Investigation of Carbon Junction and Basin Creek Gas Seepage: Response to Chevron's Adjacent Proposed Future Infill CBM Drilling at West Animas/Indian Creek and University/SE Durango Field Areas, La Plata County, CO

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EXECUTIVE SUMMARY

Chevron is actively developing its La Plata County Fruitland Formation coal bed methane (CBM) leases in an area south and east of Durango, Colorado. The Pictured Cliffs Sandstone (Pictured Cliffs) and Fruitland Formation (Fruitland) outcrop occurs near the western extent of the study area as does the active Basin Creek and Carbon Junction methane gas seeps. These seeps are present along the outcrop approximately one and a half miles from the Chevron acreage proposed for future infill development. At Chevron's request, Norwest Questa Engineering Corp. (NQE) began a comprehensive seep impact study in November 2007 to determine what effect, if any, Chevron's West Animas/Indian Creek 80-acre density infill drilling program may have on the Basin Creek gas seep. Additionally, NQE examined the effect Chevron's West Animas/University/SE Durango 80-acre density infill drilling program may have on the Carbon Junction gas seep. The study provides critical information supporting future infill drilling programs within the study area.

The study objectives were to determine if Fruitlandcoal gas and water production (de-watering the coals) has any impact on the two nearest historically known gas seeps. Potentially, the health, safety, and welfare of the local residents could be impacted if there are significant increases in methane gas and hydrogen sulfide along the existing outcrop seeps. Although no active coal fires are present within the study area, the potential for spontaneous ignition of coal fires in the future could create an additional hazard to public safety.

Norwest Questa Engineering (NQE) conducted a review of the literature and studies on the spontaneous combustion characteristics of coals. Based on the results of this research, the Fruitland coals are not susceptible to spontaneous combustion.

To determine the impact of infill drilling, NQE built a geologic model of the Fruitland coal for reservoir simulation. NQE's simulation results show that gas seepage along the entire outcrop due to gas and water production from the wells currently producing reached a peak rate of 4,000

mscfpd in 1997. Furthermore, the outcrop seepage rates will continue to decrease in the future. Production from infill drilling does not increase outcrop seepage. These wells capture methane down dip before it can migrate to the outcrop further reducing seepage below the levels predicted for the existing wells.

In 1999, the Southern Ute Indian Tribe, the Colorado Oil and Gas Conservation Commission, the US Bureau of Land Management, Norwest Applied Hydrology, and NQE participated in a much larger, combined effort, called the 3M Project, to study the Fruitlandin the Colorado portion of the San Juan Basin. The 3M Study, completed in 2000, employed reservoir simulation to study the effects that production from all existing and proposed Fruitland coal wells (160-acre infill density) in Colorado had on gas seepage at the Fruitland outcrop. The 3M Project results are consistent with the impact on outcrop gas seepage predicted by the current study. The current study undertaken by NQE sought to answer similar questions posed to the 3M Project, however, the current focus area was confined to a smaller geographic area straddling the Fruitland outcrop. The conclusion of the study reveals a positive impact on the current seepage occurring at Basin Creek and Carbon Junction, by reducing the volume of escaped methane gas through increased production from additional or higher infill density drilling within the study area.

INTRODUCTION

Chevron is actively developing its La Plata County Fruitland coal bed methane (CBM) leases in an area east and south of Durango, Colorado. The Pictured Cliffs and Fruitland outcrop in the area and two historical gas seeps, the Basin Creek and Carbon Junction natural gas seeps, exist along the outcrop approximately one and a half miles from the area under development. **Figure 1** is a location map showing the subject area. At Chevron's request, Norwest Questa Engineering Corp. (NQE) conducted a comprehensive seep impact study to determine what effect, if any, Chevron's West Animas/Indian Creek proposed 80-acre infill drilling program may have on the Basin Creek gas seep, and what effect Chevron's West Animas/University/SE Durango proposed 80-acre drilling program may have on the Carbon Junction gas seep. The study provides information for current and future infill drilling application approvals as well as other uses.

Study objectives were to determine the impact, if any, gas and water production (de-watering the coals) from the Fruitland coals has on the two nearest historically known gas seeps. Significant increases in methane gas and hydrogen sulfide within the existing outcrop seeps and/or the spontaneous ignition of coal fires, although none presently exist, could potentially impact the health, safety, and welfare of the local residents. NQE's study addresses the following key questions:

1. What are the expected increases in water production rates resulting from the drilling programs?
2. Will the increased gas and water production affect the gas seepage rate and the percentage of hydrogen sulfide in the gas, and if so, *how* will these be affected?
3. Will the drying out of the coal seams increase the potential for coal fires along the outcrop by spontaneous combustion of the coal?

NQE constructed a three-dimensional (3D) geologic model of the Fruitland coals in Chevron's area of interest. The geologic model served as the basis to build a multi-layer reservoir simulation model that was used to investigate the effect the production from infill drilling has on gas seepage at the Carbon Junction and Basin Creek sites. A survey of U.S. Bureau of Mines and other literature provided information on the spontaneous combustion of coals.

2.1 RESULTS, CONCLUSIONS, RECOMMENDATIONS

1. A review of the literature and studies on the spontaneous combustion characteristics of coals demonstrates the Fruitland coals are not susceptible to spontaneous combustion at or near the Fruitland outcrop. The outcrop area is within or near the confines of the study area which incorporates Chevron's proposed infill drilling programs at West Animas/Indian Creek, University, and SE Durango areas. Within the Chevron acreage south and east of Durango, there are 11 analyses (proximate and ultimate) of selective Fruitland coal seams captured through conventional and sidewall coring, and mud cuttings that provide data for comparison to the findings of published research. Fruitland coal rank, particle size, pyrite, and moisture and oxygen content differ significantly from those sub-bituminous and lignitic coals susceptible to spontaneous combustion. There are no active coal fires in the study area. Due to the higher coal ranking, lower moisture and oxygen content, as well as low pyrite content of the Fruitland coal seams, there is little spontaneous combustion potential at or near the Fruitland outcrop within or near the study area which incorporates Chevron's proposed infill drilling programs at the West Animas/Indian Creek, and University and SE Durango areas. While the spontaneous combustion potential is not problematic, the potential for coal fires from lightning, forest fires, and human-related causes does exist.
2. Reservoir simulation indicates that outcrop gas seepage in the study area due to gas and water production from the wells currently producing reached a peak rate of 4,000 mscfpd

in 1997. In the future, outcrop seepage rates will continue to decrease. Projected outcrop seepage is 2,200 mscfpd in 2030. Production from the proposed infill wells does not increase outcrop gas seepage. In actuality, these wells capture a portion of the methane gas that would otherwise migrate up dip and escape out of the Fruitland outcrop as seepage, further reducing the seepage rates below the levels predicted for the existing wells. The simulation predicts the impact on outcrop gas seepage from the infill wells will be a reduction in outcrop seepage rate from 2,200 mscfpd to 1,958 mscfpd in 2030.

3. The simulation also predicts that water production due to infill drilling will increase from the current rate of 3,200 bwpd to 5,800 bwpd then decline rapidly. By 2018, the predicted water production rate from infill drilling will have decreased to approximately 200 bwpd above the 2,400 bwpd rate predicted for the existing wells. Cumulative water production from the infill wells is estimated to be 2.9 mmstb greater than that from the existing wells in 2030.

4. In 1999, the Southern Ute Indian Tribe, the Colorado Oil and Gas Conservation Commission, the US Bureau of Land Management, Applied Hydrology, and NQE participated in a combined effort, called the 3M Project, to study the Fruitlandin the Colorado portion of the San Juan Basin. The project employed reservoir simulation to study the effects that production from all existing and proposed Fruitland coal wells in Colorado has on gas seepage at the Fruitland outcrop. Results presented in the May 2000 and December 2000 reports for their 3M Coalbed Methane Model Study also show that continued production from the existing wells will decrease gas seepage at the outcrop, and that production from future drilling infill wells further reduces this seepage.

5. Monitor well pressures are decreasing with continued production resulting in reduced pressure gradients to the outcrop. The continued pressure depletion contributes to mitigating the rate of gas flow to the outcrop.

6. Assuming all other criteria can be met for permitting, the study has shown that the future infill drilling locations proposed within the study area and incorporated into the model

should be approved because the expected impact overall will be a further reduction in Fruitland outcrop gas seepage.

3.1 MONITORING OF METHANE SEEPS IN LA PLATA COUNTY

Along the Fruitland outcrop on the northern rim of the San Juan Basin, seeps of methane gas have been reported since the late 1800s. However, historical information regarding methane seeps from the northern San Juan Basin of Colorado remains, for the most part, anecdotal and not well documented. Many of the seeps pre-date the time settlers migrated into the area. Anecdotally, it is reported that some of the settlers would light the seeps during celebrations.

With the advent of CBM production in the late 1980s, methane in water wells has been reported by residents in the northern San Juan Basin area. Since the early 1990s, several investigators have identified and monitored methane seeps at Basin Creek, Carbon Junction, Florida River, Texas Creek, and Pine River, as well as on several private properties. Typically, these methane seeps occur in topographically low areas where drainages pass through the dipping outcrop of the Fruitland coals along the northern rim of the San Juan Basin (Fassett, 1997).

In 1993, methane seeps gained attention at Pine River when Amoco, now British Petroleum (BP), began monitoring and performing mitigation work (HCN, 1993). This was followed in 1995 through investigations by the US Bureau of Land Management (BLM) as well as other scientific studies. The BLM began collecting surface and subsurface methane concentration readings along the Fruitland outcrop. From these readings, the Basin Creek, Florida River, and the south fork of Texas Creek seeps were discovered in addition to the Pine River and Carbon Junction locations (LTE, 2007). As a response to concern for public safety regarding exposure to methane seeps and highlighted by the 1995 reconnaissance, the BLM contracted the services of LT Environmental, Inc. (LTE) of Arvada, Colorado to monitor the Fruitland outcrop methane seeps in La Plata County with the intent to measure changes over time (LTE, 2007). LTE has used various techniques to determine methane seepage flow rates and soil gas concentrations and to conduct seep mapping. These techniques include gas flux chambers used to determine gas seepage rates, permanent soil monitoring probes for soil gas concentration monitoring, field reconnaissance surveys, and regional-scale remote sensing using infrared imagery followed by field verification (LTE, 2007).

3.11 Monitoring

LTE's monitoring program has been active since 1997 on many sites along the Fruitland outcrop including Basin Creek, Carbon Junction, Vosburg Pike (added in 2006), south fork of Texas Creek, the Hoier property, and Pine River (LTE, 2007) seep areas (**Figure 2**). However, this report is concerned only with the Basin Creek and Carbon Junction seep locations (**Figure 3**). Therefore, the following monitoring activity summary and discussion are limited only to those areas. Copies of all LTE reports made to the Colorado Oil and Gas Conservation Commission are available online at http://www.oil-gas.state.co.us/.

3.12 Field Methods

The most recent field mapping exercises conducted in 2006 by LTE, that investigated the Basin Creek and Carbon Junction seep areas, saw no appreciable change in subsurface methane concentrations from previous years. LTE conducted previous field mapping exercises in October 2002, May 2003, May 2004, and June 2005 (LTE, 2007). Basin Creek methane seep levels have been stable since 2003, while the areal extent of the seep area as defined by stressed and dead vegetation has remained consistent with previous mapping exercises (LTE, 2007). Similarly, Carbon Junction showed no sign of an areal increase. However, both seep locations continue to have methane detected in surface samples in both lowland and upland positions. Visual comparisons of gas bubble frequency of the methane seepage through stream beds in these areas are contingent upon seasonal groundwater conditions (LTE, 2007). When there is little or no water, it is difficult to quantitatively recognize the amount of methane escaping.

3.13 Soil Monitoring Probes

LTE has collected subsurface methane concentrations at methane seep sites since 1997. In 1998, they installed improved equipment so they could better monitor the quantity of the methane in the seeps. Statistically, data from these probes were evaluated over time by LTE to detect trends in the amount of methane seeping into the soils. The most recent evaluation, using measurements collected from all probes since 1998, determined that 64 percent of the statistically significant trends indicated a downward trend to subsurface methane concentrations. Nearly all Carbon Junction trends are downward (LTE, 2007). The areal extent of the Basin Creek seep is relatively unchanged since mapping began in 2002 (LTE, 2007). Soil probes indicate similar methane concentrations since monitoring began in the same areas.

3.14 Gas Flux Chamber

In 2007, LTE suspended the gas flux chamber monitoring program due to the lack of detection of any statistically important trends. This was caused by the localized nature of the flux chamber data, the difficulty of operating the equipment, and the high cost of maintaining the equipment. LTE believes mapping, regional reconnaissance, and pedestrian survey are far more effective than gas flux chamber monitoring (LTE, 2005).

3.15 Discussion of Monitoring Program

LTE's notes that the most significant findings in the areas of the methane seeps along the Fruitland coal outcrops are qualitative (LTE,2007). This was due primarily to the failure to obtain statistically important data from the gas flux chamber. Comparisons of methane subsurface concentrations are informative. However, the inability to make qualified determinations of methane seepage notes and rate changes over time precluded NQE's use of the data. The qualitative results could not be used for historic baseline comparison of seep volumes and distributions. The quantitative data necessary for simulation use from the Fruitland outcrop would have been provided by hard information from the gas flux chambers. However, the data gathered from the gas flux chamber monitoring program showed no conclusive upward or downward trends in methane seepage over an eight-year span (1998 – 2008). What remained for LTE was a *qualitative* approach to determining changes in seepage rate and distribution over time by using remote sensing, soil monitoring probes, and field mapping methods.

However, the qualitative nature of observation is not without merit for this study. A visual inspection by NQE in November 2007 of the study area's Basin Creek and Carbon Junction seeps, as well as Pine River, and South Fork of Texas Creek methane seep locations for comparison, provided vital information regarding the relative rates of methane escape at each location. While field investigators from NQE could not inspect Basin Creek seep due to dam construction, they were able to assess the remaining seep locations. The team concluded that the rate of gas seepage from the Pine River and South Fork Texas Creek seep locations far exceeded that of the Carbon Junction seep and likely the Basin Creek seep as well.

Additional qualitative information important to the monitoring process by LTE is the ability to detect hydrogen sulfide gas (H_2S). LTE confirmed the presence of H_2S in 2006 during mapping activities at Carbon Junction, Vosburg Pike, locations along the south fork of Texas Creek, and Pine River. These concentrations were less than 75 ppm (LTE, 2007). However, they were generally greater than in previous years. The H_2S, present at many seep locations, is biologically produced from a process that occurs when sulfate-reducing bacteria living in surface waters come into contact with the Fruitland coals. These bacteria are most active in anaerobic (lack of oxygen) conditions. Such occurrences are common at seep locations, where Fruitland coal seams are frequently in direct contact with surface waters.

If there is increased methane escape at the seep locations, anaerobic conditions could accelerate the development of H_2S from the sulfate-reducing bacteria. If sulfur-rich compounds are found in coals, they serve as a food source for the sulfate-reducing bacteria which produce H_2S as a product of the anaerobic digestion of sulfur. However, the Fruitland coals in the Basin Creek and Carbon Junction methane seep areas are low in sulfur (0.2 % – 0.7%). Thus, the volume of sulfur available for conversion into H_2S by sulfur-reducing bacteria is small and not likely to create a significant increase in levels of the gas.

4.1 COAL FIRES

4.11 SPONTANEOUS COMBUSTION POTENTIAL OF FRUITLAND COALS

Concerns on behalf of La Plata County commissioners have been expressed to Chevron over the potential of San Juan Basin Fruitland coals igniting by spontaneous combustion in outcrop and near outcrop areas due to dewatering of the coals. Their concerns are greatest in areas of high population density such as the Carbon Junction area. At Chevron's request, NQE examined this potential problem. The results of this study are presented in this section.

Spontaneous combustion of coal has been studied extensively before the advent of CBM production. The United States Bureau of Mines has studied this problem for many years (Kim, 1995, 1977; Kim and Chaiken, 1993; Smith and others, 1991). It can occur along surface outcrops, in open-pit and underground coal mines, coal stockpiles, and storage facilities of coal. In the spontaneous combustion of coal, the sources of heating are found in the low temperature of oxidation in combination with the adsorption of moisture by dried or partially dried coals. However, the oxidation of coal is very complex due to the diverse composition and heterogeneous nature of coal.

Simplified, the basic reaction in the oxidation of coal is: **$C + O_2 = CO_2$ + Heat (Carbon + Oxygen = Carbon Dioxide + Heat)**. This reaction is exothermic releasing heat (Speight, 1983).

If the heat cannot escape, it raises the temperature of the coal past its ignition point and a coal fire occurs. Additionally, wetting (or gaining moisture) is an exothermic process, and the liberated heat can accelerate the spontaneous heating of coal.

While changes in moisture and oxidation can explain most of the spontaneously generated heat in coal, several other key factors contribute to the spontaneous combustion potential of coal (Kim, 1977). These factors are:

1. **Coal Rank**: As the rank of coal decreases the tendency of coal self-heating increases (**Figure 4** **and** **Figure 5**).

2. **Particle Size:** Particle size has an inverse relationship to spontaneous combustion in coal. The smaller the particle size the greater surface area is available on which oxidation can take place.

3. **Temperature:** The higher the temperature the faster coal reacts with oxygen.

4. **Pyrite content:** The presence of the sulfur minerals pyrite and marcasite may accelerate spontaneous heating. These minerals may swell upon heating, causing the coal to disintegrate and reduce the particle size involved in the reactions. (Generally, pyrite must be present in concentrations greater than two percent before it has a significant affect.)

Coals susceptible to spontaneous combustion tend to be lower ranked with higher moisture and oxygen content (**Figure 6**) as well as coals with significant pyrite content (Kim, 1977). In the U.S., the sub-bituminous coals of the Powder River Basin are the most susceptible to spontaneous combustion (Lyman and Volkmer, 2001). They are low rank, sub-bituminous B and C (8000-11,000 BTU), high moisture (17.95% -39.66%), high oxygen (27.6% - 39.66%), and disintegrate to small particle sizes (Stricker and others, 2007). These combinations of factors produce exothermic reactions and when combined with a low ignition point, cause the sub-bituminous coals in the Powder River Basin to spontaneously combust when exposed to air in open-pit mines.

