number and density of water wells drilled. Scientists therefore must retain an open mind to investigate and ascertain situations when CBG gas influences might occur more readily.

4. LANDOWNER CONCERNS RELATED TO CBG DEVELOPMENT

- Methane is flammable at 5-15% concentrations in air
- Methane is non-toxic, lighter than air, has no smell or taste, displaces oxygen in unvented areas
- CBG contains no H_2S, but H_2S may form in association with methane biodegradation
- Aquifer water quantity is unlikely to be affected by ‘dry’ CBG development
- Concerns increase for ‘wet’ CBG development from coal beds above the base of groundwater protection
- Methane may naturally occur in water wells, especially in wells completed across coal beds
- Water wells completed across coals may create the same response as CBG wells (pumping causes gas release)

4.1 Overview

The rapid development of CBG has generated a number of concerns for Albertans, especially based on awareness of earlier negative reactions in the USA. Water is an invaluable resource, with many Albertans in rural areas depending on water wells to produce water for their families, livestock and irrigation needs. As a result, risks with potential negative impacts on the water supply are critical to rural landowners. Concerns associated with groundwater are related to:

- health and safety hazards;
- aquifer quality and water well integrity; and,
- other concerns.

Concerns that were considered beyond the present scope of gas migration potential are those such as related to increased industrial activity associated with CBG development including:

- changes in quality of life (e.g. increased traffic, noise, dust, surface disturbance); and,
- changes in land value.

For CBG development, public attention and focus on risks initially generated a strong negative response. This reaction is understandable given the relative lack of information available to assess and mitigate concerns about the risk events. Experience was not available to assess the likelihood of occurrence of the risk events, and mitigation options were not clearly evaluated. As an example, CBG well stimulation is often perceived as an activity that could affect the appearance, composition and production of domestic water supplies. The concept of injecting high pressure fluid to fracture coal generates concern that resulting fractures could ‘get away’. The arguments as to why this behaviour is unlikely requires awareness of complicated technical concepts related to rock mechanics, stress fields, and multi-phase flow (gas and water). Furthermore, experience and monitoring data may be proprietary or not available during early stages of resource development.

Common concerns associated with CBG development are summarized below and addressed from a risk assessment viewpoint in Sections 7, 8 and 9. However, it is important to place these concerns in perspective with background conditions. Dissolved gas is commonly encountered in Alberta well water (AAFRD 2006b), where the widespread occurrence is shown in Figure 6. Many of the wells predate the rapid CBG development that started around 2002.

4.2 Health and Safety Hazards

Health risks associated with CBG migration into an aquifer and domestic water supply focus on methane, the dominant component of CBG. Methane is tasteless, odourless, colourless and relatively chemically inert other than in high concentrations (Harder *et al.* 1965; Smith 1978; Keech and Gaber 1982; Eltschlager et al. 2001). Gas atmospheres (e.g. well pits, sheds, basements) containing 5 to 15% methane by volume may be explosive. Methane is lighter than air, and under certain circumstances could displace enough oxygen to become an asphyxiant. Consequently water wells should not be completed across known methane-bearing intervals (AAFRD 2006c), while domestic water systems known to contain methane or other gases should be properly vented. Information on how to vent water distribution systems can be found in AAFRD (2006b) “Dissolved Gases in Water Wells”.

Other gases may be found in domestic water wells including carbon dioxide, nitrogen, oxygen and H_2S (Freeze and Cherry 1979). Although H_2S is not present in CBG, it is the gas most likely to be noticed and reported. It has a strong odour and well-known toxicity based on conventional gas exploitation activity in Alberta, but its presence does not always signify gas migration. There are other sources of H2S that may be relevant to water well concerns. H_2S may form any time conditions support bacterial degradation of organic carbon, including methane, by naturally-occurring sulphate-reducing bacteria under oxygen-limited conditions (e.g. bacteria in water wells, marsh gas from wetlands, manure piles, mine tailings). Experience gathered In the USA regarding indirect links between CBG development and H_2S exposure is described in Appendix 2.

4.3 Aquifer Quality and Water Well Integrity

Rural landowners have also expressed concern about the potential for CBG exploration activity to affect water well quality and/or yield. These concerns need to be considered in relation to CBG development from either ‘wet’ or ‘dry’ coals. Most of Alberta CBG development has occurred in ‘dry’ coals. Aquifer impact is unlikely to occur as a direct result of CBG production from ‘dry’ coals because groundwater pumping is not required. The risk of aquifer contamination during well installation has been identified, and is described in more detail in Section 5.

In contrast, extracting CBG from ‘wet’ coals requires pumping out groundwater to lower the pressure and allow gas desorption. The coal contains both the gas and groundwater, possibly causing competitive use issues. In Alberta, competitive issues are unlikely to be associated with the largest potential resource of ‘wet’ coal (Mannville coal zone) because the water is generally classified as saline (TDS>4,000 mg/L).

The only CBG resources in Alberta currently known to have conditions similar to USA CBG projects are in the Ardley and Kootenay coal zones. Concerns have been expressed about water quality and quantity in relation to the potential for dewatering and/or gas release in the coal aquifer in which a water well may be screened. In Alberta, regulatory controls on groundwater withdrawals (AENV 2004) mitigate against this possibility. Furthermore experience gained from USA CBG development is relevant to assessing and addressing aquifer and well integrity issues (Section 10 and Appendices 1-3).

4.4 Other Concerns

There are other concerns associated with CBG development related to increased industrial activity such as heavy equipment traffic, pipelines and compressor facilities. These concerns are not related to gas migration potential, so are outside the present scope.

5. SUBSURFACE BEHAVIOUR OF CBG

- CBG may move either as free gas (buoyant) or in dissolved form (stays with groundwater)
- CBG solubility decreases (gas forms) with increasing temperature and decreasing pressure
- Preferential flow paths may be natural (e.g. fractures) or man-made (e.g. unsealed boreholes)

The study of situations and scenarios associated with the presence and movement of methane and other hydrocarbon gases in aquifers is essentially that of a classic groundwater transport investigation. Possible **sources** must be identified, where determination of any diagnostic characteristics of sources (e.g. stable isotopic or geochemical fingerprinting) and their spatial and temporal distributions are crucial to this phase. The possible **transport mechanisms**, including their relative strengths and any **phase transitions**, must be characterised. Finally, the possible **migration pathways** must be identified and then evaluated with respect to both the connections to sources and the relative strengths of the transport mechanisms. One might also consider the accumulation of gas within different geologic environments or man-made structures, and/or the mitigation of identified problems; however, those aspects are beyond the scope of this work.

5.1 Gas Sources

As summarized earlier in Section 2, methane and other light hydrocarbon gases may originate through a number of different mechanisms, in a variety of geologic environments. These gases are formed by the decomposition of organic matter in the absence of oxygen. In the Western Canadian Sedimentary Basin (WCSB) the gas formation processes may generally be classified as either biogenic or thermogenic (Clark and Fritz 1997). There is, however, a general gradation with depth (i.e. with pressure and temperature) from biogenic to thermogenic origins. The classifications as to gas formation process (i.e. origin) and subsequent migration characteristics may have consequences for overall gas composition, stable isotopic signature (see Section 6), and likely source location or characteristics.

Thermogenic methane is formed by the thermal breakdown of complex hydrocarbons resulting from decomposition of organic material. The organic material was largely located in ancient shales, and not in the coal-bearing formations shown in Figures 1 to 3. This process generally occurred after organic matter was buried under a sufficient thickness of sediments to generate the required high temperatures and pressures for hydrocarbon liquid and gas generation. Thermogenic methane may be associated with a wide range of heavier hydrocarbons, as either gases or crude oil liquids, and hydrogen sulphide (H_2S). Natural gases containing H_2S are considered to be “sour” and may be poisonous. Thermogenic gases typically originated at great (1000+ m) depths, but may have migrated, through geologic time, and accumulated at shallower depths. In Alberta, sour gases are primarily found only in the (deeper) Mississippian and Devonian strata, due to the mineralogical characteristics of these carbonate-dominated formations.

Most thermogenic gas reservoirs have had long periods of (geologic) time to accumulate gases. Thus, the accumulations tend to be large and homogenized. Because of the long timeframe that has been available for source production and subsequent migration, many of these accumulations are remote from the original source area. However, within the relatively short timeframes of interest for this study, the current locations of these accumulations can be viewed as stable sources of gas.

Biogenic methane is produced by bacterial decomposition of organic matter through fermentation or carbon dioxide reduction. Biogenic methane may be accompanied by small fractions of slightly heavier hydrocarbon gases (e.g. ethane or propane). This process can occur near ground surface (e.g. in muskeg, organic-rich soils, landfills, manure/sewage storage systems) and as CBG in coalbeds at depths of a few hundred metres below ground surface in the WCSB.

Gas reservoirs (i.e. sources) derived from such shallow sources have likely only had a short time to develop, and may have had limited carbon pools. Thus, although accumulation rates might have been rapid, the accumulated volumes in these potential reservoirs should be relatively small and localized, particularly in the absence of an overlying low-permeability cap. Furthermore, the slow transport mechanisms under undisturbed conditions, and the short time available for migration after such recent gas generation, mean that the location of these gas deposits is usually coincident with the source in the absence of pumping.

5.2 Coalbed Gas

CBG is typically formed, and found, at shallow to intermediate depths. Methane usually dominates the composition of CBG; however, small fractions of ethane, propane, carbon dioxide and nitrogen can be present. CBG is regarded as “sweet” because it does not contain any hydrogen sulphide (AE, 2008). In Alberta, the CBG that is primarily being exploited currently (i.e. from the Horseshoe Canyon Formation) is biogenic; however, the proportion of thermogenic gas tends to increase with depth. While shallower CBG targets (i.e. Ardley coals) have similar biogenic gas signatures, deeper targets (e.g. Mannville coals) may have an increasingly thermogenic gas signature. As an aside, these latter formations are expected to have differences in water extraction issues (volume and salinity).

In summary, natural gas sources in the subsurface are varied in nature and strength; however, the determination of the gas source is crucial for understanding the possible migration of gases and their geochemical or stable isotopic signature in the subsurface. Nonetheless, the general relationship is that gas sources grade from biogenic to thermogenic with depth. Also, most Mississippian and Devonian sources could have associated H_2S, and may tend to have more free gas, rather than low concentrations of dissolved gas. These general source characteristics are important when trying to evaluate the possible pathways that methane might have taken to reach particular water wells. We can define, and characterise, the possible sources; however, we also need consider phase transition and transport mechanisms, and possible pathways.

5.3 Phase Transitions

Methane and other gases may exist as a number of phases in the subsurface, including an adsorbed phase, a dissolved phase, or a free gas phase (Figure 4). Compounds may co-exist in two or three of these phases in the subsurface and they may transfer from one phase to another. However, in practical terms, methane and other gases can only migrate as either a free gas or dissolved in water. Adsorbed methane consists of methane molecules that are physically attracted to a solid surface (e.g. coal). The process whereby adsorbed methane is released to one of the other phases is referred to as “desorption”. Thus, to understand the subsurface behaviour of CBG, it is necessary to consider the factors controlling both phase transitions and fluid (i.e. free gas and water) migration in the subsurface.

The transition of methane between phases is largely governed by pressure and temperature, along with consideration of the available phases. The general rule is that as pressure is decreased, and/or temperature is increased, gases (i.e. methane) will transfer from the adsorbed phase (i.e. desorb), to the dissolved phase (if water is present) and/or to the free-gas phase (i.e. exsolve or de-gas). A well-known example of de-gassing is the appearance of bubbles in a carbonated beverage when the pressure is released by opening the cap.

In most cases of interest here, phase transitions due to temperature variations do not play a dominant role in the migration of methane. This is because it is rare to have large natural temperature variations over short distances in the subsurface, and heat is not used to extract CBG. One relevant exception concerns domestic wells, where pumped groundwater with dissolved methane may be heated, as in a domestic hot water heater.

However, phase transitions due to changes in pressure are actually pivotal to successful CBG extraction activities because CBG is primarily adsorbed in micro-fractures (i.e. cleats) within the coal. This gas must be liberated to a mobile (e.g. water or gas) phase to be recovered; thus, a pressure decrease is required. The two general scenarios involve the cases where the coals are ‘wet’ (i.e. saturated with water), or ‘dry’ (i.e. primarily contain gas, with only some minimal water fraction).

In the case of water-saturated coals, the groundwater must be pumped from a well to decrease the water pressure in the surrounding coal. As the water pressure is decreased, methane desorbs. This methane first dissolves in water. Because methane solubility in water is limited (about 25 mg/L under atmospheric pressure), the recovery efficiency of dissolved methane is not very high. Efficiency is increased when the water pressure in the wellbore and the formation is decreased sufficiently for methane to exist largely as a free gas phase and to migrate to the production wellbore. This migration involves the movement of both water and gas, with a continuum of mass transference from coal-to-water-to-gas between the source of methane (i.e. the coal cleats) and the wellbore. These phase transitions occur because the pressure decreases from the coal formation to the pumping well.

If the coal is ‘dry’, the desorbtion (and migration) process is much simpler because there is no ‘interference’ (i.e. additional phase partitioning) due to water. In this case, gas extraction causes the gas pressure to decrease in the wellbore, leading to a decrease in gas pressure in the coal seam. As a result, methane desorbs directly to the gas phase, and migrates towards the low pressure wellbore.

Understanding phase transitions due to changes in pressure may also be crucial in relation to many reported “environmental” problems associated with groundwater wells. Dissolved methane may exist in the groundwater near a well screen from a variety of sources. As discussed below, when the water well is pumped, water pressures in both the wellbore and the adjacent formation are decreased. Such a decrease in pressure can lead to methane degassing (if the dissolved methane reaches its saturation level at the corresponding pressure) as water is drawn into the well. If the pumping rate is increased or if adjacent water wells start to overlap and interfere with each other, the water pressure is even further decreased. Furthermore, continued pumping of a well or wells, even at a constant rate, typically leads to a slow decline in water pressure within both the well and an ever-increasing volume of the aquifer. These declines in pressure could lead to enhanced methane degassing, with the expanding zone of influence from the water well drawing water, and methane, from greater lateral distances over time.

With the understanding that there can be phase transitions between the gaseous and aqueous phases, it is now possible to consider some particular cases of methane transport. For simplicity, these cases are divided into the “free gas” and “dissolved gas” categories. However, it must be understood that there may be phase transitions within these conceptual models, and that the source or sources of the gas may vary.

5.4 Transport Mechanisms

Transport mechanisms can generally be divided into two broad classes: diffusion and advection. Diffusion occurs in response to a concentration gradient, and can lead to migration whether or not the bulk fluid is moving. Compounds will move from areas of high concentration (commonly a source) to areas of low concentration. Diffusion tends to homogenize the concentrations of compounds over time; although, the process tends to be slow in the presence of water. Because of these two factors, Chapin (1994) successfully argues that diffusion cannot be responsible for localized occurrences of high natural gas concentrations in shallow aquifers. If diffusion were the primary transport mechanism over long periods of time, the concentrations would be relatively uniform.

Advection is the movement of a compound with the bulk fluid phase (e.g. like a float moving with a river). Thus, the factors controlling fluid migration need to be evaluated. In simple terms, fluids move because of driving forces; however, their movement is also controlled by variations in the permeability or conductivity of the medium. For gases, the primary driving forces are pressure and buoyancy; gases tend to move from high pressure to low pressure, but they tend to rise due to buoyancy in water. For water, the primary driving force is pressure if flow is horizontal (e.g. along an aquifer), but more generally is hydraulic head which combines both pressure and elevation (i.e. gravity) components. Water tries to move from high head to low head, along the hydraulic head gradient.

The hydraulic conductivity (hereafter, conductivity) of a medium (a measure of how easily fluids move through it) is largely controlled by the size of the pores through which fluids must move. The larger the pore spaces, the higher the conductivity and the more readily fluids move. If two fluids are present in a region, the interference between the fluids can lead to decreased conductivity with respect to one or both of the fluids. In general terms, aquitards and cap rocks (e.g. clays and shales) have low conductivities, while aquifers and reservoirs (e.g. sands and sandstones) have high conductivities. The conductivity of cracks and fractures (natural or man-made) depends on how “open” they are, while the conductivity of boreholes and wells may depend upon a number of factors (discussed further below).

In undisturbed, natural systems there tend to be characteristic gradients for driving forces. These characteristic gradients are closely related to the conductivities of geologic media and their typical distribution in the subsurface. Hydraulic head gradients tend to be low along aquifers, but may be high across aquitards; however, because of the vastly different permeabilities of the media, natural flow along aquifers tends to predominate. Pressure gradients in the gas phase exhibit similar characteristics, although buoyancy forces do add a component of vertical flow. In aquifers subject to pumping, the act of pumping decreases the pressure at the well, increasing the lateral gradients and inducing enhanced horizontal flow towards the well. The pressure drawdown cone centred about the well will tend to expand radially over time, plus possibly inducing vertical flow towards the pumped formation.

5.5 Conductive Pathways

Conductivities of geologic materials and man-made features in the subsurface vary over multiple orders of magnitude. In contrast, gradients of driving forces for flow are commonly small, and only vary by factors of tens to hundreds. Thus, delineation and evaluation of the more conductive pathways is important for determining where fluids are likely to move via advection. While the direction of the driving force gradient is often readily determined or predicted, determination of actual flow rates requires knowing the actual conductivities and the magnitudes of the driving force gradients.

The average direction of fluid movement is controlled by the direction of the gradient; however the actual pathways will be controlled by the more conductive formations or features. Furthermore where there are multiple possible conductive pathways, the largest amount of fluid will tend to follow the pathway with the highest conductivity combined with the greater cross-sectional area. This situation is best visualized by considering a meandering set of river channels where the water flows from higher to lower elevation, but not necessarily in a straight line and certainly around the largest obstacles. Below we consider several possible scenarios relevant for the advective migration of CBG, or gases from various other sources, to shallow drinking-water aquifers. The scenarios include a range of potentially applicable natural and man-made pathways or disturbances (e.g. fractures, boreholes) and natural and man-made stresses (e.g. fluid driving forces, pumping). For most scenarios, temporal and spatial scale effects may need to be considered for specific cases.

The first scenario is an undisturbed, unstressed, natural area that represents background conditions for comparison to disturbed or stressed areas. This type of system could have any combination of gas distributions according to the “sources” outlined previously: sporadic pockets of biogenic gas in shallow aquifers, accumulations of thermogenic gas (variably associated with H_2S) in traps at depth, and variable grades of biogenic to thermogenic gas associated with (i.e. adsorbed to) coals. It may be important to note that these gas distributions only appear to be static. This is because gas accumulations developed over geologic timescales, whereas any human observation or influence has only occurred over decadal timescales. For example, gas leakage through natural fractures in a cap rock or an aquitard would appear to be a stable anomaly from the general trend; however, over geologic time such leakage could lead to depletion or relocation of a natural gas reservoir.

Disturbed, yet unstressed, natural systems also occur. The initial conceptual model is that of an aquifer or reservoir, or perhaps more importantly its adjacent aquitards or overlying cap rock, which is not currently being pumped, yet the geologic (i.e. hydrostratigraphic) units have been penetrated by boreholes. Such borehole breaches present a number of opportunities for uncontrolled, and perhaps undetected, leakage of fluids in the vertical direction. In particular, if the driving forces are favourable there is a possibility of fluids migrating upwards naturally (Figure 7) or along man-made pathways (Figure 8) to adjacent formations. Higher heads at depth could transport dissolved gas vertically, while buoyancy effects, and perhaps excess gas pressure, could cause bubbles or stringers of free gas to migrate upwards. The key to whether the fluids will move at appreciable rates depends upon the integrity of the borehole or well (e.g., Figure 9).

A simple model of some of the mechanisms by which vertical pathways might be afforded through a single borehole is shown in Figure 10. This figure, adapted from Gasda et al. (2004), depicts the abandonment of a cased (i.e. production) borehole. Essentially, the possible leakage pathways are through any of the man-made materials or, more likely, along the interfaces between different materials. Pathways through man-made materials would exist if there were connected porosity within or cracking of the cement, or if there were cracking or corrosion of the metal casing. Interface pathways could exist if there were difficulties establishing and maintaining an essentially impermeable seal around the entire circumference of the hole or casing, between the different materials, over the length of the borehole. Poor seals might exist from the time of borehole completion if the cement was inadequately placed, or might develop over time as the materials (geologic or man made) age and degrade. Similar comments apply when considering cemented seals around surface casing, which is set through both unconsolidated glacial deposits and bedrock.

This simple conceptual model can easily be extended to other scenarios:

- drilling a borehole and cementing a casing could locally fracture the surrounding formation rock;
- similar transport pathways could occur in the annulus of a currently producing or suspended well;
- historically some borehole sections did not need to be cemented throughout their entire length;
- an abandoned dry hole could have cement but no casing below the surface casing; and,
- water wells with poor completions, grouting or cement.

Fractures in the surrounding formation would enhance the conductivity of the formation near the borehole. Borehole transport, of either water or gas, along the annulus is possible for any cased well, particularly in the case of old wells where the materials have aged (Gasda et al. 2004). As noted in Section 3.2.2, borehole cementing regulations have always included the requirement that non-saline water-bearing and hydrocarbon-bearing zones must be isolated by cement (Alberta Regulation 151/71). Over time, there has been increased identification of shallow hydrocarbon zones, including recognition of hydrocarbon gas associated with coal. Accordingly, old drill holes may have had uncemented intervals that would presently require cementing. Finally, some abandoned dry holes may not have had intermediate or production casing run, and would likely not have been cemented to surface. Thus, migration pathways could exist through numerous deeper formations, including some coal zones. Furthermore, when comparing water wells to petroleum or CBG wells, there are significant differences in the regulations and practices for well construction, completion, stimulation and operation. Many older water wells had screened intervals that cross-connect multiple water-bearing intervals.

This extended discussion on pathways through unstressed systems is relevant because there are numerous possible vertical pathways for each (petroleum, gas or water) well drilled. Furthermore, these man-made discontinuities could interconnect deep reservoirs (thermogenic), CBG-bearing coals (biogenic to thermogenic), newer stratigraphic reservoirs (thermogenic to biogenic) and some aquifers (biogenic). Considering petroleum wells alone, Gasda et al. (2004) examined the number, age and distribution of wells penetrating the Viking Formation in Alberta. The Viking is a significant formation for such a characterization because it underlies most of the significant coal beds in Alberta (except Mannville Group) over much of the geographic area covered by likely CBG activities (Figure 1). Thus, any well that penetrates the Viking is likely to penetrate a coal-bearing formation. There are about 200,000 such wells (Figure 11), some of which have the possibility of providing a conduit for leakage. One side effect is that, because of the large number of boreholes that have been drilled in the WCSB, there may be few areas that could be described as “undisturbed” at the scale of, say, townships and it may be difficult to truly define background conditions prior to the start of man’s drilling activities. The degree of impact from this disturbance has yet to be quantified.

5.6 Flow Paths

The possibility that boreholes, or other conductive pathways, might provide an enhanced anthropogenic route for either water, carrying a dissolved-phase gas, or free-phase gas was established above. The addition of pumping (i.e. stressing) of aquifers, reservoirs, coal seams or large-scale subsurface systems provides a further anthropogenic effect that will tend to enhance the fluid driving force (horizontally and/or vertically) towards the well screen. Horizontal flow will likely be along the geologic formation; vertical flow may be across formations, perhaps via boreholes or fractures. The relative significance of these possible flow paths, for a number of configurations, needs to be evaluated. Below we consider generic cases of leakage via boreholes, pumping of CBG wells and pumping of water wells.

5.6.1 Boreholes

Dissolved-gas transport through boreholes is conceptually straightforward. The water and dissolved gas will flow from regions of high hydraulic head to regions of lower hydraulic head. The borehole simply provides the conduit for flow between formations. Several examples are illustrated schematically in Figures 7 and 8. Head gradients and preferential pathways cause water (and dissolved gas) to take the easiest route. Alternatively, a groundwater well could be screened below a coal seam and the borehole annulus could be largely filled with cuttings and slough (Figure 10). Pumping of the groundwater well could lead to the migration of dissolved gases, down, from the overlying coal. Depending upon the conductivity and the area of the well annulus compared to those of an overlying aquitard, significant amounts of dissolved gas may be transported via wellbores.

There are several models for what could happen when free-gas, from whatever source, leaks into and up a borehole or well annulus. The two end-member scenarios are those where the conduit is (a) devoid of liquid, or (b) filled with liquid:

(1) If the annulus is devoid of liquid (e.g. there is no leakage of water from overlying aquifers into the annulus so gas pressure ~ hydrostatic pressure), then the entire annulus could be full of gas (and, perhaps, slough). Gas could dissolve into the groundwater in overlying aquifers; however, the rate of dissolution would likely be slow because it would be limited by the rate of liquid diffusion and small contact areas. Assuming that the geologic medium is preferentially water wet, the gas can only displace the water in the surrounding formations if sufficient gas pressure can build up in the annulus to exceed the capillary entry pressure of the formation. Such casing pressure build-ups are not normally permitted in petroleum wells, based on routine monitoring of casing vents.

(2) If the annulus is full of liquid (e.g. there is leakage of water from surrounding aquifers) and/or slough, free gas might still enter the wellbore. In this case, gas invasion must be driven by reservoir pressure exceeding hydrostatic pressure. If free gas can enter the annulus, buoyancy forces would cause the gas to move vertically, probably as bubbles. The only way that this free gas could move laterally into an overlying aquifer would be if the conductivity of the borehole were much less than that of the surrounding formation. In that case, gas could accumulate beneath this restricting zone, increasing the pressure. This restriction might occur if sloughing or squeezing of fine-grained materials were to seal the annulus or if cement, perhaps associated with surface casing, were encountered. Alternatively, gases might dissolve into the water in the annulus and be transported in the dissolved phase.

The above two descriptions are primarily concerned with leakage of gas into saturated aquifers that might be used for water supplies. An alternative scenario to consider is that of methane leakage into the unsaturated zone surrounding surface casings. This has been a common problem in the Lloydminster area (CAPP 1996). The effects of these problems appear to be highly localized (i.e. within tens of metres) with no reports found that they directly affect drinking water supplies.

5.6.2 Pumping of CBG Wells

Some coal formations (e.g. Horseshoe Canyon) in the WCSB are largely ‘dry’. As mentioned earlier, pumping a CBG well in a ‘dry’ coal formation will result in decreased gas pressure in the well, which will lead to decreased gas pressure in the adjacent formation. In turn, this will lead to desorption of methane from the coal and the migration of gas to the well. The production well should be the point of lowest gas pressure within the aquifer-well system. Consequently, all of the gas released from the coal should be collected by the production well. There is no dissolved-phase transport in this scenario because the reservoir contains no mobile water. In the particular case of CBG in the Horseshoe Canyon Formation, the gas pressure is also less than hydrostatic (Bachu and Michael 2002). This implies that water should naturally flow into the formation, rather than gas flow out. The very dry nature of the formation also implies that a capillary barrier exists and that the gas and water systems have remained separate for a long period of time. Such a system should not leak gas, except by the slow, uniform, process of diffusion, particularly when the pressure is being decreased for gas production.

Most other coal formations (e.g. Ardley, Manville) in the WCSB are likely ‘wet’. Possible transport pathways of CBG from these formations in their unexploited, but potentially disturbed, state has been covered elsewhere above; migration through or along boreholes drilled to deeper targets is a possible leakage mechanism. As discussed above, exploitation of the gas contained in these formations requires that the water pressure be decreased, perhaps substantially, so that CBG will desorb and exsolve. Thus, again, the CBG well becomes one of the lowest heads in the system, and both water and gas should be collected by such a well.

5.6.3 Pumping of Water Wells

Pumping a water well reduces the hydraulic head in the vicinity of the well. This situation is most notable for water wells completed within or across coal zones, where the water well acts like a small CBG production well.

5.6.4 Effects of CBG Well Stimulation

Finally, it is possible that artificial stimulation of petroleum or CBG reservoirs could provide preferential conduits for fluid flow. Stimulation of shallow and highly cleated CBG reservoirs often results in horizontal to sub-horizontal fractures that are largely confined to the particular geologic unit (USEPA 2004). Under this scenario, well stimulation primarily enhances only the horizontal transmissivity for the migration of fluids by eliminating borehole skin effects (formation damage created during drilling). The conductivity enhancement typically occurs near the wellbore, extending radially from the well. Efforts are made to restrict influence to the formation to avoid inadvertent loss of the gas resource. Relative to the unfractured case, pumping of water and/or gas should lead to a pressure drawdown cone that has a larger lateral extent, but has a smaller magnitude in regions near the well (Freeze and Cherry 1979). The development of such a pressure distribution will result in enhanced fluid migration along the reservoir (i.e. horizontally) and decreased vertical gradients from adjacent formations, although these gradients will be distributed over a larger area.

Under some circumstances it might be possible for an induced fracture to propagate as far as an adjacent wellbore. Such a wellbore may be used for deep petroleum exploitation or groundwater extraction. This scenario is particularly possible where there is a high density of wells to formations at various depths (Figure 11). The fracture could then provide a conduit to transmit gases, either as dissolved gas or free-phase gas, between a CBG well and the nearby wellbore. The (horizontal) direction of fluid movement would, of course, depend on the fluid pressure difference between the two sites. Those fluid pressures commonly depend upon pumping rates, and either pressures or heads for ambient conditions, and the rate of fluid transmission would depend on the fracture conductivity and size, and the amount of fluid available from the source wellbore. One can imagine possible scenarios where CBG is drawn, through a fracture, to a pumping water well, or where fluids are exchanged between a CBG reservoir and a deep petroleum wellbore, for instance. However, such intersections have only been reported in some 20 isolated cases in Alberta, at distances of about 30 to 100 m (ERCB, pers. comm.).

6. GAS SAMPLING AND ANALYSIS

- In water wells, gas can be dissolved or exsolve as free gas
- AENV sampling protocol collects free gas samples for composition and stable isotope analyses
- CBG releases may be identified from forensic analyses of water and soil gas samples

6.1 Overview

The following sections on gas sampling summarize experiences developed in Canada and the USA, with greater detail regarding USA experiences provided in the Appendices. Gas may be present in the subsurface above and below the water table. Soil gas is present in the air-filled soil pores above the water table. Below the water table, gas may be present either dissolved in groundwater, or as free gas.

Gas in well waters may be present as free gas and/or dissolved in the water. Differences between these forms are easily understood by opening a clear glass soda bottle. While the lid is sealed, pressure keeps the gas dissolved in the liquid. Removing the lid causes a drop in pressure, allowing the previously dissolved gas to form bubbles (exsolve) and rise to the liquid surface. Shaking or heating the bottle causes more gas to bubble out, similar to what happens when a well is pumped hard.

Gas seeps may be identified at ground surface as zones of dead or dying vegetation, or as continuous bubbles in ponded water (e.g. ponds, sloughs, springs, rivers). Soil gas can be sampled using shallow soil gas probes (steel tubes driven by hand to depths of up to one to two meters). A typical soil gas sampling setup is shown in Figure 12. Gas bubbles in ponded water are sampled by inverting a water-filled bottle, and allowing bubbles to enter and displace the water in the bottle.

Forensic analysis refers to using analytical data to derive the source and possible influences on well water quality. This analysis relies on a variety of main indicators, including gas composition, stable carbon isotopic ratio, bacterial presence and major ion chemistry. As the water well database becomes populated, patterns of pre-drilling conditions become more clearly defined. A Scientific Advisory Panel (SAP) has been formed in Alberta to review the data collected during the first year of monitoring (May 2006 to May 2007). Results are expected to be released in early 2009.

A key caveat to these findings may be that oil and gas development had already been occurring for years to decades before water well testing was required under Directive 035. The title of Directive 035 implies that the water well testing program establishes baseline testing, but it is more accurate to say that the analyses provide a ‘Point in Time’ sampling program. In areas with historical oil and gas activity, it is possible that impacts on water resources may have occurred prior to current water well testing.

6.2 Water Well Gas Analyses

Under Directive 035, gas samples from water wells are analyzed for composition, including light-end hydrocarbons (methane, ethane, propane, and butane) and selected atmospheric gases (nitrogen, oxygen and carbon dioxide). Directive 035 also requires stable carbon isotope analysis for methane and carbon dioxide (if present). Isotopes refer to small variations in the atomic structure that can occur naturally or may be affected by various processes, and that can be measured individually. The ratio of the most abundant isotope of an element to that of a less common isotope is termed an isotopic ratio. Measurement of gas isotopes can aid in determining the source of gas. Greater detail is provided in Section 6.4.

These data are entered into AENV's Residential Well Testing Database related to shallow CBG development.

6.2.1 Free (Effervescent) Gas in Water

The water well sampling protocol in Alberta encourages aggressive pumping of a well, where any gas that bubbles out is trapped in a gas-liquid separator. This method typically provides a worst-case situation for assessing whether gas build-up might occur, but may give poor repeatability.

The USA approach to collecting gas samples from effervescent water in a domestic water well uses a 1 L bottle equipped with a cap. The bottle is submerged in a 20 L bucket filled with well water and inverted. Ensuring there is no air left in the bottle, a 1.25-cm (½") diameter polyvinyl tubing is inserted into the bottle and the flow rate is set to 8-12 Lpm. The bubbling gasses are allowed to displace water in a headspace until a ⅓ to ½ of the water in the bottle has been displaced. If the bottle opening is too narrow to accommodate the available tubing, a funnel can be used to direct the flow of bubbles into the bottle. The container is sealed under water with the septum cap tightened securely.

When sampling gases exsolving in a spring or stream, a 1 L bottle is similarly submerged to allow water to fill it. Suspended sediment is prevented from entering the bottle by allowing water to fill it near the air-water interface. When filled, the bottle is inverted and a large funnel is placed in the opening. Bubbles are allowed to enter the funnel and displace the water in a headspace as described above, and sealed under water.

Water samples taken from a surface water body or domestic well are prepared for shipping by drying the bottle and taping the cap to the bottle. The sample bottle is shipped (upside down) overnight to the sample laboratory. If no bactericide is used, sample bottles should be packed in ice.

6.2.2 Dissolved Gas

In contrast to Alberta where dissolved gas sampling is not required, jurisdictions in B.C. and the USA have required water well testing for dissolved gas. The approach taken in the USA ('wet' coals) involves pumping at a very low rate and sampling the pumped water. These regions are developing CBG from 'wet' coals. Dissolved gas analyses have been identified as being relevant for baseline testing and long term monitoring in order to address well bore integrity among neighbouring CBG wells, and to provide supporting data for assessing if any required remediation has been adequate.

6.2.3 Laboratory Measurement

Free gas samples are analyzed by direct injection into a gas chromatograph equipped with flame ionization detector (FID) to determine the hydrocarbon components or thermal conductivity detector (TCD) for atmospheric gases. The main compound is usually methane (C1 for one carbon atom), but ethane (C2) and heavier compounds (e.g. propane (C3), butane (C4), and others) may be present, depending on the gas source.

The only difference for analyzing dissolved gas samples is incorporation of an initial step to extract the gas by placing the sample under a very high vacuum. The decrease in pressure to near absolute vacuum causes the dissolved gas to bubble out of the liquid, where it is captured. The resulting gas sample is then analyzed as before.

6.3 Soil Gas Samples

Soil gas probes are used to sample natural gas seeps detected either on foot with portable Photoionization (PID), Flame Ionization Detector (FID), catalytic bead sensor, or in a roving vehicle equipped with infrared sensors. The most common method used for active soil gas sampling is referred to as direct-push technology. This does not require drilling and is based on various methods, manual and mechanical, that are used to push a hollow probe into the ground. The advantages of direct-push technologies over drilling technologies are ease of use and minimal soil disturbance.

The majority of soil gas seeps detected with portable sensors can be sampled using shallow soil gas probes. These are installed by hand to depths of up to one to two meters. Maximum depths reached depend on soil consistency and relative degree of consolidation. Once inserted into the ground, 0.64-cm (¼”) polyvinyl tubing is used to access the headspace in the vadose zone. Gas is sampled using a syringe-type or manual pump which forces the gas sample into a sample bag as shown in Figure 12.

Soil gas samples registering FID concentrations less than 10,000 ppm (1% by volume in air) are routinely collected using Tedlar™ bags. Samples are analysed using gas chromatography at the receiving analytical laboratory. Soil gas samples registering more than 10,000 ppm should be collected with Cali-5-Bond™ (5-layer) bags. These bags are sent to the receiving analytical laboratory for both chromatographic and stable isotopic analysis. Cali-5-Bond™ bags are preferable over Teflon bags because there is less chance of stable isotopic gas fractionation from diffusion loss through the bag. Stainless steel Summa canisters can also be used for sample collection, but are typically limited to use where other organic compounds may be present (e.g. landfills). The threshold concentration of methane in air that can be reliably analyzed in commercial laboratories using stable isotopic analytical methods is 10,000 ppm.

6.3.1 Field Measurement

Portable FID-PID Sensors

A flame-ionization detector (FID) detects all hydrocarbon gases that will burn in hydrogen (including methane, the lightest hydrocarbon gas). It is most sensitive to alkane hydrocarbons. A photo-ionization detector (PID) uses a lamp that also detects all organic vapours but is most sensitive to alkenes (such as ethene, butene, and pentene), and aromatic hydrocarbons such as benzene, toluene, ethylbenzene, and xylenes (BTEX). The best FIDs have a detection limit of 1.0 part per million (ppm) methane in air; the best PIDs, calibrated using isobutene (isobutylene), have a detection limit of 0.1 ppm. Detection ranges are from 0 to 10,000 ppm in air on an FID and from 0 to 500 ppm on a PID. Detection readings for the same sample on both FID and PID sensors could indicate a potential thermogenic gas source. Detection readings from just an FID sensor (no PID response) would most likely indicate that only biogenic methane is present.

Combination FID and PID field sensors are calibrated every day and verified at least once per day using certified gas standards. Once calibrated, the FID/PID unit is zeroed using ambient air, ensuring that there are no methane sources nearby. The instrument is therefore able to detect methane seeps above ambient methane levels in air. Ambient levels typically range between 1-3 ppm in air. System response is checked throughout the day using hydrocarbons sourced from either a Sharpie TM pen or a butane lighter. Portable detection units can be fitted with an extension tube and funnel. Used like a walking stick, the extension is repeatedly placed on the ground and dragged along a traverse as the surveyor walks along. Because a sample pump in the instrument continually draws ambient air from the ground surface through the FID/PID, measurements are essentially instantaneous and continuous. This allows even the smallest hydrocarbon plumes carried in air to be instantly detected. The surveyor can differentiate a gas plume carried in air from an underlying soil gas reading by alternating holding the funnel on the ground and lifting it up in the air. A GPS simultaneously records the path walked.

Portable Catalytic Bead Sensors

A catalytic bead detector operates somewhat like an FID in that it measures all combustible gases in a sample. The difference is that the catalytic bead detector measures a change in resistance due to temperature change, while an FID burns the sample with a hydrogen-fuelled flame. A catalytic bead sensor is variably sensitive to sample compositional differences, thus is best used either as a general survey tool, or when trying to detect known gases (e.g. methane leaks). As with the other sensors, daily calibration is required and the meter should be zeroed with clean ambient air. Sensitivity to methane presence can be reduced, but not completely eliminated. Methane sensitivity typically ranges from around 10-20 ppm up to 50,000 ppm (lower explosive limit).

Infrared detector

Another field-based methodology being developed relies on infrared absorption to measure gas concentrations. The instrument can be calibrated to detect methane, total hydrocarbons and carbon dioxide concentrations. This type of instrument has been used to conduct methane leakage, surface seep surveys, and in mining applications. Sensitivity is on the order of ppm levels.

6.4 Stable Isotopes in Gas

Measurement of gas isotopes can aid in determining the source of gas. As an example, the stable isotopes of carbon (^{12}C and ^{13}C) and hydrogen (^{1}H and ^{2}H) comprising methane can be measured and used to calculate the isotopic ratio between the sample and a reference standard. The isotopic ratio (detailed below) will vary depending on how the gas was produced. The basic concept is summarized below, with greater detail provided in numerous articles (e.g. Whiticar 1999).

Atomic structure of a nuclide is composed of protons and neutrons. The number of protons in a nuclide determines the elemental type of the atom (*i.e.* oxygen, nitrogen, carbon, *etc.*). The number of neutrons in an atom determines the isotope of the element. Atomic weight is calculated by summing the number of protons and neutrons in an atom. For example, most carbon has 6 protons and 6 neutrons giving it an atomic mass of 12. Approximately 1% of carbon atoms have 6 protons and 7 neutrons resulting in an atomic mass of 13. Molecules with different atomic weights will behave differently in the environment and result in isotopic fractionation and partitioning. Stable isotopic ratios represent a comparison of the two most abundant isotopes of a given element. Isotopic analysis is based on the comparison of the ratio of heavy to light isotopes in a sample to the ratio of heavy to light isotopes in a reference standard. Values are expressed using delta notation (δ) and reported in parts per thousand or per mil (‰). For carbon the equation can be expressed as the following:

$$\delta^{13}C_{sample} = \left(\frac{\left(^{13}C/^{12}C\right)_{sample}}{\left(^{13}C/^{12}C\right)_{standard}} - 1 \right) \bullet 1000 \text{ ‰}_{PDB} \qquad \text{EQN 1}$$

Values that are isotopically lighter (lower abundance of heavier isotopes) than the standard have a negative sign while values that are isotopically heavier (higher abundance of heavier isotopes) than the standard have a positive sign. For example, a $\delta^{13}C$ value of- 30 ‰ indicates that the material in the sample is depleted in the heavier isotope (^{13}C) by thirty parts per thousand compared to the standard.

For carbon the original standard was Pee Dee Belemnite (PDB), but more recently has been replaced by, Vienna Pee Dee Belemnite (VPDB). Carbon dioxide gas generated from the standard is then used as a reference for stable carbon isotopic analyses. For hydrogen the standard is distilled ocean water (Standard Mean Ocean Water (SMOW) or Vienna Standard Mean Ocean Water (VSMOW).

Stable isotopes of carbon ($\delta^{13}C_{CH4}$_and hydrogen ($\delta^{2}D_{CH4}$) in methane can help to identify methane sources (Whiticar 1999; Clark and Fritz 1997; Coleman *et al.* 1981). Methane is produced by thermal or bacterial degradation of organic matter. Bacterial oxidation of organic matter results in the production of isotopically light methane. Generally, isotopic values for carbon and deuterium isotopes from biogenic methane for $\delta^{13}C_{CH4}$ range from - 110 ‰ to - 50 ‰ and for $\delta^{2}D_{CH4}$ from -400 ‰ to -150 ‰ (Figure 13; Whiticar 1999).

The carbon in thermogenic methane is generally isotopically heavier than biogenic methane. Values of $\delta^{13}C_{CH4}$ for samples from thermogenic sources generally range from -50 ‰ to -20 ‰ (Figure 13; Whiticar 1999). The marked difference in the isotopic signatures of thermogenic and biogenic methane are the result of age and type of the carbon source (such as marine and terrestrial plants and organisms), type and magnitude of kinetic isotope effects (*i.e.* bacterial metabolic pathway) and temperature. It is anticipated that the general information provided in Figure 13 will be updated for Alberta conditions following release of the AENV database review.

Interpretation of stable carbon isotopic analyses can be confounded by several other processes that lead to isotopic fractionation. The preferential bacterial utilization of light isotopes from a closed carbon pool results in an accumulation of heavier isotopes in the residual substrate (organic matter). With time the isotopic signature of the substrate and produced methane will become enriched with heavier isotopes (Figure 14). It is possible that with sustained substrate depletion the stable carbon isotope signature of the resulting methane will approach that of the original organic matter.