In contrast to the predominantly sub-bituminous coals of the Powder River Basin, the Fruitland coals of the San Juan Basin differ significantly in their characteristics across the basin. In outcrop areas nearest to the study area, the coals are mostly high volatile A bituminous coals (12,000 to 16,000 BTU) with low moisture (0.8 % -12 %) and oxygen (1.85- 4.72 %) contents (Fassett, 2000) (**Figure 7**).

Within the Chevron acreage southeast of Durango, there are 11 proximate and ultimate analyses of Fruitland coal seams captured through conventional and sidewall coring, and mud cuttings. These analyses indicate the Fruitland coals in this area are high volatile A bituminous rank or higher (14,328-15,762 BTU) with low moisture (2.23-11.75 %) and oxygen (1.85-4.72 %) contents. Thus, there is very little spontaneous combustion potential within or near the confines of the study area.

There are only four known active coal fires along the Fruitland coal outcrop. Three of these are in the Cinder Buttes area in the southwestern part of the Colorado portion of the San Juan Basin north of the New Mexico-Colorado state line and within the Southern Ute Indian Tribal lands. These burns are halfway between the La Plata Field in New Mexico and the Valencia Canyon Field in Colorado. The other outcrop fire is approximately between the Valencia Canyon Field and the Bridge Timbers area. Along most of the western margin of the San Juan Basin, and specifically where the known active coal fires are located, the Fruitland coal rank is largely a high-volatile B-bituminous (Ambrose and Ayers 2007). All of these outcrop burns appear to be the result of lightning strikes and/or subsequent forest fires. Fruitland coal gas production downdip of these burn areas is marginally economical or non-economical.

Updip of the Chevron acreage in the area of the Fruitland coal outcrop southeast of Durango, there are no active outcrop or subsurface coal fires, although documented previous surface coal burns, ash, and shattered burned sandstone associated with old mine adits have been observed at

Basin Creek (Fassett et al 1997). These surface coal fires are believed to have extinguished themselves. Due to the coal type in the northern San Juan Basin along the Basin Creek to Carbon Junction outcrop and near-surface areas, the Fruitland coals are not susceptible to spontaneous combustion. In contrast, much further south in La Plata County where active surface and sub-surface coal fires exist along the outcrop, the predominate coal type differs. Lightning strikes, forest fires, and fires set by humans, however cannot be dismissed in the future as causes for coal fire ignition in the study outcrop area. Within the study area, future gas well drilling and subsequent gas and water production does not affect the risks of these events occurring in any way.

5.1 3M PROJECT SEEPAGE STUDY

5.11 BACKGROUND

In 1999, NQE along with industry and governmental representatives participated in a combined effort, called the 3M Project, to study the Fruitland in the Colorado portion of the San Juan Basin. The three M's in the 3M Project stand for **Mapping**, **Modeling**, and **Monitoring**. Portions of La Plata and Archuleta Counties in southwest Colorado that are underlain by the Fruitland comprised the study area. NQE prepared a basin-wide CBM reservoir model for the area, **Figure 8,** for the Southern Ute Indian Tribe ("SUIT"), the Colorado Oil and Gas Conservation Commission ("COGCC"), and the US Bureau of Land Management ("BLM"). This model, which is referred to as the 3M CBM MODEL, or simply the 3M MODEL, was designed to simulate the effects of production from all existing and proposed Fruitland wells in Colorado, and provide a tool to evaluate the effects of coalbed methane infill drilling and surface gas seepage at the Fruitland outcrop. The 3M Project was designed as a long-term project to provide tools to develop a more comprehensive understanding of gas and water production from the Fruitland and potential impacts at the Fruitland outcrop. The effects of dewatering, gas adsorption and desorption, and historical production are included in the model. At the time the

3M Project was conceived it was also envisioned that the model would incorporate information obtained from new monitor wells and provide a tool that could be periodically updated with additional production and pressure data.

The model was built on information from a separate groundwater or hydrologic model prepared by Norwest Applied Hydrology ("NAH"), which covered all of San Juan Basin.

The groundwater model simulates pre-production conditions for the reservoir model and provides estimates of the amount of groundwater flowing through the Fruitland hydrologic system.

A complete description of the 3M MODEL can be found at http://www.oil-gas.state.co.us/Library/SanJuanBasinReports.htm. The report covers the CBM simulation modeling that was performed as the **Modeling** part of the 3M Project.

5.12 3M MODEL PREDICTED GAS SEEPAGE

The 3M MODEL predicted the gas seepage at the outcrop and that seepage will continue to occur in areas where it has already been observed: on the north margin of the basin in the Pine River area and near the South Fork of Texas Creek, and along the west side at Valencia Canyon and Soda Springs. Results of the study also indicated that additional seeps may start along the ridge east of the Pine River Valley and in other areas to be determined, but most of the seepage in the model occurs at existing seep locations including Carbon Junction and Basin Creek.

To predict gas seepage in the Colorado portion of the San Juan Basin, the area was divided into six smaller model areas to facilitate the simulation run times. **Figure 9** shows the six subdivisions. Chevron's area of interest lies in the northeastern part of Area A and the western part of Area B. **Table 1** presents a summary of the 3M MODEL predicted seepage rates in these areas, and **Figure 10** and **Figure 11** show the seepage rate profiles.

Model runs with infill wells indicated that in most cases no measurable change in seepage should be expected as a result of infill drilling. The 3M MODEL indicated long-term seepage will actually diminish as a result of infill drilling because the infill wells will capture part of the gas that would otherwise have migrated updip and escaped out the Fruitland outcrop as seepage.

Differences between the 3M MODEL and the simulation model used for this study are discussed in this report in the section on the simulation model.

6.1 GEOLOGY AND GEOLOGIC MODEL

The geology and geologic model developed for the simulations of the Fruitland coals in the Chevron study area southeast of Durango, Colorado incorporated previously published literature to place the geology in a regional setting. An extensive literature review of the structure, stratigraphy, and depositional setting of the Lewis Shale (Lewis), Pictured Cliffs, Fruitland, and Kirtland Shale (Kirtland) proved essential for the development of the detailed geologic model used in this study. Referenced literature included publications by several authors including, Fassett (1988 and 2000), Condon (1997), Wray (2000), and Ambrose and Ayers (2007). This literature review permitted the detailed geologic model developed for the Chevron study area to be consistent with regional relationships of the Fruitland coals and Pictured Cliffs in the San Juan Basin.

6.11 LOCATION OF THE CHEVRON STUDY AREA

The San Juan Basin is located in southwestern Colorado and northwestern New Mexico (**Figure 12**). The Chevron study area (**Figure 13**) is along the northwest portion of the San Juan Basin south of Durango, Colorado in the vicinity of Basin Creek and Carbon Junction, the sandstones of the Pictured Cliffs and coals of the Fruitland Formation outcrop. The outcrops trend to the northeast and dip to the southeast. The Chevron acreage is located southeast of these outcrops.

6.12 General Structure of the San Juan Basin

The San Juan Basin is roughly circular in shape with gentle dips in the southern parts of the basin (1°- 4°) and steeper dips along the northern margins of the basin (12°- 56°). Bounding the basin on the north is the San Juan Uplift. The Four Corners Platform and Defiance Uplift provide the western and southwestern limits on the basin. The Chaco Slope north of the Zuni Uplift and the Puerco Platform north of the Lucero Uplift bound the southern extent of the San Juan Basin. The Nacimiento Uplift limits the basin to the southeast, while the Hogback Monocline is considered the northeastern boundary. In this area, the Hogback Monocline merges into the Chama Embayment west of the Brazos Uplift (**Figure 14**).

Along the outcrops of the Pictured Cliffs and Fruitland outcrops in the study area, the strike of the strata is to the northeast, and the dips of the strata range from 18° to 26° to the southeast in the Basin Creek and Carbon Junction areas. In the Chevron acreage to the southeast of the outcrop area, the dips of the strata rapidly decrease to less than one degree.

The San Juan Basin is one of the most prolific CBM basins in North America due to the high productivity of natural gas from the Fruitland coals. It is an asymmetric structural basin of Laramide age (70 – 35 million years ago). The deepest portion of the basin is in the northeast where a fault-zone termed the “hingeline” by Fassett (1988) was active during Late Cretaceous. This fault-generated hingeline marks the trend of an abrupt deepening in the basin which created more accommodation space during deposition of the Pictured Cliffs and Fruitland deposition in the northern and northeastern portions of the basin. South of the hingeline, the basin shallows gently toward the outcrop (**Figure 15**).

Fruitland coal cleat orientation and sandstone jointing have been well described by Condon (1997) in the outcrops near Durango, Colorado. These areas include Basin Creek and Carbon Junction where gas seeps have been observed updip of the Chevron acreage. Condon (1997) observed that the face cleat orientations within the coals of the Fruitland at Basin Creek are roughly north-south, while the butt cleat orientations are east-west (**Figure 16**). Condon also recognized two separate joint systems in the Fruitland sandstones and documented orientations of north-south and roughly east-west respectively. Additionally, Condon (1997) observed joint systems in the Pictured Cliff as having northwest-southeast and west-southwest and north-northeast orientations. In comparison, Condon determined the face and butt cleats within the Fruitland at Carbon Junction have been rotated slightly to the west. In this area, the face cleats have a north-northwest to east-southeast orientation and the butt cleats a south-southwest to north-northeast orientation (**Figure 17**). Observations similar to those of Condon were made adjacent to the Carbon Junction trailhead during a November 2007 field reconnaissance undertaken to support this study (**Figure 18** and **Figure 19**).

6.13 STRATIGRAPHY

The San Juan Basin stratigraphy includes both Mesozoic and Cenozoic-age formations that have a variety of lithologies such as carbonates, shale, sandstone, and coals. However, this study focuses on the Campanian Stage of the Late Cretaceous (**Figure 20**). Specifically, the Chevron simulation study concentrates on the carbonaceous shales and coals of the Fruitland and sandstones of the Pictured Cliffs and the sealing capacity of the shales of the Lewis below and the Kirtland above (**Figure 21**).

The Late Cretaceous section in the San Juan Basin, similar to many other Rocky Mountain basins, records the interplay of terrestrial and marine sedimentation associated with variable sedimentation rates, sea-level fluctuations, and active tectonics in and adjacent to the Cretaceous Western Interior Seaway. The stratigraphic intervals of interest for this study are the coal-bearing Late Cretaceous Fruitland and sandstones of the Pictured Cliffs. The Fruitland consists of sequences of coastal plain deposits comprised of coals, shales, and sandstones deposited coeval with and adjacent to the Late Cretaceous shoreline sandstones of the Pictured Cliffs.

This interfingering of the upper portion of the Pictured Cliffsand the coals of the lower Fruitland (Fassett, 1988, 2000; Wray, 2000; and Ambrose and Ayers, 2002) is important to the stratigraphic framework of the Fruitland in the Chevron study area near Durango, Colorado (**Figure 22**). Ambrose and Ayers (2002) measured detailed stratigraphic sections along the Fruitland-Pictured Cliffs outcrop to illustrate this interfingering relationship between the Fruitland and Pictured Cliffs. Detailed surface mapping by Streufert for the 3M Study report (Wray, 2000) shows this same intertonguing relationship between the coals and the shales of Fruitland and Pictured Cliffs sandstones. Fassett (2000), using well data cross sections, displayed similar Fruitland and Pictured Cliffs intertonguing geometries in the subsurface within the study area of this report (**Figure 23**).

As part of the geologic modeling process, a subsurface stratigraphic model within the Chevron study area was developed based upon the literature review and correlations made using vector and raster log data from 217 wells within the study area boundary (**Figure 24**). The purpose of this model was to provide a stratigraphic framework and lithologic input into the 3D geologic model constructed for the simulation. This stratigraphic model focused on the Campanian-age section of the San Juan Basin from the base of the Pictured Cliffs to the base of the Kirtland. The Sun-Craig #1 type log shows the correlation log suite used in the model development including gamma ray (GR), deep and medium resistivity (ILD, ILM), density and neutron porosity (DPHI, NPHI), and bulk density (RHOB) curves (**Figure 21**). The GR log display template highlights a given depth interval as coal if it had a RHOB value less than 1.75 gm/cc and a GR value of less than 70 API units. These coals are displayed as solid black on the type log and subsequent cross sections.

Well-to-well correlations defined the stratigraphic framework of the top of the Lewis, the top of the Pictured Cliffs, and the top of the Fruitland base of the Kirtland. Within the Pictured Cliffs, correlations include the top and the base of the Picture Cliffs and Fruitland tongues. Finally, the Fruitland was subdivided into the Upper, Middle, and Lower Fruitland intervals. These correlations established the stratigraphic position and structural geometry of the base and top seals for the geologic model used for simulation, the Lewis and Kirtland shales respectively. Additionally, this stratigraphic framework identified and correlated the Fruitland and Pictured Cliffs tongues across the study area, as described by Fassett (1988; 1997), Wray 2000), and Ambrose and Ayers (2007). Finally, the correlation of the Lower, Middle, and Upper Fruitland provided an initial internal framework from which to further subdivide the Fruitland during the 3D geologic modeling process.

A correlation grid was constructed throughout the Chevron study area (**Figure 25**). The cross sections illustrate the stratigraphic variations in the correlation grid. All the cross sections use the top of the Pictured Cliffs as a datum. Cross section B – B' (**Figure 26**) parallels the northeastward trend of depositional dip of the Fruitland and Pictured Cliffs, as well as the outcrops of the Fruitland and Pictured Cliffs intervals. Cross sections C – C' (**Figure 27**) and D – D' (**Figure 28**) parallel the trend of depositional strike.

Cross sections show the seaward (northeast) decrease in thickness and continuity of the Lower Fruitland coals. These cross sections also depict similar relationships for the coals in the Fruitland Tongue. While coal intervals can be correlated from well-to-well, it is not possible to correlate individual coal beds with any degree of reliability. Adding to the correlation difficulties, rock type changes from coal to carbonaceous shale are very common throughout the study area. In general, the net coal per Fruitland interval (Upper, Middle, Lower) decreases vertically upward in the stratigraphic section. The Upper Fruitland has only minor amounts of coal and those coals are usually less than three feet thick.

6.14 Depositional Setting of the San Juan Basin

The last major regression of the Western Interior Seaway occurred during the Campanian between 76 and 73 Ma (**Figure 29**). During this time, the San Juan Basin was positioned between the Sevier Highlands to the west and the Western Interior Seaway to the east and at the southern end of extensive coal swamps that developed in a relatively narrow band that extended from present-day Canada southward into New Mexico.

At the beginning of the Campanian, the marine muds of the Lewis were deposited in the Western Interior Seaway in the San Juan Basin area. They represent the last open-marine sediment package in the San Juan Basin and provide the bottom seal to the geologic model in the study area. With the progression of time in the Campanian, increased sediment influx and/or the reduction of accommodation space caused the shoreline to migrate gradually to the northeast. Thus, the shoreline sands of the Pictured Cliffs began a northeast seaward progradation over the finer grained muds of the Lewis. This progradation of the shoreline had some fluctuations (local transgressions and regressions) due to changes in sediment influx and/or development of accommodation space. However, the regional regressive trend to the northeast continued. Ultimately, the fluvial mud and sands of the Kirtland covered the Fruitland sediments. They provide the top seal to the source and reservoir deposits of the Fruitland and Pictured Cliffs intervals.

Within the Chevron study area, these fluctuations of sea level produced local transgressions and regressions of the shoreline. This caused some interfingering between the coals, shales, and sandstones of the Fruitland and the shoreface sandstones of upper portions of the Pictured Cliffs. These local changes in sediment influx and accommodation space are key factors in determining the distribution of coal bodies associated with the Fruitland. Finally, during the late Campanian, terrestrial mudstones and sandstones of the Kirtland covered the Fruitland across the Chevron study area.

Sediment was transported from source areas to the south and west by northeast trending fluvial channels. Gradients in these channels decreased as they crossed the coastal plain adjacent to the Western Interior Seaway. With the decrease in gradient across the coastal plain, the channels evolved from traction-load dominated streams to mixed-load dominated streams. Where the sediment entered into the Western Interior Seaway, they were deposited as wave-dominated deltas. Wave energies within the depositional basin in the form of wave flux reworked and redistributed the sediments as shoreface sands of the Pictured Cliffs along depositional strike (northwest-southeast). This is reflected in the production trends of the Pictured Cliffs in the San Juan Basin (**Figure 30**). The estimated ultimate recoveries (EUR) of gas show distinct northwest-southeast trends associated with porosity and permeability trends. The best reservoir facies, with the highest porosity and permeability, occur in the upper shoreface sands of the Pictured Cliffs. In the Pictured Cliffs, the shoreface facies trend parallel the shoreline and extend in long, narrow bands associated with the reworked, well-sorted, mature, shoreface sand deposition. Modern analogs to this type of depositional setting can be observed along the South Carolina coast (**Figure 31**).

These shoreface sands of the Pictured Cliffs provided the platform upon which the coal (peat) swamps of the overlying Fruitland accumulated. The coal swamps of the Fruitland accumulated landward (southwest) of shoreline sands of the Pictured Cliffs during this last regression of the West Interior Seaway. Developing on the platform of the underlying shoreface sands, these coal swamps are elongate parallel to depositional strike northwest-southeast (**Figure 32**). The continuity of these peat (coal) accumulations is interrupted by the northeast trending fluvial valleys carrying sands and muds to the Western Interior Seaway.

Another important influence on the Fruitland and Pictured Cliffs depositional setting was the position and movement of the hingeline introduced by Fassett (1988) and discussed previously in Section 6.12 of this report (**Figure 15**). The increased basin accommodation caused by the down to the north movement of this fault zone allowed for significant thickening of coal within the Fruitland in the northern portion of the San Juan Basin. This thickening of coals within the Fruitland has been termed the "fairway". Isopach values for the Fruitland indicate that this fairway extends roughly from Durango, southeastward toward the northern limit of the Nacimiento Uplift of New Mexico (**Figure 33**). Fruitland thickness values within the fairway can be greater than 100 feet. The EUR map of the Fruitland also highlights the orientation of the Fruitland coal fairway and its contribution to the productivity of the Fruitland within the San Juan Basin (**Figure 34**). The EURs for the Fruitland are largest northeast of the hingeline within the fairway and correspond directly with the thickest Fruitland net coal isopach values. A comparison of the Pictured Cliff and Fruitland EUR values shows that the maximum EUR values for the Fruitland coals are several times that of the Pictured Cliffs indicating that the majority of the production in the San Juan Basin comes from the coals of the Fruitland, particularly along the depositional fairway controlled by increased subsidence north of the hingeline during deposition.