A second confounding factor is when methane from more than one source is mixed together. Depending on the isotopic fractions of the end-member being mixed, the resulting isotopic signatures can be notably affected for some compounds but minimally affected for others. Calculation of the resulting mixture is calculated based on mass balances. Examples of mixing curves for end-members with differing initial compositions are shown in Figure 15 (Muehlenbachs 2006). As an example, consider the following mixture:

10% of coal gas (87.6% methane ($\delta^{13}C_{CH4}$ = -56‰) and 0.36% ethane ($\delta^{13}C_{C2H6}$ = -46 ‰))

90% of aquifer gas (99% methane ($\delta^{13}C_{CH4}$ = -70‰) and 0.0005% ethane ($\delta^{13}C_{C2H6}$ = -55 ‰))

The resulting mixture will have isotopic compositions of methane ($\delta^{13}C_{CH4}$ = -68.7‰) and ethane ($\delta^{13}C_{C2H6}$ = -47 ‰). An example calculation for methane is shown below:

$$(0.9*0.99*(-70‰) + 0.1*0.876*(-56‰)) / (0.9*0.99+0.1*0.876) = 68.7‰$$

The calculation shows the importance of knowing the end-member gas and isotope compositions in order to gain understanding from the data.

The stable carbon isotope composition of biogenic methane is primarily controlled by the isotopic signature of the carbon source and the metabolic process used by the bacteria to produce methane. Molecules with the lower isotopic masses are diffuse and react more readily. Therefore the isotopically light species are more readily used in metabolic processes. The magnitude of the fractionation is dependent upon the metabolic pathway used by the micro-organisms. Biogenic methane can be produced by one of two metabolic pathways. Bacterial reduction of carbon dioxide typically produces methane with $\delta 13C_{CH4}$ values between- 60 ‰ to- 110‰. Bacterial fermentation of substrates such as acetate, methanol or methylated amines typically produces $\delta^{13}C_{CH4}$ values of- 50 ‰ to - 60‰.

Temperature can have a significant effect on isotopic fractionation associated with bacterial methane production. Bacterial isotopic fractionation regardless of the metabolic pathway used, has been shown to decrease with increasing temperature (Whiticar *et al*. 1986). Coleman *et al*. (1981) described how bacterial oxidation of methane could lead to the gas sample appearing to have a similar isotopic composition as thermogenic gas.

6.5 Summary

Methane solubility in groundwater decreases directly with pressure and inversely with temperature. Given that groundwater pumped to surface for sampling has lower pressure and possibly higher temperature, gas solubility is expected to decrease. If the water becomes methane saturated, gas is therefore expected to exsolve (bubble out or effervesce), just as soda water does in a bottle when the sealed cap is first broken. Even in methane-undersaturated water, increased mechanical agitation and/or air displacement associated with aggressive well pumping can lead to increased gas effervescing than if the water were pumped gently. As a result, pumping water hard to collect gas and water samples will typically generate the greatest amount of gas bubbles available enabling collection for compositional and stable isotopic analysis. However, these factors may influence assessment of whether gas is present in dissolved form or as free gas.

In general, gas sampling procedures need to be accurate, reliable, and repeatable if the data are to be used to help identify changes over time in the amount and character of gas present in a well. Forensic objectives for collecting and analysing gas samples involve sampling natural gas found in groundwater (effervescing in the free phase or dissolved in water), springs, soils, and natural gas from suspected sources. Hence consistency in sampling protocols is as important as obtaining reliable analyses.

The current sampling protocol used in Alberta focuses on identifying whether gas exsolution may occur during pumping (is there any dissolved gas present), rather than determining the dissolved gas concentration. Accordingly, the methodology involves pumping water through a gas-water separator at near-atmospheric pressure (Figure 16). The volume of water pumped and volume of gas exsolved are recorded. While this method is adequate for identifying gas presence for forensic parameter analysis, it may not be reproducible for assessing the volume of gas present per volume of water pumped.

The advantage of the Alberta method is that it will typically give a conservative estimate of whether any dissolved gas might bubble out. The current sampling protocol for CBG therefore helps to quantify whether any potential risk might be associated with production of an explosive or oxygen-depleted atmosphere. This risk concept is adequate for most of the CBG development in ‘dry’ coal zones where dissolved methane is unlikely to be related to a pressure reduction. In the case of ‘wet’ coals (e.g. Ardley Coals), the focus on free gas sampling is inadequate for assessing the presence and/or changing level of dissolved methane in groundwater. Under these circumstances, experiences from the USA should be used to develop a modified sampling program.

7. RISK OVERVIEW

- Risk management provides a structured way to examine gas migration concerns
- Hazards and risk events associated with gas migration potential were identified
- Perceived likelihood and consequence scales of risk events may vary between stakeholders
- Example cases using hypothetical inputs were illustrated for industry and regulatory stakeholders

7.1 Overview

The concepts of risk and risk management are becoming more commonly used as ways to improve decision making and understand the possible effects of those decisions. A variety of approaches have been developed, but all generally comprise the same elements. One example of a risk-based approach is provided by the Association of Professional Engineers, Geologists and Geophysicists (APEGGA) who summarized the concepts and provided guidelines for their application (APEGGA 2006). The APEGGA definitions are summarized below, but are only used to reduce confusion between terms that sound similar. Other valid approaches may use different terms.

Term	**Explanation**
Risk	combination of the probability of an event and its consequences, and usually used when there is at least a possibility of a negative consequence
Risk Event	Any event or particular set of circumstances associated with a risk
Hazard	A source of potential harm, or an event with a potential of causing harm or damage
Consequence	A negative outcome of a risk event, resulting from a hazard
Risk assessment	overall process of identifying hazards combined with estimating their probability of occurring and the resulting consequences as they relate to what is acceptable by all affected parties.
Risk mitigation	Any step or strategy used to reduce the severity of a consequence and/or the associated likelihood of occurring
Risk management	Co-ordinated activities to direct and control risks through hazard identification, risk assessment, risk mitigation and communication.

Risk management is influenced by many factors including professional and personal judgement, hazard awareness, perceptions of hazard and probability, and familiarity with the issues. In many cases, potentially-affected parties may have different levels of awareness and sensitivity, such that one single scale won’t work. For these situations, it is important to consider each perspective on potential outcomes and their likelihood. This step helps identify main concerns for each group, and gain a balanced view regarding risks. This approach also helps to identify and compare ways to mitigate risks in relation to what is ‘reasonably achievable or practicable’. It is important to consider that even the concept of ‘what is reasonable’ may be in dispute.

7.2 Process

7.2.1 Introduction

The following discussion and example of assessing risks associated with gas migration potential due to CBG development is based on WorleyParsons corporate experience in environmental consulting within Alberta. Stakeholder surveys were not done to compile a statistically defensible set of outcomes. Rather, consideration of individual stakeholder perspectives is intended to be illustrative, although the resulting outcomes only represent a hypothetical evaluation. A substantial effort would be required to gather sufficient survey information to enable the risk assessment to reflect accurately the different stakeholder perspectives.

The concept of valuation is influenced by individual stakeholder perspectives. As simplistic examples, an individual company might base value on return on investment, a land owner might value land stewardship and lifestyle, while an environmental regulator measures value based on responsible protection of the environment. Accordingly, it may be challenging to find a universal valuation metric without using an instrument like litigation.

7.2.2 Risk Event Identification

The first step in developing a risk management program involves identifying the relevant hazards, their associated likelihood of occurrence and the resulting outcome of an occurrence. By combining the likelihood and severity, a risk register (list of risks) can be ranked and compared. As a follow-on step, the risk register helps show where risk mitigation activities may be best focussed to reduce the overall risk.

7.2.3 Risk Ranking

The risk ranking exercise is based on defining a series of units for measuring and comparing the consequence and likelihood of each individual risk event. The measuring unit (metric) usually depends on the perspective of the group considering the risk events. In the example, a single set of risk events was identified and assessed using different metrics for Regulators and Industry. The results show how this method might help communicate between stakeholders. The perspective of Landowners was considered too broad to generate a single hypothetical example, as discussed in Section 7.4.2. Surveys might help derive suitable input data.

7.2.4 Risk Mitigation

Risk mitigation involves identifying steps that can be taken to minimize the likelihood of a risk event occurring and/or the severity of the resulting consequence. Identification of risk mitigation alternatives can help each stakeholders understand the other perspectives, assuming there is a will to do so.

7.3 Risk Event Identification

A difficult aspect of developing the risk list associated with gas migration due to CBG development involved estimating the likelihood of occurrence or relative severity of a possible outcome, because:

- multiple stakeholders are involved with competitive interests;
- potential outcomes can be very severe;
- there are little supporting data on which to base likelihood estimates; and,
- understanding the severity of outcomes is heavily influenced by differing perspectives.

As a first step to resolve this challenging situation, a list of basic risk events was developed. An illustrative set of cases were used to show how ranking of risks (based on the combination of likelihood of occurrence and the severity of outcome) might vary when considered from the perspective of different stakeholders.

Risk events associated with methane migration were identified that could potentially result from CBG development. For clarity, the list was subdivided into either health and safety issues (Category A) or other events (Category B). It is recognized that CBG development may be associated with other risk events such as a loss of quality of life due to increased traffic, noise, dust, and altered land appearance and use. Such events are not related to gas migration, thus are not included in this report.

7.3.1 Health and Safety Concerns (Category A Hazards)

Methane is a colourless, odourless gas that is relatively insoluble in water under typical surface environmental conditions (solubility ~ 25 mg/L). Methane solubility increases with pressure and, to a lesser degree, with decreasing temperature and salinity. When methane-containing groundwater is pumped to surface, the decrease in pressure and (commonly) increase in temperature suggest that methane de-gassing (bubble formation) will occur.

Explosion

Gaseous methane is explosive when mixed with air over the range from 5 to 15% by volume (lower explosive limit and upper explosive limit, respectively). This condition can occur if gas is able to build-up in an unvented room or container. Awareness of this hazard is well-established, with several reference documents available from Alberta Agriculture.

Asphyxiation

If a well pit or pump shed is not properly vented, methane gas can accumulate and exclude sufficient oxygen to pose a risk of asphyxiation.

Vegetation Damage

Methane seeps in vegetated areas can be identified by the localized impact on vegetation. Exclusion of oxygen causes plant wilting, damage and may eventually generate a localized kill zone.

Outcrop Seeps

Gas migration can lead to creation of uncontrolled gas seeps at surface (near bedrock outcrops and/or subsurface bedrock contacts with overlying till). Well-known gas seeps unrelated to CBG should not be considered (e.g. Hells Half Acre at Turner Valley, The Hot Pot north of High Level and areas north of Peace River).

Unacceptable Bacterial Activity

Methane bubbling through the water column of a healthy water well will displace dissolved oxygen and promote the growth of noxious anaerobic bacterial colonies affecting water quality and causing biofouling of the well.

Methane gas may be attenuated in the subsurface via bacterially-mediated oxidation. If this reaction is associated with sulphate reduction, hydrogen sulphide (H_2S) gas can be released and/or cause black staining of plumbing fixtures. In addition to the known toxic and irritation effects of H_2S, other associated effects include increased turbidity, a bad taste to the water, other bacterial irritation effects (e.g. skin irritation), and increased corrosion of well casing, pump, pipes and plumbing fixtures.

7.3.2 Other Risk Events (Category B Hazards)

A number of other problems have been identified in addition to the safety risks associated with methane presence in domestic water supplies. Common problems include spurting taps, gas-locked pumps and ‘milky’ water when taps are initially turned on after having been unused for some period.

Although not linked directly to gas migration, concerns over the risk of aquifer damage may be raised in association with apparent aquifer depletion. Such concerns are relevant to developing CBG from water-saturated coal beds, where groundwater pumping is required to lower the hydrostatic pressure within the coal and enable methane desorption. Complaints are related to a loss of well yield, where the cause might be incorrectly attributed to a lowered water table when it is actually caused by reduced water well yield due to biofouling of the water well screen.

Risk events can also be associated with finding notable methane presence in a water supply, especially when methane is found around the same time that oil and gas activity is occurring. Even after considering regulatory efforts to mitigate gas migration potential, public stakeholders may find it hard to understand the technical details for how mitigation processes are expected to work.

Loss of Regulatory Confidence

The loss of regulatory confidence is well documented within the USA following the initial rush to develop CBG resources. Evolution of the American regulatory regime is discussed in the Appendices. Based on public reaction and efforts by stakeholder groups, a similar concern exists within Alberta. Regulators need to be aware of public suspicion, given the proportion of government revenue based on resource royalty payments.

Confrontation

Disputes between private citizens/landholders and Industry are commonly characterised using the image of David vs. Goliath, highlighting the confrontation as an imbalance in power. In response, each stakeholder group has attempted to increase general awareness of their viewpoint through information packages and public meetings. The difficulty is best illustrated by the inability to reach agreement on some issues of a multi-stakeholder advisory committee (MAC) developed to review CBG development issues.

Coincident Risk Event Correlation

Increased public awareness of gas migration issues has led to increased sensitivity about water wells in general. The benefit of initial efforts to educate the public about gas migration issues was associated with a greater tendency to attach water well complaints to ‘hot button’ issues such as CBG development.

7.4 Risk Ranking

7.4.1 Likelihood of Risk Event Occurrence

Estimating the likelihood of any given risk event to occur may be a challenging exercise. As examples, recent experience in Alberta might help estimate the likelihood of encountering a given well complaint related to ‘dry’ coals, while almost no data are available in Alberta to assess similar situations for ‘wet’ coals. Furthermore, the likelihood of experiencing a complaint may not reflect the true situation.

Water well complaints related to CBG development are now directed through AENV. From 2004 to 2007, approximately 140 water well complaints have been registered at AENV that mentioned a suspected link to CBG. In contrast some 6 complaints were made in 2008. From this total, there have been no confirmed links to CBG development, although links have been identified with other oil and gas activities. The contentious nature of this situation is evident from two media articles (radio and newspaper) after an Alberta Research Council review of five water well complaints (ARC 2008) found no evidence of CBG-related influence. At that time, the landowners maintained their position that impact was due to CBG development that occurred prior to introduction of the AENV baseline testing program.

Evidence has linked gas migration from conventional production facilities to subsurface areas, particularly in the Lloydminster area of northeast Alberta. A series of studies identified leakage along poorly-cemented annular spaces as being the principal pathway for gas migration (CAPP 1996). The studies identified likely gas sources using stable carbon isotope techniques. Field sampling programs identified methane oxidation coupled with sulphate reduction as an active way in which gas impacts were reduced under natural conditions.

A large amount of monitoring data has been collected in several major North American basins located across the USA. A summary of this information was prepared by Dr. Anthony Gorody in Section 10, with greater detail for several basins provided in Appendices 1 to 3.

7.4.2 Influence Of Stakeholder Perspective

When considering risks related to the public, risk management includes a political component related to perception. As noted in APEGGA (2006), public view of risks may include associated influences such as the degree to which the risk is: controllable, voluntary, bounded by scientific certainty, includes emotional associations (stigma), relies on public trust in regulatory bodies, and incorporates cultural/social influences. Given so many intangibles for this hypothetical risk assessment, the Landowner perspective was rapidly found to be too wide-ranging to capture without a comprehensive survey. The influence of perspective was therefore limited to possible viewpoints of Industry and Regulators. There is no stated or implied generic accuracy, being based on limited discussion with representatives and/or published evidence.

The following subsections attempt to identify the basic perspectives of Industry and Regulators, and examine selected risk issues from those perspectives. It is recognized that within each group, there are ranges of perspective; thus the resulting risk registers are intended only to look for major similarities and differences between groups. The goal is to look for ways that additional scientific effort, regulatory input or education might reduce differences in perceived risks.

Industry Perspective

The main goal of a CBG-producing company is to generate a profit from developing a CBG resource in a safe and responsible manner. It is assumed that Industry no longer focuses only on profitability at the expense of safety, environmental and community relations. Accordingly, a monetary measure is used to assess all risk events. This approach implies that generic cost implications can be assigned to risks associated with regulators, health, safety, environment and community relations. In reality, each company decides how they can best make a profit while following established regulations, dealing with affected stakeholders, and managing values such as corporate/socioeconomic/environmental responsibility and sustainability.

Regulatory Perspective

The ERCB is the main Regulator for CBG development, and is responsible for developing and administering policies and guidelines that ensure resources are developed in a safe and practical manner.

Within government, the ERCB rely on guidance from internal (e.g. AGS) or external groups (e.g. AENV). As an example, ERCB developed Directive 035 requiring water well testing when exploiting CBGM wells completed above the base of groundwater protection (BGWP is set by AGS). Directive 035 is based on a technical program developed by AENV, and it assigns AENV to be the one-call location for all CBG-related water well complaints.

From the Regulator perspective, major risks are associated with resource and environmental damage resulting from either setting weak regulations or not ensuring proper practices are followed. Both hydrocarbon and groundwater resources belong to the Crown, with development under government legislative control. Besides the obvious damages (loss of government resource), there is a more immediate negative political outfall resulting from a loss of public trust. This metric was therefore selected rather than indirect financial aspects related to lost royalty income and cost of cross-jurisdictional disputes.

Landowner Perspective

Landowners commonly don't own the mineral rights underlying their land. As a result, they are paid compensation for the noise and disruption associated with drilling, development and ongoing production activities on their land. Although guidelines exist for negotiating compensation (e.g. Griffiths et al. 2004; Griffiths 2007), payment amounts may not make up for quality of life losses reported by some landowners. Experience has shown that some disputes are not easily resolved.

Landowner perspectives vary, where the greatest risks could be associated with potential environmental damage to air (dust, odour, contamination), ground surface (soil, vegetation, weeds), groundwater (water wells and aquifers) or others (noise, disruption). Furthermore, lease payments are not always considered acceptable recompense for existing or potential impacts. Possible risk events with differing metrics between landowners include areas where groundwater quantity and/or quality is limited, or where the land has an emotional value. Such cases with multiple potential metrics can't be grouped, as was possible with Industry and Regulators.

8. RISK RANKING

- A sample risk ranking exercise was conducted to show the methodology
- Hypothetical viewpoints of regulators and industry were developed
- Safety issues were most important for both groups

An illustrative example of a risk-ranking exercise was carried out based on a series of Likelihood/Consequence combinations associated with selected risk events. The exercise was repeated from the hypothetical perspectives of Industry or Regulators, but not for public stakeholders due to the potential for widely varying viewpoints. The results are intended to act as an example, and are not considered definitive. A comprehensive application of risk ranking would require a broader survey effort to capture both the full range of possible risk events, as well as the ranges of likelihood and consequences scales associated with the identified data. The example case provided here illustrates how the process could generate insight when trying to communicate between stakeholder groups.

The risk ranking exercise comprised the main steps described in Section 7, as follows:

- Identify a series of risk events related to gas migration resulting from CBG gas production;
- Select a ranking system for evaluating both the likelihood and severity of consequences; and,
- Assign a combination of likelihood and severity estimates to rank the risks.

The risk map relating likelihood and consequence scales to risk ranking is shown in Figure 17, with the list of risk events used in this example application shown in Figure 18A (Industry) and 18B (Regulators). Some of the events are noted as being related only to CBG production from 'wet' or 'dry' coals to capture the different characteristics of these types of projects. The metrics chosen as examples for each group are presented in Figures 19 (Industry) and 21 (Regulators). Risks were then ranked using the likelihood and consequence matrix, as shown in Figures 20 (Industry) and 22 (Regulators). The exercise was conducted using proprietary software developed by WorleyParsons, but can be done by hand.

The basic Industry perspective used for ranking risks was profitable and responsible development of CBG resources. This statement includes Industry's recognition of the need to follow applicable regulations and awareness that safety and environment are key drivers. Accordingly, risk events are weighted using a monetary measure, and assuming a medium to large-sized company. Other scales could easily be used.

The Regulatory perspective for risk ranking was considered to be driven mostly by public trust and environmental concerns, rather than financially, as for Industry. The same risk events were considered as for Industry, but different weighting scales were used to assess the likelihood and severity rankings (Figure 21). Health and safety concerns were considered to be embedded rather than directly evaluated.

This generic approach could be re-focussed on specific issues, for example by considering an individual CBG target zone, identifying sensitive areas or developing regulatory or exploitation strategies for those areas.

8.1 Results

The results of the example risk ranking exercise for gas migration related to CBG development are summarized in Figures 20 and 22. In both cases, the highest risk rankings were associated with explosion and asphyxiation risks events due to their extremely serious outcomes. Fortunately these risk events are easily mitigated by ensuring adequate venting of the water well system and pressure tank. Government publications identify this situation, and recommend venting when gas is encountered. Furthermore, anecdotal reports of taps and natural seeps that can be flamed have been well known in some areas of Alberta for decades.

Risks related to geochemical and bacterial impacts are relatively easy to mitigate, thus rank quite low. While the underlying science associated with nuisance bacteria and their symptoms is well established, this information is not always appreciated by landowners. Further education is suggested to help well owners learn how to take care of their wells, and/or recognize when the nuisance factor might have an external cause. Education is also required about the need to properly abandon unused water wells. It is understood that a government-based partnership led by AENV has started developing educational resources for well owners through the Working Well program, as described in the following web document: (environment.alberta.ca/documents/**Working_Well**_program_update_aug08-08.pdf).

Risks associated with aquifer damage appear to rank relatively lowly when considering CBG development from ‘dry’ coals (most of the current projects in Alberta). In contrast, CBG development in ‘wet’ coals (likely to increase in Alberta) has a greater risk ranking. The risk would increase when developing shallow coal resources that might be used as aquifers. Although not specifically assessed, shallow resource development would likely have higher risk severity (combination of likelihood and consequence) depending on population and land use. Experience from CBG development under these conditions in the USA provides useful insight about monitoring and risk mitigation alternatives (Viellenave et al. 2002, Glantz et al. 2002).

Experience from both Alberta (gas migration near Lloydminster in northeast Alberta in the mid-1990s) and the USA has also provided evidence of risk related to the presence of historical oil and gas wells. Changes in regulations since drilling began during early hydrocarbon developments meant that these old wells might have been constructed and/or abandoned before the increased regulation of surface casing and cementing requirements greatly reduced the risk of associated annular leakage. For ‘dry’ coals, the annular leakage scenario is unlikely to occur. The underpressured nature of these coals means that vertical leakage is more likely to involve downward flow of groundwater rather than upward flow of gas. This situation differs from risks of gas impact on water wells in areas where conventional gas production from overpressured formations had been conducted.

The importance of perspective is most clearly exemplified by the relatively low ranking of “other” risk events from Industry perspective based on the assigned combination of likelihood and consequence scales. Such events could be of major importance when considered from a landowner perspective. This one example of a disparity in apparent risk sensitivity highlights the need for sensitivity from the petroleum company and active involvement by landowners to make their viewpoints understood.

9. RISK MITIGATION

Risk mitigation alternatives were reviewed for a number of hazards, starting from the most serious listed in Section 7.3. As examples, explosive and asphyxiation risks were considered to be easily addressed simply by modifying the water well pumping system to enable gas venting to atmosphere. This approach could also address the coincidental risks posed by low concentrations of hydrogen sulphide that may derive from bacterial activity related to methane biodegradation.

Several options are available to address the various symptoms of bacterial nuisance effects, usually through well cleaning (including biodispersants and mechanical cleaning) and treatment. In any case where CBG influence is suspected, well owners are best served by immediately contacting AENV staff. General information about water well maintenance is readily available from AENV, Alberta Water Well Association, local Health Units and other bodies. By understanding the underlying causes of water well nuisance aspects (well-related and/or tied in to CBG development activities), well owners are best prepared to make informed decisions about next steps to address the nuisance.

Independent of CBG development, monitoring of well conditions and/or quality testing (potability and bacterial testing) is recommended to landowners as a crucial step to staying aware of water well quality. Records should be kept of all water well tests (both flow and quality), and notes should be kept of any observed changes in water quality or quantity. Relevant factors include the date, weather conditions, obvious changes in nearby industrial activity, and estimated water use. There are currently no regulatory requirements for ongoing well water monitoring in association with CBG development.

Problems associated with surface land and lifestyle imposition typically require negotiation with the energy company both prior to project initiation, and as such impositions are identified. An overview of the process is available from the Environmental Law Centre website (www.elc.ab.ca/pdffiles/OilandGasDevelopmentandSurfaceRights.pdf). This document includes useful references, such as a published guide to citizens' rights related to these negotiations (Griffiths et al. 2004), and contacts for various groups that handle surface rights issues.

9.1 Mitigation Through Regulatory Change

Government response to recognizing gas migration potential associated with annular leakage is evident from the historical changes to regulations controlling casing cementing. Since at least 1971, the Oil and Gas Conservation Act has required that surface casing be cemented in over its full length to provide borehole stability and shallow aquifer protection. Further recognition of the importance of cementing for environmental protection is evident from the 1990 update, requiring full-length cementing of casing next to the surface casing if the surface casing is less than 180 m deep or less than 25 m below usable groundwater. The regulation subsequently changed to include awareness of environmental protection afforded by surface casing.

Increased shallow CBG development led to introduction of more stringent rules regarding well completions including the water well testing program, surface casing, cementing, and fracturing activities. Additional input from Regulators derived from concerns expressed at a Public Hearing into a proposed CBG project

ERCB Decision 2006-102, available at www.ercb.ca under the Industry Zone: Decisions: Decisions: 2006 tabs). The ERCB required additional field tests of potential influences of fracturing on water wells near a CBG project in Alberta. The results showed that nitrogen stimulation likely had an insignificant influence on shallower water-bearing intervals.

9.2 Mitigation Through Industrial Change

Regulations controlling the main industrial practices related to CBG development are relatively prescriptive. Industry has an obvious responsibility to follow these rules or face punishment via notices of violation and/or fines. Although not linked to gas migration concerns, efforts to reduce land and lifestyle issues related to CBG development have included use of directionally-drilled wells to reduce the extent of surface impact, and implementation of minimal-disturbance drilling practices.

10. SUMMARY OF GAS MIGRATION EXPERIENCE IN USA (A. GORODY)

- The US experience shows that regulations in cooperation with Industry can lead to effective risk mitigation when addressing methane migration risk
- US CBG projects (‘wet’ coals) differ from most current AB projects (‘dry’ coals)
- Older oil and gas well boreholes were more likely pathways than newer CBG wells
- Natural pathways included dike swarms and fractures, and updip buoyant movement
- Residences constructed near coal outcrops are more likely to have gas migration issues
- Water wells completed in coals commonly encounter gas problems
- H_2S is not in CBG, but may show up due to methane biodegradation

Case studies demonstrate that the impact of natural gas migration from coalbed seams to the surface, when it occurs as a result of commercial gas operations, is nearly instantaneous. Buoyancy rapidly drives gas upward through the nearest and largest permeable paths. The free gas phase may migrate updip towards the surface along possible pathways including shallow bedding plane boundaries, receptive permeable shallow aquifers, and shallow fracture swarms. Man made migration paths include water wells, cathodic protection wells, piers, and any other piercement structures. The USA experience has shown that methane escaping from a problematic commercial oil and gas well is most likely to surface within a 1 km radius of such a point source.

Based on limited quantitative data available from USA coalbed gas fields, older, historic wells producing oil and gas from deep conventional reservoirs are more likely to provide gas migration pathways to the surface than shallower and newer coalbed gas wells. In the La Plata County portion of the San Juan Basin, and within a 5 year period after casing heads were routinely checked for pressure, approximately 20% of the conventional wells required remedial cement or were plugged and abandoned. During the same period, approximately 3% of the coalbed gas wells were found to require remedial cementation or were plugged and abandoned. No data are available to determine which if any of these remediated and/or plugged wells may have contaminated groundwater aquifers. In the Animas River valley between Bondad, CO, and Cedar Hill, NM, groundwater aquifers were contaminated with methane migrating from the majority of historic wells that had an uncemented annulus in contact with the Fruitland Formation.

After leaky point gas sources are remediated, the effect on near-surface gas seepage is also nearly instantaneous. Gas bubbling tends to cease quickly, and areas affected by seeps are rapidly reduced to below detection levels. Declining dissolved gas concentrations in contaminated groundwater plumes, however, may not necessarily be as immediate. Gas migrating updip through aquifers can accumulate in small structural and stratigraphic gas caps along the way to the surface. In such instances, dissolved gas is entrained in groundwater flowing from the trapped gas source towards areas of lower local and regional potentiometric head. Water wells that tap such an associated groundwater plume may contain dissolved methane for numbers of years until the gas cap is dissipated.

Once a point source of contaminant gas has been effectively remediated, then dissolved methane concentrations in groundwater will ultimately decline with time. The only way to assess whether dissolved gas concentrations are increasing, decreasing, or remaining the same, is to consistently use standard sampling and analytical protocols. The assumption that the screened interval in a water well restricts water sources to specific aquifers is often incorrect. The dominant open hole and gravel pack completions used in water wells throughout the Rocky Mountain States allow fluids from otherwise stratified aquifer sources to mix. This allows methane to become variably diluted depending on the relative contribution of fluids from each contributing fluid-bearing aquifer. Fluid mixing dynamics can be monitored to determine if a source of gas has been effectively remediated. This necessitates regular sampling and analysis. The efficacy of remediation can be effectively evaluated using a combination of water quality analyses, and both chemical and isotopic analyses of dissolved gases. To address the impact of declining methane concentrations due to bacterial methane oxidation, stable isotopic analyses can be extended to include both carbon and deuterium in methane and carbon in dissolved carbon dioxide.

Groundwater contamination resulting from coalbed gas operations is not always due to gas migration conduits established along poorly constructed commercial wells or either faulty cement bonds or absent cement along well casings. Experience from the Raton Basin has shown that volcanic dike swarms can provide vertical conduits for gas migration. Such risk can be mitigated by monitoring produced water quality and water production volumes. Water production volumes far in excess of what can be expected to be normally contained in perforated coal seam intervals indicate communication with other fluid transmissive aquifers. Such aquifers may, under ideal conditions, provide a gas migration pathway to the surface.

Groundwater wells completed in coal are also at risk for methane migration. Lowered water levels in coal, whether induced by drought or by domestic aquifer pumping, can result in the release of methane into a water well. Coalbed gas operations that pump water in the vicinity of domestic water wells completed in coal can lower the local water table if the coal seam at the water well is in hydraulic communication with the producing coal seam. Free and dissolved gas monitoring is an effective way to mitigate the risk of local coal seam methane desorption resulting from lowered water tables. The risk for produced coalbed gas migration into nearby water wells can also be assessed by mapping which water wells are completed in aquifers occurring within a 30 meter vertical interval from a producing coal interval.

Coal outcrop belts are geologic hazards. Residential communities and homes constructed on top of coal seam outcrops and subcrops are at risk for methane migration. Natural gas seeps are most likely to occur along a narrow band defined by the position of coal subcrop and outcrop formation boundaries. Variability in seep intensity and seep location has been demonstrated to occur naturally as a consequence of the interaction between climatically-induced water table fluctuations and a dipping coal-bearing formation along the outcrop belt. Under natural conditions, variable surface seep intensity is controlled by imbibition and drainage phenomena which mediate two-phase flow in porous media.

Numerous useful and several pioneering approaches documented from the San Juan Basin can be applied to determine whether there is a relationship between downbasin water production and the extent and severity of gas seeps along a coal-bearing outcrop. Of those, water level analyses in clustered monitor wells completed in, above, and below coal appear to provide the most direct evidence for production-induced drawdown and potential cross-flow between layered aquifers. However, because of naturally occurring hydrogeologic heterogeneity, the extent and/or intensity of seeps potentially resulting from down-basin production practices are not likely to be evident everywhere along an outcrop belt.

Basin-wide groundwater sampling for water quality and dissolved methane is a new phenomenon in the history of groundwater hydrology. Data from USA coalbed gas basins show that only a few commercial oil and gas wells have been documented to pollute groundwater. A more remarkable observation is that more than 60% of all water wells contain naturally occurring methane of variable and mixed origins.

For example, elevated outcrop belts can be expected to have active hydrodynamic shallow, intermediate depth, and deep groundwater flow circulation patterns. Areas with trellis type drainage patterns along an outcrop will optimize the potential for incorporating both migrating thermogenic hydrocarbons and locally generated biogenic gas into recharging fluids. Accordingly, fluids circulating in shallow and intermediate depth aquifers near outcrops can entrain high dissolved methane concentrations. Such fluids tend to be discharged in stream valleys or along springs near topographic lows within an area a few tens of kilometres from outcrop recharge. Hydrocarbon-bearing bedrock aquifer fluids that discharge into alluvial sediments are also likely to mix with local alluvial aquifer fluids containing biogenic gas. For these reasons, shallow to intermediate depth groundwater wells within a few kilometres of outcrop belts are likely to contain relatively high dissolved hydrocarbon concentrations of mixed thermogenic and biogenic origin.

If commercial oil and gas wells are developed near outcrop recharge zones, then for the reasons just described, it is helpful to sample groundwater wells prior to and during development. Only periodic sampling will help establish if groundwater wells already containing entrained dissolved gas become contaminated with gas from an adjacent oil and gas well.

Regulatory action taken in response to complaints early in the history of CBG gas development in the USA has resulted in successful mitigation strategies. Routine and regular casing head gas pressure measurements in conjunction with routine and regular sampling of nearby water wells have effectively mitigated the potential for groundwater contamination. Because the produced gas composition in individual coalbed gas wells everywhere tends to be unique, combined chemical and isotopic analyses make it possible to discriminate, identify, and remediate point sources of groundwater contamination.

Experience has allowed sampling and measurement techniques for monitoring free and dissolved methane in groundwater to evolve. Measuring hydrocarbon headspace concentrations in gas chambers exposed to high volumes of flowing water does not provide reproducible results. More reliable and reproducible dissolved gas data from water wells are obtained by minimizing water flow rates and by collecting samples in VOA vials under a head of water. The natural environmental variability of dissolved methane concentrations, as measured from repeated measurements at water wells sampled within a period of 90 days, can be expected to be in the range of +/- 8 to 14 percent. Duplicate analyses also show that sampling variability is relatively insignificant and on the order of 0.02 mg/L.

Hydrogen sulphide (H_2S) is not found in CBG resources, but has been encountered in association with methane. This discussion point is presented in greater detail because of the indirect link between CBG and H_2S, and the possibility of misinterpreting gas data. Bubbling of methane through the water column of a domestic water well will displace oxygen in the well and promote anoxic (oxygen-poor) conditions. If sulphate-bearing waters become anoxic as a result of contamination, then the well is at risk for entraining dissolved hydrogen sulphide. Anaerobic sulphate reduction coupled with oxidation of dissolved methane will contribute to high dissolved sulphide concentrations. This results in an associated risk of toxic hydrogen sulphide exposure that is rarely addressed when considering the direct impact of methane migration. Note: H_2S in such cases is unrelated to CBG, being generated by biochemical reactions that occur after methane is present.

In contrast to non-toxic methane, the consequences of both short and long-term exposure to hydrogen sulphide gas in the work place have long been recognized and well-documented (Chou 2003). Exposure to this gas in the domestic home environment is rarely addressed even though it is commonplace among homes dependent on domestic water wells. H_2S is extremely toxic and even at low concentrations can have temporary deleterious effects.

At very low concentration, hydrogen sulphide in air is difficult to measure. However, approximately 80% of the human population can detect hydrogen sulphide at concentrations of 0.03 ppm in air. The odour is often likened to the smell of rotten eggs. Above 30 ppm, the odour is usually described as a sickly sweet odour. In the range of 50 to 100 ppm in air, the gas paralyzes the olfactory nerves and can no longer be detected by smelling.

Because the nose is so sensitive to H_2S, it can be used as a qualitative gauge. Gas toxicity relative to this olfactory gauge can be summarized as follows:

- Faint odour: 0.3 to 0.77 ppm. About 40% of the population senses discomfort at this range.
- Moderate odour: 0.77 to 4.6 ppm. Headaches, depression, and dizziness are common in this range. The higher end of this range is accompanied by coughing, throat irritation, and shortness of breath (2.5 – 5 ppm).
- Strong unpleasant odour: 4.6 ppm to 27 ppm. Nausea, vomiting, irritability, sleep loss, fatigue, and memory loss can occur in the range from 0.32 to 20 ppm. Loss of appetite and weight loss can occur in the range of 0.7 to 40 ppm. Ear, nose, and throat irritation and bronchitis can occur at 10 ppm. Eye irritation can occur in the range of 10 to 20 ppm.

Other complaints typical among people exposed to low concentrations of H_2S in air and water include disorientation, dry itchy skin, sensitivity to light and allergic reactions. It is not uncommon for people to complain about symptoms when bathing. The air in small, closed bathrooms and shower stalls can accumulate toxic concentrations of hydrogen sulphide when exposed to relatively small volumes of hot running water. The symptoms described above are temporary and are relieved as soon as the person is no longer exposed. The consequences of long term exposure to low concentrations of H_2S are still not fully known or documented.

The risk of short term exposure to H_2S can be mitigated by using BART^{TM} and colorimetric HACH^{TM} samples as part of a routine baseline measurement and monitoring practices. Routine Biologic Activity Reaction Test (BART^{TM}) cultures (Cullimore 2008) of water well samples collected for baseline studies in the USA reveal that a majority of wells are infected with aggressive colonies of sulphate-reducing bacteria (SRB), iron-related bacteria, and slime-forming bacteria. SRB are responsible for sulphide odours detected while sampling, high dissolved sulphide concentrations detected in the field with colorimetric HACH^{TM} tests, and grey-coloured, sometimes effervescent water. Most of the sulphide present in these wells results from poor water well maintenance practices.

Biofouling, principally mediated by IRB and slime-forming bacteria, is also commonly associated with poor water well maintenance practices. It can result in an apparent decrease in water well yield because well recharge rates are impaired. Apparent decreasing water yields due to poor maintenance practices have been blamed on CBG production operations. Such complaints are likely to become increasingly prevalent during the life cycle of CBG operations because most water wells appear to normally lose yield and “age” within a period of 30 years. The risk of increasing complaints resulting from apparent losses in water well yield can be mitigated by educating communities on the importance of good water well maintenance practices.

Litigation is a significant consequence of methane migration potentially associated with CBG development. In the U. S. during the past twenty years, the targets for litigation have shifted from gas operating and mining companies to federal and state agencies. In part, this reflects a shift in areas being developed for CBG from privately owned fee lands to split estate federal and state lands. In a split estate, the surface owner does not own the underlying mineral rights. The shift also reflects the increasing and maturing influence of well-funded non-governmental organizations and grass roots citizen groups.

11. CONCLUSIONS

The increase in CBG development in Alberta has generated a wide range of concerns about potential environmental impacts. This report focussed on concerns about gas migration related to CBG development. From a scientific perspective, issues related to CBG and gas migration processes should be considered separately for 'wet' and 'dry' coal zones.

Theoretical Considerations

When developing 'dry' coals (at irreducible water saturation), CBG is present mainly sorbed to coal and in the gaseous phase. Experience has shown that these coals are generally underpressured, meaning that the gas pressure is less than the equivalent hydrostatic water pressure at that depth. Downward water movement into the coal would likely occur if a vertically continuous pathway developed between the coal and any upper water-bearing intervals. The water would tend to saturate the coal pores and prevent upward gas migration due to buoyancy. Counterflow of both gas (upward) and water (downward) might be possible if there were a highly conductive pathway. Current regulations mitigate this situation by requiring full-length cemented casing. Such a condition might exist for an old well where cement degraded, or had not been required to seal off the coal zone.

Development of 'wet' coals has different theoretical consideration regarding gas migration issues, especially for shallow coals. Water stored in such coal zones may represent a local water resource in some areas. Secondly, the dewatering required to develop the resource may increase concerns about fugitive gas migration. Formation of gas bubbles as a result of dewatering mean that gas transport is governed by buoyancy as wells as groundwater flow. Although the gas was always present, the de-pressurizing of coals can increase risks of gas migration along vertical pathways such as exploration holes and wells. This concern is particularly relevant in areas where historical coal exploration holes were plugged and abandoned before recognition that coal could be exploited for CBG.

Alberta CBG Development

Gas migration is unlikely to pose a significant threat to water wells for CBG wells that develop 'dry' Horseshoe Canyon and Belly River coal zones. To date, there is no documented evidence of water well impacts from these cases in Alberta. The greatest potential for gas migration to generate environmental impacts is from development of shallow, water-saturated coalbeds, such as the Ardley coals (Scollard Formation). These areas would benefit most from use of focussed risk assessment methods to address possible impacts of CBG development to health, safety and the environment.

USA Case Studies

Gas migration impacts of limited extent have been documented in relation to CBG development from 'wet' coals in the USA. Impacts have taken several forms including creation of gas seeps and CBG migration into domestic water wells. The USA experience offers lessons that been learned related to 'wet' coal development. These lessons could be used to help develop and implement adequate risk mitigation protocols needed to protect groundwater resources from potential CBG contamination in Alberta. In both Canada and the USA, gas migration has also been identified due to conventional oil and gas activity.

Current Alberta Testing Protocol

Baseline testing of water well conditions in Alberta has focussed on assessing general water well quality (chemical and biological), and the potential presence of free gas. This approach is reasonable when considering production from the 'dry' coal zones noted previously. In contrast, baseline testing for impacts related to CBG production from 'wet' coals (e.g. Ardley) should consider using a similar protocol as developed in the USA, or proposed for baseline testing prior to CBG development from 'wet' coals in B.C. The protocol for 'wet' coal development should be concerned with quantifying baseline conditions followed by temporal monitoring of groundwater quality during the lifecycle of a CBG production project.

Forensic Testing

Forensic sampling data in Alberta and several basins within the USA has identified almost no gas migration issues relating to CBG development. A more common cause of gas impacts was identified as being related to inadequate sealing of historical exploration boreholes and test holes. The absence of pre-CBG development data in Alberta (water wells and coalbeds) prevents strict use of current data as a potential endmember for forensic comparisons. One step to get around this possible limitation would be to collect CBG samples for compositional and stable isotope analyses from coalbeds during the resource exploration phase. Given that old abandoned petroleum wells might provide a vertical leakage path, selection of CBG well locations should consider avoiding proximity to such old abandoned wells.

Risk Review

A hypothetical risk review was conducted to illustrate how risks associated with gas migration issues might vary when considered from generic perspectives of Industry and Regulators. The risk review did not include other environmental, health, safety, or socio-economic issues related to CBG development. A more comprehensive risk assessment program would require using the same approach to address ranges of perspectives of public stakeholders (e.g. Landowners), and would require broader input from each stakeholder group in order to be sure that their risk rankings capture the range of perspectives.

The example risk review of gas migration issues associated with CBG development identified that safety-related risks are most important for Regulators and Industry, as would also be assumed for Landowners. Based on the assumed risk data provided in Section 9, the next most important risks from Industry's perspective addressed loss of gas resource followed by public pressure/loss of trust. In contrast, the assumed input values showed that Regulatory concerns were more immediately directed at loss of public confidence and trust.

12. DATA AND KNOWLEDGE GAPS

Data gaps were identified and divided into the following three areas: technical, management of risk, and communication. It is recognized that these issues cross over to some degree.

12.1 Technical Gaps

A technical gap exists concerning how previous requirements for petroleum well construction, completion and abandonment might relate to environmental impact risks. At least back to 1971, surface casing has always required cementing, but the lengths and cementing for intermediate and production casing have gradually become stricter. Similarly, stricter requirements have developed for well and dry-hole abandonment procedures, and reporting and rehabilitation of these wells. The data gap would be in locating and identifying where current CBG activities are occurring in areas where there may be rehabilitated and/or abandoned old wells (especially wells that could not be fixed and/or remain as old, potentially leaky holes).