6.15 Considerations for the 3D Geologic Model

From this discussion of the geologic setting for the Fruitland coals and sandstones as well as their relationships to the Pictured Cliffs, it is obvious many of the observations in this section must be incorporated into the 3D geologic model constructed for the simulations. The more significant factors that must be incorporated include:

Structural Relationships – The Chevron study area is downdip of the outcrops of the Pictured Cliffs and Fruitland coals. The 3D geologic model must include the structure from outcrop into the subsurface throughout the study area.

Fruitland coal continuity laterally and vertically – Coals of the Fruitland are more laterally continuous along depositional strike (northwest-southeast) versus depositional dip (southwest-northeast). Coal zones can be correlated in the Chevron study area, but individual coals are difficult to correlate from well-to-well. Additionally, the amount, thickness, and continuity of

Fruitland coals decrease upward in the section. These must be considered in the 3D geologic model.

Interfingering of Pictured Cliffs Sandstones and Fruitland coals – Throughout most of the Chevron study area, the upper portion of the Pictured Cliffs and Lower Fruitland coal interval interfinger. In some places, Lower Fruitland coals are in contact with the sandstones of the Pictured Cliffs. Therefore, there is potential for gas to escape from the coals into the sandstones of the Pictured Cliffs. For these reasons, the 3D geologic model must incorporate the Pictured Cliffs into the simulation model.

Pictured Cliffs shoreface sandstone continuity: depositional dip vs. depositional strike – Pictured Cliffs shoreface sandstones are more continuous along depositional strike (northwest-southeast) than along depositional dip (southwest-northeast). This is reflected in the porosity and permeability trends of the Pictured Cliffs reservoirs and must be incorporated into the 3D geologic model.

Fruitland fluvial sandstone continuity: depositional dip vs. depositional strike – Fluvial sandstones of the Fruitland are isolated in finer grained overbank and coastal plain siltstones and shales. They are most continuous along depositional dip (southwest-northeast) and discontinuous along depositional strike (northwest-southeast). Occasionally, these sandstones are in contact with Fruitland coals and can become gas-charged. Thus, they must be incorporated into the 3D geologic model.

Seals – The top seal to the 3D geologic model are the shales of the Kirtland. Because of the interfingering of the Pictured Cliffs and the Fruitland, the bottom seal to the geologic model has to be the marine shales of the Lewis.

7.1 3D GEOLOGIC MODEL

7.11 Data Preparation

Schlumberger's PETREL, a seismic to simulation software package was used to build the 3D geologic model. Data from well log LAS files, well location and directional survey data, tops picked from stratigraphic correlations, cut-off criteria and a digital elevation model comprised the data for use in PETREL. Quality control checks were used to ensure data reliability.

GR curve and bulk density curve response were used to distinguish coal, carbonaceous shale, shale, and sandstone, and allow for mapping the lithologies in 3D space. Once this was accomplished, the four rock types could be located in 3D space.

7.12 Log Correlation Sections

Correlation sections were constructed along depositional strike and dip as well as laterally through all the available well data. Tops were picked for the Upper Fruitland, Middle Fruitland, Lower Fruitland, the top of the Pictured Cliffs, the Fruitland Tongue of the Pictured Cliffs, and where present, the top of the Lewis. Only seven wells penetrated the top of the Lewis in the Chevron study area. Careful correlations are critical because they form the basis for the mapped horizons that define the variations in the intervals in the 3D geologic model.

7.13 Formation Surface Generation

Once the correlations were completed in PETREL, NQE generated structural surfaces for each horizon. Structural surfaces were built for the Upper Fruitland, Middle Fruitland, Lower Fruitland, and Pictured Cliffs. These surfaces were quality checked to identify any anomalies in the data.

Due to the paucity of wells penetrating the Lewis in the Chevron study area, the Lewis structural surface had to be generated from isopach data for the interval from the Pictured Cliffs to the Lewis. Using the seven wells that penetrate the Lewis in the study area, thickness variations of the Pictured Cliffs interval were measured, and with these thickness variations and the structural surface of the Pictured Cliffs, the structural surface of the Lewis was extrapolated into areas of the study area lacking Lewis penetrations. Since the top of the Kirtland is relatively shallow, it was rarely logged. Therefore, the same process was used to place the top of the Kirtland in the model.

7.14 Outcrop Description

Outcrop mapping by the Colorado Geological Survey in the San Juan Basin provided the boundaries for the Kirtland, Fruitland, Pictured Cliffs, and Lewis. Digital air photos and a digital elevation model (DEM) of the surface topography from the United States Geological Survey were imported into PETREL and used to record the mapped outcrop formation boundaries.

Most, if not all, subsurface modeling software is designed to be used on strata that do not outcrop. In order to properly model the formations outcropping in the Chevron study area, a series of additional data points were added along the outcrop outlines. At each point, the corresponding surface was given an elevation equal to the ground elevation from the DEM. This results in the formations outcropping in the proper place at the surface. Due to time constraints of the project, the quantity of additional data points was limited. Therefore, the formations do not follow the actual outcrop when viewed at the same scale as the DEM. However, for the purposes of the 3D geologic model and eventual upscale to simulation, the density of the additional data points is sufficient to maintain the general outcrop outline (**Figure 35**).

7.15 Lithology Log

Discrete lithologic descriptions of the rock volumes were generated by combining the available GR logs and RHOB logs in wells where both existed. Due to log vintage differences, the log sets required normalization to consistent scales. Cutoffs were applied to differentiate between sandstone (SS), coal (C), carbonaceous shale (CS), and shale (S). GR counts less than or equal to 75 API Units isolated sandstones and coals from carbonaceous shale and shale groups. GR counts greater than 130 API Units isolated shale from carbonaceous shale. Strata with RHOB values less than or equal to 1.75 grams per cubic centimeter (gm/cc) and GR counts less that 75 API Units were considered to be coals. Carbonaceous shales were defined as rocks with RHOB values greater than 1.75 gm/cc and less that 2.3 gm/cc. Zones with RHOB values greater than 2.3 gm/cc and 2.4 gm/cc were delineated as shales. Sandstones were indicated by GR counts less than 75 API Units and having RHOB values greater than 2.4 gm/cc.

7.16 3D Geologic Model Development

Both a body-based model and a statistical-based model were studied during the development of the 3D geologic model. Each represents a different method of characterizing the reservoir rock volume.

The general geologic setting description provided the regional depositional strike and dip of the rocks. The Pictured Cliffs shoreface sandstones accumulated along the regional shoreline of the Western Interior Seaway. They are most continuous along depositional strike (northwest to southeast) and discontinuous along depositional dip (southwest to northeast). The Fruitland coals developed on the platform provided by the shoreface sandstones of the Pictured Cliffs. As within the Pictured Cliffs, Fruitland coals are most continuous along depositional strike and less continuous along depositional dip. In contrast, the fluvial deposits of the Fruitland are most continuous along depositional dip (southwest to northeast) and laterally discontinuous along depositional strike. These basic characteristics for the rock-volume distribution were incorporated into the development of both the body and the statistical models.

The body model uses a background rock type with other discrete rock bodies inserted. The general orientation and description of each body type is variable. In the case of the Chevron study area, the basic background rock type was shale and the bodies inserted were coal and carbonaceous shale lenses and stream channels. The coal and carbonaceous shale lenses were most continuous in a northwest-southeast direction. The length and width of each lens was determined from general variogram's major and minor axes. Sinuosity and amplitude of the sand channels were based on trial and error to approximate the sand volume represented in the logs and they were most continuous in a southwest-northeast direction. After some effort at developing an acceptable body model, it was decided that the definition of the lens and channel characteristics was insufficient to accurately represent the distribution rock types found in the logs.

The second model approach used the same general depositional strike and dip information but in a slightly different manner. A geographic and vertical variogram was developed for each rock type in each of the Kirtland, Fruitland, and Pictured Cliffs formations. For the coals, carbonaceous shale and shale, the major direction was set similar to the general depositional strike direction and by default the minor direction is similar to the general depositional dip direction. The lengths of the major and minor axes were determined directly from log data and the actual variation of the data in both principle directions. The sandstones in the Fruitland were handled similarly except the major axes approximated the depositional dip direction and the minor axis tended to honor the depositional strike direction.

The variograms established the limits of continuity in both the horizontal and vertical directions. Additionally, they described the continuity or lack of continuity within the 3D geologic model area. In general, the vertical continuity was on the order of five to ten feet. The horizontal major direction was 5,000 to 15,000 feet with the minor being a third of the major direction. Each general zone has a different variogram for each rock type. The sand channel nature of the Fruitland is honored by long, thin variograms in a depositional dip direction. In contrast, the shoreface sands of the Pictured Cliffs use a depositional strike axis direction and the ratio of magnitude of the axes lengths were nearer to one. The shales of both the Fruitland and the Pictured Cliffs had the major axis length equal to the minor axis length demonstrating no particular orientation preference but did show an axes length established by the correlation distance. The carbonaceous shales indicated a definite orientation and continuity length along depositional strike.

As defined by the lithology log, the coals decreased in the Upper Fruitland, while occupying a significant portion of the Lower Fruitland. The logs also identified some coal volume in the Pictured Cliffs and Fruitland tongues. As the density of coal was increased in the logs for any particular layer, the continuity of coal simultaneously increased due to overlapping of the variogram space. It should be noted in layers where the log indicated coal was less dense, the coal proportion was reduced. This causes the fingering of the coals to be represented in the geologic model. As an example, if a well had coal in a layer and the adjacent well did not, the coal proportion would decrease to zero some place between the wells. Thus, if the next layer had coal in both wells, the coal would become continuous between them and the finger of non-coal rock type would be established. This is demonstrated best by the coal fingers of the Pictured Cliffs Tongue and in the coal lenses of the Upper Fruitland.

Over distance, the coal fades to sand and vice versa on a geologic model layer basis. The actual logs measure the coal locally, and the variograms and the geostatistical model establish the rock type proportion between wells where no data exist. The inclusion of the Pictured Cliffs in the 3D geologic model was necessitated by the presence of the Fruitland Tongue of the Pictured Cliffs. In the geostatistical model, the stratigraphic tops are not as important as the presence of coal in the wellbore. The geostatistic model forces coal to exist in the geologic model where it exists in the wells. The variograms (spatial variation) and coal density control where the coal exists between wells. Therefore, the coal fingers or rock type proportion are represented without directly using the Pictured Cliff top.

Besides directly honoring the actual rock type for any particular layer at the wellbore, the statistical model provides a direct approach to modify the proportions of the rock types between wells. This is accomplished by varying the probability that a particular rock type will show up in a given layer. In the geostatistical approach to the 3D geologic model, this was used to increase the coal volume to levels that were more representative of the actual log-indicated proportions.

The Kirtland had mostly shale or carbonaceous shale and provided a seal to the Fruitland interval. In the simulation model, this layer was considered to be inactive. On the bottom, the Lewis provided shale layers that were continuous and provides the bottom seal.

7.17 3D Geologic Model Layer Arrangement

The 3D geologic model covers approximately 48,400 acres including the methane seepage points at Carbon Junction and the Basin Creek. This model consists of a total of 12,703,320 cells arranged in three-dimensions (213 x 213 x 280 cells). Aerially, each cell is approximately 250’ x 250’. The vertical layering is distributed into three zones: Kirtland, Fruitland, and Pictured Cliffs. The Kirtland occupies layers 1 to 50 (50 layers – each layer is on average 3.97 ft thick), the Fruitland layers 51 to 250 (200 layers – each layer is on average 1.92 ft thick), and the Pictured Cliffs layers 251 to280 (30 layers – each layer is on average 21.63 ft thick).

7.18 Upscaling the 3D Geologic Model

During upscaling, the lithologic description is used to break the Kirtland, Fruitland, and Pictured Cliffs zones into the layers described above. The rock volume in each layer is evaluated to determine which rock type dominates the layer. Next, the entire layer at each wellbore is assigned a dominate rock type identification number (0 for sandstone, 1 for coal, 2 for carbonaceous shale, and 3 for shale) and all layers throughout the 3D geologic model are processed to determine the percentage of the various rock types (**Figure 36**).

From this initial pass, the resulting coal proportion of the upscaled model was about 7.5 percent in the Fruitland. After the facies model is generated for the 3D geologic model, the model is upscaled once more to the simulation model. This upscaling involves both an increase in the aerial size of the cells that comprise the geologic model as well as an increase in the vertical thickness of each cell. The subsequent simulation grid upscaling causes a loss in the coal volume due to the loss of definition in the fine grid layers from the 3D geologic model. This loss was approximately two percent of the total zone coal volume in the fine grid 3D geologic model. Because of this loss, the resulting coal volume was insufficient to develop an accurate simulation model. Thus, the coal probability was increased about 15 percent over the original estimation (**Figure 37**). Additionally, the variograms defining the distribution for coal were increased slightly in the major and minor axes length. This modification of the variograms increased the area over which any particular coal segment could be expected to exist.

The entire process from rock type model to the reservoir simulation model upscaling was revised, and the final coal volume in the simulation grid in the Fruitland was about 9.5 percent. This was acceptable for the reservoir simulation model because it honors the amount of coal from the well logs. **Table 2** shows the original Fruitland upscaled log, the final full Fruitland upscaled 3D geologic model, and the final upscaled Fruitland simulation model facies statistics. **Figure 38** is a histogram showing the resulting facies distribution for the 3D geologic model visualization (Middle Litho), the upscaled cells, and the actual well log data.

These realizations are the result of geostatistical modeling efforts, and the values in **Table 2** represent a single realization. For the 3D geologic model, 40 cases were compiled.

Table 3 provides summary statistics for each rock type in the Fruitland for all 40 cases. For comparison, the average percentage for each rock type from the logs is included in **Table 3**. The coal results are of primary interest in this table. **Figure 39** is a histogram of the 40 cases with respect to the coal volume. The central or median case has a coal volume of 10.91 percent. **Table 4** is a ranking of all 40 cases with respect to coal volume. Case 8 in **Table 4** was considered the median value case and was used to construct the reservoir simulation model.

Figure 40 illustrates a log section view of the above results. This figure demonstrates the upscaling process and also shows the natural loss of detail during the two upscaling processes.

To illustrate the texture generated by the geostatistical model, **Figure 41** shows an aerial view of layer 234 in the Fruitland section of the 3D geologic model.

Figure 42 is a cross-section of the 3D geologic model at the Animas Carter West 7U4 well. The figure shows the lateral continuity of the fine grid model in the Fruitland (the thin layers). The thicker lower layers of the Pictured Cliffs are not as continuous. **Figure 43** shows the changes from the fine grid of the 3D geologic model (on the left vertical face) to the coarse grid (on the right vertical face) of the simulation model. Only a few layers remain continuous after upscaling. There is some loss in resolution with an 8:1 layer reduction. The reason for the significant layer reduction is to reduce simulation run times.

7.19 Simulation Model Development

The simulation model covers approximately 25,800 acres including the seep locations at Carbon Junction and Basin Creek. The simulation model is made up of a total of 293,973 cells (109 x 87 x 31 cells). Aerially, each cell is approximately 500 ft x 500 ft. The vertical layering is distributed into three zones: Kirtland, Fruitland, and Pictured Cliffs. The Kirtland occupies layer

1 (1 layer – the layer is 198.4 ft thick), the Fruitland comprises layers 2 to 24 (23 layers – each layer is on average 16.6 ft thick), and the Pictured Cliffs layers 25 to31 (7 layers – each layer is on average 92.4 ft thick)

7.20 Flow and Region Development

Figure 44 shows four major regions along the outcrop. To isolate the two seeps and allow the model to forecast gas seepage along the outcrop, separate regions were constructed for each seep and the remainder of the outcrop. **Figure 45** adds the DEM to Figure 44, and shows the portion of the model that accounts for the outcrop-atmosphere interface. **Figure 46** and **Figure 47** are cross-sections showing the simulation model as it passes through the outcrop surface. The two figures display the structural character of the geological model from two different perspectives.

Figure 48 is a close up view of the rock types at the outcrop. Rock type colors are: yellow-sandstone, black-coal, orange-carbonaceous shale, and grey-shale. The thin green line passing through the figure is the trace of the DEM. The model is designed to simulate outcrop seepage to the atmosphere; consequently it is necessary to construct model cells in the atmosphere to be able to simulate the seepage. In the reservoir simulation, the atmospheric cells are given properties representative of the atmosphere: 100 percent porosity, 0 percent water saturation, and infinite permeability. Pressure in these cells is maintained at atmospheric pressure.

Figure 49 is an aerial view of the outcropping simulation model across the Basin Creek and Carbon Junction seep locations. Cells in the simulation model with centroids above the DEM have been eliminated to allow a view of this realization's outcrop features. The rock type locations in this view are an artifact of the realization. Each different realization will have a different distribution and location of rock types showing at the outcrop. **Figure 50** and

Figure 51 are views to the southeast across the Carbon Junction seep location. **Figure 50** shows the river bottom (based on the DEM) and the outcropping simulation model cells that have centroids that are less than the DEM surface.

8.1 SIMULATION STUDY ON THE IMPACT OF INFILL DRILLING ON OUTCROP METHANE SEEPAGE

8.11 INTRODUCTION

The goal of the simulation study was to determine the impact of continued infill drilling on outcrop methane seepage. This was last studied with the 3M MODEL which found that additional infill drilling would have little impact on methane flux at the outcrop and that long-term seepage will actually diminish as a result of infill drilling. This study is consistent with the 3M MODEL results.

Since the focus of this simulation study was the outcrop gas seepage at Carbon Junction and Basin Creek, the history match emphasis was on the overall volumetric parameters. Individual well historical performance was not ignored but the timing, goals, and purpose of the study precluded exhaustive efforts to obtain individual well history matches.

In order to be able to make reasonable predictions of the future, all simulation models need to be populated with reasonable rock and fluid properties, such as porosity, permeability, fluid saturations, etc. In simulating areas where wells exist with historical fluid production data, the population of these variables is greatly improved through the process of history matching. History matching involves modifying the rock and fluid variables within reasonable ranges until both historical fluid cumulative production amounts and rate trends are recreated in the simulation within reasonable tolerances.