Although few cases of gas migration have been encountered in Alberta (e.g. CAPP 1996), further evaluation would be useful given the large number of wells drilled. A good first step would be to re-examine records and past practices to see where CBG development might be near the potential influence of old, potentially leaky wells. In these areas, consideration should be given to conducting soil gas monitoring around selected abandoned well sites to assess the extent of possible gas migration. Increasing population and density imply an increasing chance that a water well could encounter a localized subsurface leak scenario.

Assessment of groundwater impacts due to methane migration by CBG development requires showing some characteristic change(s) in local well water (quality and/or quantity). One data gap was addressed in 2006 with implementation of water well testing, including groundwater chemistry, hydraulic response to pumping, absence/sampling of gas and/or water well completion information (ERCB 2006b), and an initiative to improve understanding of groundwater resources in central Alberta (AENV 2006b). The hydrogeology database that stores results of the residential water sampling program has been reviewed by a scientific committee, but the report was not publicly available at time of writing. One suspected data gap is that there are insufficient composition and stable isotope data from CBG production zones to compare with equivalent data collected from water wells.

The baseline testing program does not really capture pristine conditions, having started in 2006. In comparison, CBG development began commercially in 2002 and conventional oil and gas production in some areas has occurred for more than sixty years. Furthermore coal mining has also been conducted near some areas of CBG activity. These activities may have had some influence on methane migration before baseline testing was conducted.

The baseline testing program typically requires a one-time sample, and does not address the issue of sampling variability or repeatability. A follow-up sample is only required if there is a water well complaint. Seasonal and/or temporal variations in hydrochemistry, gas and isotopic composition may be addressed using time-series samples from selected wells targeted by AENV. Shorter-term variation could be addressed using a passive gas sampling system recently developed at University of Calgary (McLeish, in preparation). Extended sampling is required to assess temporal changes in gas from CBG coalbeds (over the production life) and water wells.

The current sampling protocol only calls for gas composition and stable carbon isotope analysis. Experience from the USA has also identified the utility of analyzing isotope fractions for deuterium (^{2}H) and oxygen (^{18}O) in water and carbon dioxide. These refinements were relevant where carbon and hydrogen isotopes of methane were not sufficiently distinguishing by themselves. The additional isotopes could also help to address the efficacy of mitigation measures if an aquifer were to be impacted.

The current water well monitoring program involves specifically sampling for exsolved gas during aggressive pumping for flow quantity testing of a water well. This method is appropriate for identifying whether a risk exists due to methane gas presence, and for collecting compositional and stable isotopic data to assess the methane source. The method may not provide a reproducible result in terms of estimating volumetric gas presence in pumped water. In general, this problem is likely only to be a concern when re-testing water wells for assessing changes over time (i.e. when assessing efficacy of remediation measures). Experience from CBG production in the USA resulted in a move toward a more consistent sampling methodology for dissolved methane, as described in Appendix 1.

12.2 Risk Management Gaps

The illustrative assessment in Section 8 about how perception influences risk assessment was not based on factual survey information. Such an effort would assist AENV in incorporating public perspectives on the current water well monitoring program. This task is challenging, based on previous experience gained from the MAC efforts. Some questions could not be settled given competing interests. Accordingly the only approach may be to apply survey and probabilistic methods to overcome sticking points.

A major perceptual gap between stakeholders appears to be associated with alleviating concerns over the potential for stimulation and/or hydraulic fracturing of coalbeds to impact overlying aquifers. While a literature search did not identify any cases where hydraulic fracturing was identified as the cause of diminished water quality, more effort is required to demonstrate understanding of fracture behaviour. Empirical experience tends to remain proprietary as a business advantage. It is understood that scientific studies are currently underway to improve understanding and awareness of fracture propagation and extent in coal beds under field conditions.

12.3 Communication Gaps

Despite increased effort from various governmental departments to provide educational material regarding CBG development and possible influences on water resources, lack of knowledge and/or distrust of the information continue to be displayed (e.g. article Busting the Myths Behind CBM, EUB Newsletter, Across the Board, March 2006). It is understood that both ERCB and AENV are continuing to develop their educational materials, especially AENV regarding water wells and their maintenance.

The concepts of risk and mitigation coupled with a review of available evidence versus perception require widespread dissemination. As a first step, the water well complaint database within AENV needs to be made more transparent and consistent so that cases and resulting findings are more easily shared.

Although more of a policy issue, another information gap is associated with the continuing need to educate water well owners about well maintenance and abandonment of unused wells. Regular testing for both well quality and quantity should be conducted, and notes kept regarding any notable changes. Efforts must be continued to inform water well users of their responsibility for caring for their water wells. An excellent resource for this purpose is the booklet “Water Wells That Last for Generations” (AAFRD 2000).

13. CLOSURE

We trust that this report satisfies your current requirements and provides suitable documentation for your records. If you have any questions or require further details, please contact the undersigned at any time.

Report Prepared by
WorleyParsons

James Armstrong, Ph.D., P.Eng.
Principal Hydrogeologist
Technical Director, Contaminated Sites

Dr. Carl Mendoza, P.Eng.
Professor, Earth and Atmospheric Sciences
University of Alberta, Edmonton

Senior Review by

Dr. Anthony Gorody, Ph.D., P.G.
President, Universal Geoscience Consulting, Inc.

PERMIT TO PRACTICE
WORLEYPARSONS CANADA LTD.
Signature
Date
PERMIT NUMBER: P2306
The Association of Professional Engineers, Geologists and Geophysicists of Alberta

14. REFERENCES

AAFRD (Alberta Agriculture, Food and Rural Development) 2000. Water Wells That Last For Generations, Third Edition. Agdex 716(A10).

AAFRD (Alberta Agriculture, Food and Rural Development) 2006a. Methane Gas in Well Water, www1.agric.ab.ca/$department/deptdocs.nsf/all/eagdex10840, accessed February 2006.

AAFRD (Alberta Agriculture, Food and Rural Development) 2006b. Dissolved Gases in Well Water. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex637. Accessed February 2006.

AAFRD (Alberta Agriculture, Food and Rural Development) 2006c. CBM Wells & Water Well Protection, www1.agric.ab.ca/$department/deptdocs.nsf/all/eng9758, accessed February 2006.

AE (Alberta Energy) 2008. www.energy.gov.ab.ca/754.asp, accessed December 2008.

AENV (Alberta Environment) 2000. Water Act Water (Ministerial) Regulation, Alberta Regulation 205/98 with amendments.

AENV (Alberta Environment) 2004. Guidelines for Groundwater Diversion for Coalbed Methane/ Natural Gas in Coal Development, April, 2004.

AENV (Alberta Environment) 2006a. Standard for Baseline Water-Well Testing for Coalbed Methane/Natural Gas in Coal Operations. April 2006.

AENV (Alberta Environment), 2006b. Government Supports Baseline Testing for Well Water. News Release, March 6, 2006. http://www.gov.ab.ca/acn/200603/19544D15EA03D/0669/8AE8/8A9184656ADE0130.html, Accessed March 2006.

Alberta Regulation 205/98 2000. Water Act Water (Ministerial) Regulation. Queen's Printer for Alberta.

APEGGA (Association of Professional Engineers, Geologists and Geophysicists of Alberta) 2006. Guideline for Management of Risk in Professional Practice V1.0

ARC (Alberta Research Council) 2008. An Independent Review of Coalbed Methane Related Water Well Complaints Filed With Alberta Environment. Prepared for Alberta Environment. January 16, 2008.

Bachu, S. 1997. Basin-Scale Geology and Hydrogeology of Coalbed-Methane Bearing Strata in Rocky Mountain Sedimentary Basins. Alberta Energy and Utilities Board (EUB), Alberta Geological Survey (AGS), Open File Report 1997-01. September 1997, 38 pp.

Bachu, S. and K. Michael 2002. Hydrogeology and Stress Regime of the Upper Cretaceous-Tertiary Coal-Bearing Strata in Alberta. EUB/AGS Earth Sciences Report 2002-04. 74 p.

Beaton, A., C. Pana, D. Chen, D. Wynne and C.W. Langenberg 2002. Coalbed Methane Potential of Upper Cretaceous-Tertiary Strata, Alberta Plains; Alberta Energy and Utilities Board, EUB/AGS Earth Sciences Report 2002-06, 82 p.

Beaton, A. 2003. Production Potential of Coalbed Methane Resources in Alberta, EUB/AGS Earth Sciences Report 2003-03, 59 p.

Beaton, A., W. Langenberg. and C. Pana 2006. Coalbed methane resources and reservoir characteristics from the Alberta Plains, Canada. International Journal of Coal Geology 65 (2006) pp. 93–113.

CAPP (Canadian Association of Petroleum Producers) 1996. Migration of Methane into Groundwater from Leaking Production Wells near Lloydminster, Report for Phase 2 (1995). Report prepared by CAPP. Report #1996-0003, March 1996.

CAPP (Canadian Association of Petroleum Producers) 2006. Best Management Practices, Natural Gas in Coal (NGC)/Coalbed Methane (CBM), Report prepared by CAPP. Report 2005-0040, May 2006.

Chafin, D.T. 1994. Sources and Migration Pathways of Natural Gas in Near-Surface Ground Water Beneath the Animas River Valley, Colorado and New Mexico. USGS, Water-Resources Investigations Report 94-4006, Denver, Colorado. 56 pp.

Chou, S. J. 2003, Hydrogen Sulfide: Human Health Aspects, World Health Organization CICADS 53, http://www.inchem.org/documents/cicads/cicads/cicad53.htm

Clark, I.D. and P. Fritz 1997. Environmental Isotopes in Hydrogeology. Lewis Publishers.

Coalbed Methane Symposium 2005. Proceedings of the 4th Annual Coalbed Methane Symposium, June 13-14, 2005, Calgary, Alberta.

Coleman, D.D., J.B. Risatti and M. Schoell 1981. Fractionation of Carbon and Hydrogen Isotopes by Methane-Oxidizing Bacteria. Geochimica et Cosmochimica Acta. Vol. 45, pp. 1033-1037.

Cullimore, R. D. 2008, Practical Manual of Groundwater Microbiology, Second edition CRC press – The Taylor & Francis Group, 376 pp.

Davis, J.B. and R.M. Squires 1954. Detection of Microbially-produced Gaseous Hydrocarbons Other than Methane. Science, Vol. 119, No. 3090, pp 381-382.

Dawson, F.M. 1995. Coalbed Methane: A Comparison Between Canada and the United States; Geological Survey of Canada, Bulletin 489, 60 pp.

Dawson, F.M., D.L. Marchioni, T.C. Anderson and W.J. McDougall 2000. An Assessment of Coalbed Methane Exploration Projects in Canada. Geological Survey of Canada, Bulletin 549, 218 pp.

Eltschlager, K.K., J.W. Hawkins, W.C. Ehler and F. Baldassare 2001. Technical Measures for the Investigation and Mitigation of Fugitive Methane Hazards in Areas of Coal Mining. United

States Department of the Interior, Office of Surface Mining Reclamation and Enforcement, Pittsburgh, PA, September 2001.124 pp.

ERCB (Energy Resources Conservation Board) 1990. Directive 009 Casing Cementing Minimum Requirements. July 1990.

ERCB (Energy Resources Conservation Board) 1997. Directive 008 Surface Casing Depth Minimum Requirements. October 1997.

ERCB (Energy Resources Conservation Board) 2005. Bulletin 2005-04, Shallow Well Operations. January 27, 2005.

ERCB (Energy Resources Conservation Board) 2006a. Directive 027 Shallow Fracturing Operations – Interim Controls, Restricted Operations, and Technical Review. January 31, 2006.

ERCB (Energy Resources Conservation Board) 2006b. Directive 035: Baseline Water Well Testing Requirement for Coalbed Methane Wells Completed Above the Base of Groundwater Protection. May 8, 2006

ERCB (Energy Resources Conservation Board) 2006c. Directive 044 Requirements for the Surveillance, Sampling, and Analysis of Water Production in Oil and Gas Wells Completed Above the Base of Groundwater Protection (BGWP). October 31, 2006.

ERCB (Energy Resources Conservation Board) 2007a. Directive 056 Energy Development Applications and Schedules, May 1, 2007.

ERCB (Energy Resources Conservation Board) 2007b. Directive 065 Resource Applications for Conventional Oil and Gas Reservoirs. January 26, 2007.

ERCB (Energy Resources Conservation Board) 2007c. Bulletin 2007-05, “2006 Alberta Coalbed Methane Activity Summary and Well Locations. March 20, 2007.

ERCB (Energy Resources Conservation Board), ST98-2008 2008. Alberta's Energy Reserves 2007 and Supply/Demand Outlook 2008-2017. June 2008.

Fenton, M.M., B.T. Schreiner, E. Neilsen and J.G. Pawlowicz 1994. Quaternary geology of the western Plains; in Geological Atlas of the Western Canada Sedimentary Basin, G.D. Mossop and I. Shetsen (comp), Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary, Alberta.

Freeze, R.A. and J.A. Cherry 1979. Groundwater, Prentice Hall Inc., New Jersey, 604 pp.

Gasda, Sarah E., S. Bachu and M.A. Celia 2004. Spatial characterization of the location of potentially leaky wells penetrating a deep saline aquifer in a mature sedimentary basin. Environmental Geology, 46, pp 707-720.

Gatens, M. 2005. Coalbed methane development: Practices and progress in Canada. Journal of Canadian Petroleum Technology, Vol. 44, No. 8, pp. 16-21.

Glantz, P., A.W. Gorody and P. Mueller 2002. Lessons learned: risk management strategies as projects grow, mature and close. Presented to: Rocky Mountain Mineral Law Foundation, Special Institute on Regulation and Development of Coalbed Methane, November 14-15, 2002, Denver, CO.

GSL (The Geological Society of London) 1996. Coalbed Methane and Coal Geology, Gayer R. and I. Harris, eds., Geological Society Special Publication NO. 109, The Geological Society Publishing House, London UK.

Griffiths, M. and C. Severson-Baker 2003. Unconventional Gas, the Environmental Challenges of Coalbed Methane Development in Alberta. Pembina Institute, June 2003, 70 pp.

Griffiths, M., C. Severson-Baker and T. Marr-Laing 2004. When the Oilpatch Comes to Your Backyard: A Citizens' Guide. Second Edition. Pembina Institute.

Griffiths, M. 2007. Protecting Water, Producing Gas: Minimizing the Impact of Coalbed Methane and Other Natural Gas Production on Alberta's Groundwater. Pembina Institute, April 2007, 122 pp.

Harder A.H., H.M. Whitman and S.M. Rogers 1965. Methane in the Fresh-water Aquifers of Southwestern Louisiana and Theoretical Explosion Hazards. Water Resources Pamphlet No. 14. 23 pp.

Harrison, S.S. 1985. Contamination of aquifers by overpressuring the annulus of oil and gas wells. Ground Water, Vol. 23, No. 3, pp. 317-324. May-June 1985.

Hoch, O. 2005. The Dry Coal Anomaly-The Horseshoe Canyon Formation of Alberta, Canada. Paper SPE 95872, Presentation at 2005 SPE Annual Technical Conference and Exhibition, Dallas, TX, October 9-12, 2005.

James, A.T. and B.J. Burns 1984. Microbial alteration of subsurface natural gas accumulations: American Association of Petroleum Geologists Bulletin, Vol. 68, pp. 957 – 960.

Keech, D.K. and M.S. Gaber 1982. Methane in water wells. Water Well Journal, February 1982, pp. 33-36

Lemay, T.G. 2003. Chemical and Physical Hydrogeology of Coal, Mixed Coal-Sandstone and Sandstone Aquifers from Coal-Bearing Formations in the Alberta Plains Region, Alberta. Prepared for Alberta Energy and Utilities Board and Alberta Geological Survey. Report 2003-04. September, 2003.

MAC (CBM/NGC Multi-Stakeholder Advisory Committee) 2006. Coalbed Methane/Natural Gas in Coal, Final Report. January 2006. http://www.energy.gov.ab.ca/245.asp, accessed February 3, 2006.

McLeish, K.L, M.C. Ryan and A. Chu, in preparation. Combined sampling and analytical method for common groundwater gases.

McWilliams, A., M. Finn, J. Den Haan, and C. Johns 2005. The Horseshoe Canyon Coalbed Methane Play in Southern Alberta: Turns Out It's Not All Dry. Prepared by Trident Exploration Corp., Calgary, Alberta. AAPG Annual Meeting June 19-22, 2005, Calgary, Alberta.

Muehlenbachs, K. 2006. Environmental forensics utilizing carbon isotopes: estimating the source depth of unwanted gas, Presentation slides from seminar: Maxxam Analytics, Calgary, AB, April 6, 2006.

Rice, D.D. and G.E. Claypool 1981. Generation, accumulation, and resource potential of biogenic gas. AAPG Bulletin, Vol. 65, pp 5-25.

Rieb, B.A. and T.T. Leshchyshyn 2005. The production success of proppant stimulation on Horseshoe Canyon coalbed methane and sandstone commingled wells. Paper SPE 96864, Presentation at 2005 SPE Annual Technical Conference and Exhibition, Dallas, TX, October 9-12, 2005.

Rowe, D. and K. Muehlenbachs 1999. Low-temperature thermal generation of hydrocarbon gases in shallow shales. Nature, Vol. 398, pp 61-63.

Smith, I.C. 1978. Impacts of the Natural Gas Industry on Drinking Water Quality and Human Health. Contract RP-138-99. Catalog No. L51379e. Prepared for the Line Pipe Research Committee of Pipeline Research Council International, Inc. Prepared by the following Research Agencies: Midwest Research Institute. June 1978.

Taylor, R. 2005. Recommended Practices for CBM Hydraulic Fracturing, Presentation in: Proceedings of the 4th Annual Coalbed Methane Symposium, June 13-14, 2005, Calgary, Alberta.

USEPA (United States Environmental Protection Agency) 2004. Evaluation of Impacts to Underground Sources of Drinking Water by Hydraulic Fracturing of Coalbed Methane Reservoirs, Office of Water, Office of Ground Water and Drinking Water (4606M), EPA 816-R-04-003.

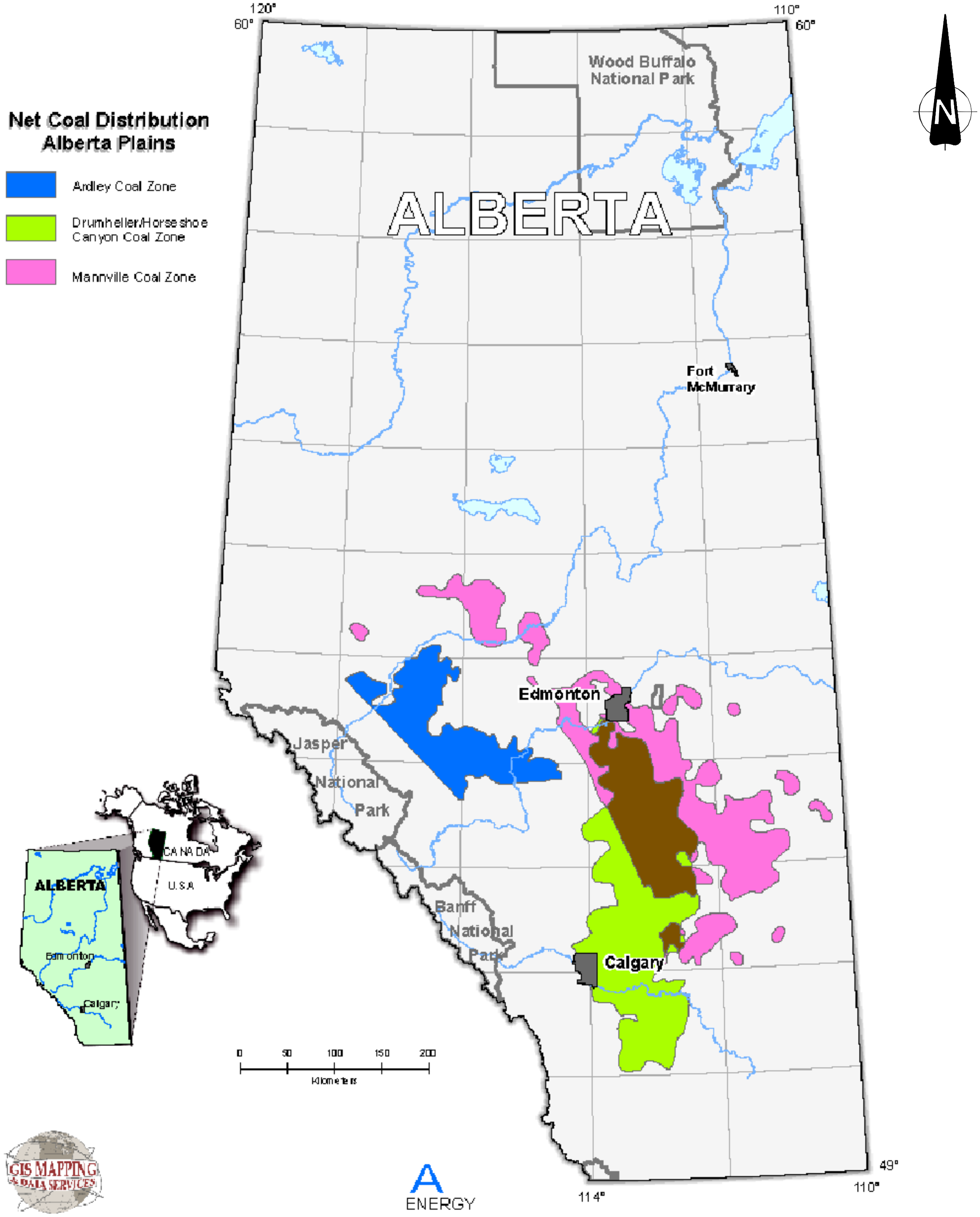
Van Voast, W.A. 2003. Geochemical Signature of Formation Waters Associated with Coalbed Methane. AAPG Bulletin, Vol. 87, No. 4, pp. 667-676.

Viellenave, J.H., A.W. Gorody and J.V. Fontana 2002. Environmental risk assessment methods useful for coalbed methane development: cost-effective ways to manage risk 9th Annual International Petroleum Environmental Conference: Special Symposium: Environmental Issues in the Production of Coal Bed Methane, October 22-25, 2002, Albuquerque, NM.

Whiticar, M.J., E. Faber, and M. Schoell 1986. Biogenic Methane formation in marine and freshwater environments: CO_2 reduction vs acetate fermentation – isotope evidence. Geochimica et Cosmochimica Acta, Vol. 50, pp. 693-709.

Whiticar, M.J. 1999. Carbon and hydrogen isotope systematic of bacterial formation and oxidation of Methane. Chemical Geology, Vol. 161, pp 291-314.

Figures



SOURCE:
www.energy.gov.ab.ca/NaturalGas/754.asp#Potential

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

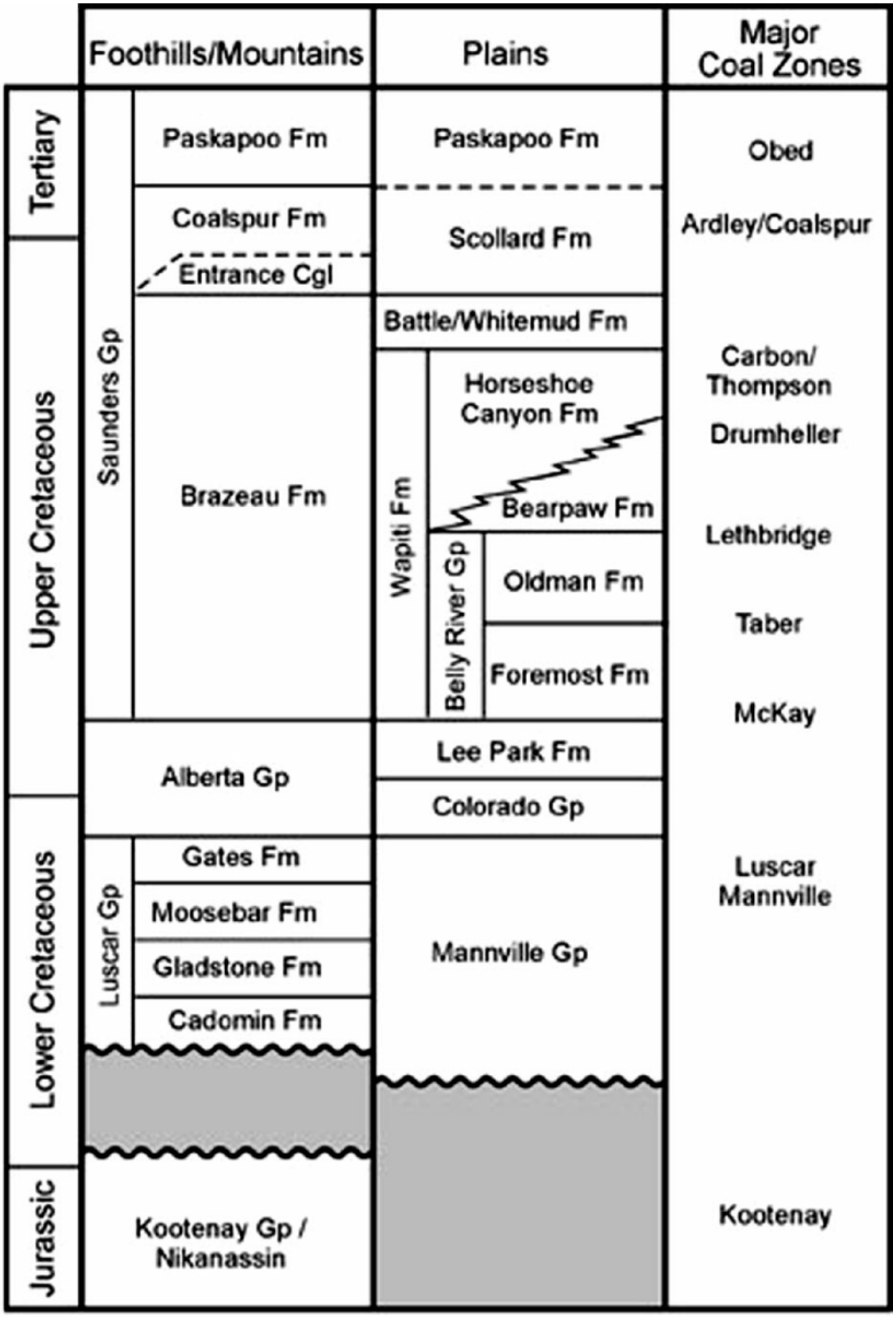
NET COAL DISTRIBUTION FOR ALBERTA PLAINS

WorleyParsons
resources & energy

16-DEC-08	date	-	edited by	OTHERS/KMS	drawn by		app by	PROJECT NUMBER: C67020000	FIGURE: 1

FILE: J:\67020000\CoalDistribution.DWG Issued By: Calgary CAD

This is a PDF - 8.5x11



SOURCE: EUB/AGS, "Alberta Coal Occurences and Potential Coalbed Methane (CBM) Exploration Areas', 2005.

Infrastructure & Environment

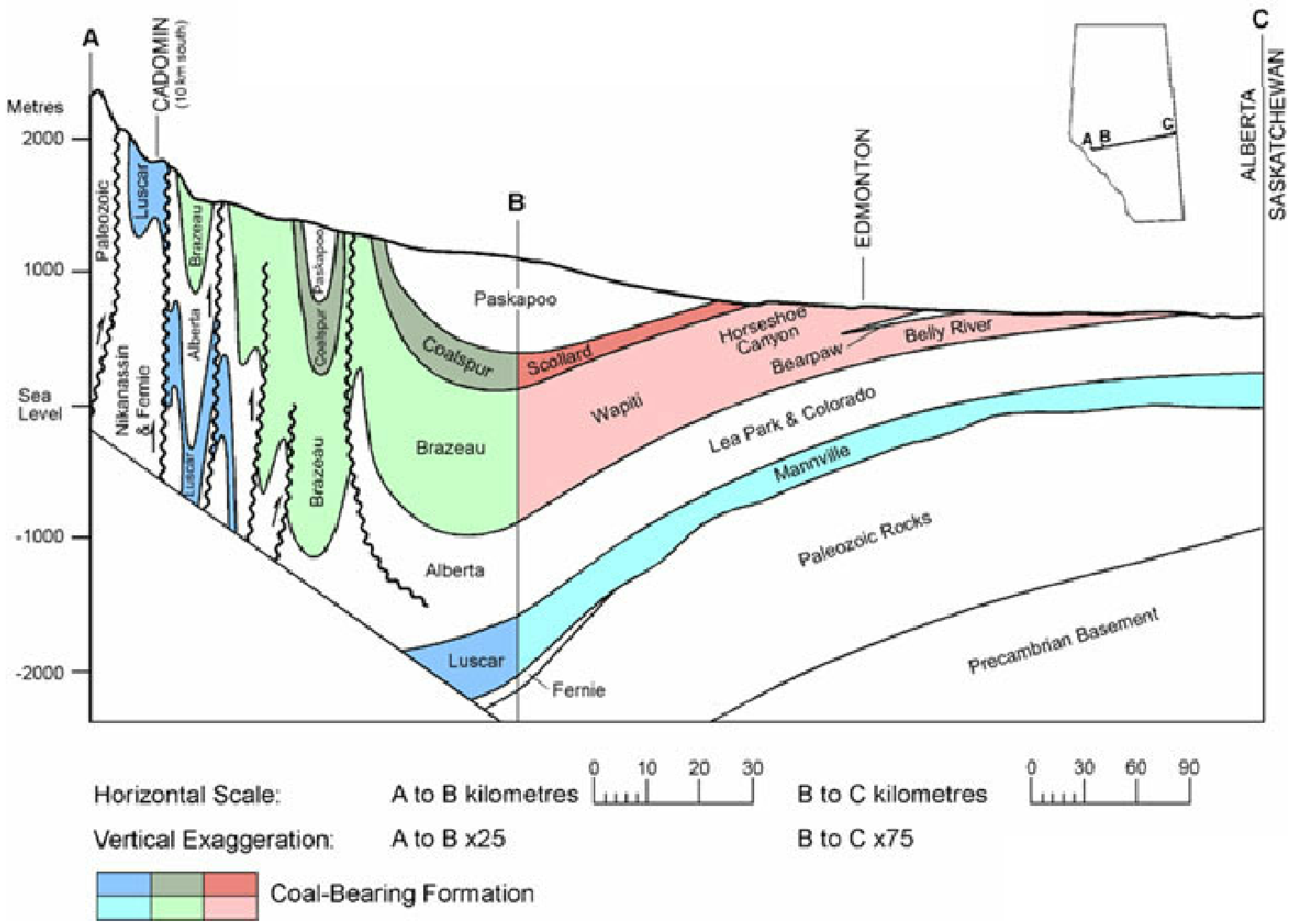
POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

STRATIGRAPHY OF COAL-BEARING FORMATIONS IN ALBERTA

WorleyParsons
resources & energy

12-OCT-08 date	K.M.S. edited by	OTHERS/C.D. drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: 2

FILE: J:\67020000\Stratigraphy.DWG Issued By: Calgary CAD



SOURCE: AGS/EUB, "Alberta Coal Occurrences and Potential for Coalbed Methane (CBM) Exploration Areas", 2005.

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

REPRESENTATIVE CROSS-SECTION SHOWING CENTRAL ALBERTA'S SIGNIFICANT COAL BEARING FORMATIONS

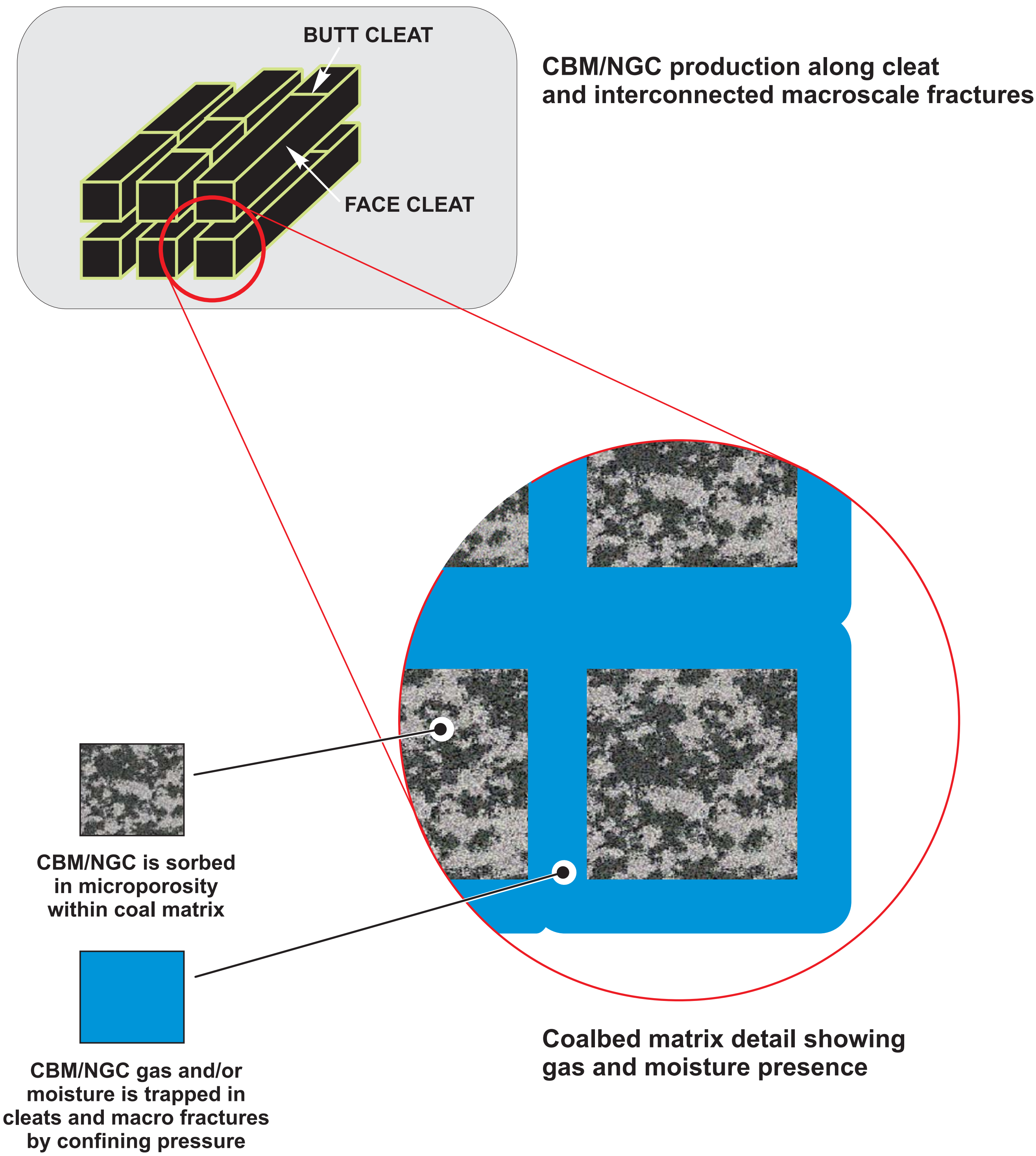
WorleyParsons
resources & energy

10-OCT-08 date	K.M.S. edited by	OTHERS/C.D. drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: 3

PREPARED SOLELY FOR THE USE OF OUR CLIENT AS SPECIFIED IN THE ACCOMPANYING REPORT. NO REPRESENTATION OF ANY KIND IS MADE TO OTHER PARTIES WITH WHICH WORLEYPARSONS HAS NOT ENTERED INTO A CONTRACT.

FILE: J:\67020000\FORMATIONS.DWG Issued By: Calgary CAD

This is a PDF - 8.5x11



Infrastructure & Environment

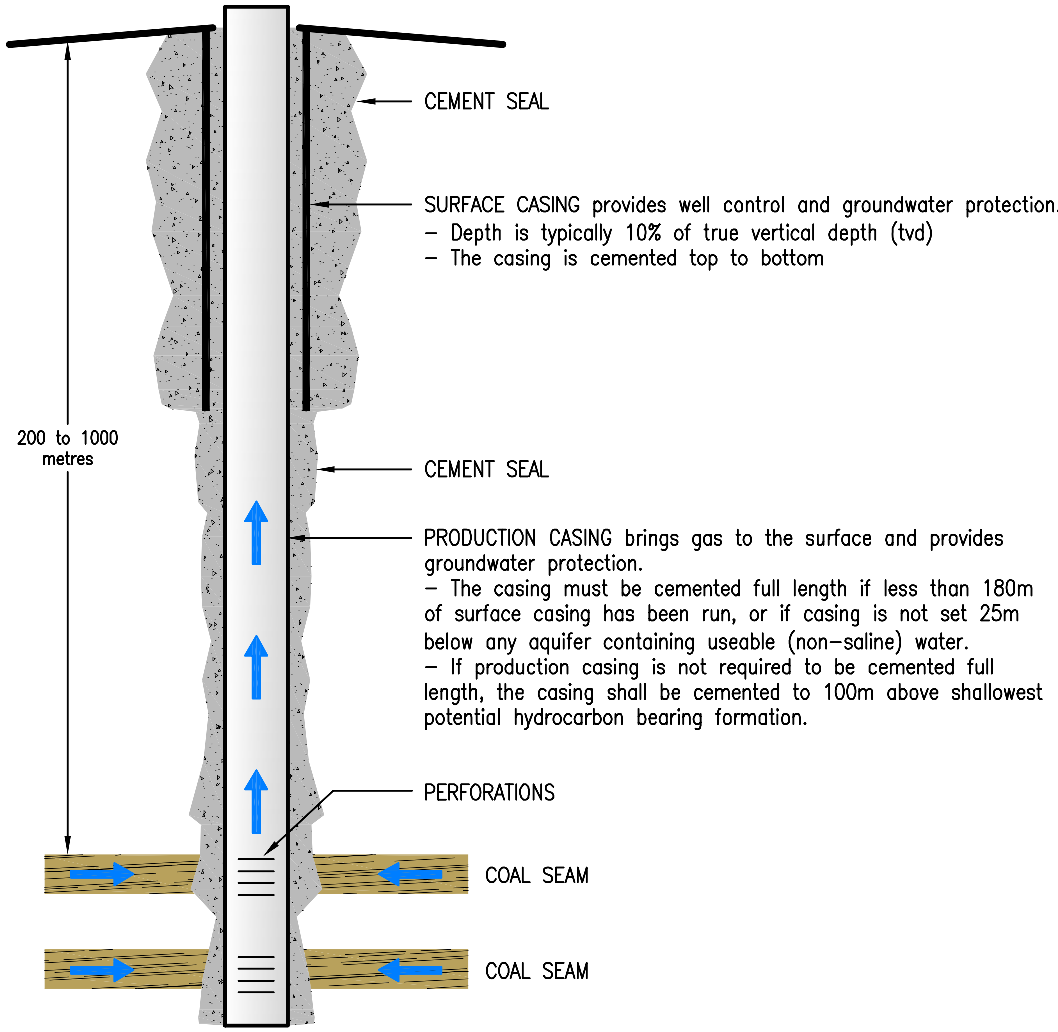
POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

CBG PRESENCE IN COAL

WorleyParsons
resources & energy

30-MAR-09	date	B.M.F.	edited by	M.Y.T.	drawn by	app by	
PROJECT NUMBER:	C67020000	FIGURE:	4				

FILE: J:\67020000\CBM_matrix-Ver2.CDR Issued By: Calgary CAD



SOURCE: ALBERTA AGRICULTURE, FOOD AND RURAL DEVELOPMENT, "Coalbed Methane (CBM) Wells and Water Well Protection", 2005.

NOT TO SCALE

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

TYPICAL CBG WELL IN THE HORSESHOE CANYON FORMATION

WorleyParsons
resources & energy

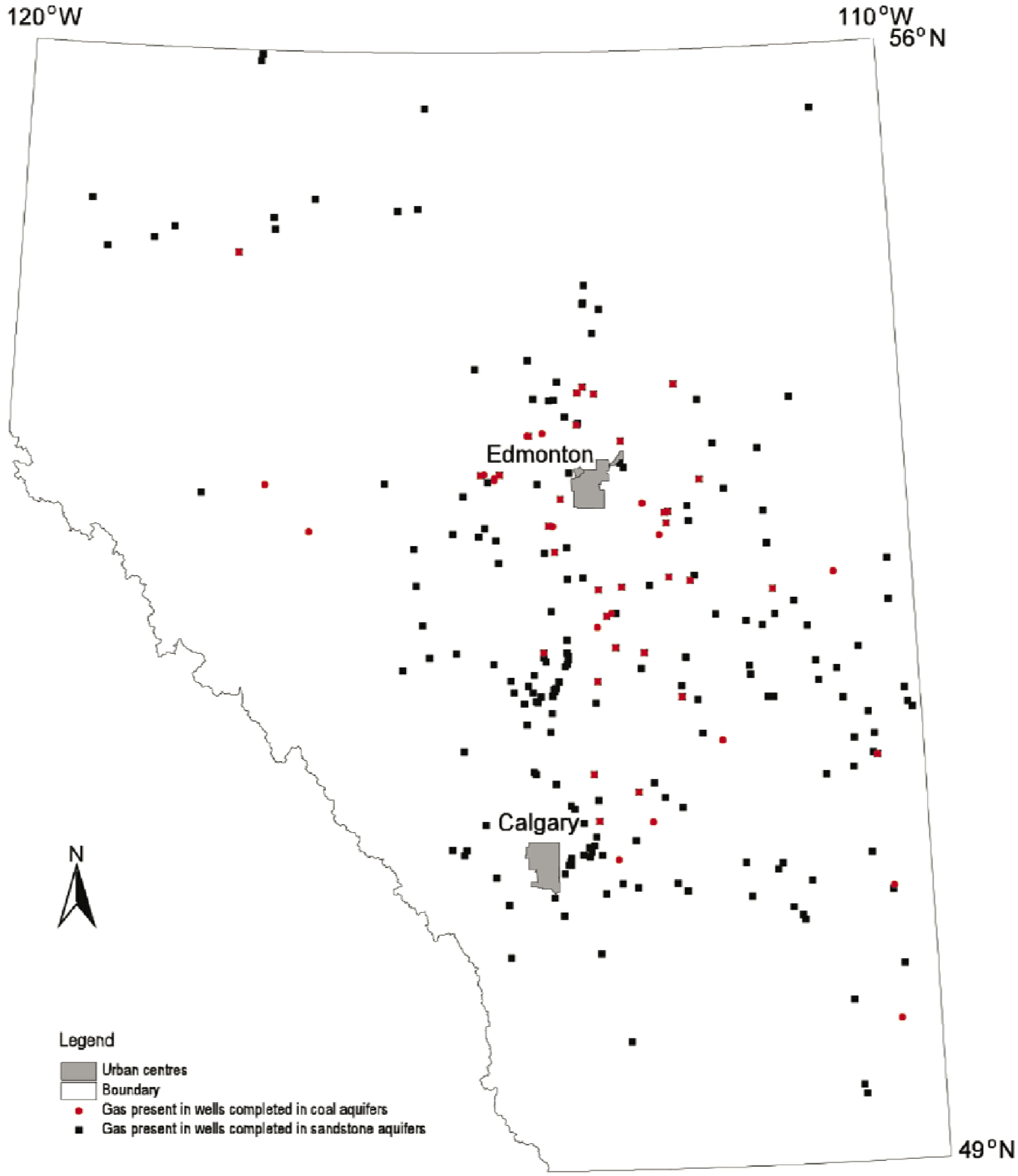
30-MAR-09 date	B.M.F. edited by	OTHERS/C.D. drawn by	app by

PROJECT NUMBER: C67020000

FIGURE: 5

This is a PDF - 8.5x11

FILE: J:\67020000\CBMwell.DWG Issued By: Calgary CAD



SOURCE: ALBERTA ENERGY AND UTILITIES BOARD, EUB AGS EARTH SCIENCES REPORT 2003-04, "Chemical and Physical Hydrogeology of Coal, Mixed Coal-Sandstone and Sandstone Aquifers from Coal-Bearing Formations in the Alberta Plains Region, Alberta".

SCALE 1 : 5,000,000

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

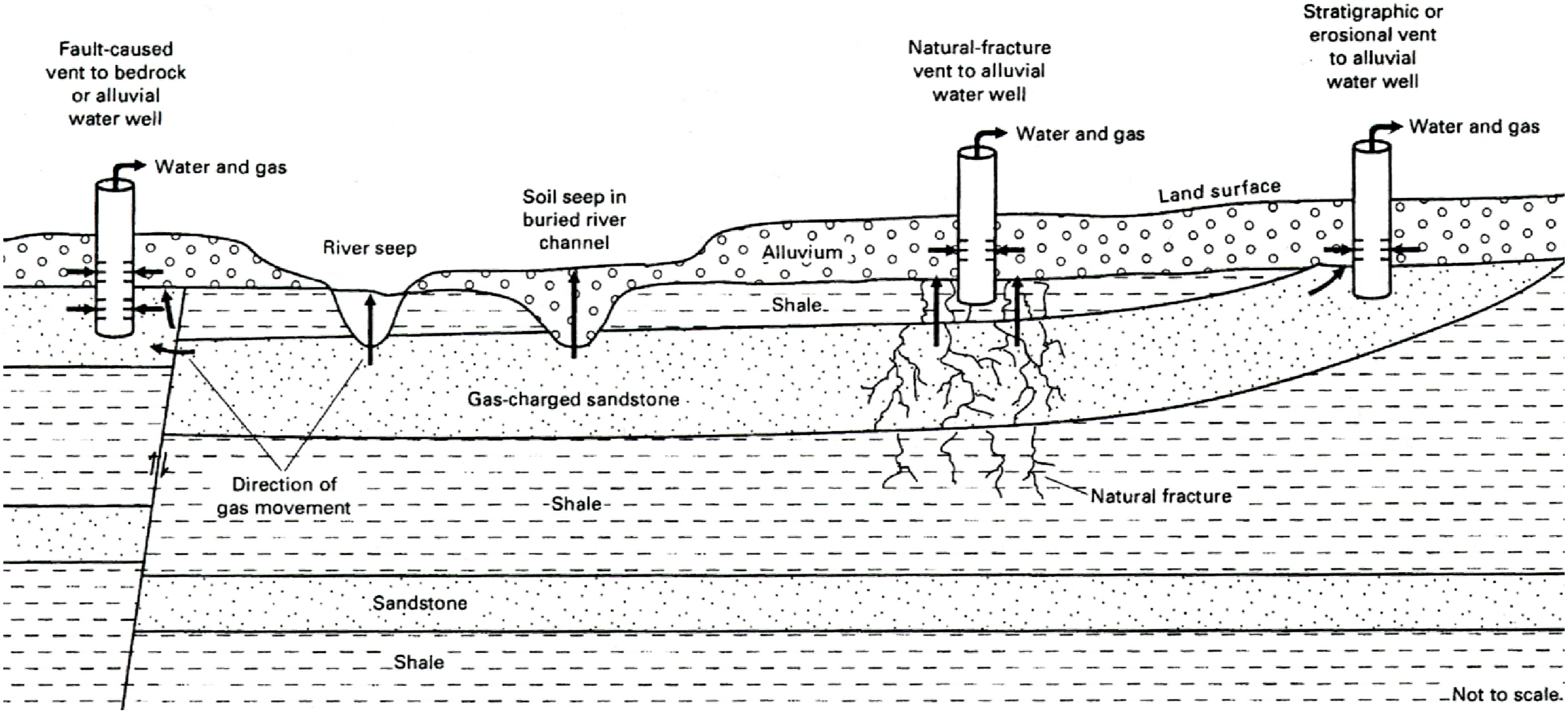
LOCATIONS OF WELLS WHERE GAS WAS NOTED

WorleyParsons
resources & energy

30-MAR-09 date	B.M.F. edited by	OTHERS/C.D. drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: 6

FILE: J:\67020000\map-wells.DWG Issued By: Calgary CAD

This is a PDF - 8.5x11



SOURCE: U.S. Geological Survey, "Sources and Migration Pathways of Natural Gas in Near-Surface Ground Water Beneath the Animas River Valley, Colorado and New Mexico", by Daniel T. Chafin, Water-Resources Investigations Report 94-4006, 1994.

Infrastructure & Environment

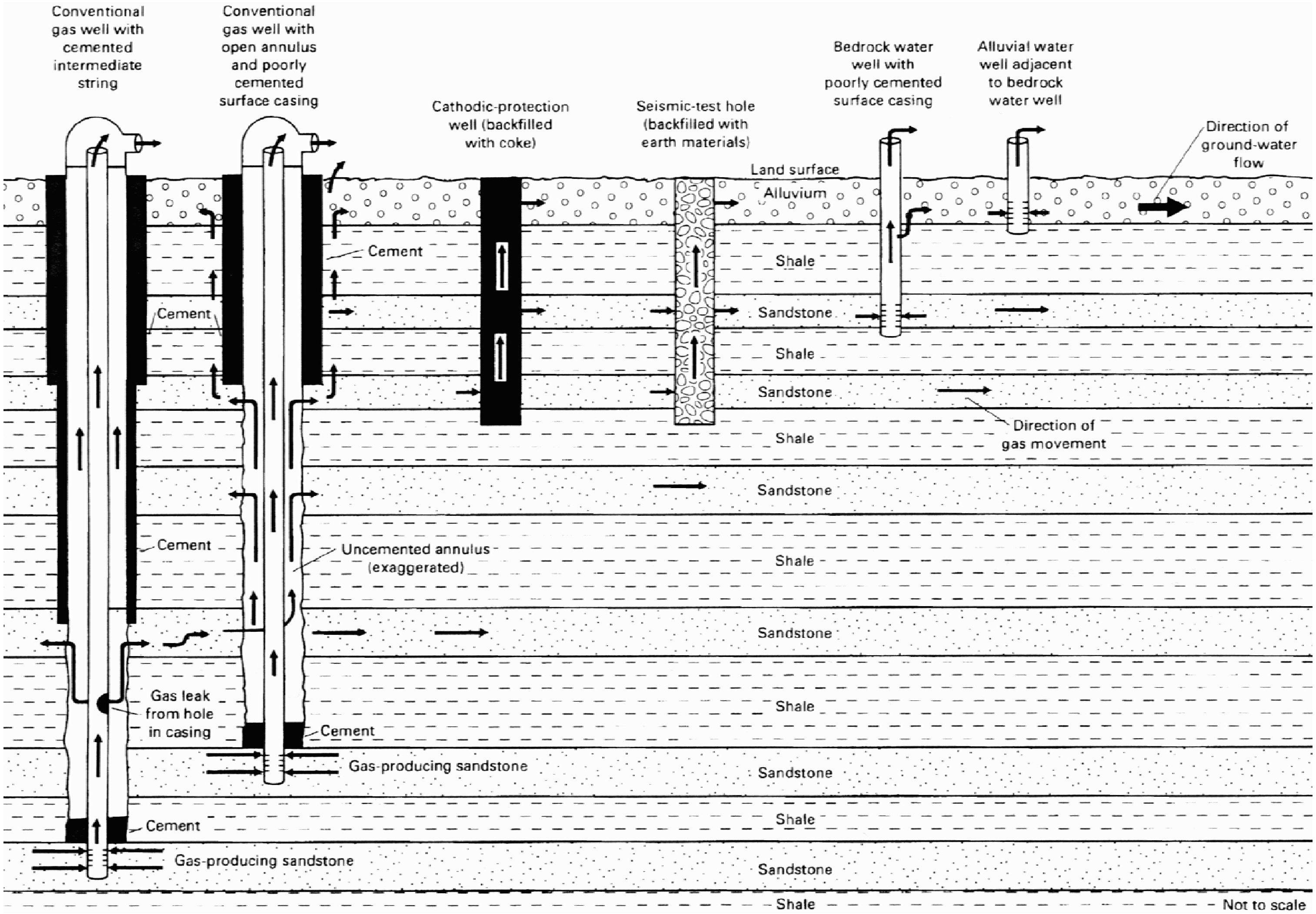
POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

NATURAL PATHWAYS OF GAS MIGRATION

WorleyParsons
resources & energy

30-MAR-09 date	B.M.F. edited by	OTHERS/C.D. drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: 7

FILE: J:\67020000\Migration.DWG Issued By: Calgary CAD



Infrastructure & Environment

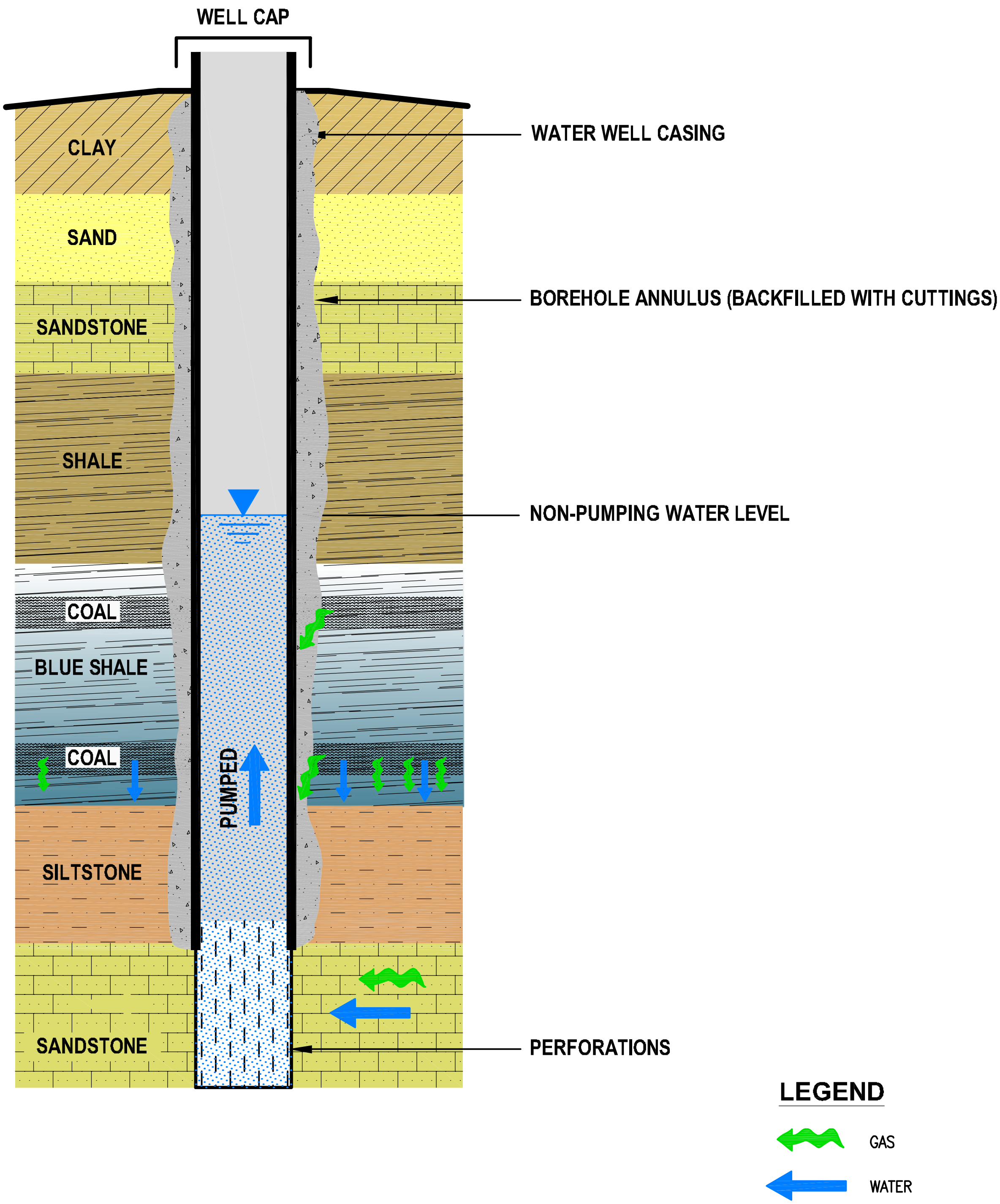
POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

MANMADE PATHWAYS OF GAS MIGRATION

WorleyParsons resources & energy

30-MAR-09 date	B.M.F. edited by	OTHERS/C.D. drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: 8

SOURCE: U.S. Geological Survey, "Sources and Migration Pathways of Natural Gas in Near-Surface Ground Water Beneath the Animas River Valley, Colorado and New Mexico", by Daniel T. Chafin, Water-Resources Investigations Report 94-4006, 1994.



SOURCE: ALBERTA AGRICULTURE, FOOD AND RURAL DEVELOPMENT, "Coalbed Methane (CBM) Wells and Water Well Protection", 2005.

NOT TO SCALE

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

TYPICAL WATER WELL

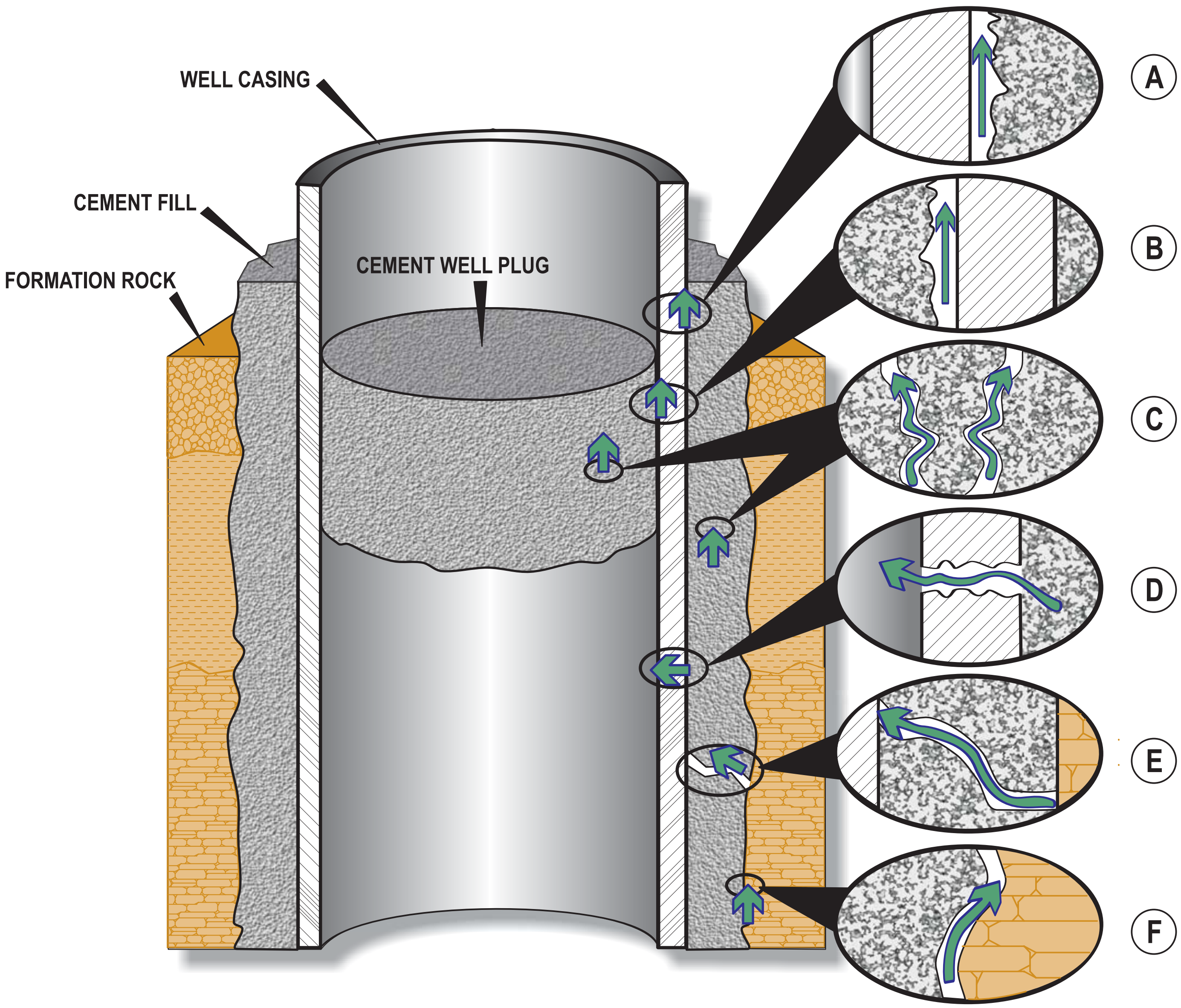
WorleyParsons
resources & energy

30-MAR-09 date	B.M.F. edited by	OTHERS/C.D. drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: 9

PREPARED SOLELY FOR THE USE OF OUR CLIENT AS SPECIFIED IN THE ACCOMPANYING REPORT. NO REPRESENTATION OF ANY KIND IS MADE TO OTHER PARTIES WITH WHICH WORLEYPARSONS HAS NOT ENTERED INTO A CONTRACT.

FILE: J:\67020000\WaterWell.DWG Issued By: Calgary CAD

This is a PDF - 8.5x11



From: Gosda et al., 2004

Infrastructure & Environment

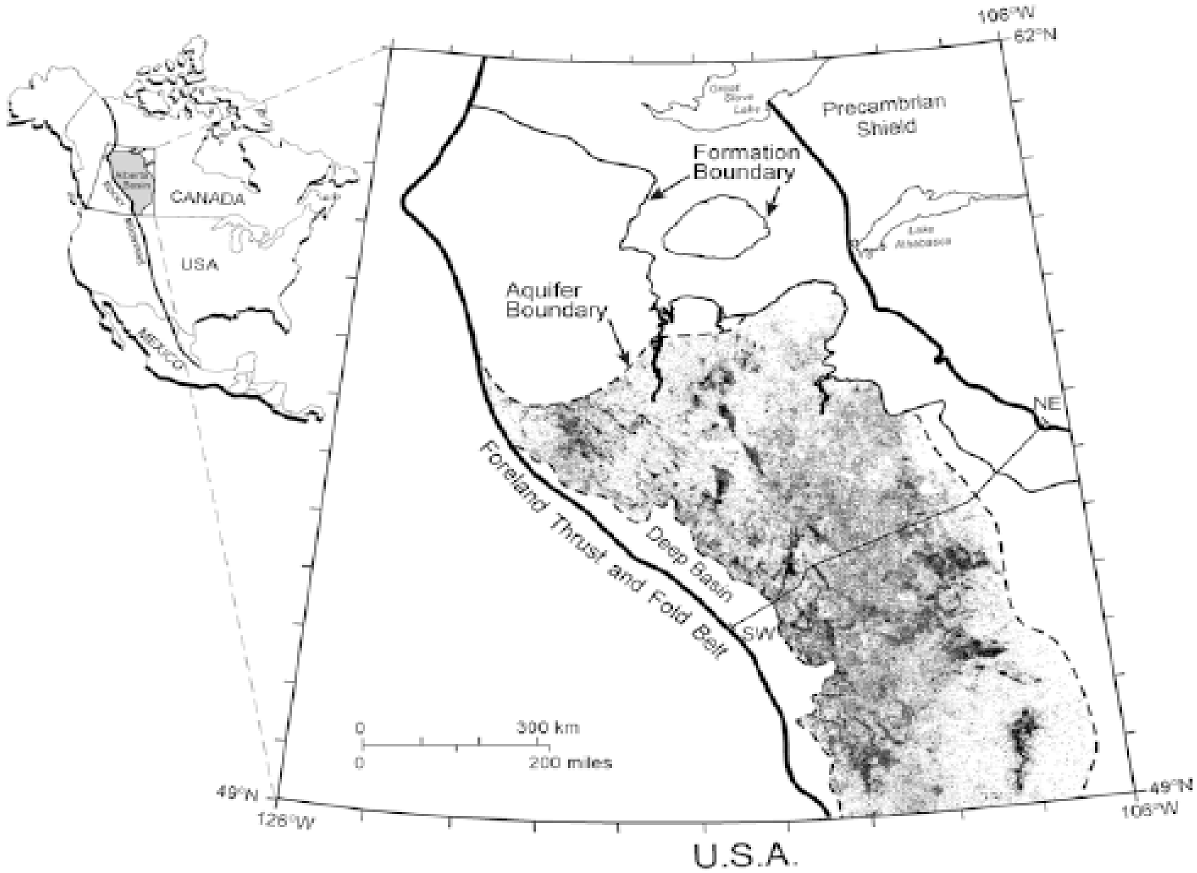
POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

POTENTIAL FLUID LEAKAGE PATHWAYS IN AN ABANDONED WELL

WorleyParsons
resources & energy

30-MAR-09 date	B.M.F. edited by	M.Y.T. drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: 10

FILE: J:\67020000\PotenLeakPaths.CDR Issued By: Calgary CAD



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATIOJN SUE TO COALBED METHANE DEVELOPMENT

Locations of wells penetrating the Viking Aquifer (~189,500 by 2001, from Gasda et al., 2004)

WorleyParsons
resources & energy

30-MAR-09	date	**B.M.F.**	edited by	**ia**	drawn by		app by

PROJECT NUMBER:	FIGURE:
C67020000	**11**

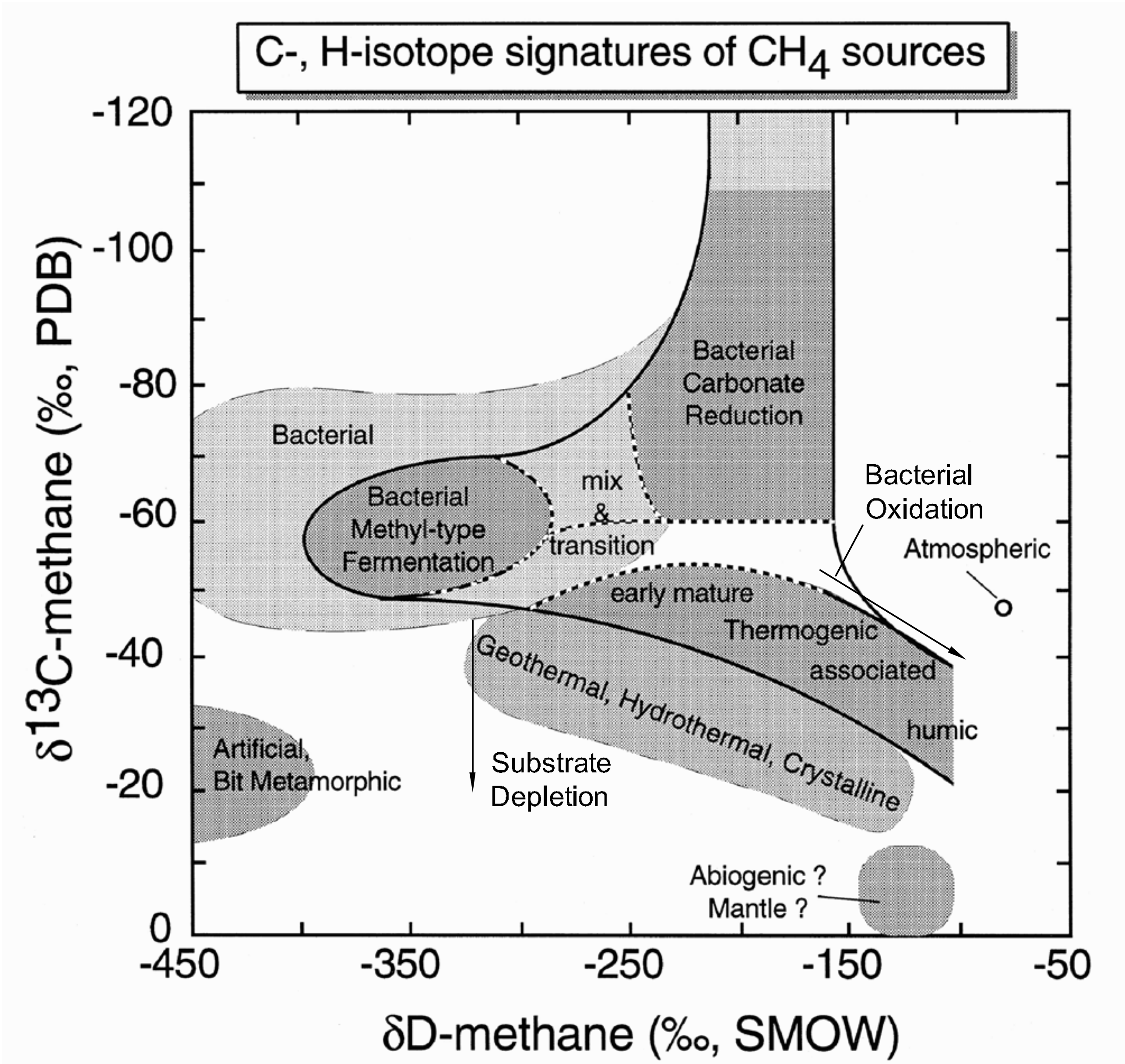
Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Typical manual installation steps for a shallow direct push soil gas probe showing hollow probe insertion, polyvinyl tubing inserts, and syringe pump sampling (Photos courtesy of Vista Geoscience).

WorleyParsons resources & energy

19-Oct-08	date	ia	edited by	ia	drawn by		app by	PROJECT NUMBER: C67020000	FIGURE: 12



SOURCE: "Carbon an hydrogen isotope systematics of bacterial formation and oxidation of methane", by Michael J. Whiticar, 1998.

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

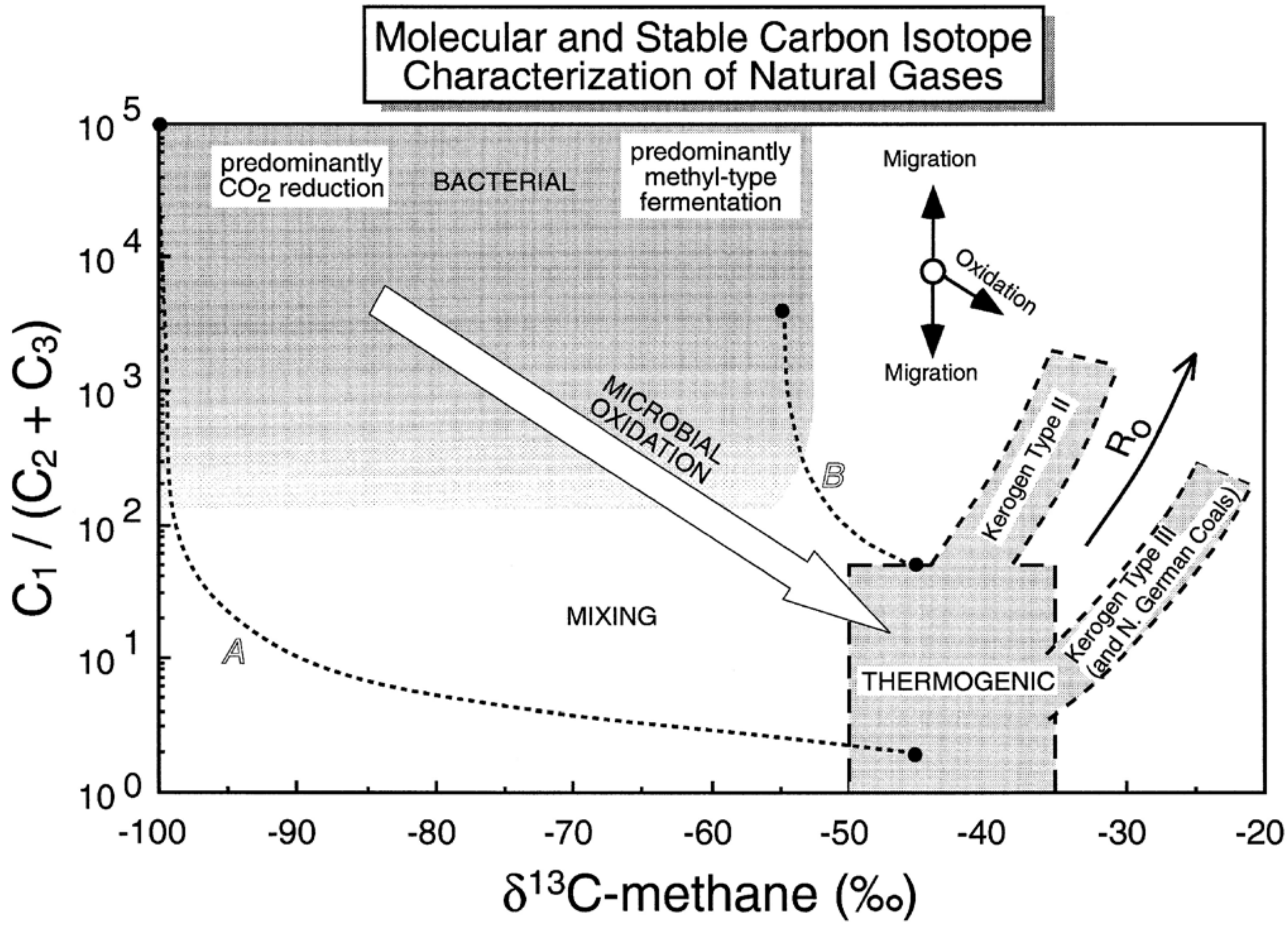
CLASSIFICATION OF BACTERIAL AND THERMOGENIC NATURAL GAS BY THE COMBINATION OF δ^{13} C_{CH4} AND δD_{CH4} INFORMATION

WorleyParsons
resources & energy

30-MAR-09 date	B.M.F. edited by	OTHERS/C.D. drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: 13

FILE: J:\67020000\CD-diagram.DWG Issued By: Calgary CAD

This is a PDF - 8.5x11



SOURCE: "Carbon an hydrogen isotope systematics of bacterial formation and oxidation of methane", by Michael J. Whiticar, 1998.

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

CLASSIFICATION OF BACTERIAL AND THERMOGENIC NATURAL GAS BY COMBINATION OF δ^{13} C_{CH4} AND MOLECULAR COMPOSITION INFORMATION

WorleyParsons resources & energy

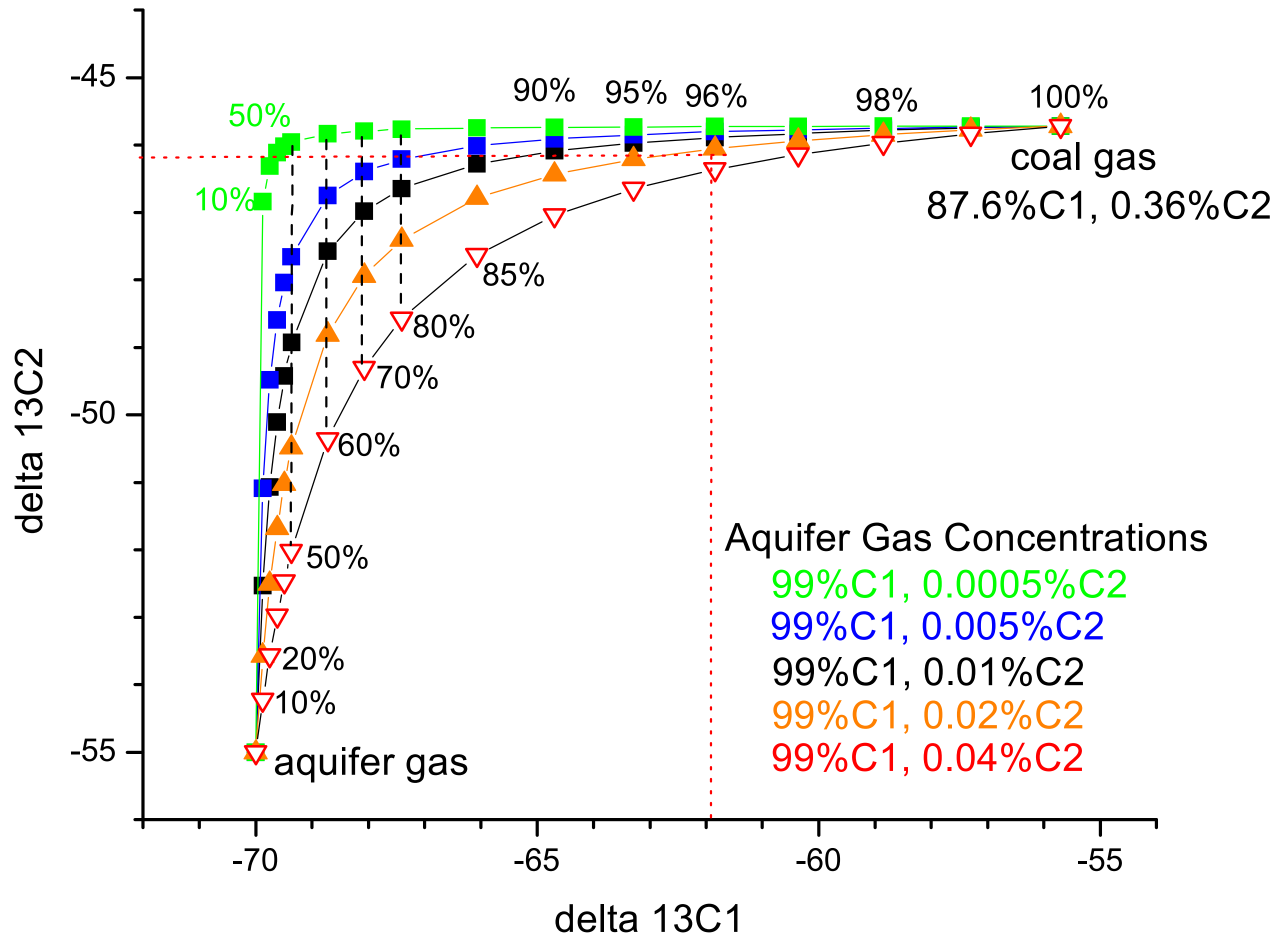
30-MAR-09	date	B.M.F.	edited by	OTHERS/C.D.	drawn by		app by

PROJECT NUMBER: C67020000

FIGURE: 14

FILE: J:\67020000\CD-diagram.DWG Issued By: Calgary CAD

This is a PDF - 8.5x11



Infrastructure & Environment

POTENTIAL GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Calculated isotopic composition of C1 & C2 in a water well after mixing aquifer and CBM gases (Muehlenbachs, Nov 28, 2006)

WorleyParsons
resources & energy

20-Oct-08	date	**ia**	edited by	**ia**	drawn by	app by	PROJECT NUMBER: **C67020000**	FIGURE: **15**

FIGURE 16   FREE GAS SAMPLING VIA GAS-WATER SEPARATOR

Risk Map

		Consequence					
		Insignificant 1	Minor 2	Moderate 3	Major 4	Catastrophic 5	**Sample Metrics** **Project-specific**
							Safety and Health
							Environment
							Prod'n/Schedule
							Reputation
							Business Impact
							Financial
Likelihood	A Almost Certain	High		Extreme			
	B Likely	Moderate					
	C Moderate	Low					
	D Unlikely						
	E Rare						

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Risk Map

WorleyParsons
resources & energy

17-Dec-08 date	**ia** edited by	**ia** drawn by	app by	PROJECT NUMBER: **C67020000**	FIGURE: **17**

Category	Risk Description	Existing Controls
A	Change in natural methane in well leads to well complaint	Complaint investigation
A	Methane-related chemistry change leads to well complaint	Complaint investigation
A	Methane-related bacterial change leads to well complaint	Complaint investigation
A	Gas buildup in house/shed causes explosion/asphyxiation	Vent pumping system
A	Health effects lead to well complaint	Complaint investigation
B	Uncontrolled methane release from dry coalbed affects subsurface	Regulations on CBM wells
B	Uncontrolled methane release from wet coalbed affects subsurface	Drill regulations
B	Gas splutter at pump leads to well complaint	Complaint investigation
B	Gas source confusion increases investigation effort	Scientific study
B	CBM impact on water well means drill new water well	Complaint investigation
B	Gas resource loss lowers production	Completions technology
B	Credibility/confidence loss affects stock	Scientific study, public relations
B	Missing monitoring data prevents baseline assessment	Government regulation
B	Lost opportunity to get data prevents baseline assessment	Scientific study
B	Wrong data collected prevents baseline assessment	Scientific study
B	Data misinterpreted leads to baseline confusion	Science panel
B	Public pressure affects stock	Review panels (MAC, Science)
B	Industry pressure increases costs	Review panels (MAC, Science)
B	Political pressure increases costs	Consulation
B	Regulatory change increases completion effort/cost	Communication

Infrastructure & Environment

POTENTIAL FOR FAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Risk Event List - Industry

WorleyParsons
resources & energy

17-Dec-08 date	ia edited by	ia drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: 18A

Category	Risk Description	Existing Controls
A	Uncontrolled methane release from dry coalbed causes well complaint	Regulations on CBM wells
A	Uncontrolled methane release from wet coalbed causes well complaint	Regulations on CBM wells
A	Change in natural methane in well causes well complaint	Regulation on baseline testing
A	Methane-related bacterial change causes well complaint	Regulation on baseline testing
A	Gas buildup in house/shed causes explosion/asphyxiation	Vent pumping system
A	CBM impact on water well causes well complaint	Complaint investigation
A	Health effects require Regulators to respond	Complaint investigation
B	Methane-related chemistry change causes well complaint	Regulation on baseline testing
B	Gas splutter at pump causes well complaint	Well treatment: vent
B	Gas source confusion affects baseline assessment	Characterize methane sources
B	Gas resource loss decreases royalties	Regulations on resource
B	Credibility/confidence loss affects approval/polls	Public relations
B	Missing monitoring data affects baseline assessment	Regulation on baseline testing
B	Lost opportunity to get data affects baseline assessment	Regulation on baseline testing
B	Wrong data collected prevents baseline assessment	Regulation on baseline testing
B	Data misinterpreted affects baseline assessment	Scientific committee
B	Public pressure affects approval/polls	Public relations
B	Industry pressure causes Regulators to respond	Consultation
B	Political pressure requires Regulators to respond	Consultation
B	Regulatory change affects approval/polls	Consultation

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Risk Event List - Regulators

WorleyParsons
resources & energy

17-Dec-08	date	**ia**	edited by	**ia**	drawn by		app by

PROJECT NUMBER: **C67020000**

FIGURE: **18B**

Likelihood

Rare	Unlikely	Moderate	Likely	Almost Certain
Highly unlikely to occur on this project (1 in 1000 chance of occurring)	Given current practices and procedures, this incident is unlikely to occur on this project (1 in 100 chance of occurring)	Incident has occurred on a similar project (1 in 10 chance of occurring)	Incident is likely to occur on this project (1 in 2 chance of occurring)	Incident is very likely to occur on this project, possibly several times (>1 in 2 chance of occurring)

Consequences	Insignificant	Minor	Moderate	Major	Catastrophic
Safety and Health	Near miss / Hazard	First aid treatment required	Medical treatment required, no lost time	Lost time injury(s)	Potential fatality / multiple LTIs
Financial	<$25,000	$25,000 - 100,000	$100,000 - 500,000	$500,000 - 1,000,000	>$1,000,000
Environment	No attempt made to classify these consequences				
Production/Schedule	No attempt made to classify these consequences				
Reputation	No attempt made to classify these consequences				
Business Impact	No attempt made to classify these consequences				

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Likelihood and Consequence Scale - Industry

WorleyParsons
resources & energy

19-Oct-08 date	**ia** edited by	**ia** drawn by	app by	PROJECT NUMBER: **C67020000**	DRAWING: **19**

Category	Rank	Risk Description	Existing Controls	Risk Severity Before Treatment				
				Likelihood		Consequence		Before Treatment
A	1	Gas buildup in house/shed causes explosion/asphyxiation	Vent pumping system	E	Rare	5	Catastrophic	*High*
B	2	Gas resource loss lowers production	Completions technology	E	Rare	4	Major	*High*
B	3	Uncontrolled methane release from wet coalbed affects subsurface	Drill regulations	D	Unlikely	3	Moderate	*Moderate*
B	4	Credibility/confidence loss affects stock	Scientific study, public relations	D	Unlikely	3	Moderate	*Moderate*
B	5	Public pressure affects stock	Review panels (MAC, Science)	C	Moderate	2	Minor	*Moderate*
B	6	Industry pressure increases costs	Review panels (MAC, Science)	D	Unlikely	2	Minor	*Low*
B	7	Political pressure increases costs	Consulation	D	Unlikely	2	Minor	*Low*
B	8	Regulatory change increases completion effort/cost	Communication	D	Unlikely	2	Minor	*Low*
B	9	Uncontrolled methane release from dry coalbed affects subsurface	Regulations on CBM wells	E	Rare	2	Minor	*Low*
B	10	Gas source confusion increases investigation effort	Scientific study	E	Rare	2	Minor	*Low*
A	11	Health effects lead to well complaint	Complaint investigation	E	Rare	2	Minor	*Low*
B	12	CBM impact on water well means drill new water well	Complaint investigation	E	Rare	2	Minor	*Low*
A	13	Methane-related bacterial change leads to well complaint	Complaint investigation	D	Unlikely	1	Insignificant	*Low*
A	14	Change in natural methane in well leads to well complaint	Complaint investigation	D	Unlikely	1	Insignificant	*Low*
B	15	Missing monitoring data prevents baseline assessment	Government regulation	E	Rare	1	Insignificant	*Low*
A	16	Methane-related chemistry change leads to well complaint	Complaint investigation	E	Rare	1	Insignificant	*Low*
B	17	Gas splutter at pump leads to well complaint	Complaint investigation	E	Rare	1	Insignificant	*Low*
B	18	Lost opportunity to get data prevents baseline assessment	Scientific study	E	Rare	1	Insignificant	*Low*
B	19	Wrong data collected prevents baseline assessment	Scientific study	E	Rare	1	Insignificant	*Low*
B	20	Data misinterpreted leads to baseline confusion	Science panel	E	Rare	1	Insignificant	*Low*

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Risk Management Plan - Industry

WorleyParsons
resources & energy

17-Dec-08 date	ia edited by	ia drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: 20

Likelihood

Rare	Unlikely	Moderate	Likely	Almost Certain
Highly unlikely to occur on this project (1 in 1000 chance of occurring)	Given current practices and procedures, this incident is unlikely to occur on this project (1 in 100 chance of occurring)	Incident has occurred on a similar project (1 in 10 chance of occurring)	Incident is likely to occur on this project (1 in 2 chance of occurring)	Incident is very likely to occur on this project, possibly several times (>1 in 2 chance of occurring)

Consequences

	Insignificant	Minor	Moderate	Major	Catastrophic
Environment	No impact or only localised impact. No long term damage and minimum clean up	Localised impact. No long term damage but significant clean up required	Localised impact but a breach of regulated limits	Large impact but with reinstatement of loss	Regional impact. Serious long term effects and major loss of flora and fauna
Reputation	Localised temporary impact	Localised, short term impact	Localised, long term impact but manageable	Localised, long term impact with unmanageable outcomes	Long term regional impact
Safety and Health	No attempt made to classify these consequences				
Financial	No attempt made to classify these consequences				
Production/Schedule	No attempt made to classify these consequences				
Business Impact	No attempt made to classify these consequences				

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Likelihood and Consequence Scale - Regulators

WorleyParsons
resources & energy

19-Oct-08	date	ia	edited by	ia	drawn by		app by	PROJECT NUMBER: C67020000	FIGURE: 21

Category	Rank	Risk Description	Existing Controls	Risk Severity Before Treatment				
				Likelihood		Consequence		Before Treatment
A	1	Gas buildup in house/shed causes explosion/asphyxiation	Vent pumping system	E	Rare	4	Major	*High*
B	2	Public pressure affects approval/polls	Public relations	B	Likely	3	Moderate	*High*
B	3	Political pressure requires Regulators to respond	Consultation	B	Likely	3	Moderate	*High*
B	4	Credibility/confidence loss affects approval/polls	Public relations	C	Moderate	3	Moderate	*High*
B	5	Industry pressure causes Regulators to respond	Consultation	C	Moderate	3	Moderate	*High*
B	6	Lost opportunity to get data affects baseline assessment	Regulation on baseline testing	A	Almost Certain	2	Minor	*High*
B	7	Regulatory change affects approval/polls	Consultation	C	Moderate	2	Minor	*Moderate*
A	8	Uncontrolled methane release from wet coalbed causes well complaint	Regulations on CBM wells	D	Unlikely	2	Minor	*Low*
A	9	CBM impact on water well causes well complaint	Complaint investigation	D	Unlikely	2	Minor	*Low*
B	10	Missing monitoring data affects baseline assessment	Regulation on baseline testing	D	Unlikely	2	Minor	*Low*
A	11	Uncontrolled methane release from dry coalbed causes well complaint	Regulations on CBM wells	E	Rare	2	Minor	*Low*
B	12	Gas source confusion affects baseline assessment	Characterize methane sources	E	Rare	2	Minor	*Low*
A	13	Health effects require Regulators to respond	Complaint investigation	E	Rare	2	Minor	*Low*
B	14	Gas resource loss decreases royalties	Regulations on resource	E	Rare	2	Minor	*Low*
B	15	Data misinterpreted affects baseline assessment	Scientific committee	E	Rare	2	Minor	*Low*
A	16	Change in natural methane in well causes well complaint	Regulation on baseline testing	C	Moderate	1	Insignificant	*Low*
B	17	Methane-related chemistry change causes well complaint	Regulation on baseline testing	C	Moderate	1	Insignificant	*Low*
A	18	Methane-related bacterial change causes well complaint	Regulation on baseline testing	C	Moderate	1	Insignificant	*Low*
B	19	Gas splutter at pump causes well complaint	Well treatment: vent	C	Moderate	1	Insignificant	*Low*
B	20	Wrong data collected prevents baseline assessment	Regulation on baseline testing	D	Unlikely	1	Insignificant	*Low*

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Risk Management Plan - Regulators

WorleyParsons
resources & energy

17-Dec-08	date	**ia**	edited by	**ia**	drawn by		app by	PROJECT NUMBER: **C67020000**	FIGURE: **22**

Appendices

Appendix 1 USA Experience: The San Juan Basin

APPENDIX 1
SAN JUAN BASIN

1. INTRODUCTION

The San Juan Basin ranks as the most prolific gas producing basin in the U. S. and was the first major gas province to be commercially developed for coalbed gas (CBG). The first field-wide development efforts, initiated during the late 1970's to mid 1980's, were concentrated along the Animas River between Bondad, CO, and Cedar Hill, NM. There, the Fruitland Formation was know to be productive on the basis of gas shows and blow outs encountered while drilling for deeper targets in Mesaverde and Dakota Formation sandstones.