As a general rule, the longer the historical production time and the larger number of wells that are history matched increases the models predictive capabilities. The process of history matching is one of diminishing returns in that the improvements in a simulation's predictive capability is not directly related to the amount of time expended obtaining a perfect recreation of the actual observed history in the simulation. Early large-scale modifications to the rock and fluid properties generally prove to be the most beneficial, while later localized modifications targeting an individual well performance provide much more limited improvements to the predictive capabilities of the simulation. This is especially true when considering large-scale fluid movement and not individual well performance such as the impact of continued infill drilling on outcrop seepage which is the subject of this simulation.

8.12 SIMULATION INPUT PARAMETERS

The simulation was accomplished with Roxar's MORE reservoir simulation program, a commercial program, capable of simulating coalbed methane (CBM) reservoirs using coal desorption and diffusion properties. The following sections describe the input parameters, including the 3M MODEL that were utilized in the study.

8.13 FLUID PROPERTIES, RESERVOIR TEMPERATURE, AND PRODUCTION DATA

Gas properties were determined based upon an average of gas compositions provided by Chevron. Gas gravity was determined to be 0.568 with a CO_2 molar fraction of 0.01033. Gas properties used in the simulation are shown in **Figure 52**. Water properties are determined internally by MORE based upon water density. Based on water sample data, a water specific gravity of 1.01 was representative of the formation waters.

The simulation used a reservoir temperature of 112 Fahrenheit. In reality, temperature is variable across the simulation area with the lowest temperature found at the outcrop and the highest temperature at the maximum depth in the simulation. The simulator, however, is isothermal and a single temperature must be specified; subsurface measurements provided the temperature data.

The sources for the individual well gas and water historical production data used in the simulation include Chevron, COGCC, and IHS Energy data service company.

8.14 GEOLOGIC CHARACTERIZATION

A detailed discussion of the geologic characterization and simulation input can be found in sections 6.1 and 7.1 of this report.

8.15 ROCK PROPERTIES

The geologic model created for this simulation study contained four separate rock types or facies: Sand, Coal, Carbonaceous Shale, and Shale. Each of these rock types was given representative properties of porosity, permeability, compressibility, and ash + moisture content. Values of porosity and permeability can be and were modified to improve the history match both on a global and well-level. Other parameters, such as compressibility and ash + moisture content, were fixed at simulation initiation and not modified as part of the history matching. The initial global parameters can be found in **Table 5**. The permeability in **Table 5** is the butt cleat permeability in the model's I-direction. The face cleat permeability was set at 2.5 times the butt cleat permeability and is in the model's J-direction. The model was oriented to have the face cleats in the J-direction. Vertical permeability was set to 0.1 times the face cleat permeability.

Setting the shale porosity equal to zero causes the model to make the shale inactive. This results in reducing the total active simulation cell from 293,973 to 70,383 which aids computation speed. Since shales typically are non- productive and have low permeability and porosity, nothing is lost by making the shale inactive. The primary role of shale is to act as baffles and barriers to flow, which is preserved even when the shales are made inactive.

8.16 Coal Properties

Chevron provided NQE with multiple isotherm and gas content data for the area. At the beginning of the study a composite isotherm was created that represented an average of the available data used in the simulation study. During the history matching process it became apparent that more gas was required in the simulation area in order to match the historical produced gas. As a result, the final Dry Ash Free (DAF) isotherm that was utilized was the GRI #1 Basal Isotherm (32N-10W-17, La Plata, CO). Chevron provided isotherms and gas content data as shown in **Figure 53**.

Since no trend was observed in the gas content data and gas production was immediate in almost all of the historical production data, initial gas content was assumed to be saturated. Coal density was set at 1,876 ton/acre-ft and the Langmuir (sorption) time set to 1 day. Ash content was based on data provided by Chevron and area experience as is shown in **Table 5.**

8.17 Initial Fluid Saturations

History matching of the simulation area indicated that the system required some additional gas above what is adsorbed on the coals to match historical production. This is predominately the result of gas flux across the model boundary areas from the south and east (downdip to updip flow of gas). Additionally, small initial gas saturations were placed in the coal (12%) and sand (6%) to achieve the history match of gas production. The initial gas saturations placed in the coals and sands are consistent with the observed historical gas seeps pre-dating CBM production which support free gas saturations. Previous simulation studies performed by NQE for other clients in the San Juan Basin have also utilized initial gas saturations to achieve history matches so this was not unanticipated. History matched initial gas saturations are shown in **Figure 54**.

8.18 Relative Permeability Curves

The relative permeability curves utilized for the simulation were obtained from the 3M MODEL. Although the 3M MODEL was a single-layer model, these curves can be used in this simulation since the permeability has been adjusted during the history match. Flow is a function of the product of relative permeability, cell permeability, and the cell cross-sectional area to flow; therefore relative permeability is only one of three variables. Alternative relative permeability curves can be utilized, although the simulation cell permeabilities and possibly initial fluid saturations would have to be modified during a history match to accommodate the change.

The two relative permeability curves utilized for this study are shown in **Figure 55** and **Figure 56**. The dry curves impact rock regions 1 through 4 which are the sand, coal, carbonaceous shale, and shale found downdip in the Fruitland reservoir. The dry outcrop curves impact, as the name suggests, the sand, coals, carbonaceous shale, and shale found at the outcrop, rock regions 5, 6, 7, and 8 respectively. Rock region 9 represents the atmosphere where methane release at the outcrop occurs, and uses a simple straight line set of curves. **Figure 57** displays the variation in rock regions.

8.19 Fluid in Place Regions and Original Gas-in-Place

The simulation was set up with multiple fluids in place regions (FLIPS) to allow for accounting of fluid movements between the atmosphere, outcrop, and Fruitland reservoir. FLIP regions 6 and 7 represent Chevron's internal division of the Fruitland reservoir. Regions 8 through 11 represent the general areas along the outcrop that have known seeps such as 9 and 10, which represent Basin Creek and Carbon Junction respectively. FLIP regions are illustrated in **Figure 58** .

Area B in the 3M MODEL is the closest analog for this study's simulation area. As a check, the original gas-in-place (OGIP) for this simulation was compared to the 3M's Area B after normalization through the simulation acreage.

NQE"s simulation contained 41 percent more gas volume than did the 3M MODEL simulation Area B. The bulk of the additional gas volume was introduced to the simulation to account for gas movement into the simulation area from downdip. The small initial gas saturation added to the coal and sands increases OGIP by less than 10 BCF or 0.5 percent. As mentioned previously since gas seeps were observed predating CBM production, initial free gas saturation would be expected. Gas migration updip and across the simulation boundaries is also not unanticipated.

Comparison between the calculated OGIP/Acre utilizing just coal properties and volumes, no history match modifications, indicates that this simulation is 13 percent more than the 3M Model, which indicates good agreement between the models. Original water in place cannot be compared because the 3M MODEL was a single-layer model of the coal only, while the current simulation is of the entire Fruitland formation.

8.20 INITIAL PRESSURE

The simulation was initialized in non-equilibrium using the initial pressure maps that were created from the 3M MODEL. The initial pressure is illustrated in **Figure 59**.

8.21 HISTORY MATCH

Since the focus of this simulation study was the outcrop methane seepage, the history match emphasis was on the overall volumetric parameters. Individual well historical performance was not ignored but the timing, goals, and purpose of the study precluded exhaustive efforts to obtain individual well history matches which as discussed in above in Section 8.11 would not have materially improved or impacted the simulation's predictions.

The history match encompassed almost 25 years from October of 1982 to August 2007. A total of 87 wells were simulated with 84 having some production data, and the remaining 3 being counted as pressure observation wells only. Eight wells in the simulation area had some pressure data that was used in the history match. The history match was driven on gas production, in that each well was told to produce its historical gas rate for each month if it could and still maintain a minimum bottom-hole pressure (BHP) of 50 psia, pump intake pressure. Water production is a function of the reservoir properties and fluid saturations at each well and the simulator was not told how much to produce. Each well was completed in the entire Fruitland section without regard to perforated interval since most wells have been hydraulic fractured. The exception was the pressure monitoring wells which were completed in productive zones either near or opposite of the perforation record.

The history match was obtained through global modifying the following parameters within reasonable ranges:

- Porosity
- Permeability
- Initial gas and water saturations
- Choice of isotherm

As discussed previously, changes were made to increase the gas available along the south and eastern boundary areas. These changes resulted in an additional gas volume added to the system through location specific modifications to both gas saturation and porosity.
Figure 60 illustrates some of the porosity modifications made to the global values. The modifications can be identified by the increased porosity surrounding a well as a square. Similar modifications were made to permeability to achieve the history match and are illustrated in **Figure 61** .

The coarse nature of the simulation grid also has an impact on the reported pressures. Since the pressure measurement is calculated at the center of a 500 foot square grid block, a well location can be off by up to 354 feet. This is not a great problem in either a single-layer or structurally flat model; however it does add uncertainty to the simulated pressure in this model especially near the outcrop where many of the pressure monitoring wells are located. This is illustrated in **Figure 62**. Pressure Monitoring wells 88040000 and 88150000 are located in cell I=32, J=38. If the well location is shifted to the adjacent cell I=31, J=38 the elevation change results in a decrease in the pressure of approximately 50 psi due solely to the elevation difference between the cells. This does not imply that the pressure match is invalid, it does illustrate that matching pressure magnitudes exactly is difficult due to the cell sizes and variable vertical pressures in the well column.

Field-level history matches are shown in **Figure 63**, **Figure 64**, and **Figure 65**. As expected, gas production is matched very well since the simulation was driven on gas. The water match is also very good, within 4.4 percent on a cumulative basis with historical data. The water production trend is also very good, especially later in the history from 1991 to 2007.

Figure 66 through **Figure 73** display the simulation pressure versus the observed pressure at the eight wells inside of the simulation area that had historical pressure data. Several of the wells show excellent matches. The matches indicate that the model is volumetrically calibrated to history.

It should be noted that the multi-layered nature of the simulation model coupled with the statistical nature of the geomodel results in each well layer having the potential to have variable pressure in the well column. The plotted zones represent layers that are generally either sand or coals located either at or near the well's actual perforations. This pressure is different than the pressure reported in the simulation as the bhp, as all zones that are open are represented in that value.

As discussed in Section 7.18, upscaling is required to achieve reasonable simulation run times. Alternative cells sizes would not change the predicted outcrop behavior, but would result in slightly different history matched values for permeability, porosity, and initial fluid saturations.

8.22 PREDICTION CASES

The focus of the study is on the effects on infill wells on methane out gassing at the outcrop. To assist in monitoring the methane production, 13 atmospheric (ATM) wells were placed in the FLIP regions to handle seepage at the outcrop. These wells were set to produce any time the pressure exceeded 11.5 psia. Therefore any gas production coming out of the outcrop is captured in the air FLIP regions and produced out of the ATM wells as shown in **Figure 74**.

Two future prediction cases were run out to the year 2030. One with continued production from the existing wells and another representing proposed future infill wells. Infill well locations and first production dates were provided to NQE by Chevron. Chevron provided NQE with a total of 52 infill well bottom-hole locations, of which 38 were inside of the simulation area as shown in **Figure 75.**

Figure 76 displays the predicted methane flow at the outcrop from the summation of all the outcrop FLIP regions and atmospheric wells. As can be seen in the figure, infill drilling reduces the predicted methane production at the outcrop. All atmospheric wells exhibited similar behavior with lower gas production with infill drilling. **Figure 77** and **Figure 78** show the predicted seepage at the Basin Creek and Carbon Junction locations.

8.23 SIMULATION CONCLUSIONS

- The simulation indicates that infill drilling will have a positive impact on methane production at the outcrop by capturing gas downdip before it can migrate to the outcrop. This result is consistent with the 3M MODEL.
- All outcrop regions exhibited a reduction in methane production with infill drilling over the existing well case.

8.24 3M Project and Chevron Study Modeling Differences

Both the 3M Project and the Chevron Study investigated the impact existing wells and infill drilling have on gas seepage at the Fruitland outcrop. Both studies employed reservoir simulation to model the seepage and predict future gas seepage. Although the results of both studies are consistent, the studies are differentiated by:

- the size of the two study areas,
- amount of infill drilling,
- development in the subject area,
- amount of production since the 3M study,
- improvements in 3D geologic and reservoir simulation modeling capabilities,
- available data, and
- the technical approach.

Study Areas

Figure 9 shows the 3M and Chevron study areas. There is no direct overlay of the two areas; Chevron's area, approximately two townships, occupies the northeastern part of 3M Study area A and the western part of 3M Study area B. Areas A and B encompass approximately eight townships. At the time of the 3M Study, there were 126 wells in the Chevron study area, now the area has 217 wells. These differences make the present study more focused and detailed.

Development and Production Data

The 3M MODEL is based on history matching 16 years of production data from the wells drilled at the time of the 3M Study. Since the 3M Study, there have been eight years of infill drilling development, production, and pressure depletion creating a reservoir response that provides an improved basis for the simulation history matching process. The result is a better model for predicting the behavior of the Fruitland coals.

Improvements in Geologic and Reservoir Modeling Capabilities

The rapid increases in computer memory, processor speed, and visualization hardware spawned the development of more sophisticated and higher capability 3D geologic and reservoir simulation models. At the time of the 3M Study, the existing commercial CBM models could not handle a project of that size, scale and detail and NQE wrote a simulator for the project.

Technical Approach

Another significant difference between the two studies lies in the approach used to model the Fruitland coals. For the 3M Project, a single horizontal layer was used for modeling the Fruitland coals. The additional 91 wells drilled since the 3M Project have allowed for the construction of a more detailed and accurate model. The current 3D geologic model used 281 layers to model the vertical and areal distribution of the Fruitland coal seams, shales, carbonaceous shales and siltstones comprising the lithologies of the Fruitland formation. Additionally, the 3D geologic model includes the Fruitland coals that tongue into the Pictured Cliffs. The 281 layers were up-scaled to 31 layers for the reservoir simulation. This provides a superior representation of the spatial distribution and continuity of the Fruitland coal seams that better describes the flow of gas and water in the coals and gas migration to the outcrop. The reservoir model used monitor well pressure data in the history match. These data were not available at the time of the 3M Study.

These four differences allow the Chevron Study to better model the geologic characteristics of the Fruitland coals, and better simulate the flow of fluids, resulting in a more focused, detailed, and realistic model than the 3M MODEL.

FIGURES

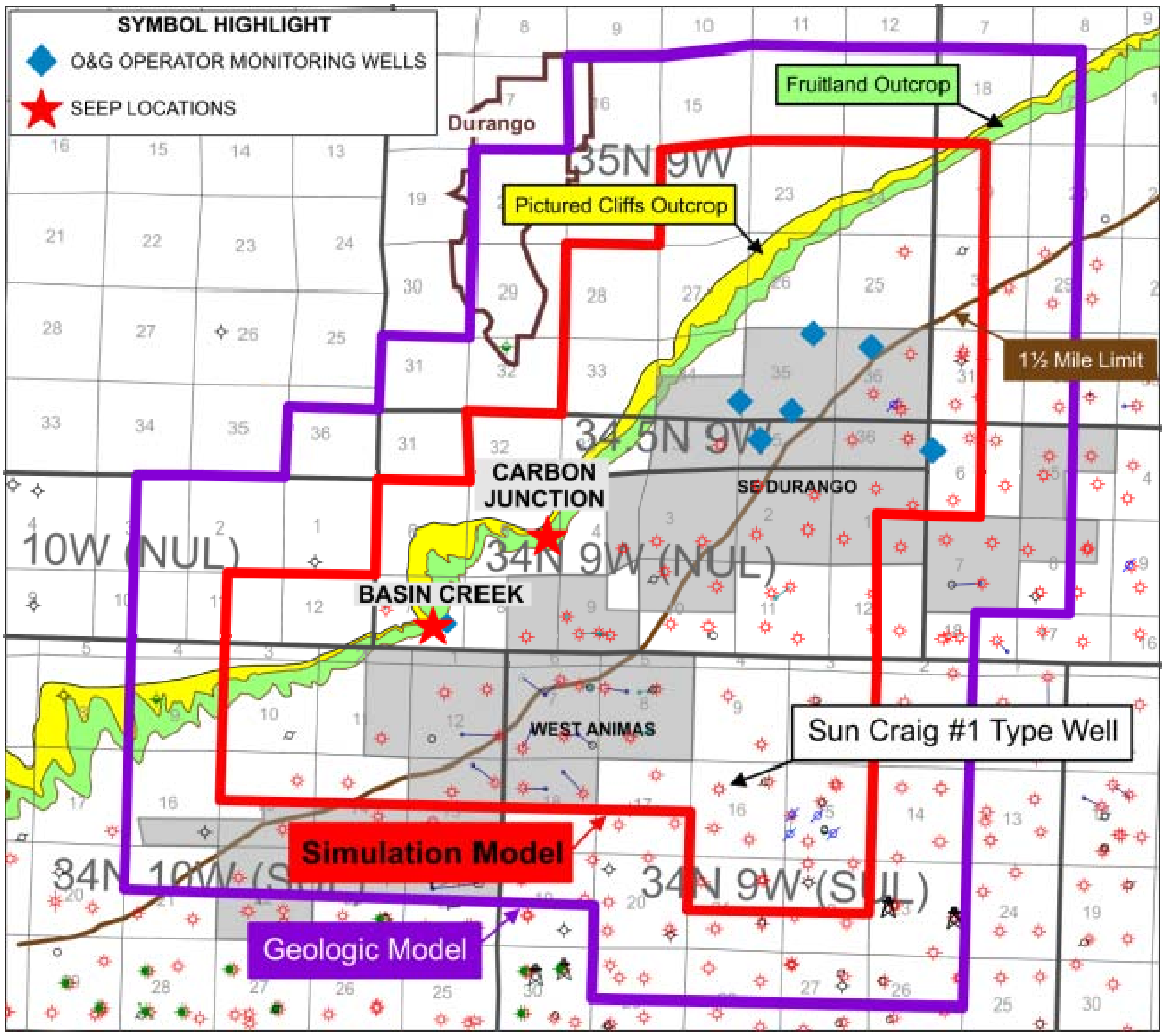

Figure 1 Location Map

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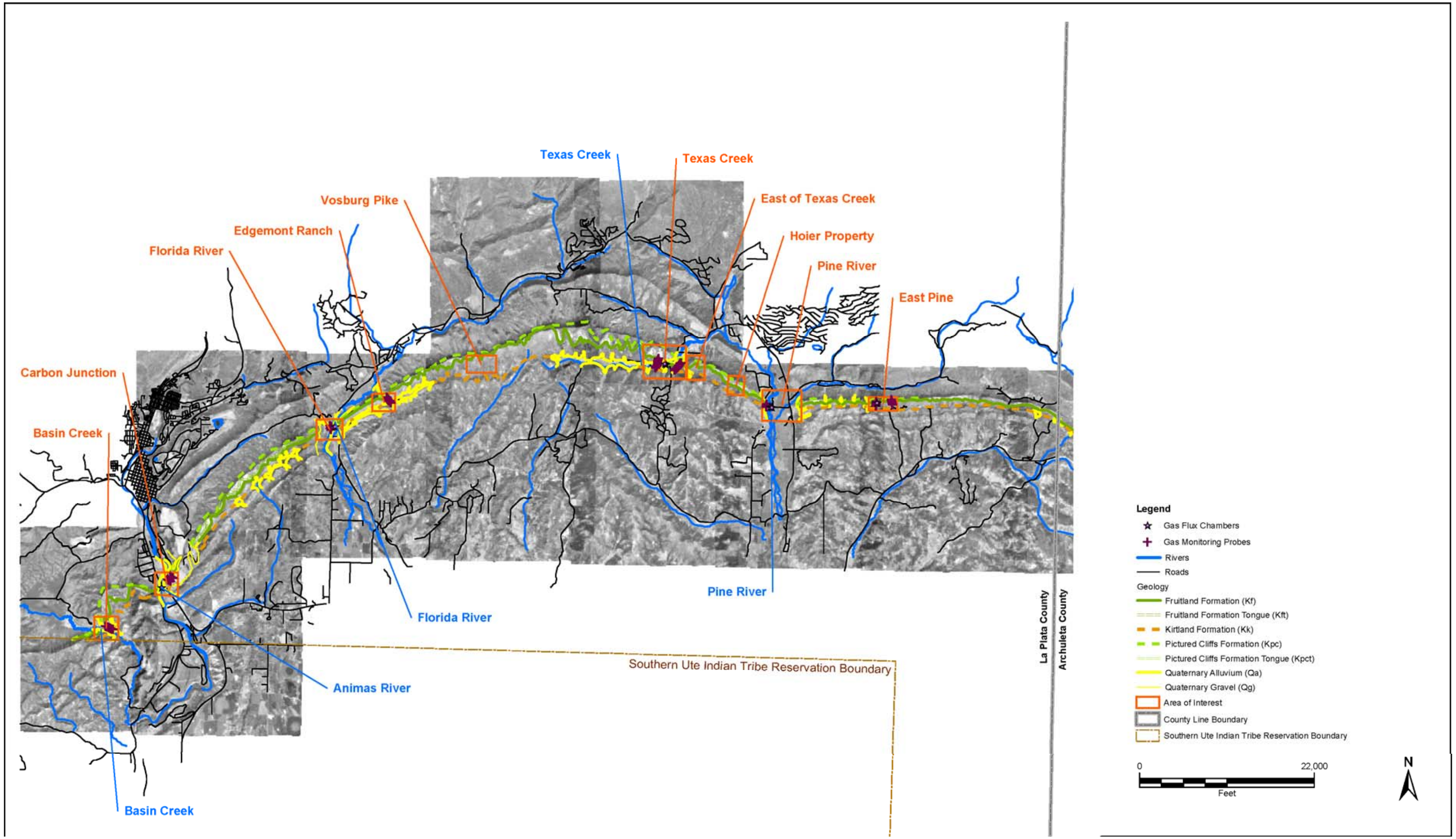

Figure 2 Regional Seep Basemap

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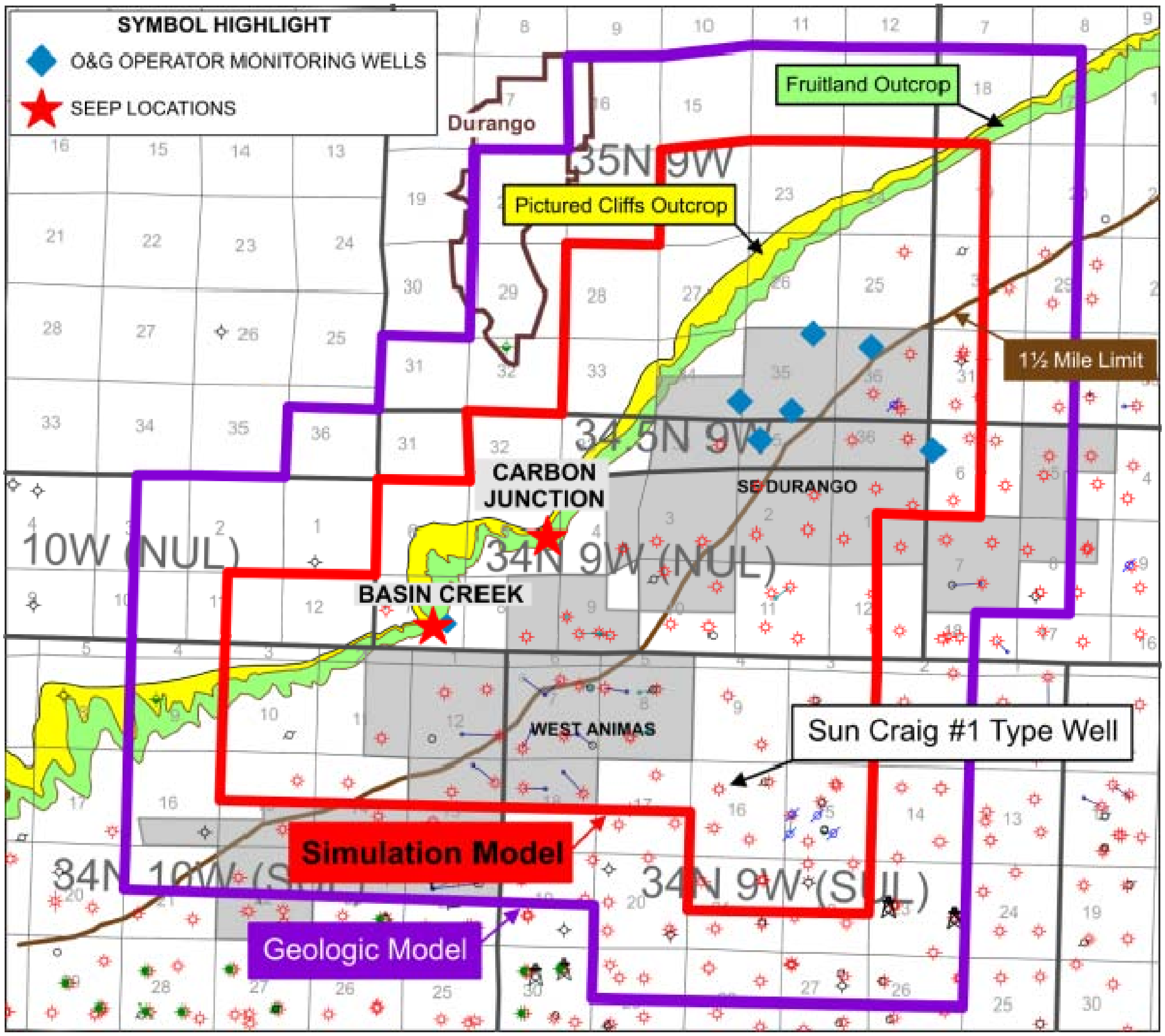

Figure 3 Chevron Study Area Basemap Showing the Location of the Basin Creek and Carbon Junction Seep Areas and Monitoring Wells (red stars).

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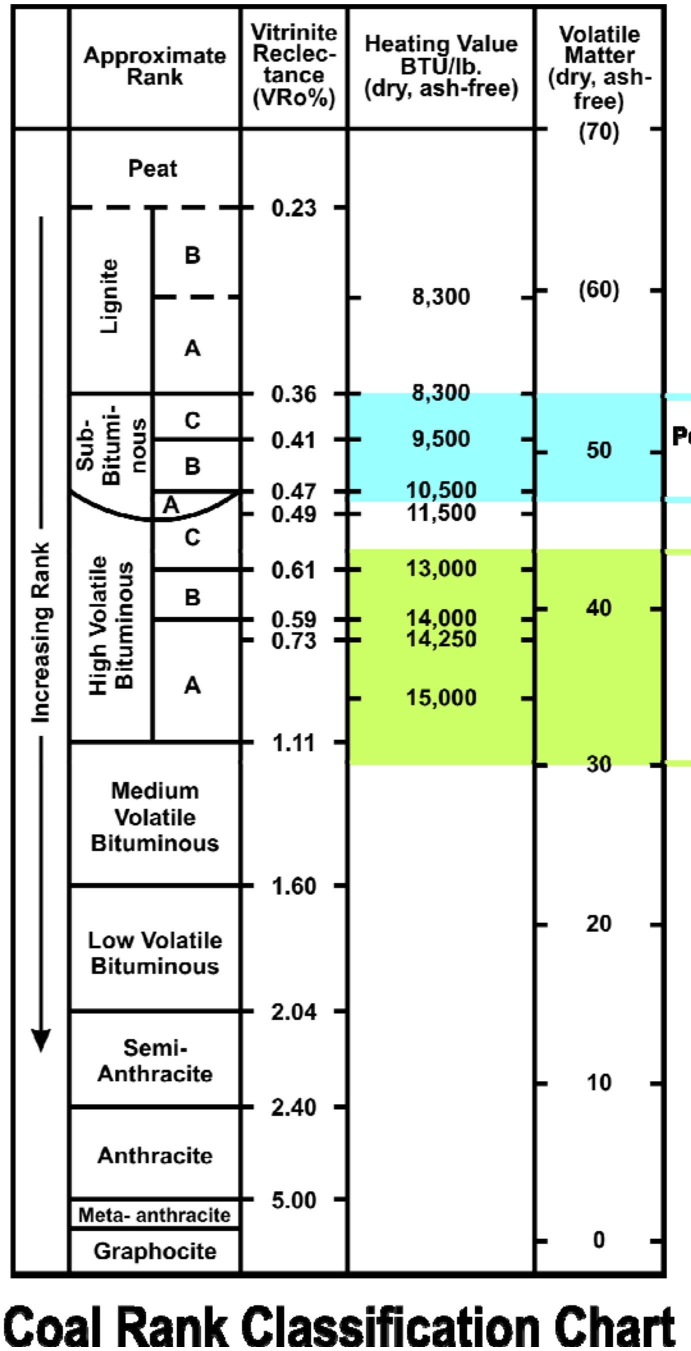

Figure 4 Coal Rank Classification Chart

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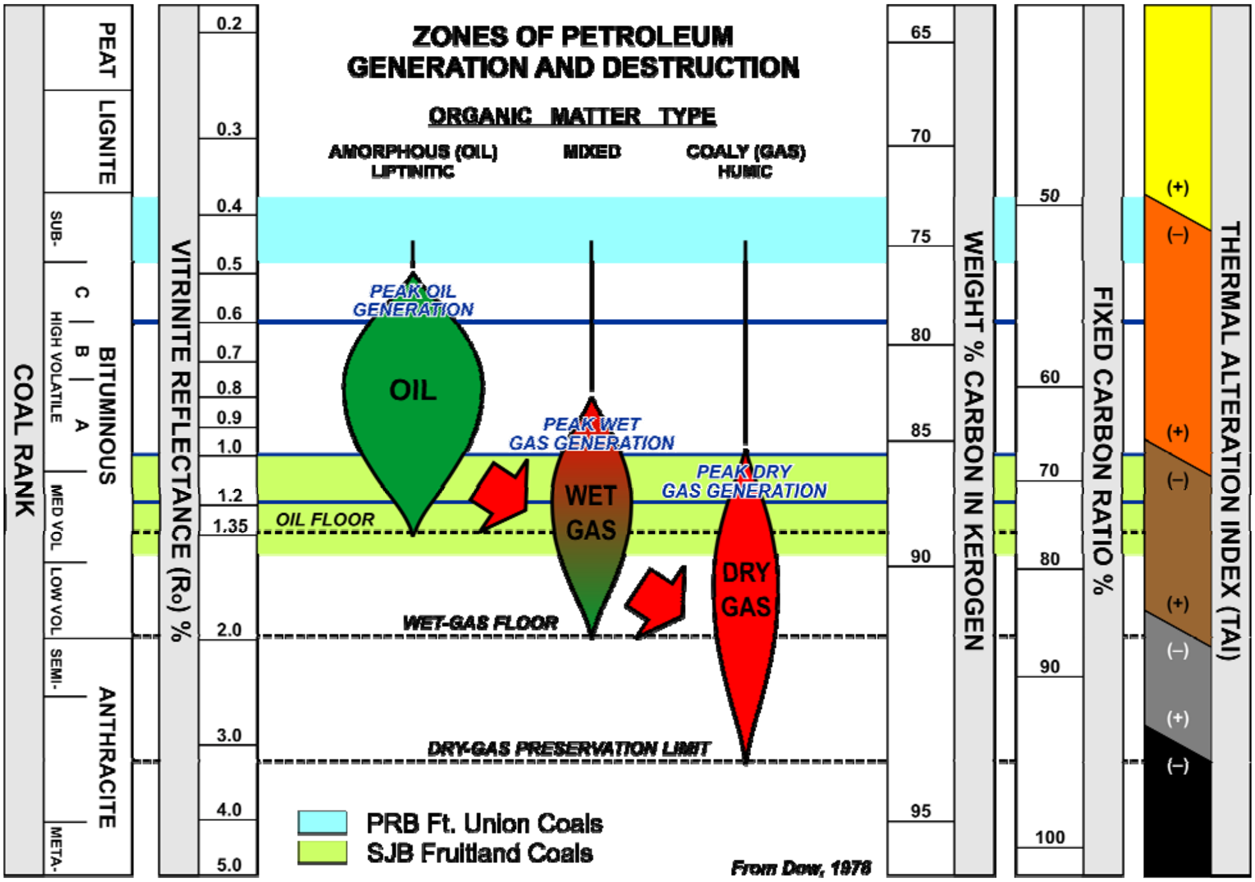

Figure 5 Coal Rank versus Zones of Petroleum Generation and Destruction

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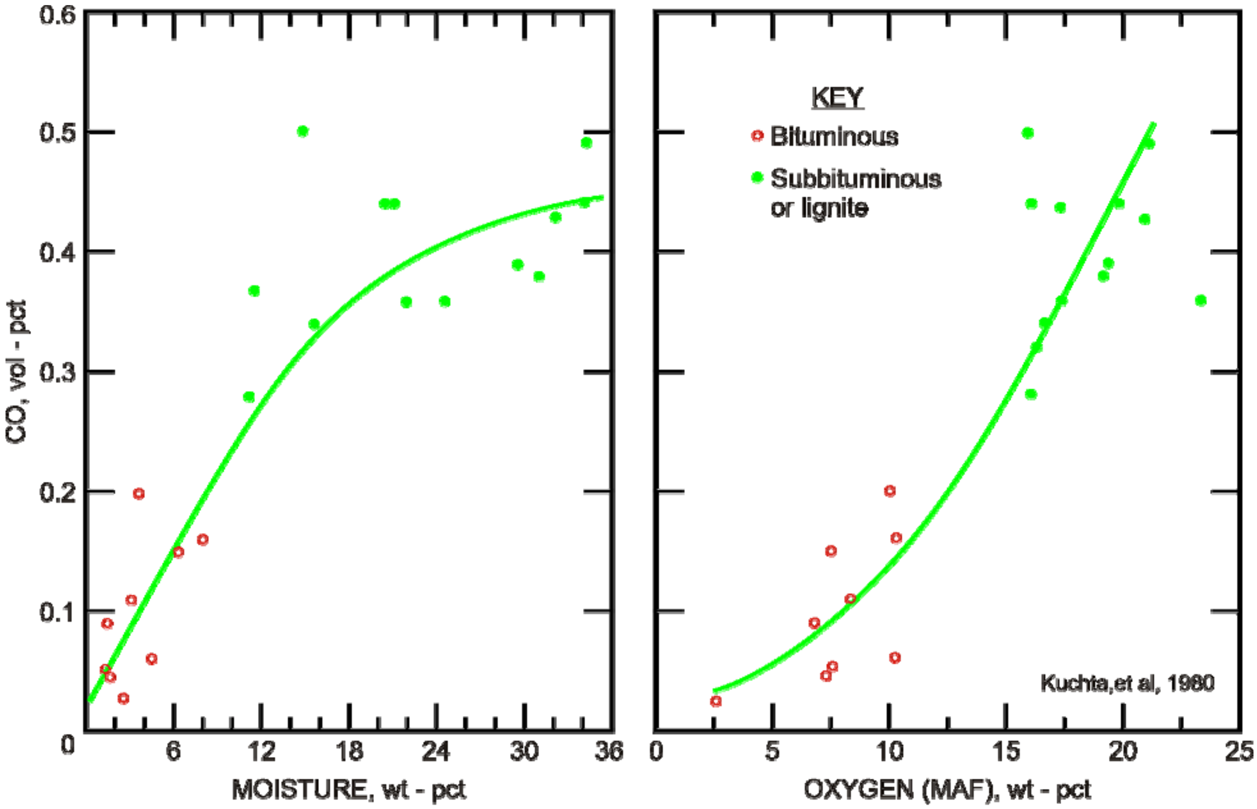

Figure 6 Effects of Coal Rank, Moisture, and Oxygen Content on the Susceptibility of Coal for Spontaneous Combustion