Shortly after development in the Animas River began, complaints arose regarding gas seeps in fields and wells. Ensuing investigations related to addressing natural gas seeps in the central portion of the San Juan basin, both associated with and not associated with CBG development, were the first of their kind and scope. Sampling, analytical, and investigative techniques, developed to address the source of natural gas in groundwater at the time, have since evolved into standardized methods and protocols used throughout Colorado. Today, similar monitoring and risk mitigation protocols are used by both operators and regulators to address baseline groundwater conditions in advance of drilling throughout many unconventional gas provinces.

Starting in 1993, there were complaints and observations that resulted in increasing concerns regarding the impact of CBG production on Fruitland outcrop seeps. Since then, numerous large-scale and in some cases pioneering investigations have been launched to address factors controlling the distribution and flux of methane seeps along the Fruitland outcrop belt. These will be summarized in this section to synthesize lessons learned regarding the general applicability of the approaches used. Such approaches may be instrumental in addressing how to monitor and mitigate the risk of methane migration along outcrop belts in other CBG basins.

Seeps Related to Casing Leaks and Uncemented Casing Annuli

Shortly after limited Fruitland coal gas development began in the area along the Animas River between Bondad CO and Cedar Hill NM, natural gas seeps were being reported in the area. Bubbling was observed along the river bank, and increasing patches of dying vegetation observed in farmer's alfalfa fields alarmed the community. Methane gas was discovered migrating into 10 groundbed cathodic protection wells and into surface casing heads (bradenheads) in 11 of 81 producing wells in the area (Beckstrom and Boyer, 1993). Natural gas in a few water wells prompted pumps to cavitate, and several pump houses exploded when methane gas accumulated in confined spaces (Fisher, 1992).

Chromatographic and isotopic analysis of dissolved gases sampled from groundwater in the area over a period of several years indicated two potential sources for the gas: casing leaks from conventional wells completed in formations underlying Fruitland coals, and Fruitland Formation gas (Chafin, 1994). Coalbed gas was migrating from the Fruitland formation in some but not all older historic wells where an uncemented annulus was in direct contact with the formation. A widespread program of remedial cementing and plugging and abandonment of selected wells ultimately mitigated the problem (Beckstrom and Boyer, 1993).

The Animas River groundwater environment is extremely corrosive to casing. This is a natural consequence of vertical layering between very fresh water in Animas alluvium and highly saline sulfate-bearing water in underlying Nacimiento aquifers. Conductive steel casing that intersects this layering is susceptible to induced currents that are very corrosive. Prior to the advent of cathodic protection technology in the early 1960’s, conventional Animas River Valley wells were continually developing casing corrosion leaks at depths typically on the order of several hundred meters. As a result, a few wells introduced large quantities of oil and gas into shallow aquifers along the valley floor. Water well testing conducted as a result of Fruitland development in the mid 1980’s revealed that some water wells were still being impacted by hydrocarbons accidentally released prior to the 1960’s into shallow bedrock aquifers. Such persistent plumes can only be explained if hydrocarbons had accumulated in shallow bedrock aquifers within small stratigraphic and structural traps.

1.1 Risk Mitigation Measures and Regulations

1.1.1 Casing Cement Program

In 1988, the Colorado Oil and Gas Conservation Commission issued rules 112-60 and 112-61 which identified the Fruitland Coal as a distinct gas producing horizon and mandated a 320 acre production well spacing rule (2 wells per section). A COGCC tax levy on the sales of oil and gas also helped establish and maintain a reclamation fund for problem or orphan wells. By the end of 1992, most of the spacing units in the Ignacio Blanco Field had been drilled. Accelerated development had been spurred by expiring federal tax incentives, initiated in 1980, to encourage unconventional gas resource development. The COGCC also required oil and gas developers to circulate cement to the surface of both surface and production casing strings of all CBG wells in the Ignacio Blanco Field. The Bureau of Land Management (BLM) also followed suit in 1988 for CBG wells drilled on Federal and Indian lands (BLM San Juan Resource Area).

1.1.2 Casing Head Pressure Testing

Both COGCC (Order 112-85) and BLM (Notice to Lessee MDO-91-1) orders instituted a mandatory annual casing head testing program in 1990. Instituted to protect the groundwater environment and preserve natural gas resources, this mandate was viewed as a screening tool for evaluating the mechanical integrity of existing well bores. The casing head is a flanged steel fitting welded to the surface casing. It provides a housing for the slips and packing assembly used to suspend intermediate and/or production casing strings. Annular spaces between casing strings are sealed off with valves fitted with pressure gages to monitor pressure.

New regulations instructed operators to survey all wells and measure and record tubing, casing, and intermediate casing pressures in all wells. Should casing pressures be encountered, a mandated testing protocol is used to determine if they are due to leaky casing. Beginning with the casing head valve, annular spaces are opened sequentially and the blow down time and flow rates recorded. As each annular space is blown down, the pressure in the adjacent annulus is monitored for any changes at five minute intervals for up to 30 minutes. A drop in pressure in the adjacent annular space usually indicates a leak. Wells with residual pressures after a 30 minute test interval may also indicate a casing leak. A pressure of 25 psig is also established as the minimum threshold pressure required for sampling and laboratory analysis of both produced and casing head gases. If gases are similar in composition, and/or if a casing leak is detected, the operator must file and implement remedial action plans. Such testing began in environmentally sensitive areas first, with all wells in the Ignacio Blanco field being tested by the end of 1992.

Positive pressure on the casing head does not necessarily signify that gas and water are travelling around the surface casing shoe and up the outside of the surface casing. Elevated casing pressures found in some wells were attributed either to the presence of indigenous gas or to gas migrating outside of the cemented well bore environment through local faults and fractures. Historically, both mud logs and monitor wells have identified the presence of indigenous shallow gas in commercially non-productive Animas, Ojo Alamo, San Jose, McDermott, Kirtland, and Farmington Sandstone Formations. For this reason, some operators are voluntarily choosing to run mud logs and geophysical logs in shallow formations drilled. This practice is generally reserved for the first vertical well drilled off a multi-well drilling pad in unconventional gas basins where there is no regulatory requirement to cement an intermediate casing string to the surface.

Reported results of bradenhead tests in lands under federal jurisdiction conducted between 1991 and 2006 (BLM, 2007) have demonstrated that bradenhead testing is a successful risk mitigation, and remediation effort. According to the COGCC, by the end of 2000, there were 2150 wells in La Plata County. Approximately half of them were CBG wells. During that time, the bradenhead testing program was instrumental in helping to identify 254 wells that had to be either remedially cemented or plugged and abandoned. Of those, 34 were CBG wells; the rest were conventional gas wells completed in the Mesaverde and Dakota Formations.

1.1.3 Water Well Testing for Dissolved Methane

From 1990 to 1998, there were numerous groundwater sampling events conducted by the United States Geologic Survey (USGS), the BLM, the Colorado Division of Water Resources, the COGCC, and various local task forces. The objective of these events was to determine if and to what degree domestic water wells had been contaminated by oil and gas operations in the basin. These sampling events are summarized below.

- 1985 – NMOCD collected 6 water samples based on complaints;
- 1989 – NMOCD and operators sponsored a water fair in the spring of that year. Residents brought in 143 samples for analysis;
- 1989 – NMOCD staff returned in the fall to sample 25 residential wells in which methane had been detected;
- 1990 – Amoco Production Company sponsored its own sampling event on the basis of NMOCD results;
- 1990 – USGS collected water samples from 71 domestic wells and one spring in Colorado, and 132 water wells and one spring in New Mexico, along the Animas River valley, between Durango, CO and Aztec, NM (Chafin, 1994);
- 1991 – Ignacio-Blanco Groundwater Task Force and the State of Colorado Division of Water Resources collected 354 samples. A random sample was collected in each section where both water wells and producing gas wells were present (Velez, 1993). Task force members represented the COGCC, BLM, San Juan Citizens Alliance, Southern Ute Indian Tribe, La Plata County, San Juan Health Department, Colorado Division of Water Resources (Water Quality Control Division), State Engineers Office, Office of Senator Ben Nighthorse Campbell, Colorado Department of Local Affairs, and private citizens;
- 1993 – BLM sampled approximately 201 domestic water wells in the vicinity of the HD Mountains (BLM, 1994);
- 1993 – The Pine River Fruitland Coal Outcrop Investigative Team (IT) sampled 49 sites (BLM 1995);
- 1994 – COGCC and BLM sampled 383 sites including the following: 320 water wells not tested in the 1993 BLM study, 49 sites visited in 1993, and 14 new sites in the Pine River Ranches Subdivision area (COGCC and BLM, 1995);
- 1995 – BLM conducted a further investigation of an area southeast of Durango in the Animas River valley near the junction of Highway 550 and Highway 160. Nine additional domestic water wells and 5 gas wells were tested plus several other domestic water wells were re-tested;
- 1996 – BLM sampled approximately 100 wells in the HD Mountains and Bondad/Sunnyside Areas of Colorado;
- 1998 – COGCC and BLM collected water samples from approximately 140 wells previously sampled and located near remediated gas wells; and,
- 1999 – Amoco Production Company began voluntary baseline testing of water wells in advance of drilling new Fruitland water wells.

The results of these investigations established that the presence dissolved methane in water wells was widespread throughout the basin, predominantly at concentrations well below methane saturation. On the basis of chromatography and stable carbon isotopes in methane, these studies further determined that the origins of dissolved gas in groundwater were varied. Natural gas in groundwater was attributed to originate from bacteria, thermogenic indigenous gas in shallow bedrock aquifers, contamination from historic production practices near conventional oil and gas wells, and contamination from the Fruitland Formation. None of the published results by either the COGCC or the BLM have provided readily accessible data to quantify how many water wells may have been directly affected by producing wells which either required remedial cementing or plugging and abandonment.

By 1994, the COGCC and BLM had identified defined 17 environmentally sensitive and relatively populated areas in the Colorado portion of the San Juan Basin where measured dissolved methane concentrations exceeding 1.1 mg/L in domestic groundwater wells appeared to occur in clusters (COGCC and BLM, 1995). The 1.1 mg/L value was chosen on the basis of theoretical considerations for the likelihood of methane exsolving from water in sufficient quantity to reach the lower explosive level in air (Harder et al., 1965). For comparison, at average ground level elevations in the San Juan Basin between 6800 and 7400 feet above sea level (2070 and 2255 masl) the saturation concentration of dissolved methane in water is approximately 19 mg/L.

Stable isotopic data allowed the COGCC and BLM to conclude that 6 of the 17 areas contained biogenic gas, and the remaining 11 areas appeared to contain methane of thermogenic origin. Results of producing gas well sample analyses further indicated that source gases from the Dakota, Mesaverde, Pictured Cliffs, and Fruitland Formations could be differentiated on the basis of the presence of C3+ methane homologs, methane to ethane ratios, and a unique range in stable carbon isotope ratios of carbon in methane. The BLM also proposed a threshold value of δ^{13}C-methane of -55 ‰ to distinguish more negative biogenic gas sources from more positive thermogenic gas sources. These results set the standards for regulating baseline groundwater monitoring in advance of drilling additional wells.

In 2000, the COGCC mandated testing of groundwater wells prior to and following drilling additional optional wells in the Fruitland Formation (Orders 112-156 and 112-157). The new rules decreased the allowable well spacing from 320 to 160 acres (4 wells per section). As a condition for obtaining a drilling permit, operators are required to sample the 2 closest domestic groundwater wells within a ½ mile radius of each planned additional optional infill well in the Fruitland Formation. If dissolved methane is detected in a concentration exceeding 2 mg/L, chromatographic analysis of the gas and carbon isotopic analysis of methane carbon is required to determine gas type (thermogenic, biogenic, or a mix of both). If test results reveal biogenic gas, no further isotopic testing is necessary. If the carbon isotope tests result in a thermogenic or mixing signature, annual testing is required. If the methane concentration level increases by more than 5 mg/L between sampling periods, or if the concentration increases to more than 10 mg/L, the operator responsible for testing must submit an action plan to determine the gas source.

As of 2004, approximately 2109 data records containing measurements of dissolved methane concentrations in groundwater were available in the COGCC database.

Groundwater samples had been collected from 1034 different water well sites. Of those, there were 445 sites with single water quality analyses, and 589 sites with multiple water quality analyses. Dissolved methane was measurable at 674 water well sites (65% of all wells sampled, Figure A1.1).

Factors Affecting Dissolved Methane Concentration

Analysis of baseline groundwater data collected by the COGCC provided a unique opportunity to address whether CBG operations were influencing the concentration of dissolved methane in groundwater (Gorody, 2005). Multiple data sets from individual water wells also allowed the COGCC to evaluate in detail the factors that influence dissolved methane concentrations in groundwater. The availability of concurrent sample analysis results, including major ion analyses, dissolved methane concentration, and stable isotopic analyses, made it possible to investigate environmental variability for the first time. Prior to that, the COGCC and BLM had addressed factors affecting sampling and analytical variability in quantifiable detail.

The COGCC's study of available groundwater data from the San Juan Basin showed that methane concentrations in selected wells with multiple sampling results collected within a sampling period of 90 days was variable. Short term variability was addressed using 87 pairs of consecutive methane concentration measurements from 43 different water wells. Regression analysis of maximum and minimum values at any given site over the short term showed that maximum values differed from minimum values by a factor of 1.14% + 0.55 mg/L (Gorody, 2005). A recent unpublished study of over 1400 samples in the Piceance basin shows that total short term sampling and analytical error in measured methane concentrations can be reduced to +/- 8% provided that field crews are trained to follow strict sampling protocols (Gorody, personal communication).

When compared to short term variability, long term variability between the minimum and maximum dissolved methane concentration among multiple samples collected at 397 water well sites in the San Juan Basin exhibited an average variability of +/- 54%. These results were based on all historical data available from the Colorado portion of the San Juan Basin.

Data from 292 sample pairs of water well samples collected prior to and after drilling optional additional Fruitland wells were used to evaluate the impact of drilling new Fruitland Formation gas wells. Of those sample pairs, 179 (61%) had consecutive measurements below detection limits of 0.0001 mg/L. There were 113 sample pairs in which dissolved methane was detected at least once. Of those, 61 (54%) had pre-drilling methane concentrations that were higher than post drilling values. Of the remaining 52 wells, 14 had post-drilling methane concentrations that were both greater than pre-drilling values and that exceeded the expected variability over the short term. Only 10 of the 14 water wells sampled in consecutive years contained more than 2 mg/L dissolved methane. Because the COGCC only mandated chromatographic and stable isotopic analysis on samples containing 2 mg/L of methane or more, those 10 sites were the only ones with extended analytical results.

Eight of those sites contained biogenic methane. The remaining 2 sites contained methane with stable carbon isotope measurements of thermogenic origin.

Detailed analysis of the data from both remaining sites with dissolved thermogenic methane demonstrated that the observed increase in post-drilling methane concentration was not due to drilling new Fruitland wells. Factors affecting the differences between pre and post drilling dissolved methane concentrations were revealed basin-wide for the first time as a direct consequence having multiple data sets from individual wells. The two principal environmental factors controlling methane concentrations in water wells can be described as follows:

- There are numerous, vertically stratified, confined and unconfined aquifers at all locations in the basin. Each has a unique chemical composition which can be identified on the basis of standard major ion analyses. The four main water types in the basin, in order of the shallowest to deepest aquifers, are calcium-magnesium bicarbonate (dissolved lime composition), sodium sulfate (dissolved glauber salt composition), sodium bicarbonate (dissolved baking soda composition), and sodium chloride (dissolved table salt composition). Most water wells appear to tap more than one of these aquifers even though they may be screened across thin completion intervals. Depending on the relative contribution of water to a well from any of these layered aquifers at any given time, dissolved methane originating in water from one aquifer can be variably diluted. Alternatively, dissolved methane of different origins can become variably mixed depending on the relative contribution and mixing rates of different aquifer fluids in a water well. Major ion analyses and stable isotope analyses of water are the best and cheapest variables to measure to demonstrate temporally variable mixing rates in a well.
- The domestic wellbore environment is an oxidizing one, with a strongly dynamic oxygen gradient that exists between the air-water interface and the bottom of the well. Due to poor water well maintenance practices, the overwhelming majority of water wells in the basin have been documented to contain in excess of 1 million colony-forming units of bacteria per mL of water. These bacteria occupy laterally and vertically different niches in the well bore principally depending on their ability to compete for available dissolved or chemically bound oxygen. Many of these bacteria consume methane as a source of carbon to build proteins, and effectively do so at very high rates.

The chemical effects of bacterially-mediated aerobic and anaerobic methane oxidation can be readily observed on the basis of stable isotope ratios for carbon in methane and dissolved carbon dioxide, and deuterium in methane. Bacteria preferentially consume methane with the lightest isotopes. Accordingly, bacterially-mediated methane consumption leaves a residual pool of dissolved methane enriched in heavy isotopes. Bacterial respiration, on the other hand, generates a dissolved carbon dioxide pool which becomes correspondingly depleted in heavier isotopes. If bacterial methane consumption rates are higher than the rate at which dissolved methane is introduced into a water well, then methane concentration will decrease, the stable isotopes of residual methane will become enriched, and the stable carbon isotopes in dissolved inorganic carbon will become increasingly depleted. The opposite becomes true if the rate at which methane is introduced into a well outpaces the ability of bacteria to consume it. Temporal analyses of stable isotopes in methane and dissolved inorganic carbon from water in a well are necessary to document either variable source methane mixing dynamics or increasing methane concentrations resulting from a contaminant plume.

Factors Affecting Dissolved Methane Composition

Stable isotopic analyses of both gaseous methane and gases dissolved in groundwater demonstrate that there are multiple methane sources in the San Juan Basin. These include biogenic methane derived from both fermentation and carbon dioxide reduction reactions, and thermogenic methane from Fruitland, Mesaverde, and Dakota Formations. Along the outcrop belt (Amoco, 1994), and in groundwater wells sampled within 5 miles of the outcrop, chemical data reveal that at any given location, methane is derived from mixed sources. The origin of these mixed sources has been hypothesized to result from the following groundwater and gas interactions (Gorody, 2001).

Recharging waters become saturated with a mixture of thermogenic Fruitland Formation methane and biogenic alluvial and bedrock aquifer methane along the outcrop belt. Fruitland gas migration introduces thermogenic methane into overlying Kirtland and Animas Formation sediments in areas where the aquifers are unconfined and in vertical communication through swarms of shallow fractures. This unconfined recharge zone probably extends a distance of several tens of meters basinward of the outcrop belt. At some point, groundwater flow becomes partly unconfined. There, additional Fruitland methane can be introduced into overlying sediments through fracture swarms along bedding boundaries (Eaton et al., 2007). This zone probably extends a distance of a several hundreds of meters basinward of the outcrop belt. Beyond that, groundwater flow becomes largely confined and the Animas Formation contains entrained mixtures of thermogenic and biogenic methane.

The result of such dynamic interactions is that groundwater in the Animas Formation, the formation in which many water wells south are the outcrop belt are completed, contains variable saturations of mixed methane sources with an isotopic signature indicative of mixing with Fruitland Formation gas. When Animas Formation groundwater containing mixed methane sources discharges into the alluvium of river and stream valleys, usually within a distance of several kilometres of the outcrop belt, entrained dissolved methane can once again become mixed with alluvial methane of bacterial origin. Upward directed Animas groundwater flow in local anticlines also has the effect of liberating free methane from groundwater fluids saturated in methane. In the discontinuous sands of the fluvial-dominated Animas Formation, upward directed groundwater can liberate gas to form small, localized free gas caps. These can be classically described as combination structural and stratigraphic traps.

Numerous water wells within a distance of 10 kilometers of the outcrop belt contain relatively high dissolved concentrations of methane with carbon isotope ratios more positive than $\delta^{13}C$ methane of -55.0 ‰ (parts per thousand). To determine if thermogenic gas at a water well originates from the underlying Fruitland Formation, it is standard procedure to sample and analyse produced gas from the three closest

Fruitland Formation production wells. At the same time, the wells are monitored for bradenhead pressures.

Established Sampling and Analysis Protocols

A significant result of the historic multiple groundwater sampling events conducted in the San Juan Basin was that the methods used to sample and analyse dissolved hydrocarbons gradually became standardized. This was in large part due to complaints regarding both the inability to compare reported results among surveys and inadequate quality control measures. The BLM's method of quantifying dissolved methane in water became the field testing and laboratory testing standard for San Juan basin samples (BLM 1994, COGCC and BLM, 1995).

The BLM's procedure was to first collect a purged well water sample in an 40 mL VOA vial that is inverted under a head of water in a 5 gallon bucket. Tubing is used to convey water into the vial, and when filled, the VOA is sealed under water with a Teflon septum cap. The sample is then inspected to insure that there are no bubbles in the vial. Using a syringe and needle valve, a fixed 20 mL volume of water is then displaced with ambient air. The sample is agitated every 5 minutes for a period of 40-45 minutes to allow dissolved gases to equilibrate in the headspace. A sample of headspace gas is then withdrawn and analysed with a calibrated portable organic vapour analyser in chromatography mode.

The peak area on the resulting chromatograph is measured and converted to headspace concentrations of methane in air based on calibration results. The measured concentration of methane in air is then converted to a dissolved methane concentration in water using conversion factors that account for methane volume, temperature, and the Bunsen coefficient (Henry's law). The accuracy of the analytical method was demonstrated to be within +/- 2.5%. The method sensitivity was also found to be reliably in the range of 0.0001 mg/L.

The BLM used a dynamic headspace sampling method to collect gas samples for stable isotopic analysis (Chafin et al, 1993). It is just as effective, however, to collect bulk water samples for extraction of dissolved gas in the laboratory (as described in a previous section in this report).

The COGCC has mandated carbon isotopic analysis of methane as a baseline sample screening tool to distinguish gas sources. However, to adequately address complaints and litigation, both repeat sampling and additional analyses are necessary. Stable isotope analyses of deuterium in methane, oxygen and deuterium in groundwater, and stable carbon isotope analyses of carbon in both produced CO_2 and dissolved inorganic carbon (DIC), are necessary to definitively address the origin and fate of dissolved gas in groundwater.

1.2 Improperly Abandoned Wells

There have been a few incidents recorded in La Plata County basin related to gas seeps related to abandoned wells. In Colorado, plugged and abandoned wells are cemented, and the surface casing is cut below grade. The most recent incident, is well documented in files on the COGCC web site, and provides a good case study for methane migration from a faulty abandoned well.

On February 12, 2005, an explosion destroyed a residence in Bondad, N. M. Soil gas surveys, used to pinpoint the point source for the methane, traced the likely source to an abandoned well, the Bryce 1-X. Excavations conducted in August of 2005, uncovered the abandoned well within the mapped main gas seep area. This confirmed that methane was migrating from the Fruitland Formation and up the well bore of the abandoned well. The gas moved vertically upward along the well bore and out of the well where casing was either absent or structurally compromised. From there, gas migrated laterally updip into permeable layers and aquifers of the Nacimiento Formation and under and around the home. The abandoned well casing was entered and repaired between late July 2006 and early August 2006. By the next month, continued monitoring of the seep site established that there was no longer any detectable gas seepage at the ground surface. The problem has been entirely mitigated.

To mitigate the risk of methane migration from compromised abandoned wells, some operators have been conducting soil gas surveys prior to drilling new wells in areas known to harbor abandoned wells.

1.3 Outcrop Seeps

The San Juan Basin is a typical asymmetric Rocky Mountain foreland basin (Figure A1.2). Along its northern and eastern margins, the Fruitland and the overlying Kirtland Formations rise steeply from a basin margin hingeline axis and emerge to form a trellis valley basinward of the Pictured Cliffs Sandstone Hogback Monocline (Figures A1.2 and A1.3). Gas seeps along the Fruitland outcrop belt have been historically documented to exist since the 1930's, well before oil and gas drilling operations. The best know of these, from east to west, include the area intersected by the Los Piños (Pine) River, Carbon Junction, Basin Creek, an area known as "stink hill" between Valencia Canyon and Iron Springs Canyon. In the early 1990's seeps appeared to intensify at both the Pine River and Valencia Canyon sites. These areas became the focus of intense geologic and hydrologic studies sponsored by federal and state regulatory agencies and CBG operators (Amoco, 1994, BLM, 1995, Fasset et al., 1997).

The first complaints from a resident in the Pine River Ranches subdivision, where the Pine River and Fruitland Formations intersect, were registered in July of 1993. Subsequent investigation showed that 4 homes were affected by methane seeps. These homes were built directly on top of a narrow strip of Fruitland outcrop which at the time was emanating gas observed to be bubbling vigorously in overlying ponds and killing vegetation. In the spring of 1995, a Southern Ute Indian Tribal geologist reported above normal gas seepage rates along the Fruitland outcrop near Valencia Canyon. Parallel to the outcrop belt, patches of pinion and juniper trees, and sage bushes were dying. The perceived outbreak of increasing seep rates along the Fruitland outcrop spurred regulatory intervention, operator involvement, citizen group participation, and litigation. By August of 1997, all 4 properties at the Pine River Ranches subdivision were purchased by an operating company as part of litigation settlement and subsequently abandoned. Since then, an additional 4 parcels of property have been purchased along the outcrop.

Several hypotheses have been forwarded to account for the apparent increasing seep intensity observed in the early to mid 1990's:

a) Down-basin water production is causing drawdown of Fruitland coals near the outcrop, allowing gas-saturated coals to desorb (Questa Engineering, 2000, Applied Hydrology Associates, 2002, Cox and Young, 1995);

b) Methane desorbing from downdip coal bed gas production is migrating updip into the outcrop (Questa Engineering, 2000);

c) Long term drought is causing drawdown at the outcrop; and,

d) New seeps emerge periodically as a natural consequence of outcrop weathering (Riese et al., 2005).

All the proposed hypotheses invoke shallow fracture systems as vertical conduits to the surface for either gas or water.

A number of different approaches have been applied to map seeps, to understand the factors controlling their aerial extent and gas flow rates, to predict future impacts, and to address risk mitigation. No other coalbed basin has been investigated to this extent and with so many independent investigative techniques. These will be summarized in the following sections from the perspective of their applicability to risk assessment and mitigation.

1.3.1 Pedestrian Soil Gas Surveys

During a pedestrian soil gas survey, a field investigator uses a portable flame ionization detector (FID) and a GPS locator to find and identify gas seeps. From 1995 to 2007, numerous pedestrian surveys were conducted along the outcrop belt. The majority of those extend 23 miles along the outcrop belt in the areas between Basin Creek and the Pine River (Stonebrooke, 1995, and LT Environmental, 2007). Results have document numerous areas with active seeps (Figure A1.4). Seeps in these areas are generally restricted to narrow strike-parallel belts where either Fruitland coal seams outcrop or are present in the shallow subcrop below alluvium. Gas has been documented to emanate principally from Fruitland coal seams, and the shaly transition zone between the Fruitland and overlying Kirtland Shale Formations.

In all cases, stressed, dying, or dead terrestrial vegetation has been observed in areas with active seeps. These are visible in aerial photos compiled since 1950 and in recent infrared imagery. Vegetative stress is due to the displacement of normal soil gas oxygen concentrations in the pore space by venting methane. A decreasing partial pressure of oxygen negatively impacts normal terrestrial plant root respiration. Wetland vegetation, on the other hand, is relatively unaffected even in areas with high methane fluxes.

Results of pedestrian FID surveys suggest that there are no consistent trends in the areal extent along the outcrop affected by methane seeps. In some areas, seep extent appears to have increased; in others, seep extent appears to have decreased. Although areas with diminishing methane seeps are reported to outnumber those with increasing seeps, the survey methodology is not consistent and results from one year to another cannot be strictly compared (LT Environmental, 2007). Such equivocal results emphasize the need to plan, design, and implement surveys in a more systematic manner. Fixed grid surveying methods have been proposed as an alternative survey method.

1.3.2 Soil Gas Probes

Approximately 180 permanent shallow soil gas probes have been installed in small transects across the Fruitland Formation, perpendicular to depositional strike. Since 1998, 160 permanent soil probe monitoring sites have been installed and sampled by the BLM approximately 6 times per year. These are arranged in a cluster of dip-oriented linear transects across the Fruitland Formation. Statistical analysis of methane concentration headspace data from 152 of the BLM probes reveals that only 33 exhibit statistically significant trends. The majority of probes without discernible trends had methane headspace values at or near zero. Among the probes showing trends, 12 (36%) show an increasing methane concentration, and 21 (64%) show a decreasing methane concentration (LT Environmental, 2007). No obvious seasonal variations were evident in those data.

Soil gas and seep surveys conducted along the Pine River have demonstrated that the surface expression of underlying seeps will migrate in strike-parallel bands across a distance of tens of meters (Oldaker, 2007, Riese, 2005). At times of high precipitation and recharge rates, seeps appear to migrate northward; at times of low precipitation and recharge rates, they migrate southward. The observed extent of strike parallel movement coincides in part with the movement of the linear intersection between a level water table and a steeply dipping formation. For example, at a dip angle of 30 degrees, a linear contact between a dipping bed and the water table will shift by 1.73 meters for every meter drop or rise in water level. Strike-parallel lateral changes in the surface expression of seeps have also been commonly observed along the Fruitland outcrop belt. Such observations are common wherever seeps are observed. This is due to capillary effects that govern the flow path of gas in response to changing water levels in both saturated and unsaturated zones. Based on such observations, soil gas probes installed for long term monitoring should not just be deployed along single line transects. They should be ideally deployed along spatially distributed equal area networks that overlap zones where seeps are observed. However, such deployment options may not always be practical or affordable.

1.3.3 Flux Chambers

Flux chambers of various types have been installed over alluvial sediments along the Pine River and Valencia Canyon seeps (Bennet, 1998, Oldaker, 2003, LT Environmental, 2007). Based on measured flux chamber rates at three Pine River Ranches sites that were compiled over a period of 5 years, the estimated daily methane flux to the atmosphere is between 883 to 1,412 Mcfd (thousand ft^3/day; Bennett, 1998). A flux chamber installed over a small 2000 sq. ft. area in Valencia Canyon recorded variable seepage rates of between 10 to 25 Mcfd.

Available flux chamber data records have not demonstrated any systematic increases in gas flux throughout since the onset of the new infill drilling rules. Maximum and minimum recorded gas flow rates during the observation period at both outcrop sites have been positively correlated to coincide with average annual precipitation, including snow melt (Bennett, 1998, Oldaker, 2000 and 2003). Average flux rates, highest in 1999, corresponded to a period when total annual precipitation rates exceeded a 60 year high; flux rates were lowest in 2002, when total annual precipitation was the second lowest ever observed in a 60 year record. Flux chambers also recorded a seasonal response to aquifer recharge. High seep flow rates are correlated to periods when the water table is high in response to the wet spring season; lowest gas flux rates are observed when the water table is low in response to the dry fall season.

The relationship between water table levels and gas flux can be understood on the basis of two phase flow properties in porous media. An elevated water table will allow water imbibition into the smallest capillary pore spaces open to gas flow. This reduces the overall cross-section of seepage, increases the gas pressure gradient to the surface, and funnels underlying gas migration through fewer large pores and fractures. On the other hand, the reduced pressure of a lower water table distributes gas flow in the saturated zone through smaller capillaries first, and then distributes flow further as gas migrates through a thicker volume of unsaturated alluvial overburden.

Flux chamber monitoring along the outcrop belt is likely to be discontinued for the following reasons. The data have not shown any conclusive upward or downward trends during eight years of operation, the equipment is highly susceptible to weathering and corrosion, solar-charged batteries are too susceptible to frequent discharge, and maintenance costs are high (LT Environmental, 2007).

1.3.4 Monitor Wells

A series of monitor water wells were drilled and completed in multiple horizons near the Pine River Ranches Fruitland outcrop as part of the Pine River Ranches investigation launched in the early 1990’s. Numerous inflatable packer tests provided the zone isolation needed to help investigators address hydrodynamics in Pine River alluvium, the Kirtland Formation, the shaly transition zone between the upper Fruitland and Kirtland Formation, selected coal intervals in the Fruitland Formation, and the underlying Pictured Cliffs formation.

Four water level monitoring wells have been drilled and maintained by the COGCC along the outcrop belt between Basin Creek and the Archuleta County border (Norwest Applied Hydrology, 2007). Each of those is completed in one or more coal-bearing intervals in the Fruitland Formation. In all, seven completion intervals are being monitored for possible water level declines.

Water Level Monitoring

Water level monitoring at Pine River Ranches over a period of 9 years from 1994 to 2003 demonstrated no observable decline in water levels among monitor wells completed in either the Kirtland or Fruitland Formations close to or along the outcrop. The potentiometric head in formations below the Pine River alluvium was at all times higher than the elevation of the river at the same locations. Monitor wells completed ½ mile to 1 mile south of the outcrop, on the other hand, show pressure declines occurring at rates similar to those measured in the closest shut-in Fruitland well, the Gurr Federal #1.

The discrepancy in results between monitor wells along the outcrop and those ½ a mile or further down-dip has been attributed to the presence of a hydrologic discontinuity between the outcrop and down-basin monitor wells. There has been no consensus on the nature of the discontinuity. Detailed correlation of Fruitland coal seams show marked stratigraphic discontinuities between coal seams intersected in monitor wells along the outcrop and those intersected in monitor wells and producing wells further downdip (Fasset et al. 1997 and Fasset, 2003).

Three of the four monitor wells monitored by the COGCC are shallow wells completed in coals between 264 and 578 feet below ground surface. These are located at Basin Creek, the South Fork of Texas Creek, and Shamrock Mines. The fourth well, at Beaver Creek, is completed in coal seams within a field of producing gas wells. Pressure monitoring from 2002 to 2007 shows that coal seam pressures in all wells but the one at Shamrock Mines are gradually declining, presumably in response to down-basin production.

Pumping and Interference Tests

Pumping tests conducted on monitor wells along the outcrop belt showed hydrologic continuity of wells completed in coal. However, the coal seams in those wells could not be demonstrated to be in hydrologic continuity with other monitor well ½ mile downdip. Cox and Young (1995) postulated the existence of a linear barrier or reduced permeability zone.

Downhole Video Monitoring

Downhole video monitoring in monitor wells near the Fruitland Outcrop at Pine River Ranches was useful for showing zones of water influx, gas migration, and gas desorption from coal seams. There, the dominant source for gas observed in monitor wells was demonstrated to originate from the transition zone between the upper Fruitland Formation and the Kirtland Shale (Oldaker, 1998). Lesser amounts of gas were observed desorbing from upper Fruitland coal seams, and migrating out of deeper coal seams and the underlying Pictured Cliffs sandstone. These results are consistent with data from domestic water wells downdip of the outcrop belt that document the occurrence of both free and dissolved gas in each of these formations.

1.3.5 Chemical Analysis of Monitor Well Fluids

Geochemical analyses of dissolved ions in water have been instrumental in helping to address hydrologic communication between recharging fluids and down basin production. Riese et al. (2005), and Oldaker (2003), have shown that major ion concentration analysis, trace metal concentration analysis, stable isotope of water, and strontium isotope 87Sr/86Sr ratios are useful variables for evaluating groundwater sources and mixing in San Juan Basin aquifers. Major ion analyses are most useful for differentiating fluids in alluvial and bedrock aquifers. Stable isotope analyses of oxygen and deuterium in water are useful because they are relatively unreactive with the aquifer matrix. In this basin, an observed trend of deuterium enrichment in water isotopes has been attributed to high rates of bacterially-mediated methanogenesis. Strontium isotope ratios in groundwater, resulting from mineral dissolution and cation exchange reactions, are also useful for identifying groundwater sources and aquifer mixing (Frost and Toner, 1994).

Repeated sampling and analyses of these variables at Pine River Ranches, has been particularly helpful for addressing aquifer interactions. For example, the fluid chemistry of recharging shallow alluvial aquifers at the outcrop exhibit climatic and seasonal variations. In contrast, Fruitland Formation fluids at the outcrop show little or no variation. Furthermore, chemical signatures between alluvial and Fruitland fluids are distinctly different. Based on these analyses, Riese et al. (2005) demonstrate that at Pine River Ranches, the Fruitland Formation is not being recharged by shallow alluvial aquifers. Such conclusions are consistent with results from water level measurements.

1.3.6 Chemical Analysis of Produced Fluids

Spatial analysis of both major ions and stable isotopes of water, and temporal analysis of major ions and produced water volumes are useful for addressing hydrologic discontinuities. Such data also help to constrain reservoir models particularly when produced water volumes significantly exceed those estimated to be indigenous to coal. Near outcrop belts in particular, combining produced water geochemistry with reservoir water production can be particularly useful for differentiating between incremental water sources. High water production volumes in wells close to the outcrop to either the absence of vertical zone isolation or to hydrologic connection with recharge at the outcrop. Two examples are shown here to illustrate such differences.

Pine River Ranches Case Study Results

Produced water volumes among Fruitland wells in La Plata County are variable (Figure A1.5). Most of the water produced in excess of that predicted to be indigenous to the Fruitland coal has been attributed to originate from porous and permeable underlying Pictured Cliffs sandstones (Questa Engineering, 2000). At Pine River, a Pictured Cliffs water source for the largest water producer in the area, the Dulin D#1 can be demonstrated with the help of produced fluid composition data.

The total dissolved solids content of producing wells near the Pine River outcrop is low and spans a significant range (Figure A1.6). Water is dominantly composed of sodium bicarbonate variably mixed with up to 20% sodium chloride. Thus, salinity and percent chloride are good mapping parameters. Figure A1.7 shows that there is a well-defined decreasing salinity gradient towards the outcrop, particularly towards the northwest corner of the map. Also shown are relative chloride concentrations and proposed hydrologic boundaries inferred on the basis of interference tests (Amoco, 1994, and Cox and Young, 1995).

Figure A1.8 shows that water quality in the Dulin D#1 sampled first in 1993 and again 1996 exhibit significant changes. Over that time, salinity increased by 23%, and the relative concentration of chloride increased by 5%. Such a result would not be expected if the Dulin well were drawing fresh water from the outcrop. Dual induction and filtrate invasion logs in this area also show that the Pictured Cliffs Formation is porous and permeable.

Valencia Canyon Case Study Results

The shallow hydrologic environment at Valencia Canyon is dominated by sulfate reduction reactions. In 1995, the strongest methane seeps along the canyon entrained hydrogen sulphide at life-threatening concentrations of nearly 400 parts per million. Tailings from an abandoned shallow coal mine near the heart of the seep area had been completely cemented with the iron minerals goethite and limonite over a period of just 50 years. These iron minerals give the nearby Iron Springs their name. Outcrop exposures of Fruitland coal also contained extensive clinker and ash horizons indicative of historic coal fires. Pyrite oxidation in coals and shales along Valencia Canyon imparts a significant imprint of dissolved sulfate to recharging waters. Clinker deposits are a source of magnesium sulfate (epsomite), and coal and shale deposits are a source of sodium sulfate (glauber salt).

Produced water data from Valencia Canyon are unique because of their abundance. One operator collected produced water monthly from 22 wells in the field for more than 2 ½ years. All samples were analysed for major ions. The two largest water producing wells along Valencia Canyon are the Valencia 17-1 and Valencia 30-1 (Figure A1.5). These two wells, respectively located at the northernmost and southernmost well locations sampled in the field, are also the most proximal to the outcrop. The trilinear diagram in Figure A1.9 shows water quality results from the Valencia 17-1 well samples. These show that water composition varies along a mixing line of relatively dilute magnesium sulfate composition and more saline sodium bicarbonate composition. This well taps multiple coal seam intervals and the mixing in the total well bore fluid is a result of differing fluid contribution rates from each interval. Figure A1.10 also shows that compared to other wells in the field, the Valencia 17-1 well produces the most dilute fluids.

These data therefore suggest that at least one completed interval in the well may be drawing fluids from coal seams recharged at the outcrop.

Figure A1.11 shows that there is a direct correlation between high monthly water production volumes, low monthly salinity, high monthly relative dissolved sulfate concentrations, and high monthly water to gas production ratios. The large change observed in 1994 is related to a field-wide shut-in for the purposes of connecting a distribution pipeline to all wells. Shutting in this well allowed recharging fluids to increase fluid pressure and shut down gas desorption. Analysis of similar data for all wells showed that at least one coal seam completion interval in each of 5 different wells were drawing water from recharge (Gorody and Casey, 1998). These wells were subsequently shut in and used as pressure monitor wells.