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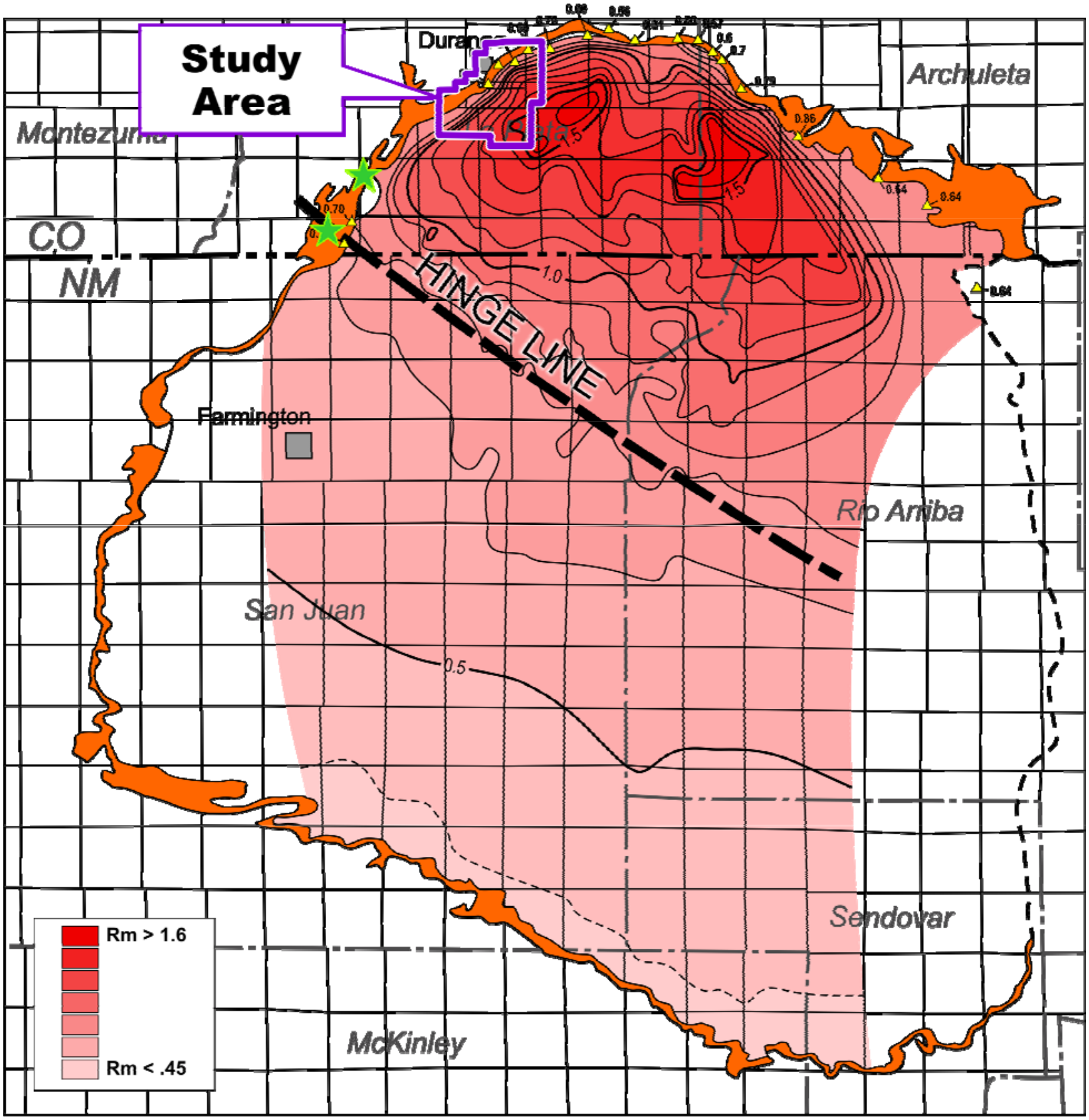

Figure 7 Thermal Maturity of San Juan Basin Fruitland Coals

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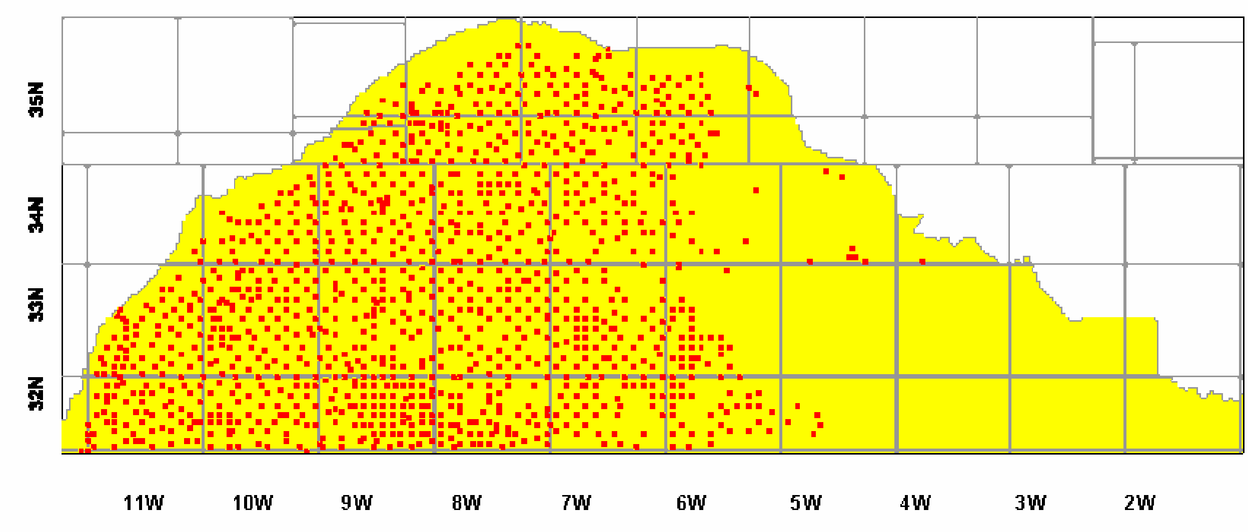

Figure 8 3M Project Study Area Showing Existing Wells as of 1999

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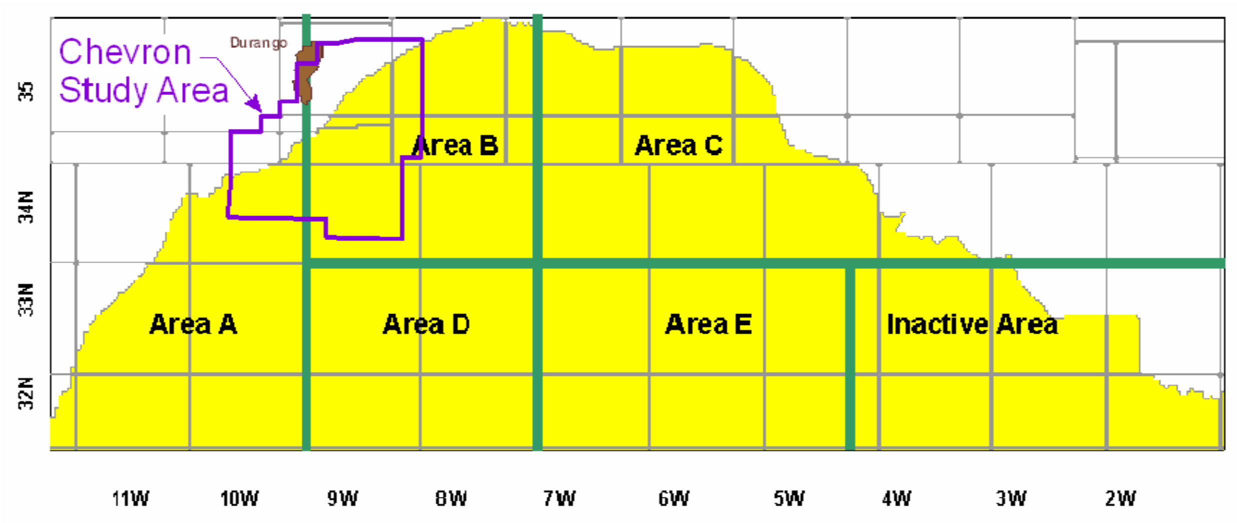

Figure 9 Five Subdivisions of the 3M SJB Study Area – Chevron Study Area also shown

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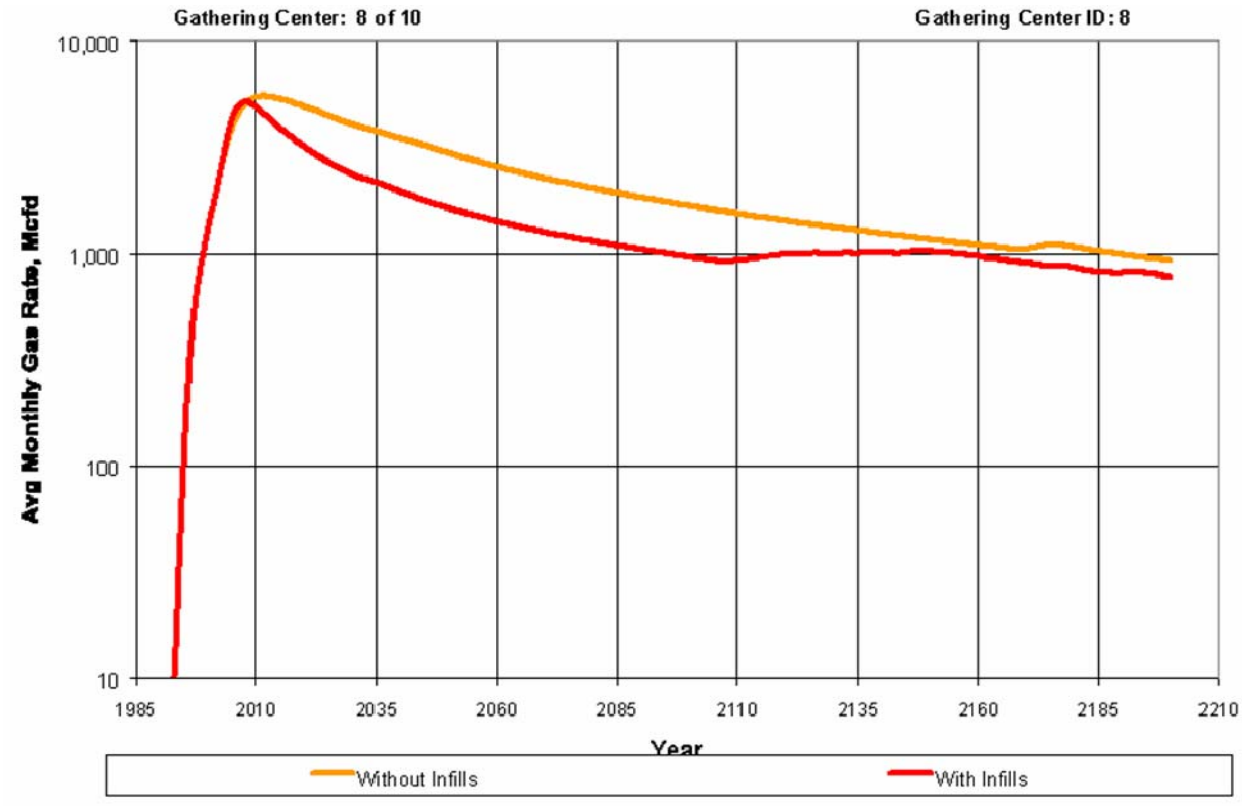

Figure 10 3M CBM Model Predicted Gas Seepage, Area A

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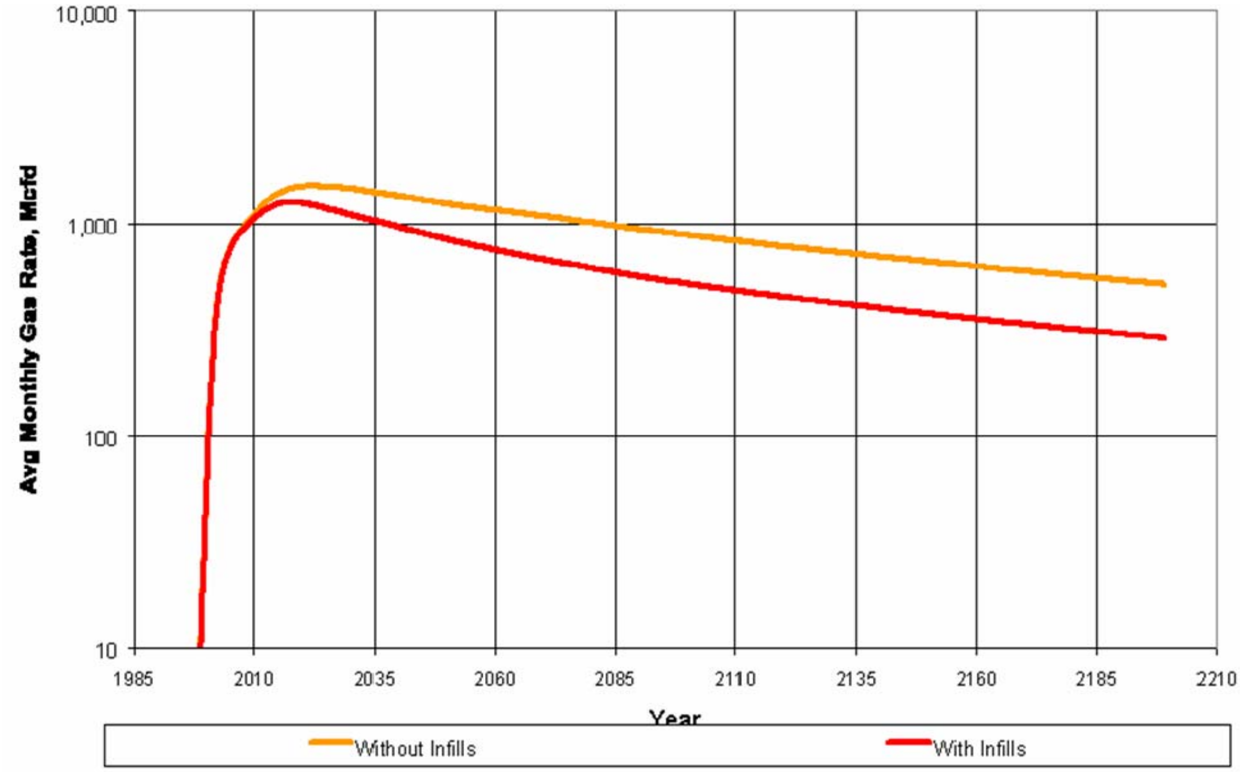

Figure 11 3M CBM Model Predicted Gas Seepage, Area B.

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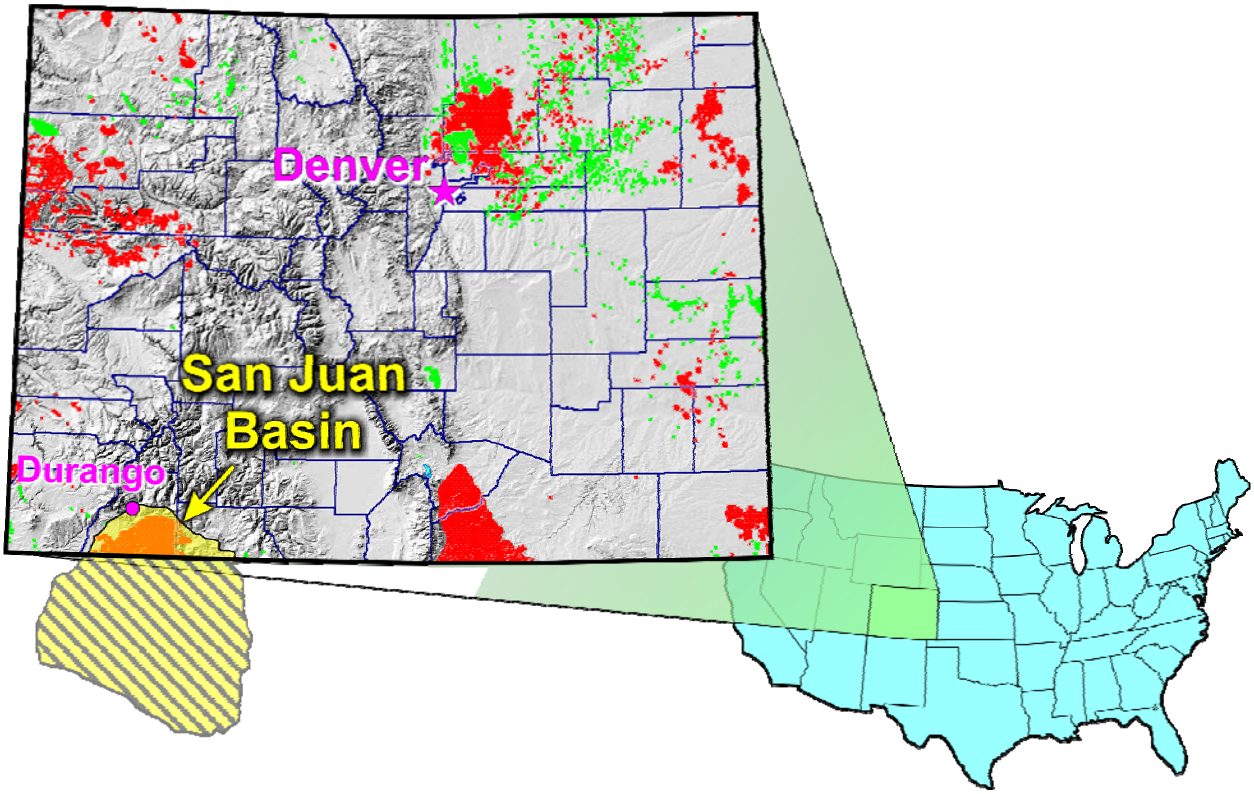

Figure 12 General Location Map of the San Juan Basin of Colorado.