1.3.7 Age Dating

There has been pioneering research in the San Juan Basin regarding the age of fluids in the Fruitland Coal Formation. They are the first to address age dating approaches for groundwater in a producing coal seam reservoir. Techniques used for dating water have been varied. Analysis of radioactive tracers include radioactive iodine $^{129}I/I$ ratios and chloride $^{36}Cl/Cl$ ratios (Snyder et al, 2003, Snyder and Fabryka-Martin, 2005, and Riese et al. 2005). Other studies have focused on noble gas analysis techniques (Zhou et al., 2005, and Sorek, 2003). A comparison of conclusions reached from these independent studies reveals that there remains a fair amount of academic disagreement on the age of Fruitland Formation fluids sampled near the center of the basin and along the high gas production fairway near the Colorado-New Mexico border. However, all studies are in agreement that the age of Fruitland Formation fluids increase away from the basin margin. Formation fluids within a few of miles basinward of the outcrop belt indicate relatively recent recharge less than ten thousands years ago.

1.3.8 Hydrologic and Reservoir Modeling

During the late 1990's, in anticipation of proposed regulations reducing the infill drilling spacing of CBG wells, the Southern Ute Indian Tribe (SUIT), the COGCC, and the BLM sponsored a regional groundwater and Fruitland modelling effort known as the 3M project (mapping, modelling, and monitoring). The objective of the project was to develop a quantitative model to help understand and mitigate the potential impacts of increased well density and accelerated production of Fruitland coal gas on gas seeps along the Fruitland outcrop belt. A series of four monitoring well clusters were also sited and installed to monitor water level changes associated with CBM development.

Two contractors were selected to perform the study: Questa Engineering was hired to evaluate and develop a Fruitland water and gas production model (3M CBM Model), and Applied Hydrology Associates (AHA) was hired to provide a groundwater hydrologic model for the basin (3M Hydrologic Model). The project was completed in 2000 for a combined sum of $1.8 million dollars.

3M CBM Model

Questa's 3M CBM model is based on up to 16 years of production data from 1,060 wells, 4,870 pressure measurements from 591 wells, thickness data from 742 wells, and water chemistry data from 572 wells. These data were used to develop a reservoir production model calibrated to match historical production data, and data observed in pressure monitor wells along the outcrop belt. The model was initialized on the basis pre-development potentiometric heads and water recharge rates estimated by the AHA hydrologic model. The Colorado side of the San Juan basin was divided into 31,893 active grid blocks, with each grid block covering 17.778 acres, or 1/36 of a section. Grid blocks coinciding with the outcrop belt were selected based on results from the mapping project which provided a digitized contact boundary between the Fruitland and Pictured Cliffs Formations. To facilitate analysis and minimize computation time, the grid blocked basin was divided into 5 areas. To further simplify the model, the Fruitland Formation was treated as a single layer reservoir.

3M Hydrologic Model

AHA's hydrologic model is based on data from over 2200 geochemical analyses of produced water from over 600 wells, more than 200 initial formation pressure measurements, and precipitation data from 23 rain stations around the basin. Using MODFLOW v 2.8.2 and a single layer model for the Fruitland Formation, the study developed a steady-state groundwater model to represent pre-development conditions and a recharge-discharge water balance over the entire San Juan Basin on a half-mile grid spacing.

3M CBM Model results

The estimated 5 million ft^3/day (MMcfd) total gas seepage rate along the outcrop during the year 2000, was projected to peak to 10 MMcfd by the year 2009. Two areas along the outcrop were projected to develop new seeps. In most areas with existing seeps along the outcrop, no significant change in seepage was to be expected as a result of infill drilling. Cumulative seepage, starting from 1985, was projected to reach more than 100 Bcf by 2030. Declining seep rates after 2009 were projected on the basis of mitigating effects. These were attributed to the potential for infill wells to capture gas that would otherwise migrate updip and escape along the outcrop.

In the initial runs, the outcrop was modeled with perfect connection to the basin. This led to simulated gas seepage rates 10 to 100 times higher than those measured and observed. To match observed gas seep rates and pressure declines measured at and near the outcrop, it was necessary to significantly reduce the relative flow rates of gas and water within the Fruitland coals updip of the structural hingeline. Those results were interpreted to indicate an open but restricted connection between down-basin production and the outcrop. No conclusions were reached regarding whether flow restriction was related to the structural hinge line between the coals in the basin and the outcrop, stratigraphic changes in the coal, coalbed geometry, capillary pressure or relative permeability effects, multi-layer effects, high absorptive capacity in shallow coals, or any other unidentified causes.

3M Hydrologic Model results

The following summarizes the results of the hydrologic model. The potentiometric head of water in the Fruitland Formation gradually declines from elevated recharge points along the margins of the outcrop towards the San Juan River. Most recharging water travels a relatively short distance to one of several nearby, lower-elevation river gaps, where it is discharged to alluvium; some is discharged at springs on the outcrop. A small fraction of the water migrates through the basin and is discharged in the San Juan River in New Mexico, the lowest point in the basin. With the exception of well-documented barriers to flow, such as known faults at Valencia Canyon and 44 Canyon, the outcrop and down dip basin are hydrologically connected within a confined Fruitland aquifer.

Groundwater velocities are relatively high. Based solely on chloride concentration data and stable isotopes of produced water, formation fluids at 2-3 miles from the outcrop were recharged during the last glacial epoch which ended 10,000 years ago. Groundwater up to ten miles from the outcrop has a stable isotope and chloride composition characteristic of groundwater recharge from the outcrop.

1.3.9 Seep Mitigation Measures

No-Drilling Buffer Zone

As a result of investigations conducted along the outcrop and results modelled by the 3M project, the COGCC in 2000 required a commission hearing prior to approving a drilling permit for a well site located within one and one-half (1½) miles of the outcrop contact between the Fruitland and Pictured Cliffs Formations (Order 112-156). No new wells have been approved for drilling within the defined buffer zone.

Shutting In Wells

Along the Pine River, 1 producing gas well (Gurr Federal #1) was voluntarily shut in by Amoco Production Company in November 1993 and converted to a pressure monitor well. This well was the closest well to the Pine River outcrop seeps.

Five producing gas wells, drilled to shallow Fruitland coal seam depths between 377 and 753 feet in Valencia Canyon, were shut-in in 1995 and converted to pressure monitoring wells. These wells were among the highest water producers near the Valencia Canyon outcrop seeps.

Drilling Horizontal Wells

Four slant holes were drilled through basal Fruitland coal seams from outcrop exposures at Valencia Canyon. Separated by a distance of ¼ mile, the holes were oriented in a W pattern, towards one another at depth. Only shallow surface casing was set in each well, and the wells were left as open hole completions for distances ranging between 500-1000 feet. The southernmost pair of slant wells were drilled from a well pad adjacent to an 85 foot long by 10 feet wide gas flux chamber. Gas production rates from the directional wells were variable and ranged between 10 and 120 Mcfd. In response to gas production from the horizontal wells, the gas flux chamber showed seep rates declining erratically from 25 Mcfd to 12 Mcfd over a period of two years (BLM, 1999). There is no other published information available regarding slant well or flux chamber gas rates after 1999.

4M Study to Address Mitigation of 80 Acre Infill Spacing

The COGCC began approving drilling permits for 80 acre-spacing (8 wells per section) beginning in 2006. Plans are underway to evaluate options for funding the next study to address options to mitigate natural gas seeps at the outcrop. Industry representatives are more interested in exploring options to produce gas inside the outcrop buffer zone as a mitigation measure.

1.4 Archuleta County, HD Mountains

The hydrologic environment along in the Fruitland Formation on the northeastern margin of the San Juan Basin in Archuleta County is distinctly different from that described in La Plata County. There is little or no water produced from coals in this area. Both the BLM and COGCC have sampled water wells in this area. As part of the BLM's Environmental impact study, they sampled 70 wells largely on the periphery of the sparsely inhabited interior of the HD EIS study area. Only a few water wells have been found to contain high levels of thermogenic gas of Mesaverde origin. No water wells were found to contain dissolved Fruitland Formation Gas.

Recently, the COGCC has also funded soil gas surveys along approximately 18 miles of Fruitland outcrop. The survey extended from the La Plata County – Archuleta County boundary southeast along the outcrop to the Southern Ute Indian Tribe (SUIT) Reservation Boundary near the confluence of the Piedra River and Stollsteimer Creek. Methane seeps were neither observed along the outcrop nor detected in any of the permanently installed gas monitoring probes.

1.5 Summary of Risk Assessment and Mitigation Measures

Case studies from the San Juan Basin show that the impact of natural gas migration from coalbed seams to the surface, when it occurs as a result of gas operations, is nearly instantaneous. Buoyancy rapidly drives gas updip into aquifers and upward through the nearest and largest permeable paths. Shallow fractures naturally conduct gas up through shallow bedrock aquifers and into alluvium and soils. Man made migration paths include water wells, cathodic protection wells, piers, and any other piercement structures. After leaky point gas sources are remediated, the effect on seepage is also nearly instantaneous. Gas bubbling tends to cease quickly, and the areas affected by seeps are rapidly reduced to below detection levels.

The effect of remediated gas sources on dissolved gas in groundwater, however, may not necessarily be as immediate. Gas migrating updip through aquifers can accumulate in small structural and stratigraphic gas caps along the way to the surface. In such instances, dissolved gas is entrained in groundwater flowing from the trapped gas source towards areas of lower local and regional potentiometric head. Water wells that tap such an associated groundwater plume may contain dissolved methane for numbers of years until the gas cap is dissipated.

Regulatory action taken in response to complaints early in the history of CBG gas development has resulted in successful mitigation strategies. Routine and regular casing head gas pressure measurements in conjunction with routine and regular sampling of nearby water wells have effectively mitigated the potential for groundwater contamination. Because of the unique gas chemistry found in gas wells throughout the basin, combined chemical and isotopic analyses make it possible to discriminate, identify, and remediate point sources of groundwater contamination.

If a point source of contaminant gas has been effectively remediated, then dissolved methane concentrations in groundwater will decline with time. The only way to assess whether dissolved gas concentrations are increasing, decreasing, or remaining the same, is to consistently use standard sampling and analytical protocols. The assumption that the screened interval in a water well restricts water sources to specific aquifers is wrong. The dominant open hole and gravel pack completions in water wells throughout the San Juan Basin allow fluids from otherwise stratified aquifer sources to mix. Fluid mixing dynamics have to be understood to determine if a source of gas has been effectively remediated. This necessitates regular sampling and analysis. The efficacy of remediation can be effectively monitored using a combination of water quality analyses, and both chemical and isotopic analyses of dissolved gases. To address the impact of bacterial methane oxidation, isotopic analyses must be extended to include both methane and dissolved carbon dioxide.

Basin-wide groundwater sampling for water quality and dissolved methane is a new phenomenon in the history of groundwater hydrology. Results from the San Juan Basin show that only a few wells are responsible for polluting groundwater. The more remarkable observation is that more than 60% of all water wells in the San Juan Basin contain naturally occurring methane of variable and mixed origins. Groundwater wells near basin margins can contain large dissolved gas concentrations which appear partly thermogenic in origin. This is a consequence of hydrologic factors. Groundwater recharge along the outcrop will entrain both thermogenic and biogenic dissolved gas sources. Such dissolved gas, when transported to discharging zones, can further interact with biogenic gas native to shallow groundwater and alluvial aquifers. The need to address such issues, on a well to well basis, is a consequence of regulation and risk mitigation.

Coal outcrop belts are geologic hazards. In the San Juan Basin, seeps along the steeply dipping outcrop belt have been documented to occur along a narrow band defined by the position of the subcrop and outcrop formation boundaries between the Pictured Cliffs, Fruitland, and overlying Kirtland Formations. Numerous useful and several pioneering approaches have helped to establish whether there is a relationship between downbasin production and the extent and severity of gas seeps along the outcrop. If there has been any consensus among the many studies conducted, it is that a hydrologic connection exists, notably in a region within a few kilometres basinward of the outcrop belt. However, such a connection is variably restricted by permeability baffles and flow barriers occurring somewhere between the structural hingeline and the outcrop. Documented barriers and baffles include faults and stratigraphic heterogeneity. The source of gas is predominantly attributed to gradual water level declines; the associated pressure decline allows methane to desorb off the Fruitland coals and migrate updip.

REFERENCES

Amoco, 1994, Pine River Fruitland Coal Outcrop Investigation: Southern Rockies Business Unit, Amoco Production Company, Denver, Colorado.

Applied Hydrology Associates, 2000, 3 M Project San Juan Basin, Colorado and New Mexico, Hydrologic Modeling Report, Report to the Southern Ute Indian Tribe, Colorado Oil and Gas Conservation Commission, and the Bureau of Land Management.

Beckstrom, J.A. and Boyer, D.G., 1991, Aquifer Protection Considerations of Coalbed Methane Development in the San Juan Basin, in: Proceedings of Low-Permeability Reservoirs Symposium; Denver, Colorado, April 1991, Society of Petroleum Engineers, p. 371-386.

Bennet, P. C., and Marineau, D. T., 1998, Hydrogeochemistry of the Pine River Methane Seeps: Final Report to the Colorado Oil and Gas Conservation Commission, 50. pp.

Bureau of Land Managment, 2007, 2005 Bradenhead testing: comparison with prior data, http://oil-gas.state.co.us/ , Library, San Juan Basin, 2006 BHRPT.

Bureau of Land Managment San Juan Field Office, 1999, A Brief History And Environmental Observations: A Working Document, http://oil-gas.state.co.us/ , Library, San Juan Basin.

Bureau of Land Managment, 1993, Bradenhead testing and groundwater protection program overview and 1992 test results, 33 pp.

Bureau of Land Managment and Colorado Oil and Gas Conservation Commission, 1995, 1994 Groundwater monitoring San Juan Basin, La Plata County, Colorado: Comprehensive infill testing including data obtained in the Pine River Fruitland Coal Outcrop investigative study, Final Report with tables and appendices.

Bureau of Land Managment, 1994, Dissolved methane concentrations in groundwater, La Plata and Archuleta Counties, Colorado: HD Mountains EIS study area and selected lands peripheral to federal jurisdictional lands, 33 pp. with tables and appendices.

Bureau of Land Managment, 1995, Groundwater Monitoring Report Pine River Ranches Subdivision, La Plata County, Colorado, Pine River Fruitland Coal Outcrop Investigative Team Study, 40 pp. with tables and appendices.

Brown, D., 2002, CBM development and water issues, In: Coalbed Methane Development In The Intermountain West, Conference Proc., Natural Resources Law Center, University of Colorado School of Law, p. 22 – 228.

Chafin, D. T., 1994, Source and Migration Pathways of Natural Gas in Near-Surface Ground Water Beneath the Animas River Valley, Colorado and New Mexico, USGS Water Resources Investigations Report 94-4006, p. 1-2.

Chafin, D. T., Swanson, D. M., and Grey, D. W., Methane Concentration and Methane Isotope Data for Ground Water and Soil Gas in the Animas River Valley, Colorado and New Mexico, 1990 – 1991, U. S. G. S. Water Resources Investigations Report 93-4007, 86 pp.

Colorado Oil and Gas Conservation Commission staff, 2000, Summary Report Of Bradenhead Testing, Gas Well Remediation, And Ground Water Investigations San Juan Basin, La Plata County, Colorado
http://cogcc.state.co.us/Library/sanjuanbasin/3m_project/water_quality/SJBWaterQuality.htm

Colorado Oil and Gas Conservation Commission and Bureau of Land Managment, 1995, 1994 Groundwater Monitoring San Juan Basin, La Plata County Colorado: Comprehensive infill testing – Including data obtaine in the Pine River Fruitland Coal Outcrop Investigative Study,

Cox, D.,1998, Preliminary Analysis of Long-Term Seepage Potential in the Valencia Canyon Area, Questa Engineering, Denver, CO.

Cox, D. and Young, G. B. C., 1995, Well testing in coalbed methane (CBM) wells: An environmental remediation case history, Soc. Pet. Eng., Paper # 30578, 1995 SPE Ann. Tech. Conf.,Dallas TX p. 487 – 500.

Eaton, T. T., Anderson, M. P., and Bradbury, K. R., 2007, Fracture control of groundwater flow and water chemistry in a rock aquitard, Gound Water, V. 45, p. 601 -615.

Fassett, J. E. 2000, Geology and Coal Resources of Upper Cretaceous Fruitland Formation, In: Kirschbaym, M.A., L.N.R. Roberts, and L.R.H. Biewick, Geologic Assessment of Coal in the Colorado Plateau, Arizona, Colorado, New Mexico, and Utah. United States Geological Survey, Professional Paper 1625-B.

Fassett, J. E., Condon, S. M., Huffman, A. C., and Taylor, D. J., 1997, Geology and Structure of the Pine River, Florida River, Carbon Junction, and Basin Creek Gas Seeps, La Plata County, Colorado, USGS Open-File Report 97-59.

Fasset, J. E., 2003, Fruitland Formation Coal-Bed-Gas Seeps, Northern San Juan Basin, Colorado, RMAG 55th Annual Mtg., Abstract.

Fisher, B. J., 2001, Environmental Issues and Challenges in Coalbed Methane Production, 2001 8th Annual International Petroleum Environmental Conference
Houston, TX - November 6-9. http://ipec.utulsa.edu/Conf2001/conf_toc.html

Frost, C. D., and Toner, R. N., 2004, Strontium Isotopic Identification of Water-Rock Interaction and Ground Water Mixing, Ground Water, V. 42, p. 418 – 432.

Gorody, A. W., Baldwin, D., and Scott, C., 2005, Methane in water wells, San Juan Basin, Colorado: Analysis of data submitted in response to COGCC orders 112-156 and 112-157, IPEC 12th Ann. Symp. Proc., http://ipec.utulsa.edu/Conf2005/Papers/Gorody_DISSOLVED_METHANE_IN_GROUNDWATER.pdf

Gorody, A. W., 2001, The origin of shallow gas in groundwater overlying the Ignacio Blanco gas field, San Juan Basin, near Bayfield, La Plata County, Colorado, In: D. Stillwell (ed.), Wyoming Gas Reservoirs and Technology, Wyo. Geol. Assn. 52nd Conf. Guidebook, p. 9-21.

Gorody, A. W. and Casey, T., 1998, Using temporal changes in produced water geochemistry as a guide to assess reservoir compartmentation in coal bed methane reservoirs, Am. Assoc. Petrol. Geol. 1998 Ann. Mtg. Abstract.

Harder, A.H., Whitman, H.M., and Rogers, S.M., 1965, Methane in the Fresh-Water Aquifers of Southwestern Louisiana and Theoretical Explosion Hazards, Department of Conservation, Louisiana Geological Survey, Louisiana Department of Public Works, 14 pp.

LT Environmental, 2007, Fruitland Outcrop Monitoring Report, http://oil-gas.state.co.us/ Library, San Juan Basin.

Norwest Applied Hydrology, 2007, Colorado Oil and Gas Conservation Commission Monitor Wells Summary Report, 3M Project Monitoring Program, La Plata County, Colorado, www.oil-gas.state.co.us Library, Area Reports, San Juan Basin, 3M Project Reports, Monitoring Well Reports.

Oldaker, P., 2003, Annual report of groundwater monitoring at the Pine River Ranches: Report to BP and Colorado Oil and Gas Conservation Commission

Oldaker, P., 2000, A comparison of similarities and differenced of the Pine River and Valencia Canyon gas seeps: Proc. RMAG Conference on Coalbed Methane in the Rockies, June 20 – 21.

Oldaker, P., 1998, Pine River Gas Seep Delineation Using Downhole Video Logs AAPG Bulletin, Abstract, V. 82 (1998), No. 13 (Supplement)

Questa Engineering Corporation, 2000, The 3M CBM Final Report, Volume I: Analysis of Resuts, Report to the Southern Indian Ute Tribe, Colorado Oil and Gas Conservation Commission, and U. S. Bureau of Land Management, 70 pp.

Riese, W. C., Pelzmann, W. L, and Snyder, G. T., 2005, New insights on the hydrocarbon system of the Fruitland Formation coal beds, northern San Juan Basins, Colorado and New Mexico, USA, In: Warwick, P. D., ed., Coal Systems Analysis: Geol. Soc. Am. Special Pap. 387, p. 73-111.

Shuey, C. 1990. Policy and regulatory implications of coal-bed methane development in the San Juan Basin, New Mexico and Colorado, in: International Symposium on Oil and Gas Exploration and Production Waste Management Practices, I", Proceedings, New Orleans, p 757 – 769.

Snyder, G.T., Riese, W.C., Franks, S., Fehn, U., Pelzmann, W.L., Gorody, A.W., and Moran, J.E., 2003, Source and history of waters associated with coal-bed methane: 129I, 36Cl, and Stable Isotope Results from the Fruitland Formation, CO and NM, Geochimica et Cosmochimica Acta, 67, 4529-4544.

Snyder, G. T., and Fabryka-Martin, J. T., 129I and 36Cl in dilute hydrocarbon waters: Marine-cosmogenic, in situ, and anthropogenic sources, Applied Geochem. V. 22, I No. 3, p. 692-714.

Sorek, P. D., 2003, Evaluation of Helium-4 in a coalbed methane system, and implications for regiona hydrogeology, Fruitland Formation, Colorado and New Mexico, [M. S. Thesis] Fort Collins, Colorado State University, 75 p.

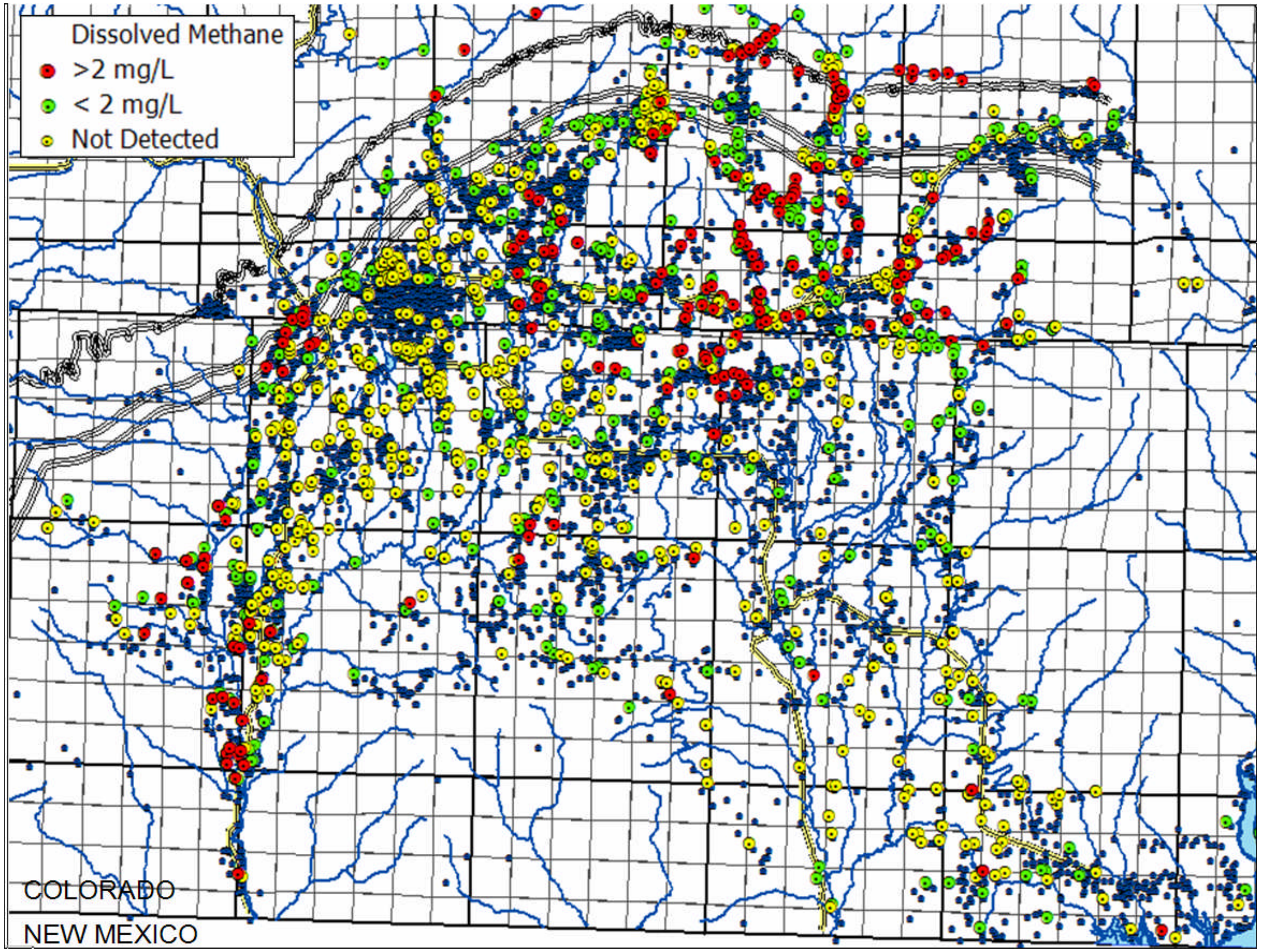
Stonebrooke Resources, Inc., 1996, Fruitland Formation Outcrop Gas Seep Study, La Plata County, Colorado, Final Report, 48 pp.

U.S. Geological Survey, Central Energy Resources Team, and Fassett, J.E., 2000, San Juan Basin Geology: U.S. Geological Survey, Denver, CO.

Velez, N., 1993, Baseline groundwater quality study and database, Ignacio-Blanco Task Force.

Zhou, Z., Ballentine, C. J., Kipfer,Schoell, M. and Thibodeaux, S., 2005, Noble gas tracing of groundwater/coalbed methane interaction in the San Juan Basin, USA, Geochim. et Cosmochim. Acta, V. 69, p. 5413-5428.

Zhou, Z., and Ballentine, C. J., 2006, 4He dating of groundwater associated with hydrocarbon reservoirs, Chemical Geology. V. 226, p.309-327.



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

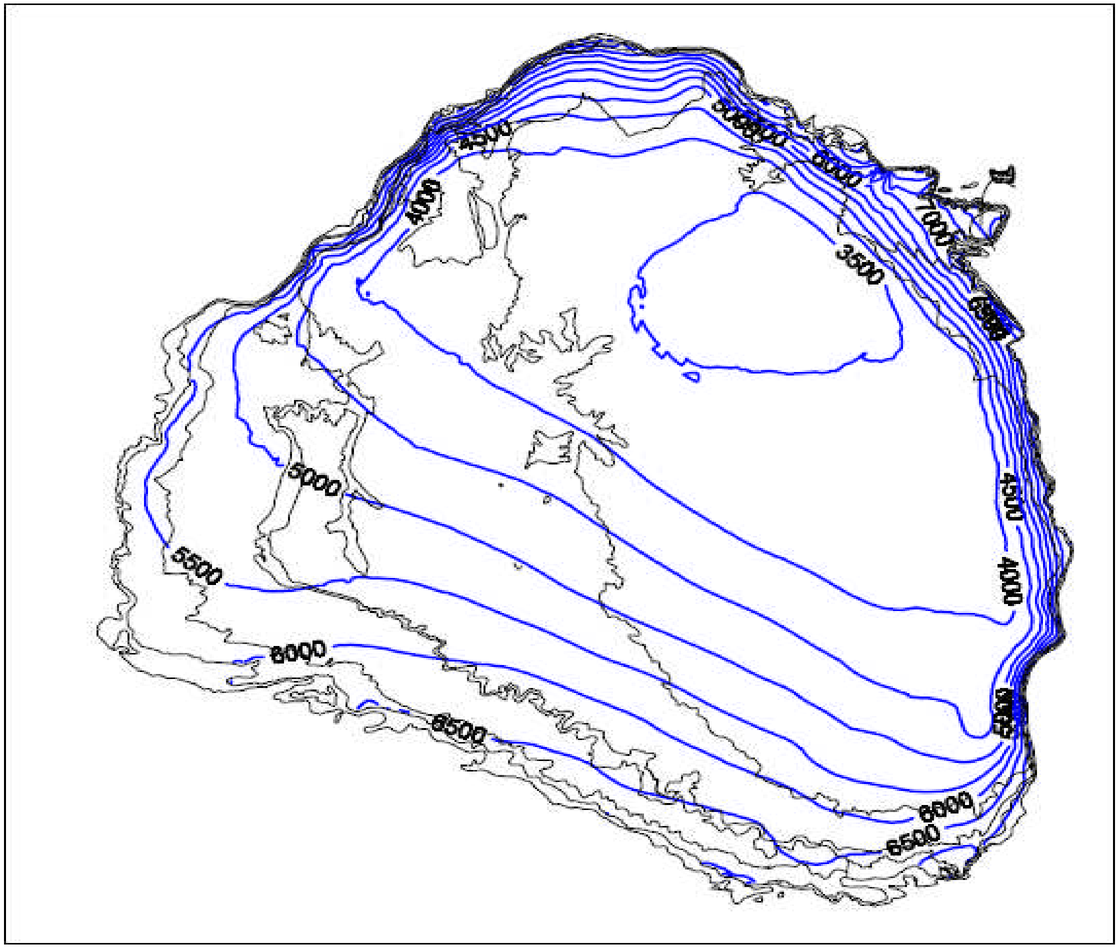
San Juan Basin water wells tested for dissolved methane (yellow, green, and red dots). Small blue dots represent all permitted water wells in the Colorado Division Of Natural Resources data base as of 2005. The northernmost band of black lines represents the Fruitland outcrop.

WorleyParsons
resources & energy

19-Oct-08	date	**ia**	edited by	**ia**	drawn by		app by

PROJECT NUMBER: **C67020000**

FIGURE: **A1.1**



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Elevation at the top of the Fruitland Formation (adapted from Applied Hydrology Associates, 2000).

WorleyParsons
resources & energy

19-Oct-08 date	ia edited by	ia drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: A1.2

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Aerial photo of the Pictured Cliffs outcrop looking Northwest from the HD Mountains along the Pargin River valley, Northeastern San Juan Basin (adapted from http://pelzmann.smugmug.com/gallery/3816101/14/220426587#220426086.

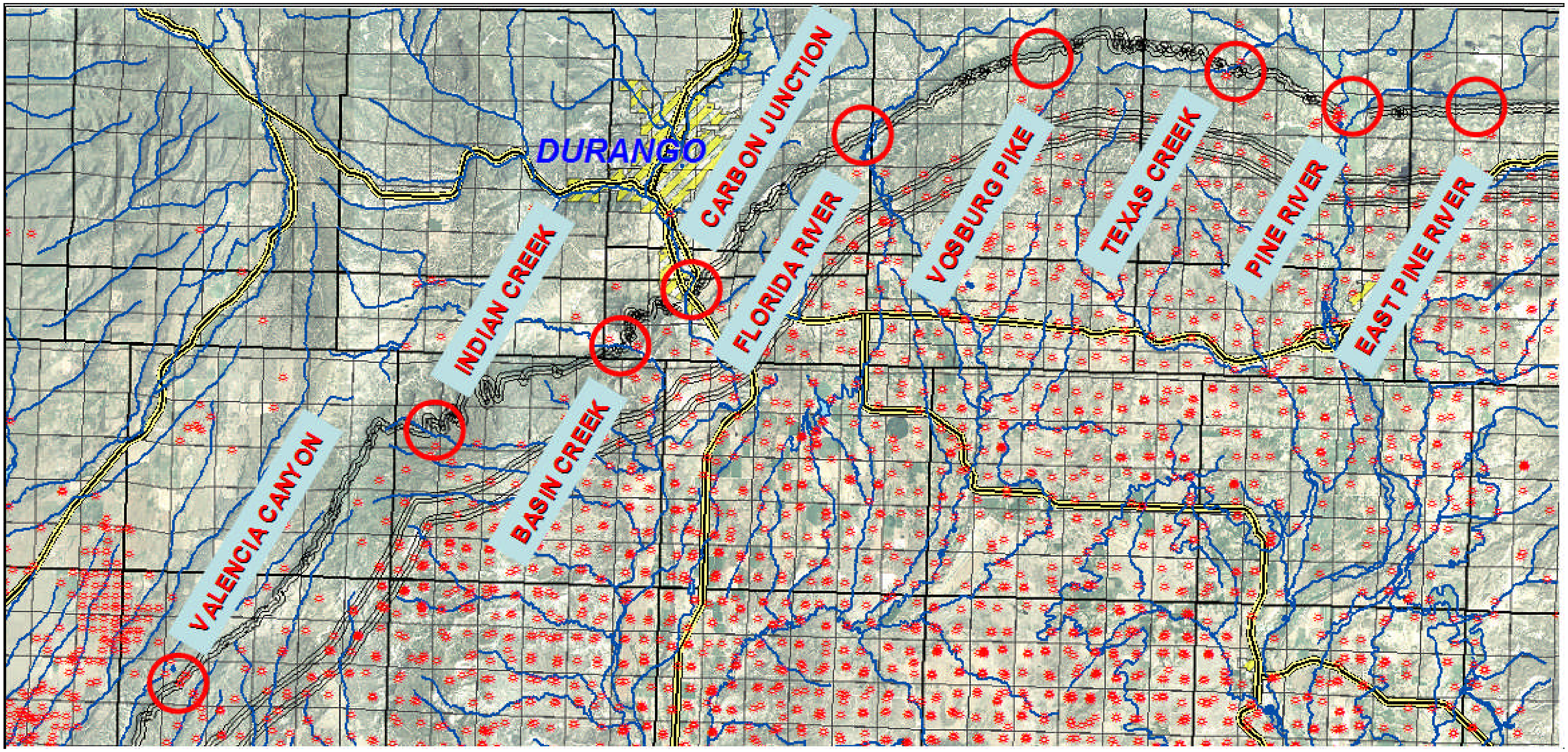
WorleyParsons

resources & energy

19-Oct-08	date	ia	edited by	ia	drawn by		app by

PROJECT NUMBER: C67020000

FIGURE: A1.3



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

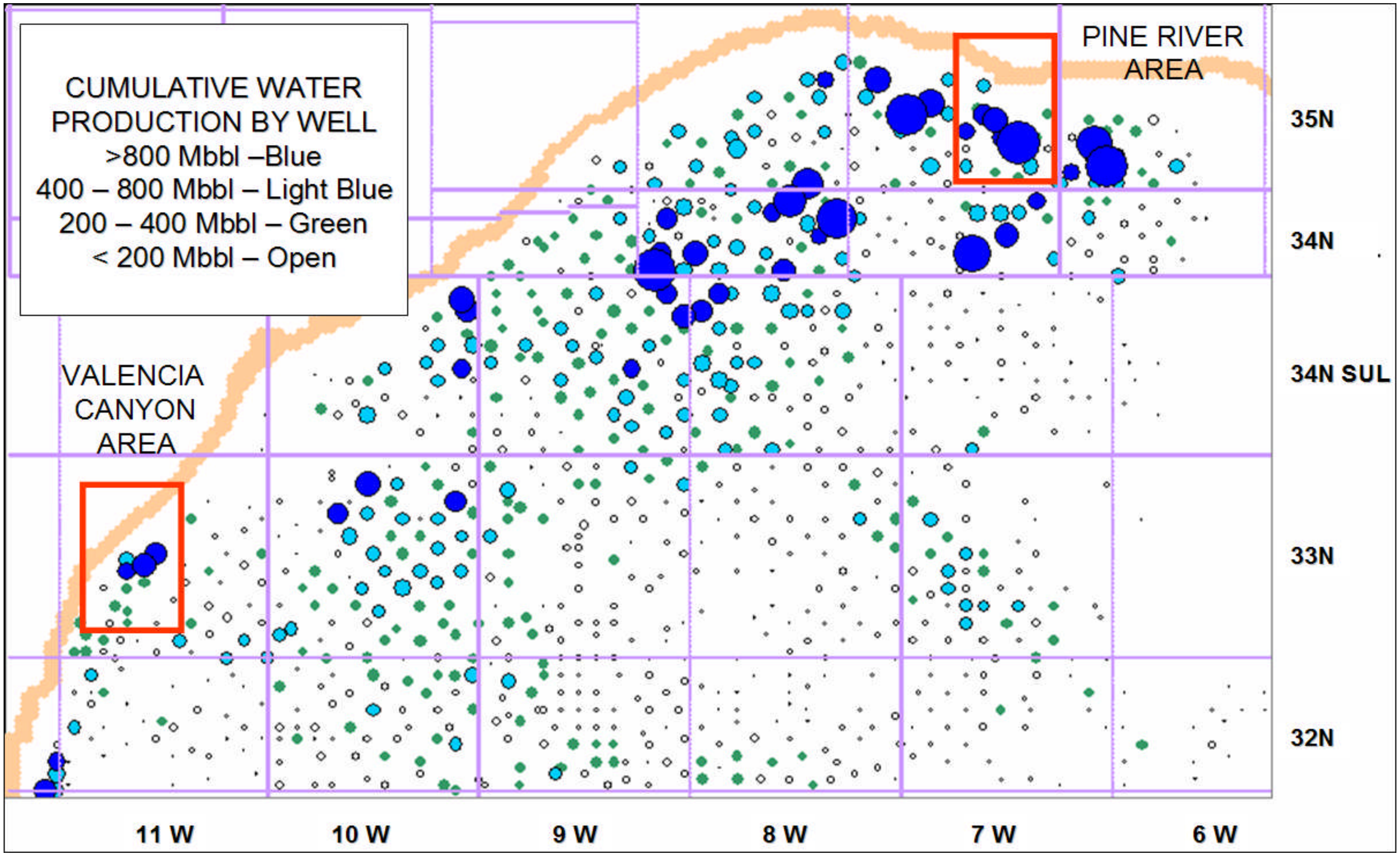
Fruitland Formation outcrop seeps along the northern margin of the San Juan Basin. The northernmost black band represents the Fruitland outcrop belt; the southernmost band is the outer limit of the no-drilling buffer zone established by the COGCC.

WorleyParsons
resources & energy

19-Oct-08	date	ia	edited by	ia	drawn by		app by

PROJECT NUMBER: C67020000

FIGURE: A1.4



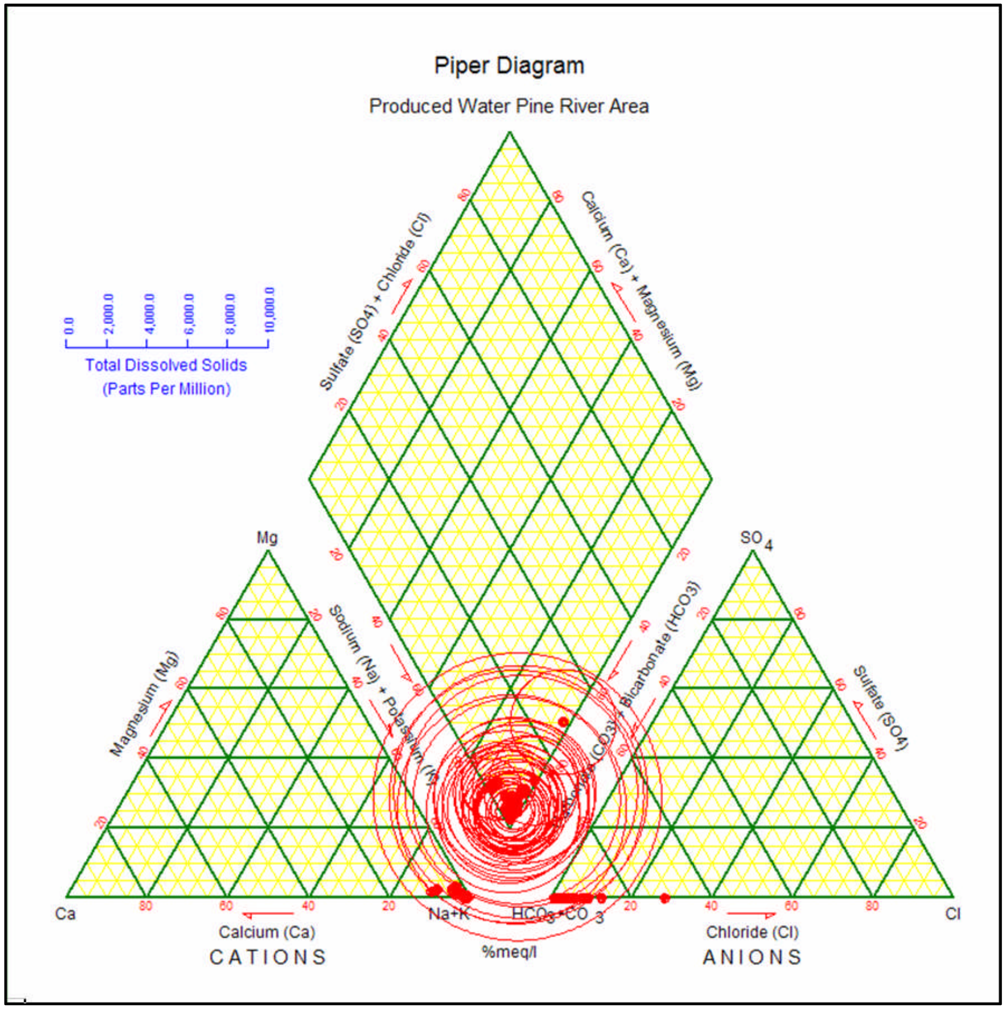
Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Bubble map of cumulative water production showing the Fruitland outcrop belt and two areas of investigation (Adapted from Questa Engineering, 2000).

WorleyParsons
resources & energy

19-Oct-08 date	ia edited by	ia drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: A1.5



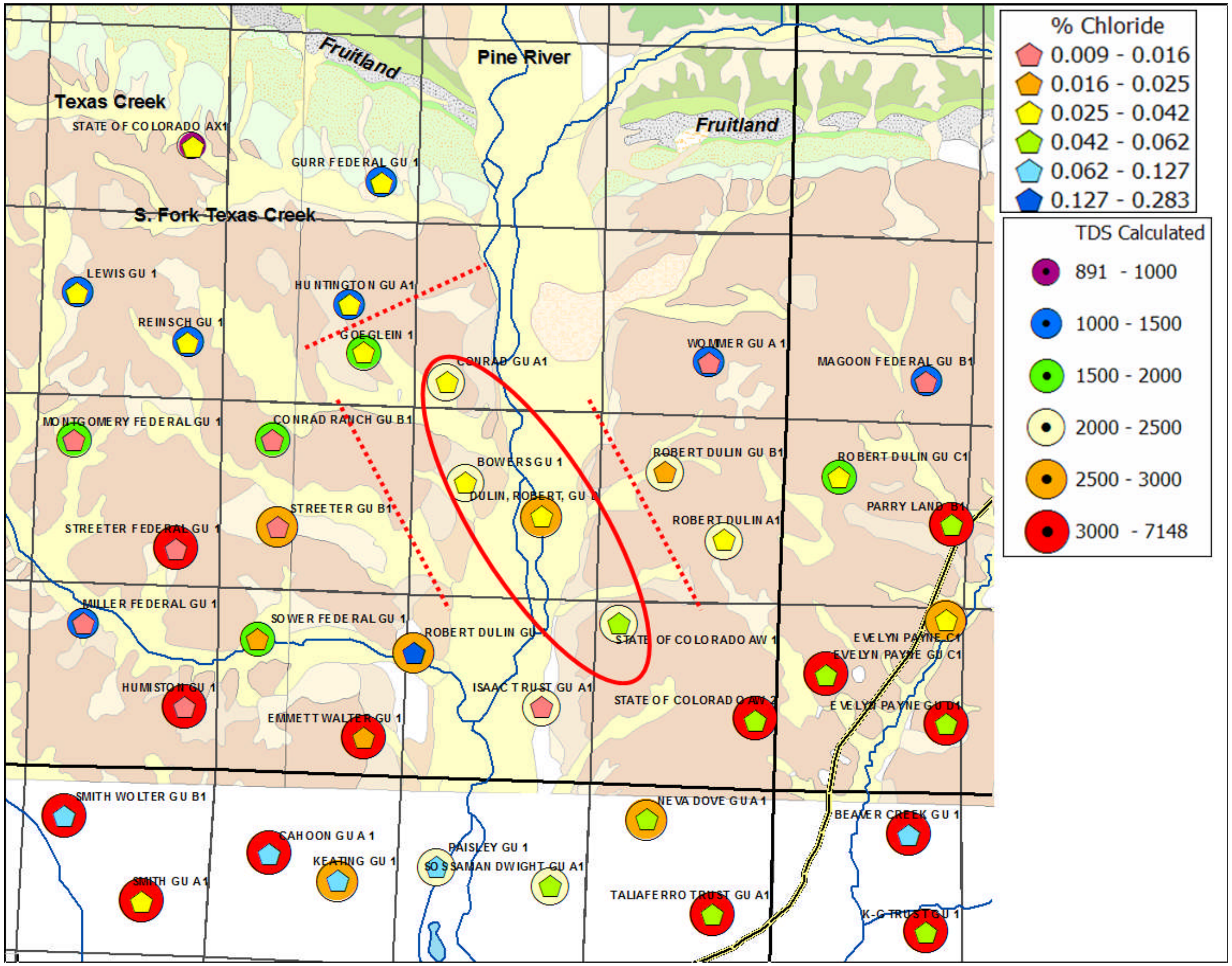
Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

A trilinear diagram for fluids produced from Fruitland Formation wells illustrates that TDS and the relative percent of chloride show the greatest variation and are useful mapping parameters.