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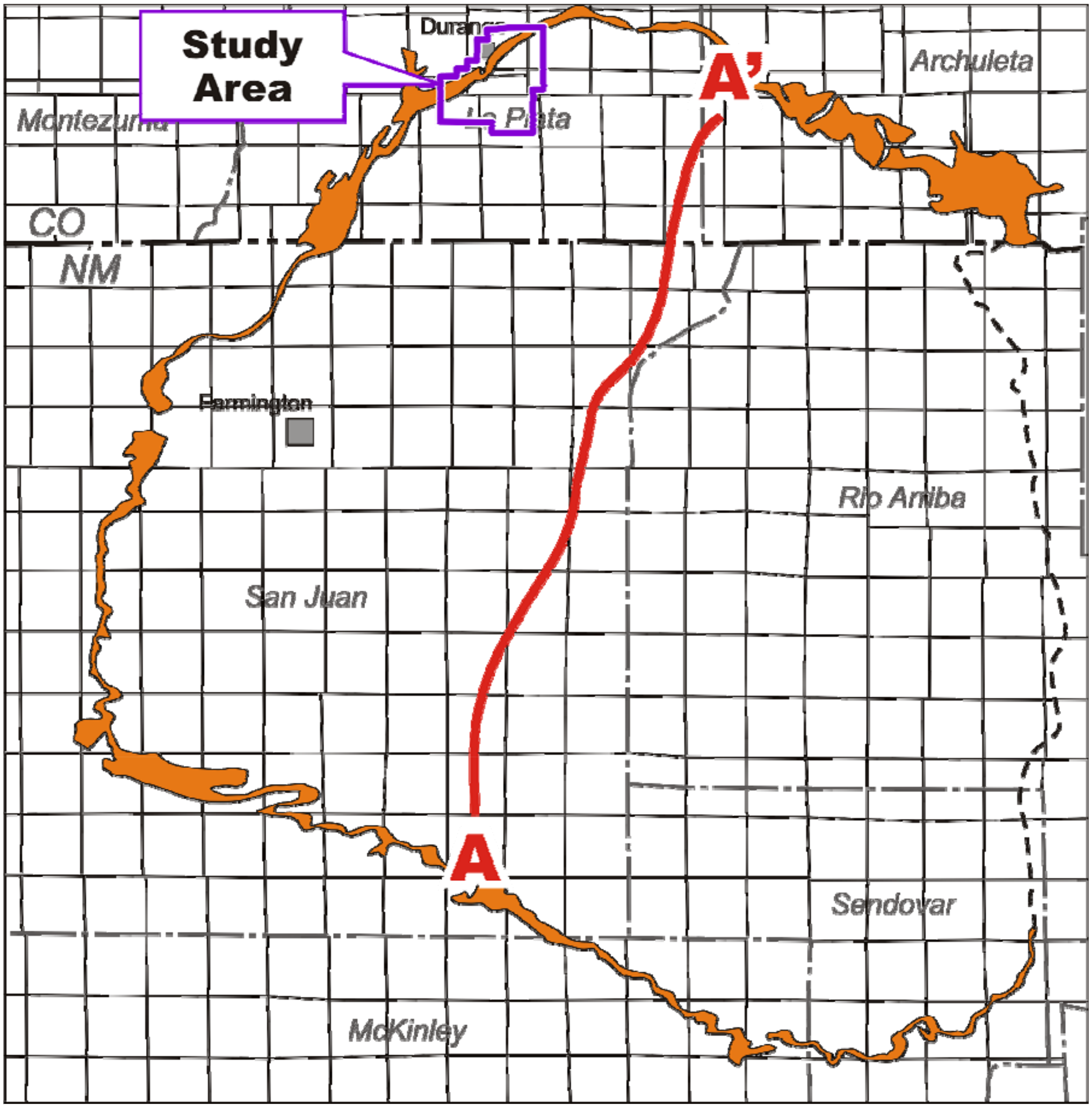

Figure 13 San Juan Basin Map with Township Grid Showing Position of Pictured Cliffs Outcrop, Study Area Location and Line of Stratigraphic Cross-Section A-A'
(Modified from Ambrose and Ayers, 1990)

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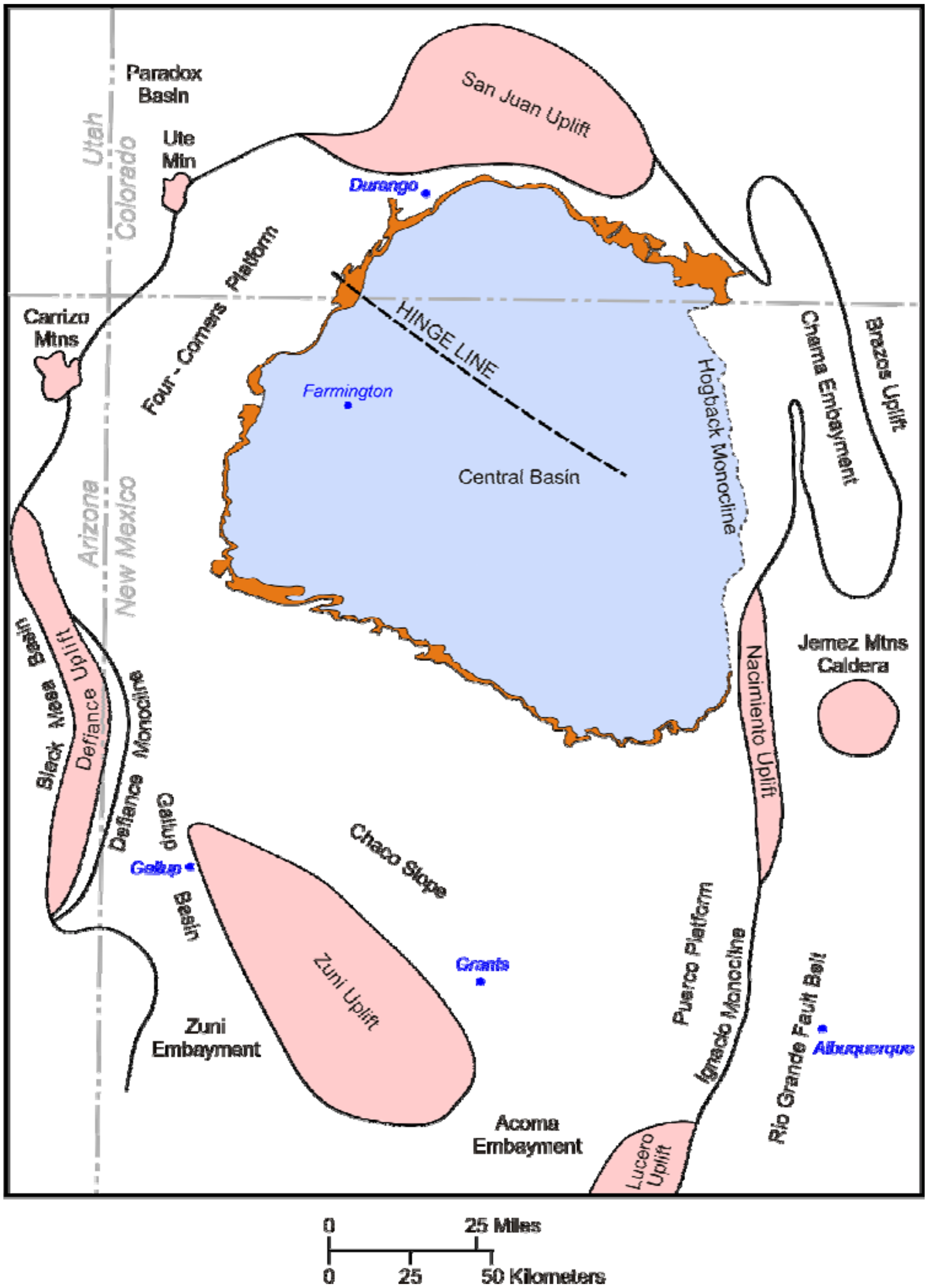

Figure 14 San Juan Basin Map Showing Relationship to Major Structural Elements in Southwestern Colorado and Northwestern New Mexico
(Modified from Rice, 1988).

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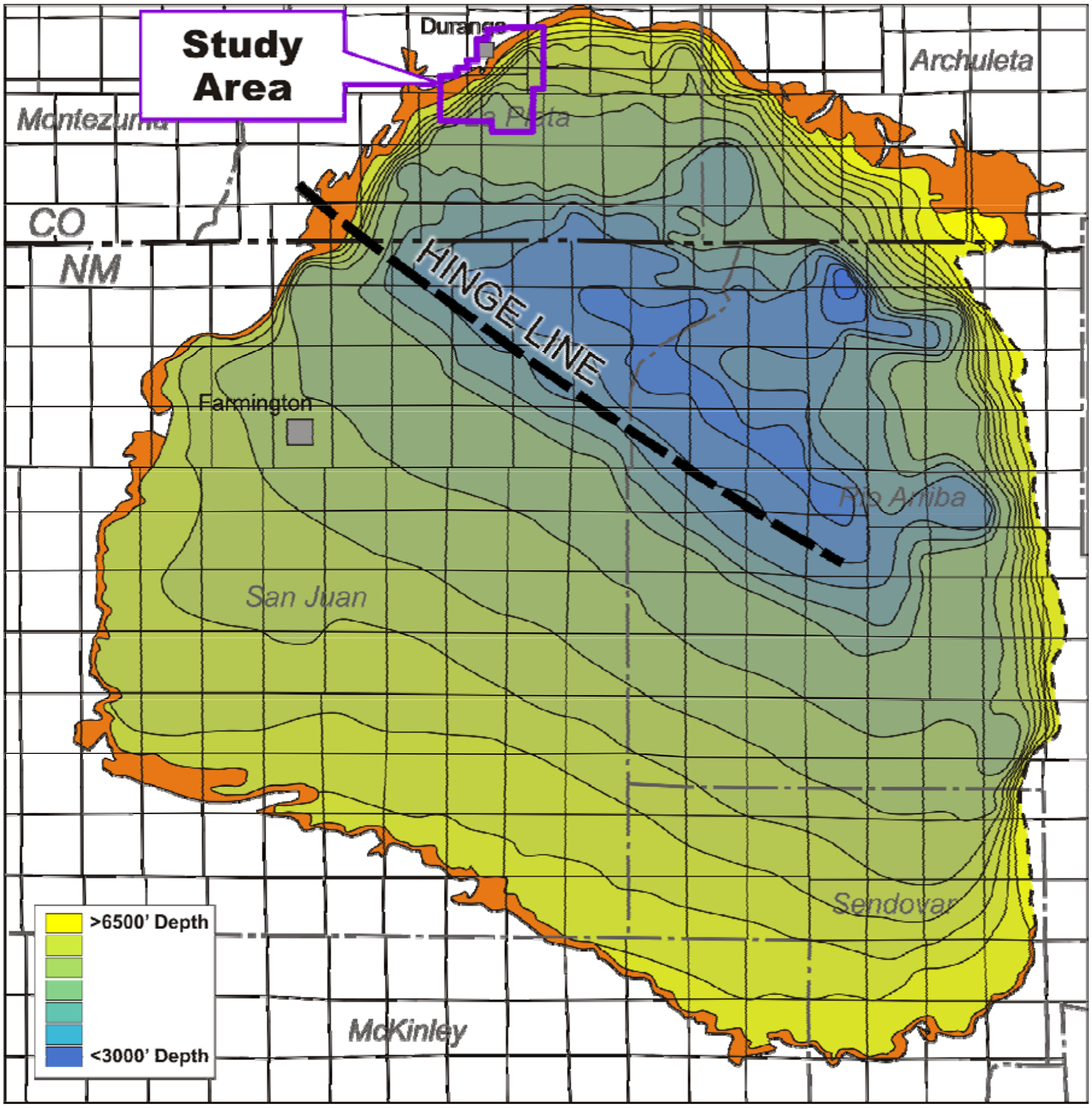

Figure 15 San Juan Basin Structure Map Showing Top of Pictured Cliffs and Position of the Hingeline.
*Note the basin deepening to on the northeast, down-thrown side of the hingeline. (Modified from Ambrose and Ayers, 1990)

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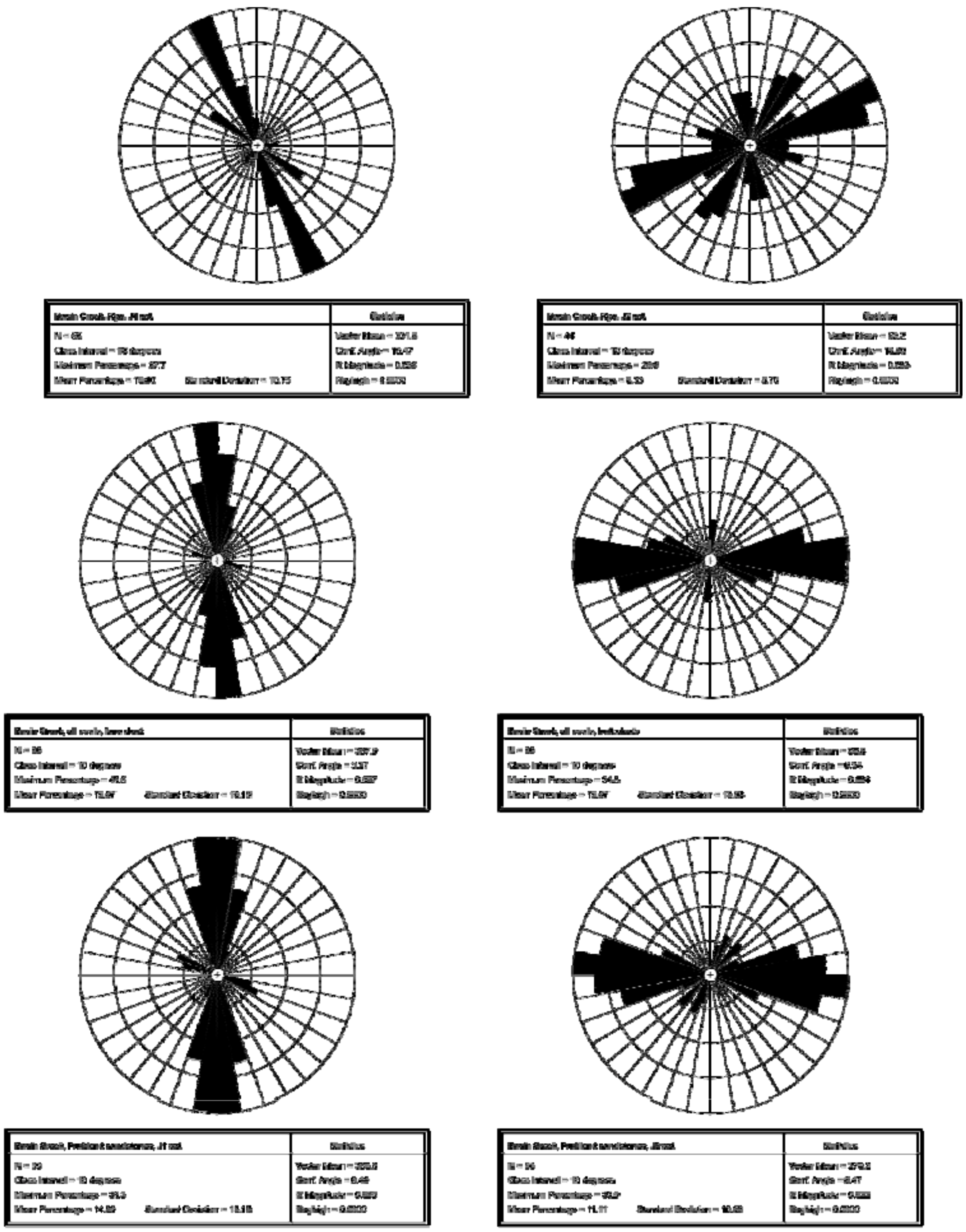

Figure 16 Basin Creek Area Rose Diagrams Showing Fruitland Formation Face and Butt Cleat Orientations.
(Modified from Condon 1997).

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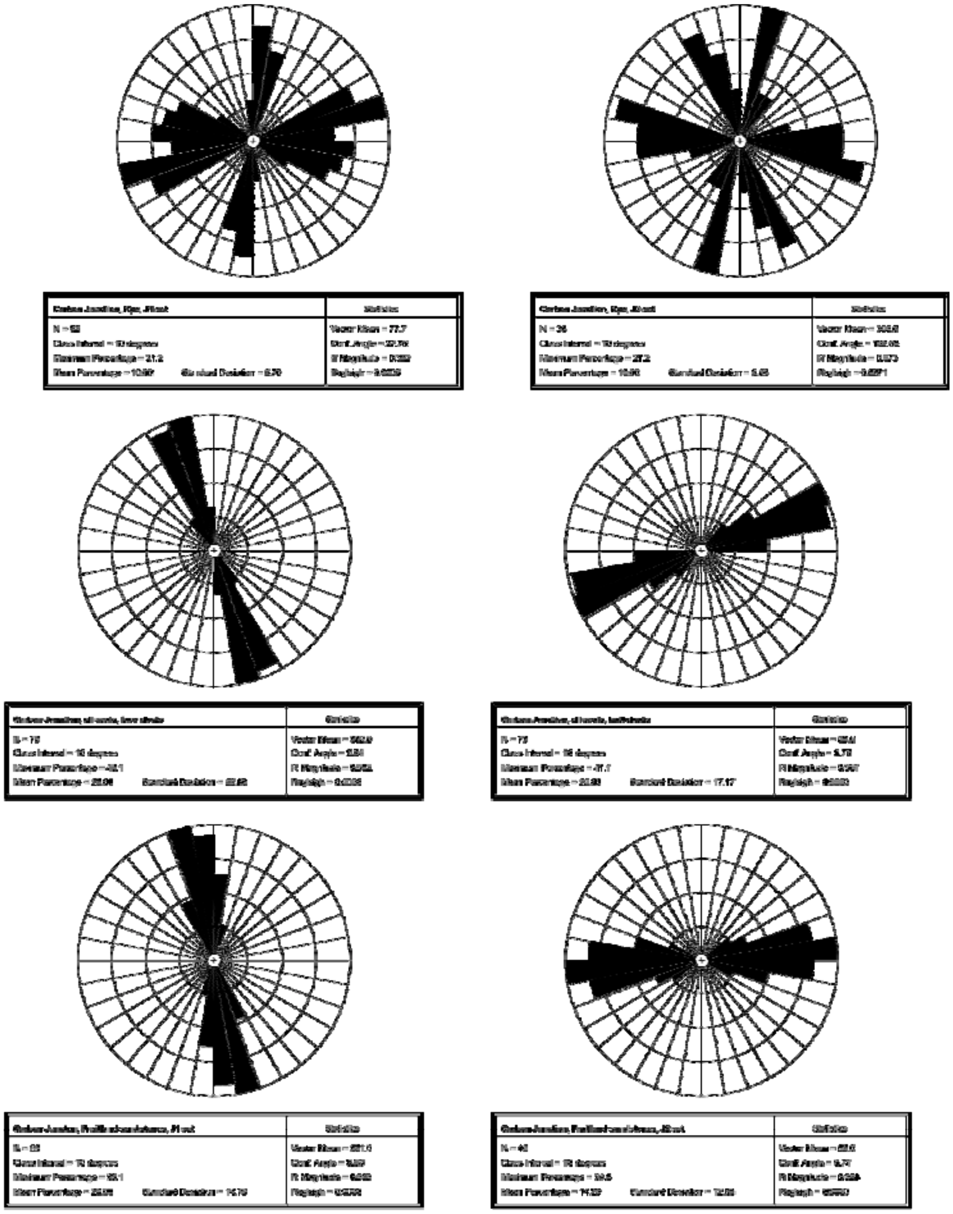

Figure 17 Carbon Junction Area Rose Diagrams Showing Fruitland Formation Face and Butt Cleat Orientations.
(Modified from Condon 1997).