WorleyParsons resources & energy

19-Oct-08	date	**Initial**	edited by	**Initial**	drawn by		app by	PROJECT NUMBER: **C67020000**	FIGURE: **A1.6**



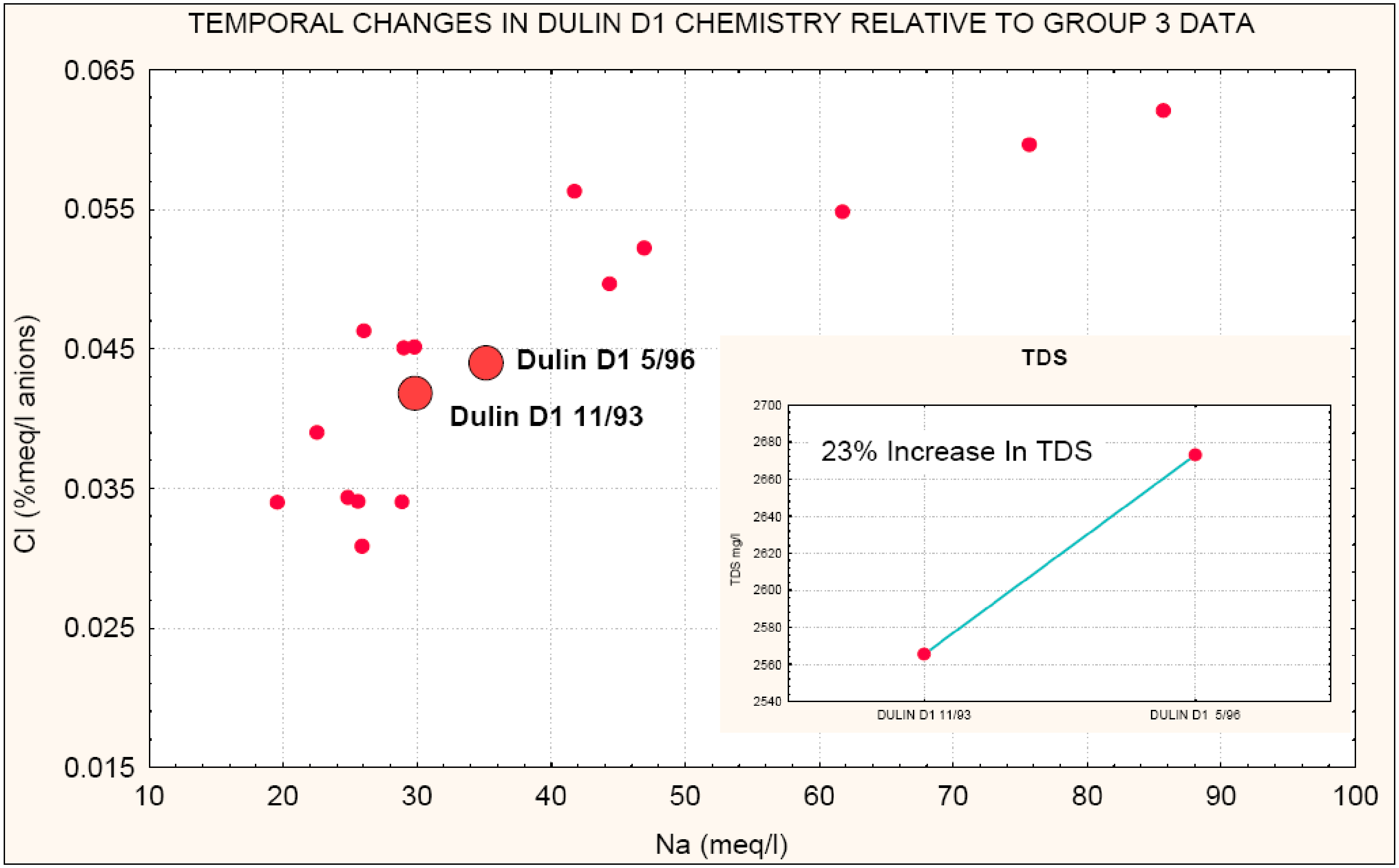
Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

The chemical composition of produced fluids in wells near the Pine River outcrop belt exhibit a strong salinity gradient towards the outcrop. The oval circle depicts wells known to be in hydrologic communication based on well tests. Dotted lines represent proposed hydrologic boundaries established on the basis of well tests.

WorleyParsons
resources & energy

19-Oct-08 date	ia edited by	ia drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: A1.7



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

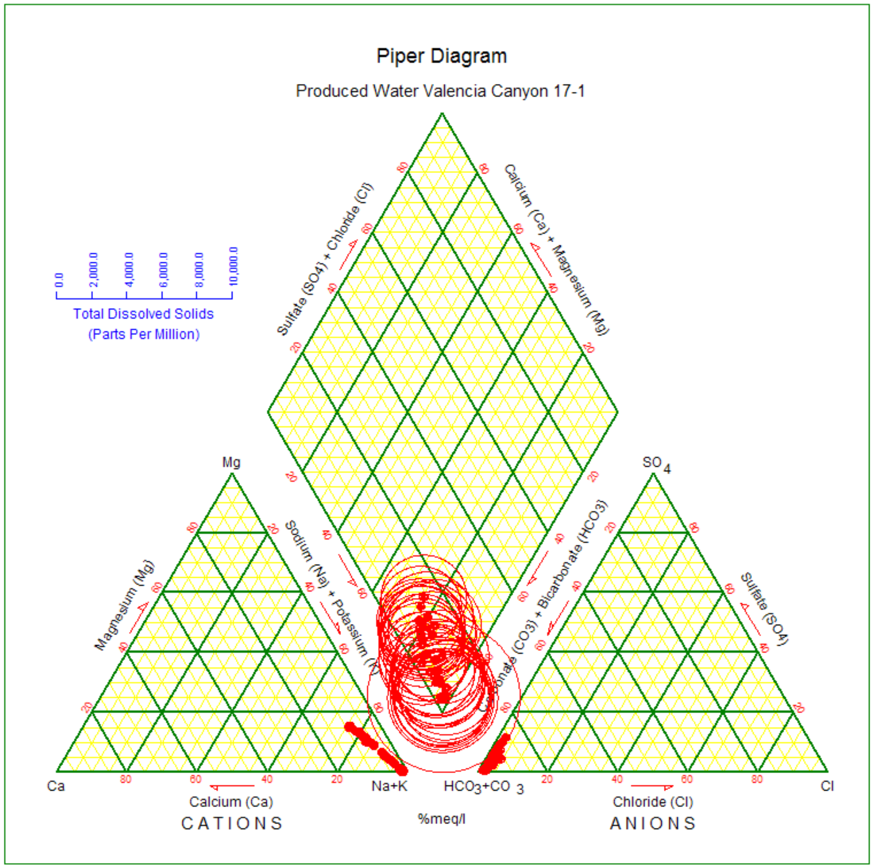
Repeated analysis of fluid composition from the Dulin D1 well near the Pine River show an increase in TDS and sodium chloride salinity derived from the underlying Pictured Cliffs Formation.

WorleyParsons resources & energy

19-Oct-08	date	**ia**	edited by	**ia**	drawn by		app by

PROJECT NUMBER: **C67020000**

FIGURE: **A1.8**

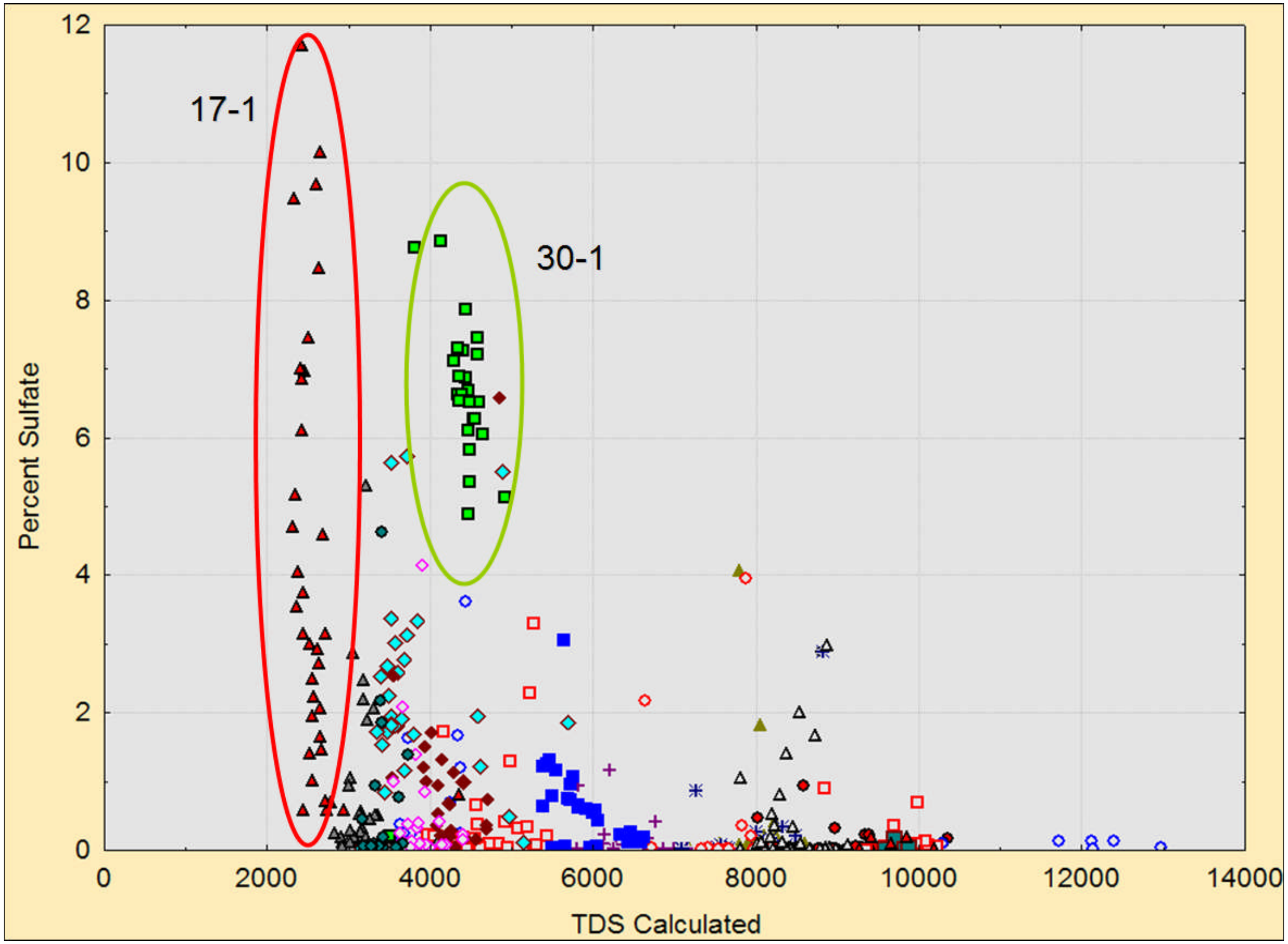


POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Repeated analysis of fluid composition from the Dulin D1 well near the Pine River show an increase in TDS and sodium chloride salinity derived from the underlying Pictured Cliffs Formation.

WorleyParsons
resources & energy

19-Oct-08 date	ia edited by	ia drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: A1.9



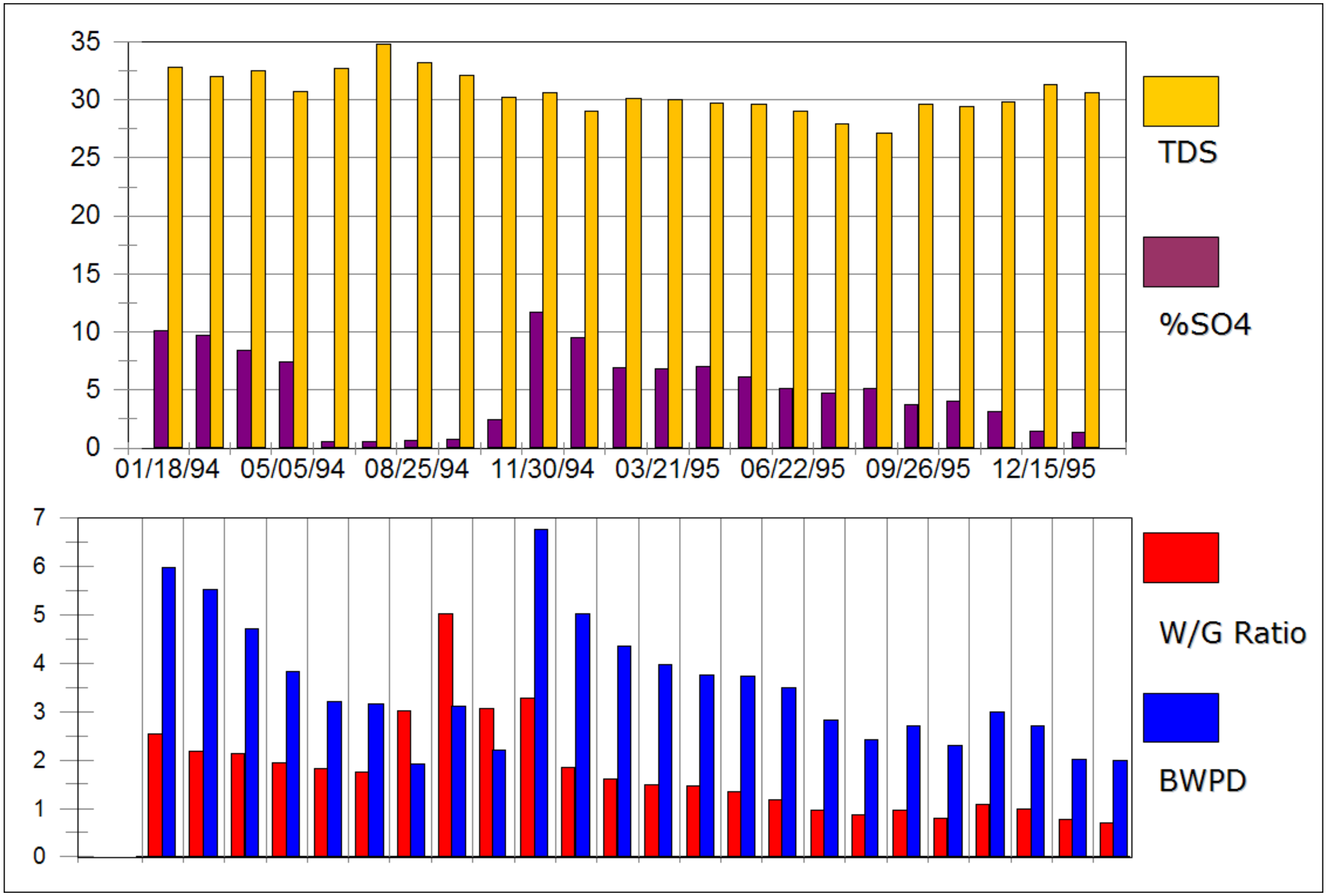
Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

The Valencia Canyon 17-1 and 30-1 wells are the biggest water producers close to the outcrop. Relative to basinward wells (symbols not grouped) both wells produce dilute fluids with elevated sulfate concentrations.

WorleyParsons
resources & energy

19-Oct-08 date	ia edited by	ia drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: A1.10



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Monthly measurements show the direct correlation between increasing produced water volumes, higher water to gas ratios, and increasing dissolved sulfate derived from oxidized (weathered) pyrite along the Fruitland outcrop.

WorleyParsons
resources & energy

19-Oct-08	date	**ia**	edited by	**ia**	drawn by		app by

PROJECT NUMBER: **C67020000**

FIGURE: **A1.11**

Appendix 2 USA Experience: Powder River, Washakie and Black Warrior Basins

APPENDIX 2
POWDER RIVER, WASHAKIE AND BLACK WARRIOR BASINS

1. POWDER RIVER BASIN

1.1 Outcrop seeps

Rawhide Village was developed in 1975 along the Wyodak coal outcrop near Gillette Wyoming on the north side of Little Rawhide Creek, a tributary to the Little Powder River. Local ranchers were aware of historic seeps along Rawhide creek by the outcrop, and it was amusing to at times light the creek on fire during winter months prior to subdivision development. Also prior to development, cores taken to address soil properties in the area were reported to contain gas. At the time subdivision construction began, Amax began developing the Amax Coal Mine on the south side of the creek.

In February 1987 seeps began emerging from cracks in the pavement and into homes on the southern side of the subdivision adjacent to Rawhide creek. Only the southern side of the subdivision was situated directly above the coal outcrop. Subsequent soil gas surveys revealed that gas seeps, emanating at concentrations above the upper explosive level for methane, were also entraining dangerous concentrations of hydrogen sulfide. One home was found to have dangerous concentrations of methane and hydrogen sulfide. Alarmed, state and municipal agencies began selected home evacuations beginning in late February. By the end of May, several residents complained of medical problems and illnesses, and there were two confirmed cases of hydrogen sulfide poisoning. Symptoms included dizziness, nausea, sore throat, and rashes.

In early June, the Campbell County Board of County Commissioners evacuated all 180 families from the entire subdivision. The order was rescinded by late June on the condition that residents install gas detectors in their home. On September 4, President Reagan declared the subdivision a disaster area, overruling a Federal Emergency Management Agency denial for relief. Rawhide Village residents received federal relief aid and were granted $2,000,000 from the Abandoned Mine Reclamation Fund.

Several lawsuits arose as a consequence of these events. Plaintiffs sought compensation from both Amax and the County for loss of value and use of property, including loss of all payments on property, loss of value of improvements to property, additional costs, expenses, interest, and other amounts to obtain new housing, and diminished value of replacement housing. Other claims included emotional distress as a consequence of property loss and as a consequence of denied due process and fairness arising from the evacuation orders. Causation was cited as resulting from mine development which had created a cone of depression in the coal, thereby allowing it to desorb methane that could migrate to the surface.

Based on data from monitor wells, coring, and water level monitoring, it was determined that coal along the outcrop contained less than 5cf of gas per metric ton, and that mining had potentially induced a water level drop of less than a meter near the subdivision. Therefore, the source of seeps could not be attributed to dewatering (Glass et al., 1987 and Jones et al. 1987). One monitor well drilled nearly 1 km. west of the subdivision, produced gas from coal and sandstone at a depth of 110 meters a rates exceeding 1.2 MMcfd.

Mass balance calculations showed that this much gas could not be derived from coal even if all the coal within an area of greater than 26 sq. km had been completely drained of gas. Interference testing further established a direct connection between gas pressures at the monitor well site, and seepage along Rawhide Creek. Opening the gas valve at the monitor well caused seeps at the creek to respond and abate in less than 30 minutes. The gas at the site was interpreted to have accumulated in a fractured reservoir created in response to differential compaction of coal and sand at the edge of a large sandstone channel. Subsequent legal claims attributed causation as resulting from lowered threshold capillary gas entry pressures in the fracture system induced by small changes in stress associated with the observed water level declines. The monitor well was converted in following years to the first commercial coalbed gas well in the Powder River Basins, and the seeps were mitigated.

In an environmental impact assessment for coalbed gas development in the Powder River Basin, the BLM established a 50 foot water level decline along the outcrop as the minimum drawdown required to allow coal to desorb methane at the outcrop (BLM, 2003- Chapter 4: Environmental Impacts). This was established on the basis of monitor wells and observations at the Belle Ayr Mine, also near Gillette Wyoming. The BLM proposed that gas monitoring of enclosed well house and basement spaces would be sufficient to mitigate the threat of gas migration in homes inside a 50 foot contour line of mapped water level declines. The BLM further recognized the potential for gas migration near production areas close to the outcrop where methane migration to the surface could be enhanced by oriented shallow faults, fractures, and sandstone layers.

1.2 Abandoned wells

In their 2003 environmental impact statement, the BLM recognized the risk that conventional wells in the vicinity of CBM production may be inadequately cased or plugged. Such wells could allow gas to migrate to the surface, particularly in areas where CBG development occurs near the outcrop. The BLM also cited boreholes drilled to evaluate uranium potential as inadequately plugged and a potential risk for methane migration to the surface. Although not mentioned, improperly abandoned coal exploration wells are also a potential source of methane contamination. Photo documentation shows several of such wells spewing gas and water early in the DBG development history of the basin.

2. WASHAKIE BASIN, ATLANTIC RIM CBG PLAY

The Atlantic Rim Field, along the eastern margin of the Washakie Basin is the most recent CBG development in the Rocky Mountains (Lamarre and Ruhl, 2004). Coalbed gas production, which began in 1999, is from coal seams in the Allen Ridge and Almond Formation of the Mesaverde Group. Water disposal via injection into deep aquifers began in 2001. Figure A2.1 shows the location of the Mesaverde Group outcrop, the structure on the top of the Almond Formation, and the location of several large gas seeps. The seeps are referred to by the BLM as “mud pots” because of their similar appearance to geothermal springs in Yellowstone National Park. Figures A2.2 and A2.3 show photos of two of these seeps. The mapped seeps were observed by the USGS in 1963, and show up on air photos taken in 1975 and 1994. The BLM also reported seeps in the area in the early to mid 1980’s.

In 2007, litigation arose in response to the BLM’S Record of Decision (ROD) allowing the development of up to 2,000 new coalbed gas wells in the area. Approximately 1,800 wells are to be drilled to develop CBG in the Mesaverde Group, and another 200 wells are to be drilled to access deeper conventional natural gas resources. Five conservation groups, including Natural Resources Defense Council, Biodiversity Conservation Alliance, Wyoming Outdoor Council, Western Watershed Project and Wyoming Wilderness Association sued the BLM. These groups sought an injunction to halt drilling in the Atlantic Rim Project Area on the grounds that the BLM’s Environmental Impact Statement (EIS) failed to adequately discuss, analyze and evaluate the environmental impact of a possible increase in methane seeps and adverse impacts on groundwater quality, recreation, wildlife, and habitat.

The court denied the injunction because it found no evidence of imminent and irreparable harm and no evidence that methane seeps have ever injured hikers or campers in the past. It also found that in its EIS document, the BLM appropriately noted the potential increased risk of methane seeps that might contaminate groundwater and destroy vegetation. Furthermore, both the BLM FEIS and the BLM ROD discussed requirements to install groundwater monitoring wells and the collect isotopic data as risk mitigation measures.

The installation of monitor wells, chemical and isotopic analysis of gas in both producing CBG gas wells and seeps, and chemical and isotopic analysis of water from production wells, springs, and gas seeps is under way. The BLM, the University of Wyoming, and CBG operators are currently all involved in collecting and analyzing data. Results of sample analyses using strontium isotopes, and stable carbon, oxygen, and deuterium isotopes in water will soon be published (Fred McLaughlin personal communication).

3. BLACK WARRIOR BASIN

Although there are natural gas seeps in the Black Warrior Basin (Clayton et al. 1994), none are known to be associated with coalbed gas production (Jack Pashin, personal communication). The absence of seeps and be attributed to the strong degree of reservoir compartmentation and thick mudstone units that separate the different coal seam targets in the basin (Pitman et al., 2003, Pashin 2004, and 2005). Recent investigations related to the potential for sequestering CO_2 in Black Warrior Basin coals have evolved into discreet fracture network modeling efforts used to address gas containment. Such models may be useful to address the risks of coalbed gas migration to the surface.

4. SAN RAFAEL SWELL, FERRON COAL TREND

Stolp et al., 2006, reported on a joint USGS and Utah Department of Natural Resources, Division of Oil, Gas, and Mining program to monitor soil gas and selected groundwater sites in methane-gas production fields near residential areas. Twenty perimeter sites around Price, Huntington, Orangeville, and Ferron were monitored annually to determine whether or not methane concentrations were detectable and/or increasing near populated areas. A total of 420 samples were collected from 174 shallow soil gas probes (2- to 4-ft depth) and 15 ground-water sites. Multiple samples were collected from 75 sites for the purposes of monitoring trends in methane concentration with time.

Twenty samples from 11 sites had concentrations greater than 10,000 parts per million by volume (ppm). Such relatively high concentrations were potentially attributed to either coal-bed gas drilling activities or well maintenance activities that disturbed the groundwater environment. At 15 of the 75 sites where temporal data were collected, soil-gas methane concentrations were inconsistent. Results did not show any obvious, widespread, or consistent migration of methane gas to the near-surface environment. If anything, there appeared to be a decrease in methane concentration with time. There were no analyses of gas composition reported that could have been used to determine gas sources.

5. SUMMARY OF RISK

5.1 Litigation

Litigation is a significant consequence of methane migration potentially associated with CBG development. In the U. S. during the past twenty years, the targets for litigation have shifted from gas operating and mining companies to federal and state agencies. In part, this reflects a shift in areas being developed for CBG from privately owned fee lands to split estate federal and state lands. In a split estate, the surface owner does not own the underlying mineral rights. The shift also reflects the increasing and maturing influence of well-funded non-governmental organizations and grass roots citizen groups.

5.2 Risk of hydrogen sulfide toxicity

The consequences of both short and long-term exposure to hydrogen sulfide gas in the work place have long been recognized and well-documented (Chou, 2003). Exposure to this gas in the domestic home environment is rarely addressed even though it is commonplace among homes dependent on domestic water wells. H_2S is extremely toxic and even at low concentrations can have temporary deleterious effects.

At very low concentration, hydrogen sulfide in air is difficult to measure. However, approximately 80% of the human population can detect hydrogen sulfide at concentrations of 0.03 ppm in air. The odor is often likened to the smell of rotten eggs. Above 30 ppm, the odor is usually described as a sickly sweet odor. In the range of 50 to 100 ppm in air, the gas paralyzes the olfactory nerves and can no longer be detected by smelling.

Because the nose is so sensitive to H_2S, it can be used as a qualitative gage. Gas toxicity relative to this olfactory gage can be summarized as follows:

- Faint odor: 0.3 to 0.77 ppm. About 40% of the population senses discomfort at this range.
- Moderate odor: 0.77 to 4.6 ppm. Headaches, depression, and dizziness are common in this range. The higher end of this range is accompanied by coughing, throat irritation, and shortness of breath (2.5 – 5 ppm).
- Strong unpleasant odor: 4.6 ppm to 27 ppm. Nausea, vomiting, irritability, sleep loss, fatigue, and memory loss can occur in the range from 0.32 to 20 ppm. Loss of appetite and weight loss can occur in the range of 0.7 to 40 ppm. Ear, nose, and throat irritation and bronchitis can occur at 10 ppm. Eye irritation can occur in the range of 10 to 20 ppm.

Other complaints that are typical for people exposed to low concentrations of H_2S in air and water include disorientation, dry itchy skin, sensitivity to light, and allergic reactions. The symptoms described above are temporary and are relieved as soon as the person is not longer exposed. It is not uncommon for people to complain about symptoms when bathing. The air in small, closed bathrooms and shower stalls can accumulate toxic concentrations of hydrogen sulfide when exposed to relatively small volumes of hot running water. The consequences of long term exposure to low concentrations of H_2S are still not fully known or documented.

Routine Biologic Activity Reaction Test (BART™) cultures (Cullimore, 2008) of water well samples collected for baseline studies in the US reveal that a majority of wells are infected with aggressive colonies of sulfate-reducing bacteria. These are responsible for sulfide odors detected while sampling, high dissolved sulfide concentrations detected in the field with colorimetric HACH™ tests, and grey-colored, sometimes effervescent water. Most of the sulfide present in these wells is due to poor water well maintenance practices.

Anaerobic sulfate reduction coupled with oxidation of dissolved methane will contribute to high dissolved sulfide concentrations. Bubbling of methane through the water column of a domestic water well will displace oxygen in a well and promote stagnant conditions. If sulfate bearing waters become stagnant as a result of contamination, then the well is at risk for entraining dissolved hydrogen sulfide.

REFERENCES

Bureau of Land Management, Rawlins Field Office, 2006, Final Environmental Impact Statement Atlantic Rim Natural Gas Field Development Project.

Bureau of Land Management, 2003, Final Environmental Impact Statement and Proposed Plan Amendment for the Powder River Basin Oil, and Gas Project: Wyoming State Office, Buffalo, Wyoming, Oil & Gas EIS Amendment of the Powder River.

Chou, S. J., 2003, Hydrogen Sulfide: Human Health Aspects, World Health Organization CICADS 53, http://www.inchem.org/documents/cicads/cicads/cicad53.htm

Clayton, J. L., J. S. Leventhal, D. D. Rice, J. C. Pashin, B. Mosher, and P. Czepiel, Peter, 1994, Atmospheric methane flux from coals— preliminary investigation of coal mines and geologic structures in the Black Warrior basin, Alabama, in D. G. Howell, ed., The future of energy gases: U.S. Geological Survey Professional Paper 1570, p. 471– 492.

Cullimore, R. D., 2008, Practical Manual of Groundwater Microbiology , Second edition CRC press – The Taylor & Francis Group, 376 pp.

Glass, G.B., Jones, R.W. and De Bruin R.H.,1987, Investigation of the Potential for Near-Surface Explosive Concentrations of Methane to Occur in the Rawhide Village Subdivision, Campbell County, Wyoming: Geological Survey of Wyoming Report for the Wyoming Department of Environmental Quality (unpublished), 7p., 3 plates.

Jones, R.W., De Bruin, R.H., and Glass, G.B. 1987. Investigations of Venting Methane and Hydrogen Sulfide Gas at Rawhide Village, Campbell County, Wyoming, in Rawhide II Project Report, Appendix I, Geology: Wyoming Department of Environmental Quality, Cheyenne, Wyoming (unpublished), 23p., 12 plates.

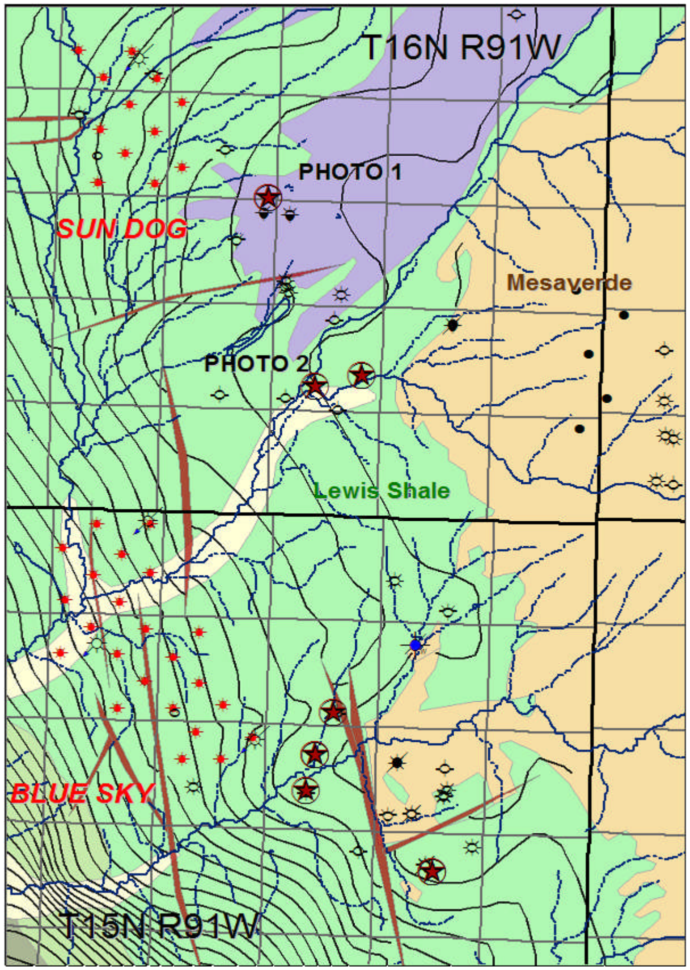
Lamarre, R. A. and Ruhl, S. K., 2004, Atlantic Rim Coalbed Methane Play: The Newest Successful CBM Play in the Rockies, AAPG Rocky Mtn. Sec. Mtg., Denver CO, 5. p.

Pashin, J.C., 2004, Geologic heterogeneity and coalbed methane production - experience from the Black Warrior Basin, in: Warwick, P.D., ed., Selected presentations on coal-bed gas in the eastern United States, U.S. Geological Survey Open-File Report 2004-1273, p.61-92.

Pashin, J. C., 2005, Coalbed Methane Exploration In Thrust Belts: Experience From The Southern Appalachians, USA, Tuscaloosa, Alabama, University of Alabama, College of Continuing Studies, 2005 International Coalbed Methane Symposium Proceedings, Paper 0519, 14 p.

Pitman, J. K., Pashin, J. C., Hatch, J. R., and Goldhaber, M. B., 2003, Origin of minerals in joint and cleat systems of the Pottsville Formation, Black Warrior basin, Alabama: implications for coalbed methane generation and production: American Association of Petroleum Geologists Bulletin, v. 87, p. 713-731.

Stolp B.J., Burr A.L., and Johnson K.K., 2006, Methane Gas Concentration in Soils and Ground Water, Carbon and Emery Counties, Utah, 1995-2003, USGS Scientific Investigations Report 2006-5227, 19 pp.



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Stars show the location of "mud pots" mapped by the BLM in the Atlantic Rim field. The contour interval on top of the Almond Formation is 200'. Faults, contour data, and well locations are provided courtesy of Andarko Petroleum. The Almond Formation is not differentiated in the geologic map of the Mesaverde.

WorleyParsons
resources & energy

19-Oct-08 date	ia edited by	ia drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: A2.1

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Large gas seep identified in Figure A2.1 as "PHOTO 1".

WorleyParsons
resources & energy

19-Oct-08	date	ia	edited by	ia	drawn by		app by	PROJECT NUMBER: C67020000	FIGURE: A2.2

Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Smaller gas seep identified in Figure As.1 as "PHOTO 2".

WorleyParsons
resources & energy

19-Oct-08 date	ia edited by	ia drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: A2.3

Appendix 3 USA Experience: Raton Basin

APPENDIX 3
RATON BASIN SECTION

1. COGCC RATON BASIN BASELINE SURVEY

In 1996, the Spanish Peak Field, along the Purgatoire River just west of Trinidad, CO, had 53 active wells. Since then, more than 2500 additional wells have been drilled on the Colorado side of the basin. As shown in Figure A3.1, the heart of the productive coalbed gas fairway is located between the Apishapa River and the Colorado -New Mexico border, along the Purgatoire River just west of the Trinidad reservoir. Gas production comes from multiple coal seams of the Upper Cretaceous Vermejo and overlying Raton Formations.

Between 2000 and 2003, the Colorado Oil and Gas Conservation Commission (COGCC) sponsored an environmental baseline study encompassing a large area within both Las Animas and Huerfano counties. The study was designed to help regulators address whether there were any links between coalbed gas development and natural gas in the shallow surface and groundwater environment. Specific objectives were as follows:

- to collect, compile, analyse, and interpret a variety of environmental baseline data;
- to make the data widely available to COGCC staff, industry, and the general public;
- to describe useful methods for addressing complaints related to groundwater, and;
- to recommend protocols for future monitoring, sampling, and analysis.

Sponsored activities included mapping of current and historical coal mines and coal exploration wells, a soil gas survey using a truck-mounted infrared detection sensor, water and gas sampling of 50 producing CBG wells and 100 domestic groundwater wells throughout the basin, and compiling historic water quality data from both producing gas and domestic water wells. Data and reports are available at the COGCC web site (http://oil-gas.state.co.us/).

Several important observations and conclusions from the COGCC survey are relevant to the issues of risk analysis and mitigation in this report.

1.1 Soil Gas Survey Results

The truck-mounted infrared soil gas detection survey covered 2749 line miles. Along route, 67 seeps of varying magnitudes were detected. The majority of seeps were clustered within the Purgatoire River drainage basin in an area defined by outcropping and shallow subcropping gassy Raton Formation coals. The survey detected seeping hydrocarbons along exposed Raton Formation coal seam outcrops, well-known historic natural gas seeps bubbling up along the banks of the Purgatoire River, fractured fairways associated with both shallow coal seam subcrops and intrusive dikes from the Spanish Peaks volcanic complex (Figures A3.2 and A3.3). All detected naturally-occurring gas seeps were associated with dead or dying vegetation anomalies expressed along broad patches of ground or sharply defined linear alignments. The most numerous gas seeps were detected near man-made conduits of gas from Raton Formation coals to the surface. These included conduits associated with active and abandoned coal mines, coal gas development infrastructure, electric and telephone utilities infrastructure, and water wells. There was no obvious spatial correlation between the distribution of seeps and the distribution of producing gas wells. Such results illustrate the importance of identifying natural and man-made conduits for CBG associated with coal seam outcrops and subcrops that are not associated with CBG production.

1.2 Results of Sampling and Analysis of Natural Gas From Producing Gas Wells and Dissolved Natural Gas in Domestic Water Wells

Of the 100 domestic water wells sampled by the COGCC, 72% contained measurable amounts of dissolved methane. By including an additional 147 data points from producers in the basin collected before 2004, results show that 47% of domestic water wells contained measurable amounts of dissolved methane. Dissolved methane concentrations ranged from 0.02 μg/L to 38 mg/L. 15% of all samples contained more than 2 mg/L methane, and 8% contained more than 10 mg/L. 10 mg/L is the arbitrary limit established by the COGCC requiring stable isotopic analysis of methane found dissolved in domestic water wells. The spatial distribution of water wells containing dissolved methane was principally contained within the same area where gas seeps were detected - where Raton Formation coals are either exposed at the surface or buried below thin overburden Cuchara Formation sediments or alluvium (Figure A3.4).

Selected domestic water well samples were analyzed for dissolved gas composition and stable isotopic ratios of deuterium, carbon in methane, and carbon in dissolved inorganic carbon. Produced gas samples were also sampled and similarly analyzed to provide benchmarks for comparison against dissolved gas data from domestic water wells. Results show that methane and ethane were the only hydrocarbon gas constituents observed in all samples. Methane to ethane ratios were all in excess of 1000, indicating a biogenic component to gas origins in the basin (Whiticar, 1999). Stable isotope ratios for deuterium and carbon in methane among all samples extend along a large range of values (Figure A3.5). On this basis, the COGCC concluded that these stable isotope ratios are useful for forensic analysis of gas origins in groundwater.

Stable isotope data for carbon in dissolved inorganic carbon (DIC) are also useful discriminators of water origins. Figure A3.6 illustrates that there is a bimodal distribution of carbon isotope ratios in DIC. The strongly positive $\delta^{13}C_{DIC}$ ratios exhibited among produced gas well samples, centered near a value of + 25 per mil, show that produced methane originates in some part from the bacterial reduction of CO_2 to methane. Groundwater samples, on the other hand have $\delta^{13}C_{DIC}$ ratios that are negative, and centered on a value of -12 per mil. Such values correspond to DIC in equilibrium with normal soil gas values for CO_2

at ambient groundwater temperatures. The histogram further shows that the ratio of $\delta^{13}C_{DIC}$ in producing wells tail towards negative values and that the ratio among groundwater wells tail towards more positive values. Figure A3.7 illustrates that there is a linear relationship between $\delta^{13}C_{DIC}$ and $\delta^{13}C_{Methane}$. The data fall along a mixing line with what appear to be end member compositions of primary biogenic gas in groundwater, and secondary biogenic gas in produced gas samples.

The relevance to this report of discussing stable isotope values from the Raton Basin is two-fold. Geochemical variables useful for differentiating produced CBG gas from naturally occurring gas in groundwater are limited to methane/ethane ratios, stable isotopes ratios of carbon and deuterium in methane, and stable isotopes of carbon in DIC and/or CO_2. Results show that there is a large spread of values, particularly among the stable isotopes, that are useful for forensic analysis of gas origins. More important is the observation that stable isotope ratios may be useful indicators of mixed produced gas and groundwater sources resulting from either vertical or lateral migration of natural gas in groundwater.

1.3 Results of Sampling and Analysis of Water From Producing Gas and Domestic Water Wells

Water quality analysis of produced waters can provide valuable information on potential links with fluids that are not entirely confined within coal seam aquifers. Data from the Raton Basin provide a good example of this. Surface and shallow groundwaters have two hydrochemical water type end member compositions: calcium-magnesium bicarbonate, and sodium sulfate. Although sodium chloride is a minor component in some of these fluids, almost all samples can be characterized as comprising mixtures of both end-member water types (Figure A3.8). Calcium-magnesium bicarbonate is characteristic of low TDS surface waters and shallow alluvial aquifers; sodium sulfate is characteristic of higher TDS bedrock aquifers where oxidized pyrite is the likely source of pyrite. The median TDS value for 290 groundwater samples was 610 mg/L; the mean value for all samples was 910 mg/L.

Produced water samples from Vermejo coal seam aquifers are composed of two different hydrochemical water types: sodium bicarbonate and sodium chloride (Figure A3.8). Almost all produced water samples can be characterized as comprising mixtures of these end-member water types. The median TDS value for produced water samples was 3295 mg/L; the mean value was 3372 mg/L.

Figure A3.9 graphically illustrates the spatial distribution of TDS values from sampled producing gas wells and wells containing sulfate ions. Sulfate values illustrated are based on the percent of sulfate, in milliequivalents per liter (meq/L), relative to the total concentration of all anions in meq/L. Results show that high TDS fluids with little or no sulfate are centered in the area with the highest gas production rates, along the Purgatoire River, just west of the Trinidad reservoir. Low TDS fluids containing a large dissolved sulfate component are clustered at the southwestern corner and the northern-most grouping of wells in the illustration.

1.4 Analysis of Water Production Rates

Figure A3.10 shows a graphic summary of water production data from 604 gas wells in the Raton Basin. The totals represent cumulative production for the first six years of production. Among the 454 gas wells in the heart of the coalbed gas trend, the average total production per well was 290,000 barrels. All of these wells produced commercial quantities of gas. By comparison, 50 wells just south of the Cucharas River in the Purgatoire River Field of Huerfano County, produced an average total of 4.5 million barrels per well in the first six years of production or less. Only a few of these wells have produced commercial quantities of natural gas. Furthermore, unlike the 454 gas wells that produced increasing volumes of gas with corresponding decreasing volumes of water, water production rates from the 50 wells has not declined.

Wells which were identified as producing low TDS fluids with dissolved sulfate identified in the previous section are among the highest water producers and lowest gas producers in the basin. Such results demonstrate that produced fluids in the Purgatoire River Field cannot be entirely derived from Vermejo Formation coals. Those wells were singled out in the COGCC baseline study as indicating a potential for vertical and lateral communication of Vermejo coal seam aquifers with shallow groundwater aquifers and or nearby mines. The report recommended continued investigation and temporal monitoring of water quality to determine whether Vermejo coal aquifers in the area were in vertical communication with shallow aquifers.

2. RECENT GAS SEEPS IN THE RATON BASIN

2.1 Purgatoire River Field Water Wells

In May of 2007, within the area defined as the Purgatoire River Field in Huerfano County, the COGCC received its first complaint that methane was bubbling through the water column in a domestic water well (Dillon et al, 2007). Shortly before that time, several large volume pumping CBG wells were installed in the field to accelerate dewatering rates. In June of 2007, an explosion occurred in a water well pump house associated at a residence located in the NE¼ NW¼ Section 15 Township 29 South.

Range 67 West. A week later, the COGCC received another complaint regarding gas in a water well which, later confirmed with a combustible gas detector in the SW¼ NW¼ Section 3 Township 29 South, Range 67 West. Subsequent detailed investigations of all water wells in a 13 square mile area revealed that 26 of 70 domestic water wells in the area were contaminated with methane (Norwest Questa Engineering, 2007, Figure A3.11). A few of those domestic water wells were documented to be producing in excess of 10 MCFD of methane. Stable isotopic analyses of deuterium and carbon in methane from 2 water wells confirmed a source of gas from Vermejo Formation coals. Consequently, in July, 2007, Petroglyph voluntarily and temporarily shut in its Huerfano County wells until a satisfactory mitigation plan could be proposed to the COGCC.

In December 2007, other reports released by Norwest Questa Engineering (available on the COGCC web site) documented results of their investigations. These summarized CGB well water production volumes, water wells surveyed for gas content, gas flow rates in water wells, casing head (bradenhead) pressure monitoring results, potentiometric head measurements in both producing gas and water wells, results of an airborne laser survey to detect seeping soil gas methane, and reservoir engineering reservoir models. Data collected for their study are available on the COGCC web site in Microsoft Excel spreadsheet format.

Although the Norwest Questa study failed to identify a specific source location for the gas seeps, the conclusions reached were that buoyant methane may be migrating vertically along intrusive dike swarms in the immediate area. It is significant that the area targeted for more detailed evaluation on the basis of the COGCC baseline survey corresponds to the area of recent gas seeps around the Purgatoire River Field

2.2 Water Wells Completed in or in Close Vertical Proximity to Coal Seams

The COGCC baseline study, and Watts, 2006, both identified water wells at risk of methane contamination and water level drawdown if they were completed in close vertical proximity to producing coal seams. Both reports cite that a vertical separation of less than 30 meters between a producing coal seam interval and a screened water well interval puts a water well at risk for either water level drawdown or methane contamination. Based on gas well and water well completion data, only two small areas in the basin were identified in these reports as areas where water wells are at risk of being influenced by CBG operations.

Only one Raton Basin water well, completed in coal, has been documented to contain high levels of dissolved methane (Norwest Questa Engineering, 2007). There are also a few undocumented anecdotal stories that CBG operators in the basin have replaced a few water wells completed in producing coal seam intervals.

2.3 Seeps Along Outcrops

In 2004, the COGCC received 2 complaints about methane seepage near coal seam outcrops. According to both residents, the impact of seeping methane was observed on the basis of growing patches of stressed and dying vegetation. The seep areas appear to be growing, but the COGCC has not been able to attribute a direct link to CBG production. The nearest producing well is approximately 1 mile down dip of the seep areas.

In the Norwest Questa risk mitigation report on the Purgatoire River Field, they mention that an airborne laser survey detected 22 emission points for soil gas methane along the Vermejo Coal outcrop belt (Figure A3.11). By comparison, only one methane seep was detected along the same outcrop area in the 2001 COGCC baseline study. Because the two independent soil gas survey methods were not similar, it is difficult to ascertain whether downdip production may be contributing to increased seep rates along the outcrop belt. According to the Norwest Questa reports, water level data from domestic water wells do not support a hypothesis that down-basin water production is linked to dewatering and associated desorption of coal at outcrop seeps. The reports do not address the potential for updip methane migration, and no stable isotope measurements were made to establish the source of gas. Additional planned soil gas seep monitoring of the outcrop belt over the next few months of 2008 should shed more light on this topic.

2.4 Abandoned Wells

There has been one documented explosion in the Raton Basin due to gas seeping from an abandoned gas well. In 2007, a new home site was placed on an abandoned well pad because the land surface had been graded. As the roof and exterior walls were being closed in, the home exploded. Several people were injured as a result of the explosion. The explosion was attributed to the build up of natural gas seeping from a plugged and abandoned well. The abandoned well casing was cut off below grade and buried at the pad site.

3. RISK AND CONSEQUENCE ASSESSMENT SUMMARY

- Outcrop belts are geologic hazards;
- Improperly abandoned natural gas wells are geologic hazards;
- Water wells completed in coal seams will always have the potential to release methane if the aquifer becomes depleted in response to either consumption, drought, or both. Risk assessment should include mapping the distribution of water wells completed in coal;
- Water wells completed in intervals within 30 meters of a producing coal seam interval are at risk of being influenced by production. Risk assessment should include mapping the distribution of both water well completion interval depths and producing coal interval depths;
- At times, several factors considered in combination are required to address risk for methane migration;
    - Water production rates that are far in excess of that predicted to originate from coal seams are an indication that either a coal seam aquifer is not confined or that the seam is in communication with another productive aquifer;
    - Analysis of produced water chemistry should be used to complement concurrent potentiometric measurements, particularly if source chemistries from a variety of aquifers can be distinguished. In the Raton basin, low salinity fluids containing dissolved sulfate are a harbinger of communication with shallow aquifers. Risk assessment should include temporal sampling, analysis, and mapping of changes in water quality among CBG wells that produce statistically large volumes of water.

- Baseline surveys in the Raton Basin established that intrusive dikes provide natural gas with pathways for vertical migration to the surface. CBG wells in areas of the basin with large intrusive dike swarms and large produced water volumes should be carefully monitored throughout their productive life.

- Water wells in proximity to CBG production areas at risk for vertical methane migration should be regularly sampled and analysed for their dissolved gas content and composition.

REFERENCES

O'Leary, M. H.,1981, Carbon isotope fractionation in plants, Phytochemistry, V. 20, p. 553-567.

COGCC, 2007, Cause No. 1-E, Order No. 1E-6 http://oil-gas.state.co.us/orders/orders/1E/6.html

COGCC Staff, 2003, Raton Basin COGCC staff conclusions, http://oil-gas.state.co.us Library, Raton Basin.

Dillon, D., Ash, M., and Gintautas, P., 2007, COGCC Petroglyph hearing staff presentation, http://oil-gas.state.co.us (Raton Basin, Huerfano County, COGCC Staff Presentation at Petroglyph Hearing.pdf (12/12/2007) 2.4 mb.

Gorody, A. W., 2003, Slide Presentation Overview of the Raton Basin Baseline Study, http://oil-gas.state.co.us Library, Raton Basin.

Gorody, A. W. 2002-2003, Raton Basin COGCC summary slides and notes: Results of a COGCC-sponsored baseline environmental data survey, Raton Basin, Colorado, http://oil-gas.state.co.us Library, Raton Basin.

Norwest Questa Engineering, 2007, Methane investigation, monitoring, and mitigation program report, Report number: QE-24420071206 http://oil-gas.state.co.us/

Hemborg, H. T., 1998, Spanish Peak field, Las Animas County, Colorado: geologic setting and early development of a coalbed methane reservoir in the central Raton basin: Colorado Geological Survey Resource Series 33, 34 p.

Watts, K.R. , 2006, Hydrostratigraphic Framework of the Raton, Vermejo, and Trinidad Aquifers in the Raton Basin, Las Animas County, Colorado, USGS Scientific Investigations Report 2006-5129.

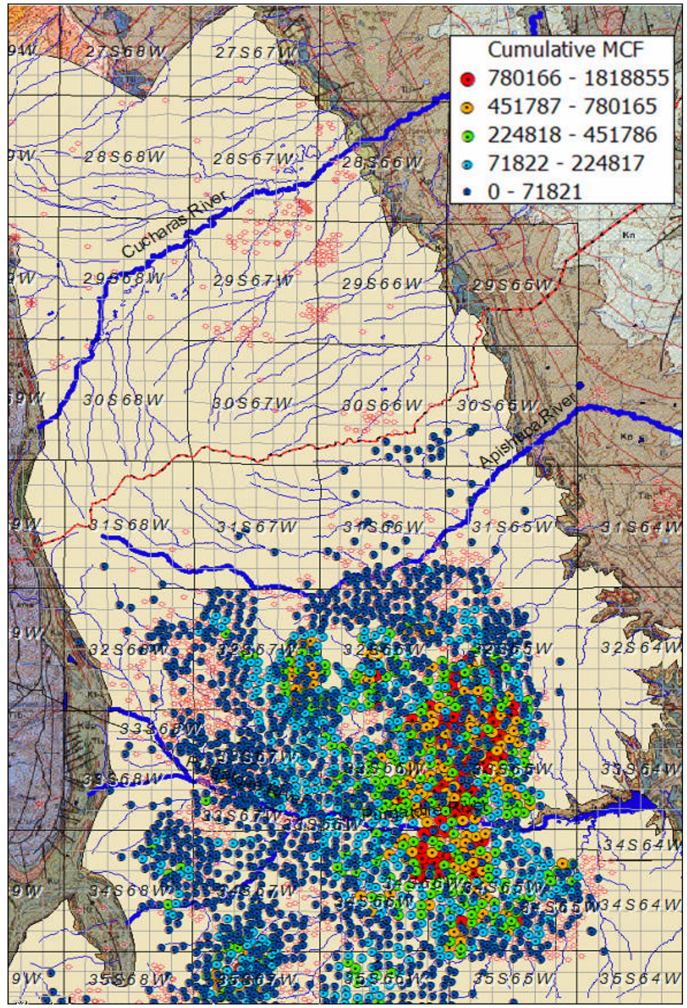
Park, R. and S. Epstein, 1960, Carbon isotope fractionation during photosynthesis, Geochim. et Cosmochim. Acta, V. 21, p. 110-126.

Prinzhofer, A., Mello, M. R., and Takaki, T., 2000, Geochemical characterization of natural gas: a physical multivariable approach and its applications in maturity and migration estimates, AAPG Bull. V. 84, p. 1152 – 1172.

Watts, K. R., 2006, A Preliminary Evaluation of Vertical Separation between Production Intervals of Coalbed-Methane Wells and Water-Supply Wells in the Raton Basin, Huerfano and Las Animas Counties, Colorado, 1999-2004, http://pubs.usgs.gov/sir/2006/5109/

Whiticar, M. J., 1999, Carbon and hydrogen isotope systematics of bacterial formation and oxidation of methane, Chem. Geol., V. 161, p. 291 – 314.

VanVoast, W., 2003, Geochemical signature of formation waters associated with coalbed methane, AAPG Bulletin, v. 87, no. 4 (April 2003), pp. 667–676.



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Raton Basin producing well locations in Colorado with cumulative gas production data from wells between 1999 and 2004 (USGS).

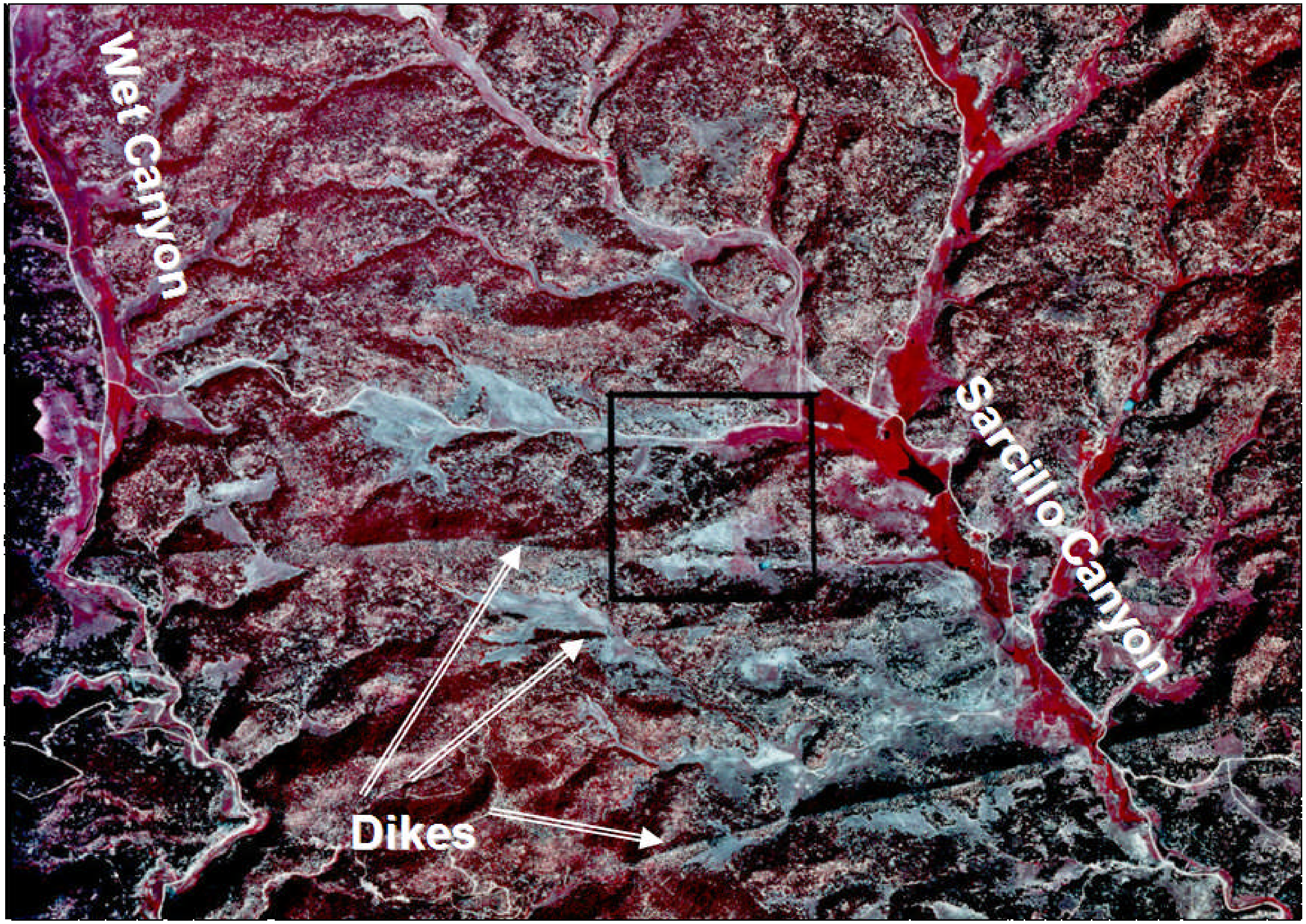
19-Oct-08	date	ia	edited by	ia	drawn by		app by

PREPARED SOLELY FOR THE USE OF OUR CLIENT AS SPECIFIED IN THE ACCOMPANYING REPORT. NO REPRESENTATION OF ANY KIND IS MADE TO OTHER PARTIES WITH WHICH WORLEYPARSONS KOMEX HAS NOT ENTERED INTO A CONTRACT.

WorleyParsons
resources & energy

PROJECT NUMBER: **C67020000**

FIGURE: **A3.1**



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Infrared image showing grey-colored vegetation anomalies associated with gas seeps along intrusive dike margins.

WorleyParsons
resources & energy

19-Oct-08	date	ia	edited by	ia	drawn by		app by

PROJECT NUMBER: C67020000

FIGURE: A3.2

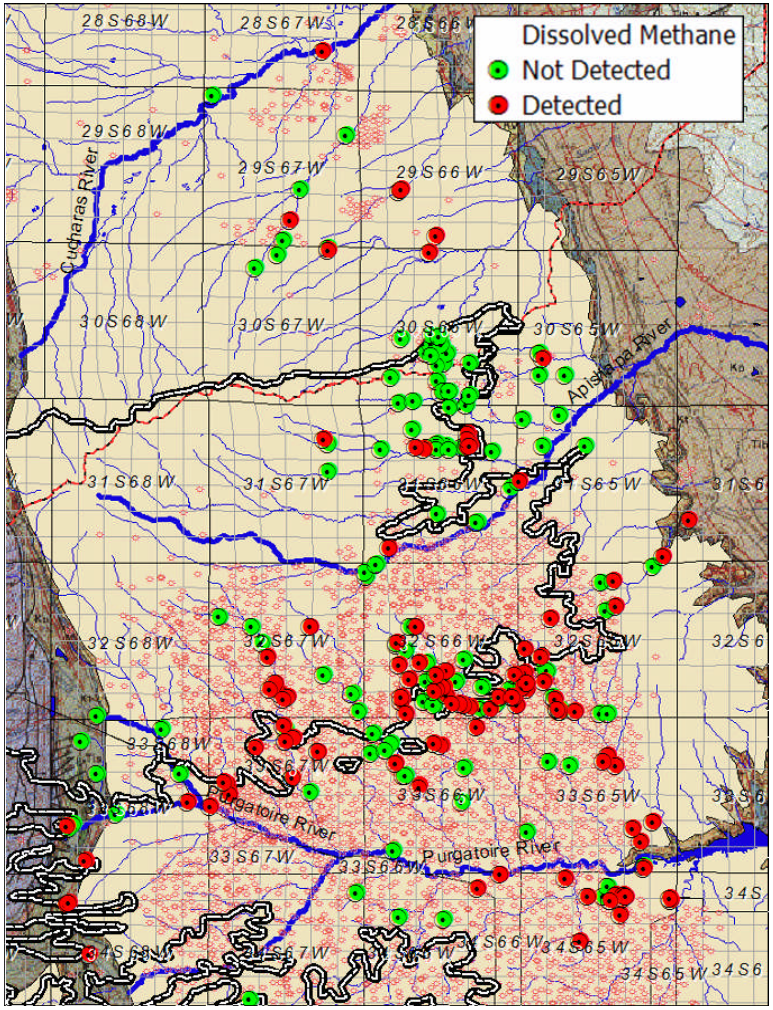
Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Small gas seeps and associated vegetation anomalies along fracture swarms in shallow coal seam subcrops below alluvium.

WorleyParsons
resources & energy

19-Oct-08 date	ia edited by	ia drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: A3.3



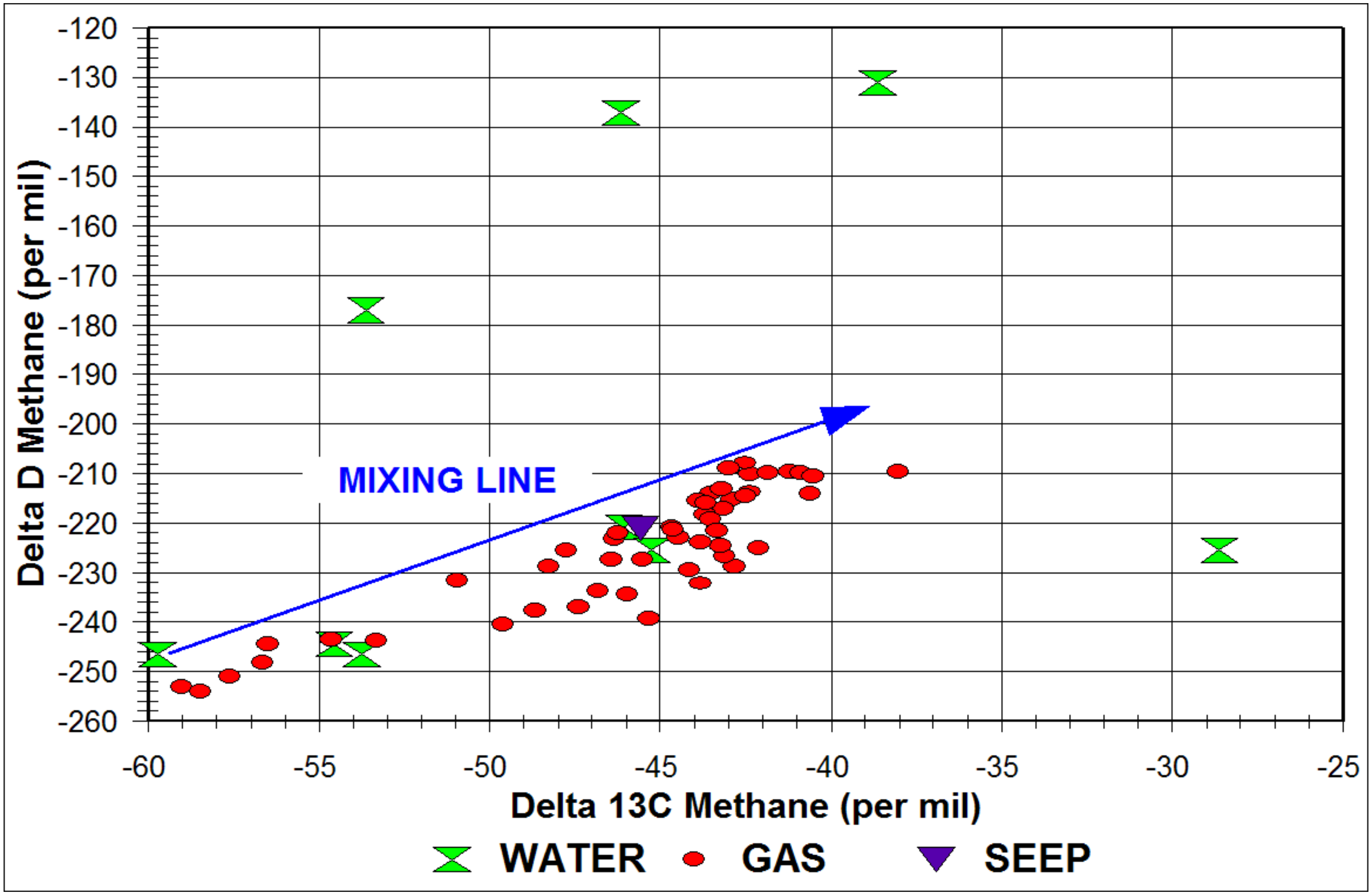
Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Distribution of water wells containing methane based on samples collected by both the COGCC and producers. The black dashed line represents the boundary between the Cuchara and Raton Formations.

WorleyParsons
resources & energy

19-Oct-08 date	ia edited by	ia drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: A3.4



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

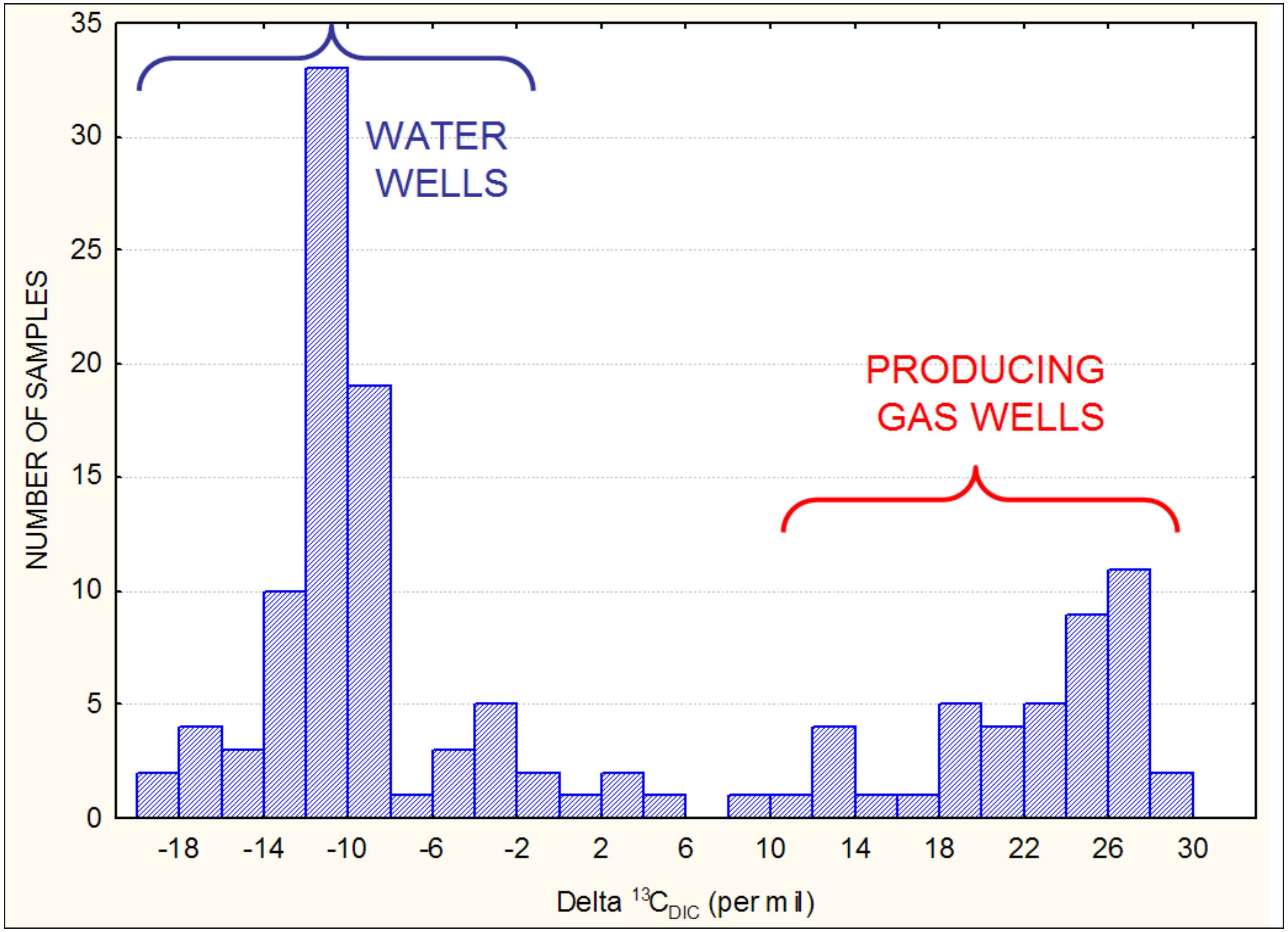
Stable isotope ratios for dissolved methane in domestic water wells, producing gas wells, and a historic seep in the Purgatoire River.

WorleyParsons
resources & energy

19-Oct-08	date	**ia**	edited by	**ia**	drawn by		app by

PROJECT NUMBER: **C67020000**

FIGURE: **A3.5**



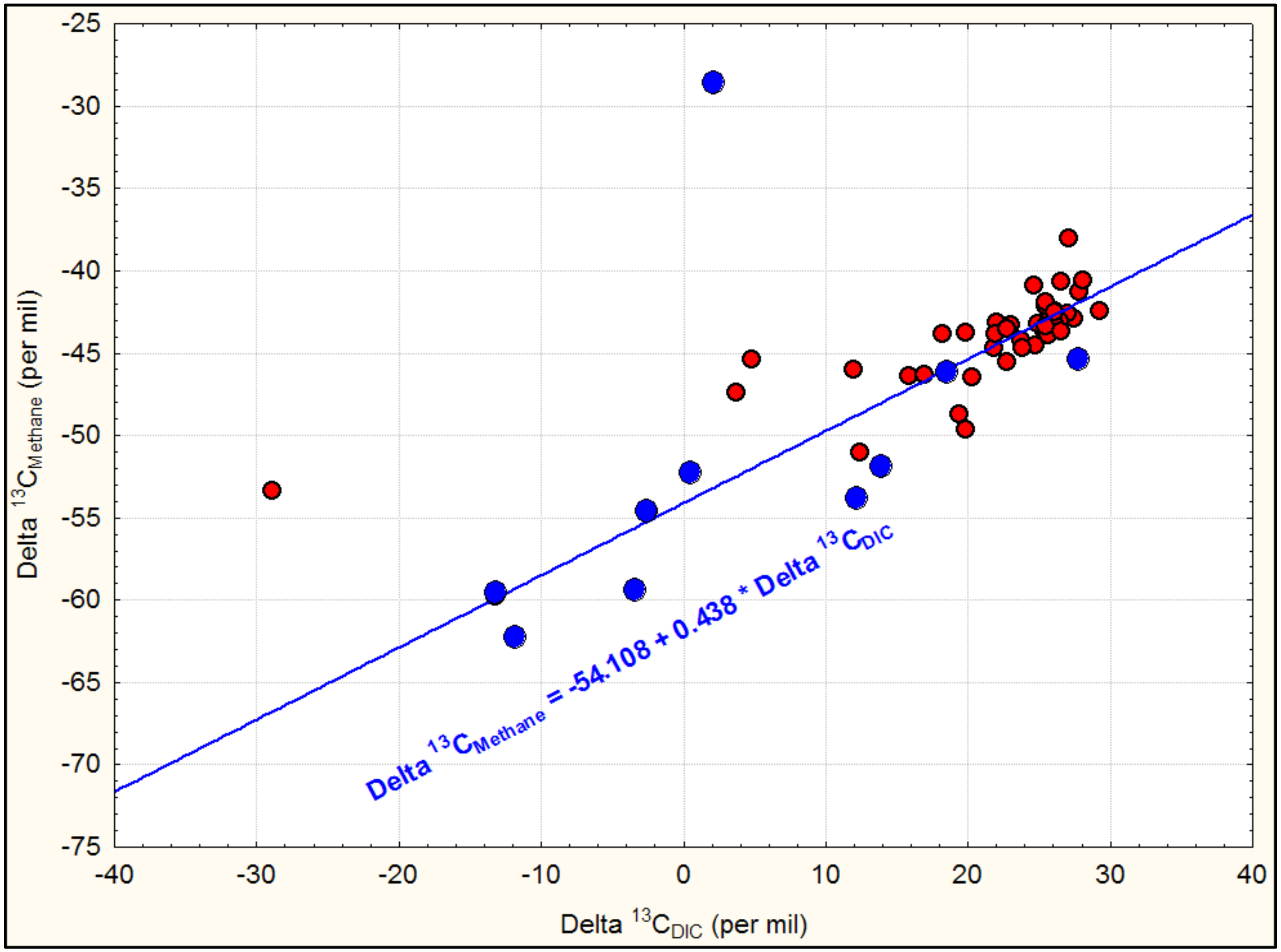
Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Stable isotope ratios of carbon in dissolved inorganic carbon among domestic water wells and produced gas wells show bimodal distribution.

WorleyParsons
resources & energy

19-Oct-08 date	ia edited by	ia drawn by	app by	PROJECT NUMBER: C67020000	FIGURE: A3.6



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

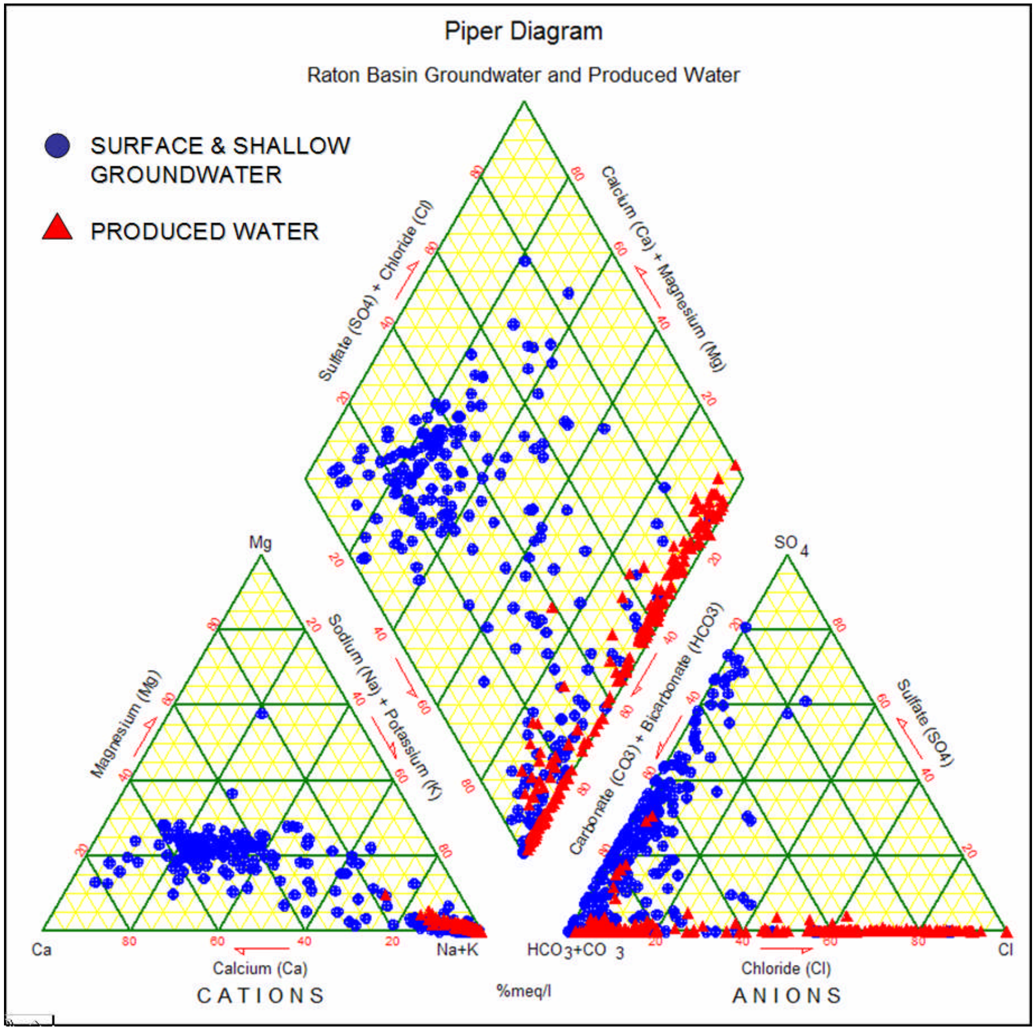
Linear relationship between stable isotopes of carbon in dissolved inorganic carbon and methane not only suggests that there is a genetic relationship between the two, but that there is also mixing of end-member gas source compositions.

WorleyParsons
resources & energy

19-Oct-08	date	**ia**	edited by	**ia**	drawn by		app by

PROJECT NUMBER: **C67020000**

FIGURE: **A3.7**



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

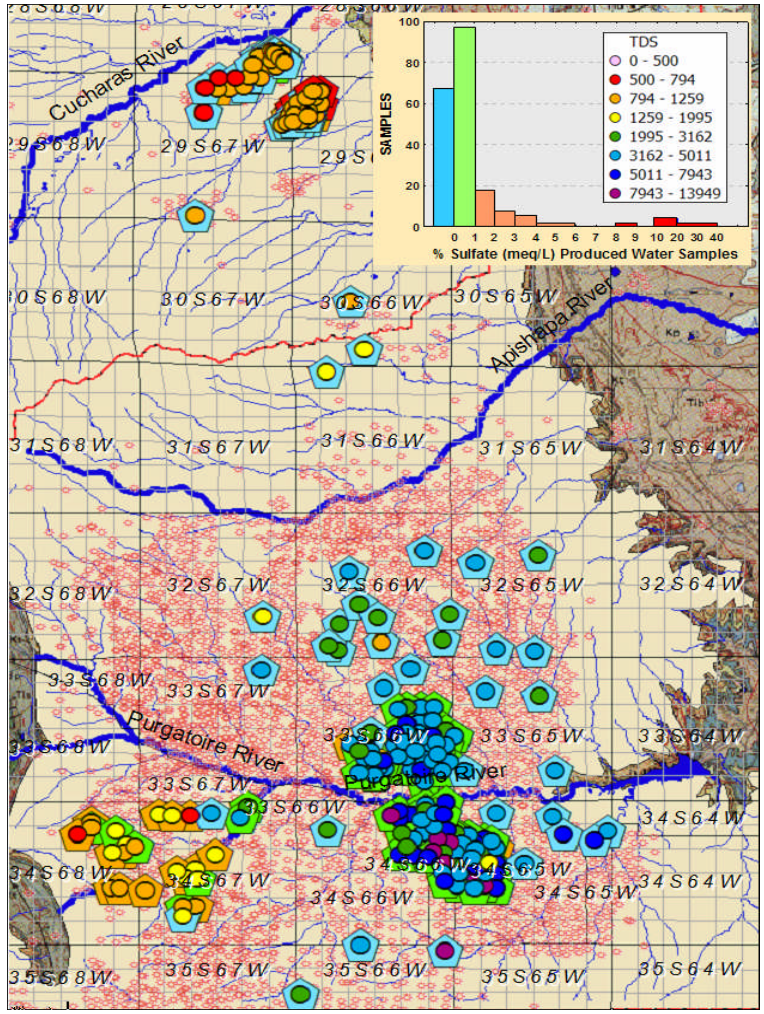
Water quality data show a distinct difference in composition between surface and shallow groundwaters (calcium-magnesium bicarbonate and sodium sulfate water types) and produced groundwater (sodium bicarbonate and sodium chloride water types).

WorleyParsons
resources & energy

19-Oct-08	date	**ia**	edited by	**ia**	drawn by		app by

PROJECT NUMBER: **C67020000**

FIGURE: **A3.8**



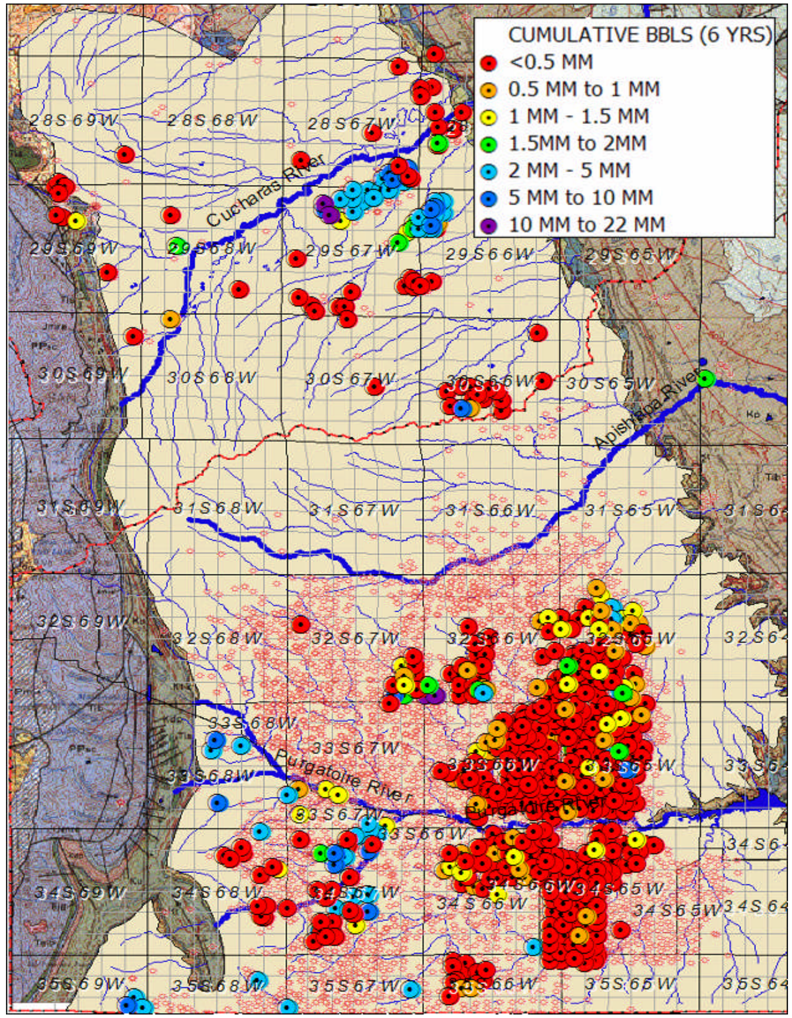
Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Produced water data showing percent sulfate (pentagonal symbol colors from histogram inset) and total dissolved solids concentrations (circles from inset).

WorleyParsons
resources & energy

19-Oct-08 date	**ia** edited by	**ia** drawn by	app by	PROJECT NUMBER:	**C67020000**	FIGURE:	**A3.9**



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Cumulative produced water volumes for a period of 6 years are unusually high among wells containing low TDS and high sulfate concentrations.

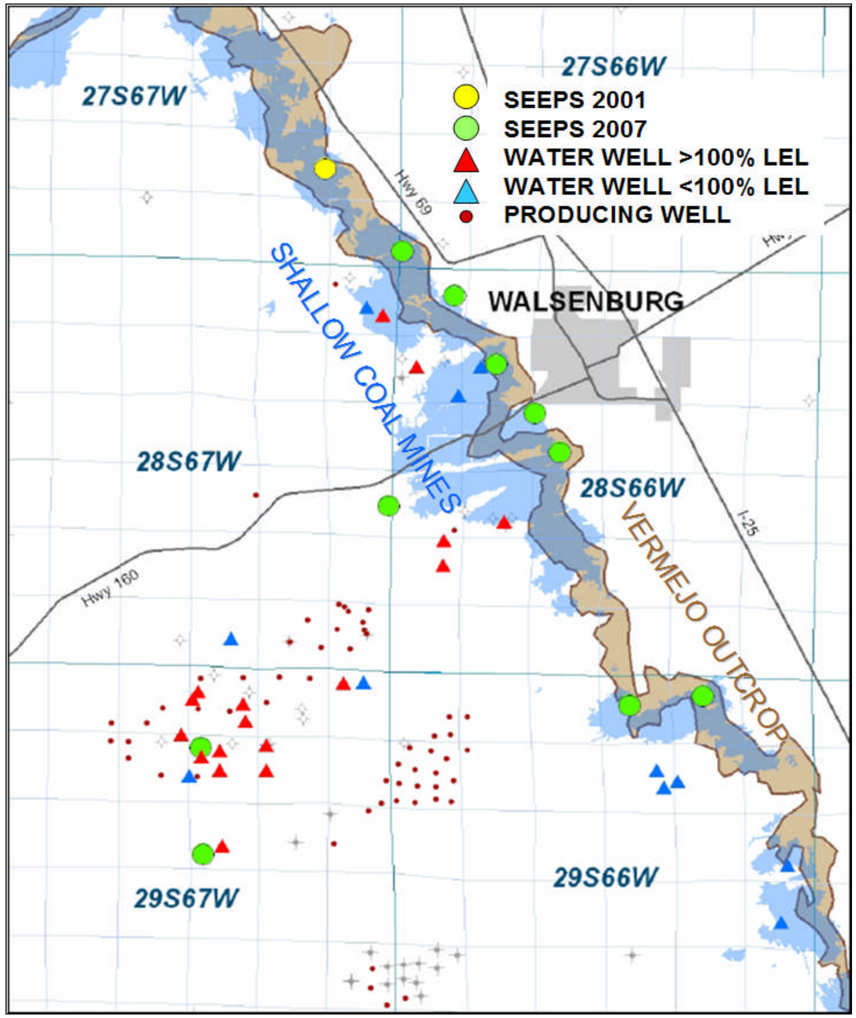
WorleyParsons
resources & energy

19-Oct-08 date	**ia** edited by	**ia** drawn by	app by

PREPARED SOLELY FOR THE USE OF OUR CLIENT AS SPECIFIED IN THE ACCOMPANYING REPORT. NO REPRESENTATION OF ANY KIND IS MADE TO OTHER PARTIES WITH WHICH WORLEYPARSONS KOMEX HAS NOT ENTERED INTO A CONTRACT.

PROJECT NUMBER: **C67020000**

FIGURE: **A3.10**



Infrastructure & Environment

POTENTIAL FOR GAS MIGRATION DUE TO COALBED METHANE DEVELOPMENT

Methane in groundwater and outcrops observed following increased water production rates, Raton Basin (adapted from COGCC web site report Petroglyph_0711-GA-02_Engineering.pdf).

WorleyParsons
resources & energy

19-Oct-08	date	ia	edited by	ia	drawn by		app by

PROJECT NUMBER: **C67020000**

FIGURE: **A3.11**