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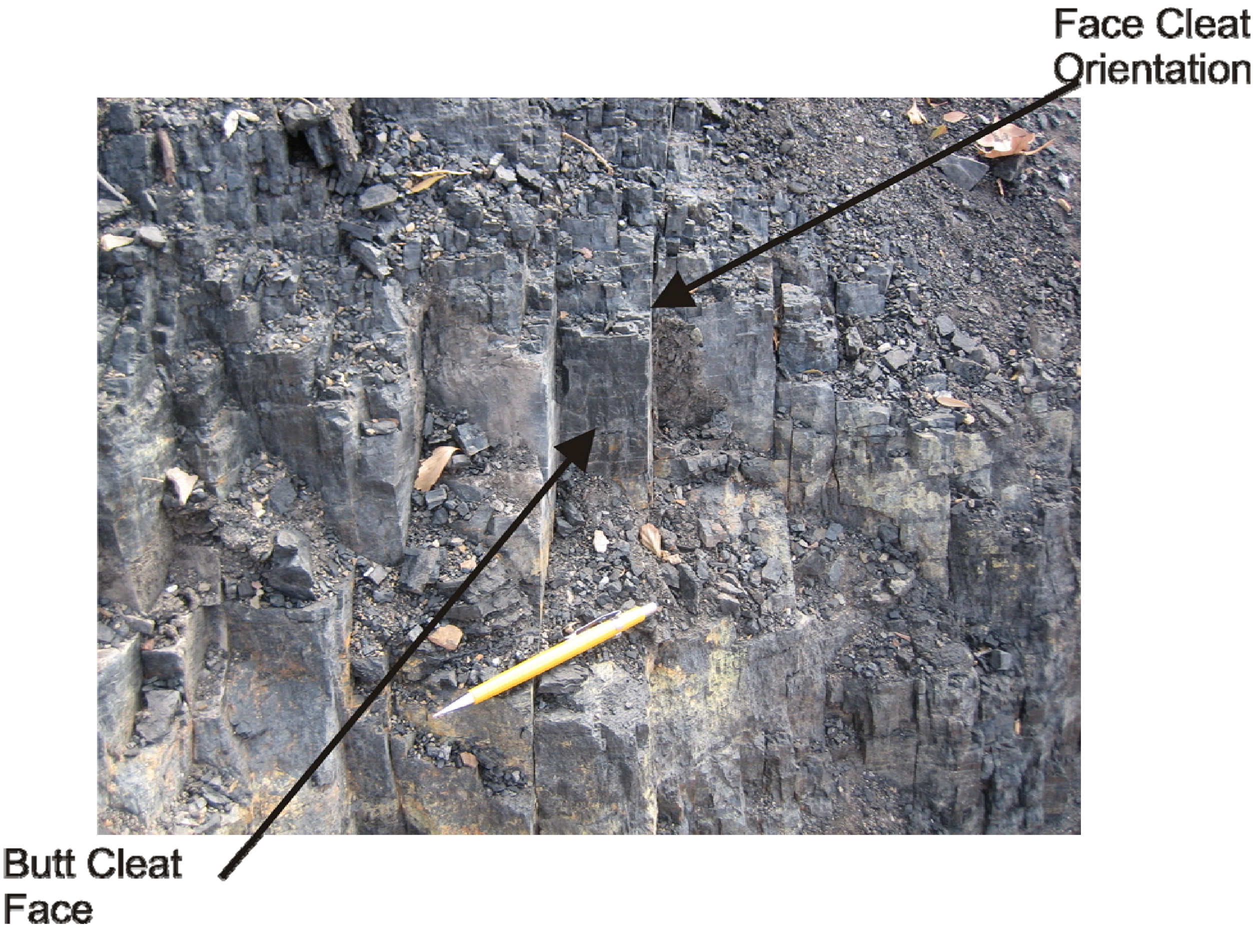

Figure 18 Outcrop Picture of Fruitland Coal at Coal Junction Trailhead Showing Relationship of Face and Butt Cleats.

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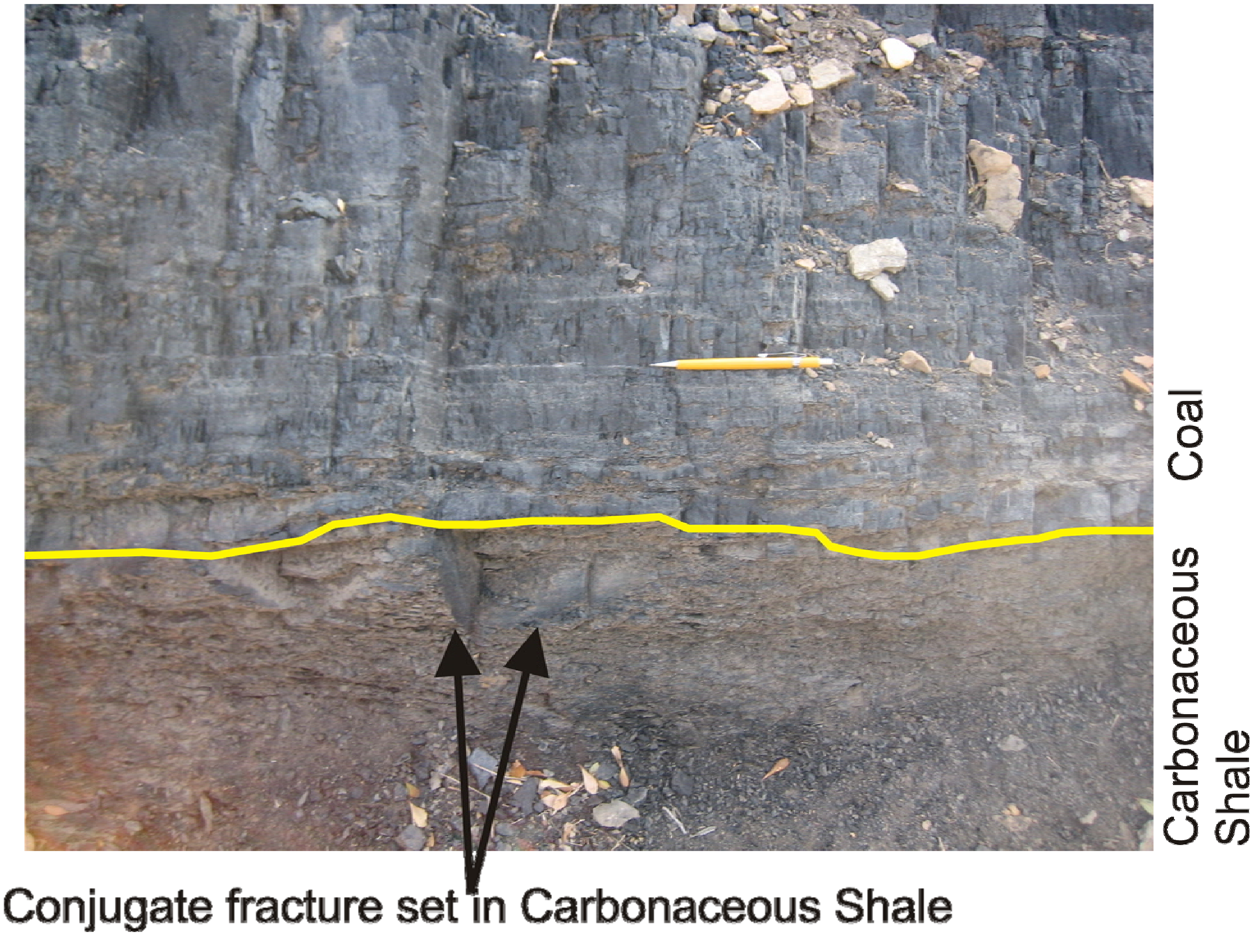

Figure 19 Photograph of Lower Fruitland Formation Coals Showing the Orientation and Spacing of the Face and Butt Cleats Taken from the Carbon Junction Trailhead.

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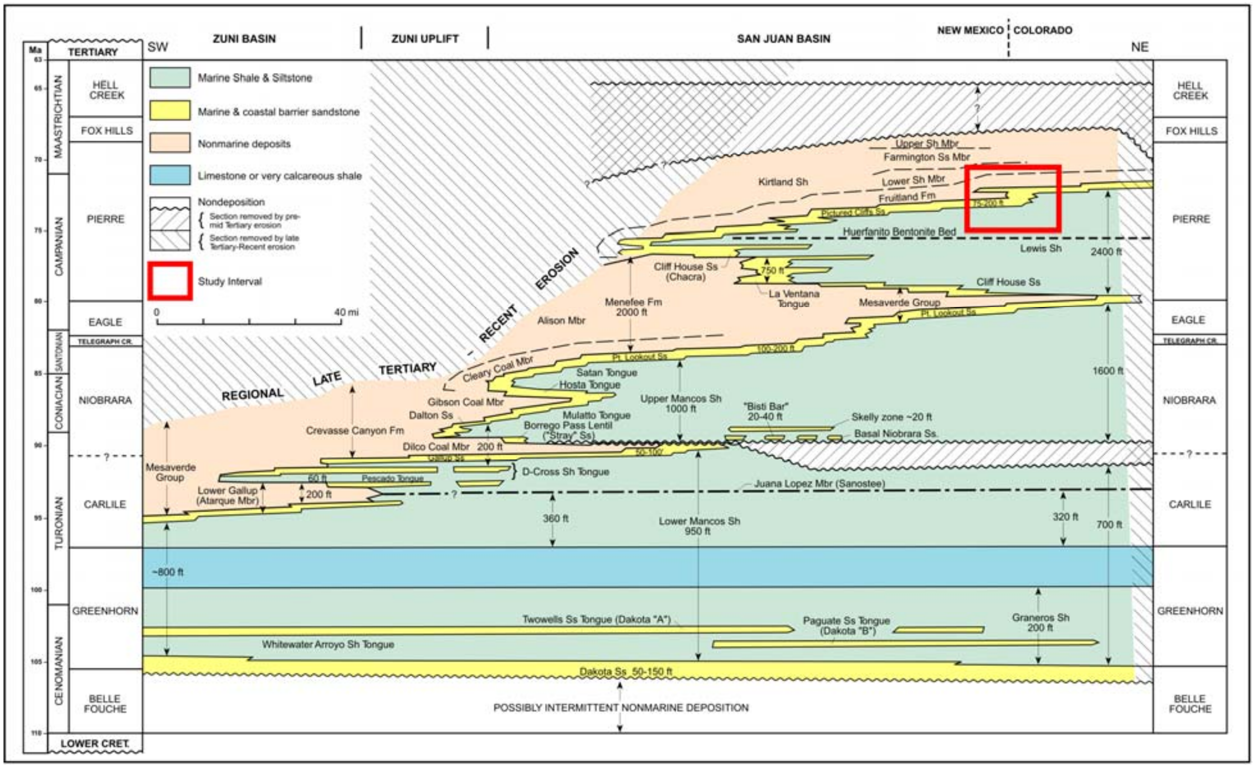

Figure 20 Generalized Stratigraphic Section of the Upper Cretaceous Section of the San Juan Basin.

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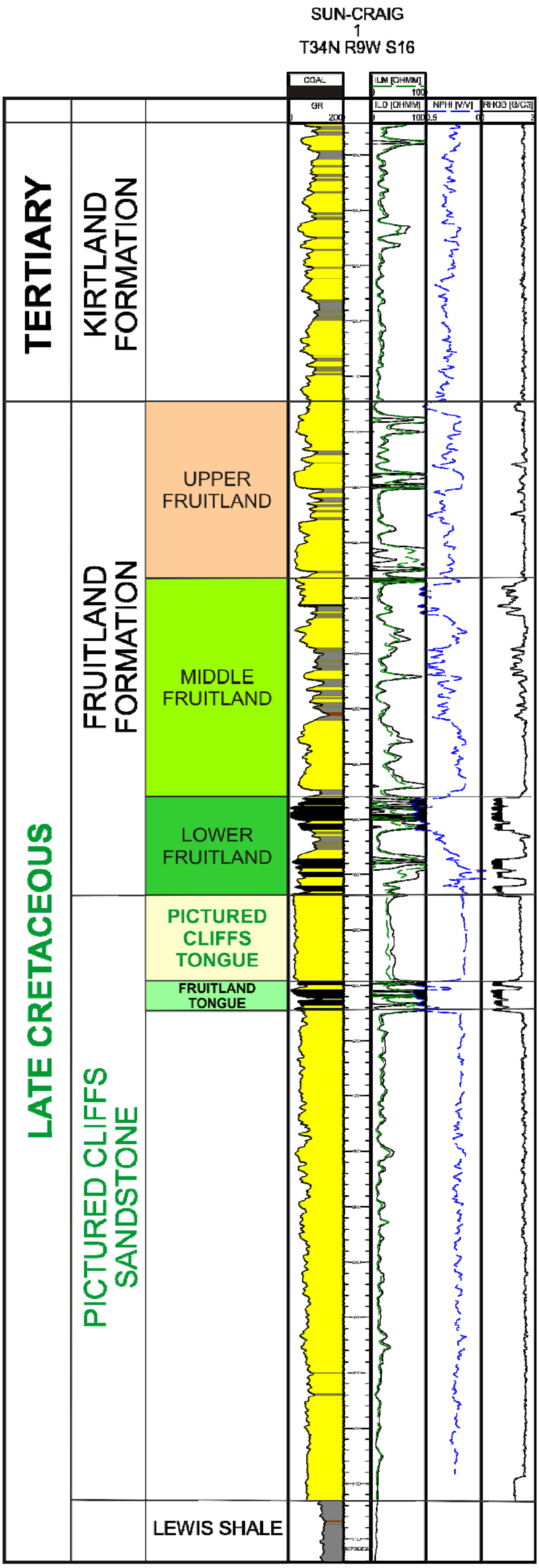

Figure 21 Sun-Craig #1 Well Type Log for the Chevron Study Area

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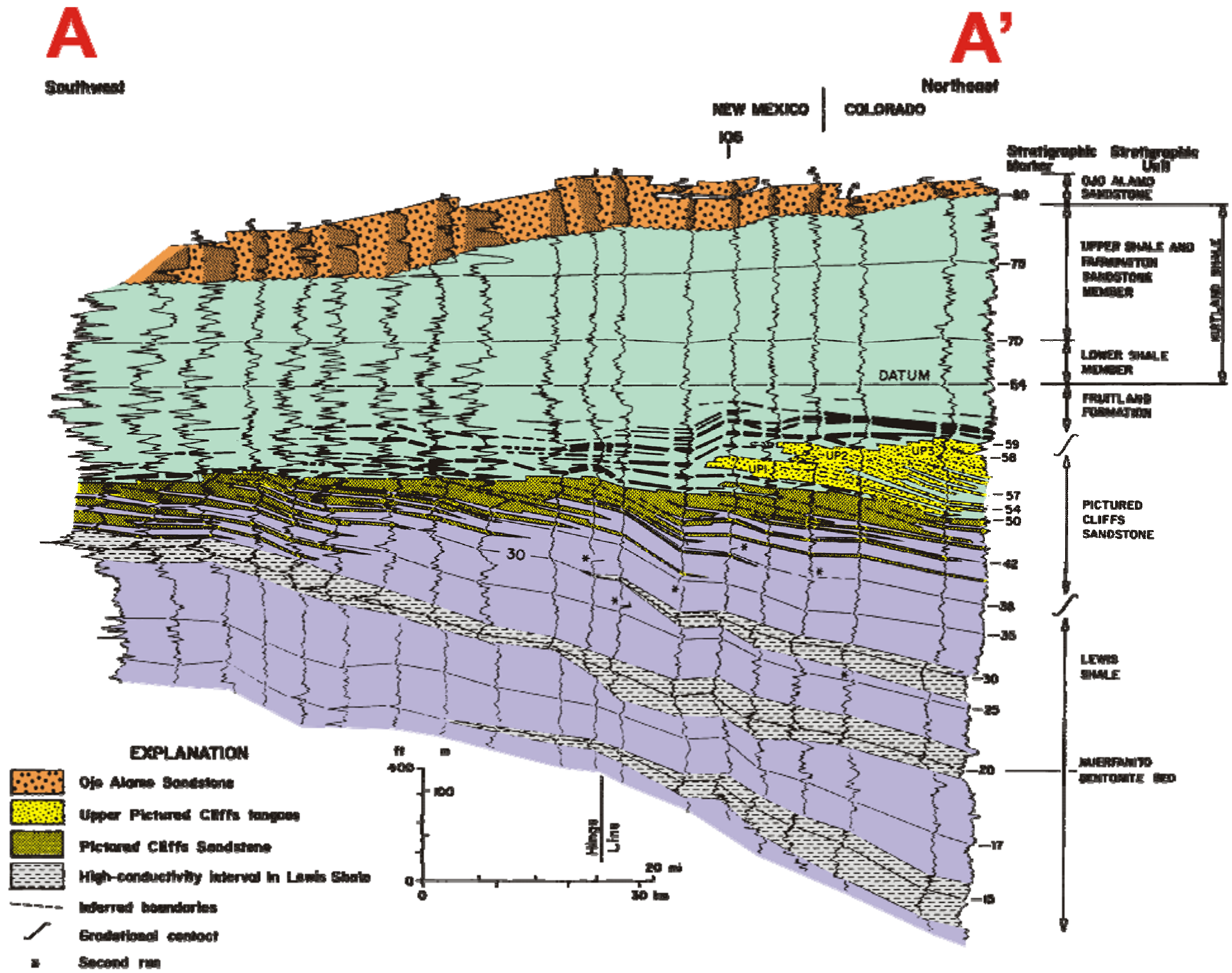

Figure 22 Regional Stratigraphic Cross Section A-A' Across the San Juan Basin Showing Relationship of Stratigraphic Units of the Late Cretaceous.

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Geology and Coal Resources of the Upper Cretaceous Fruitland Fm., San Juan Basin, New Mexico and Colorado

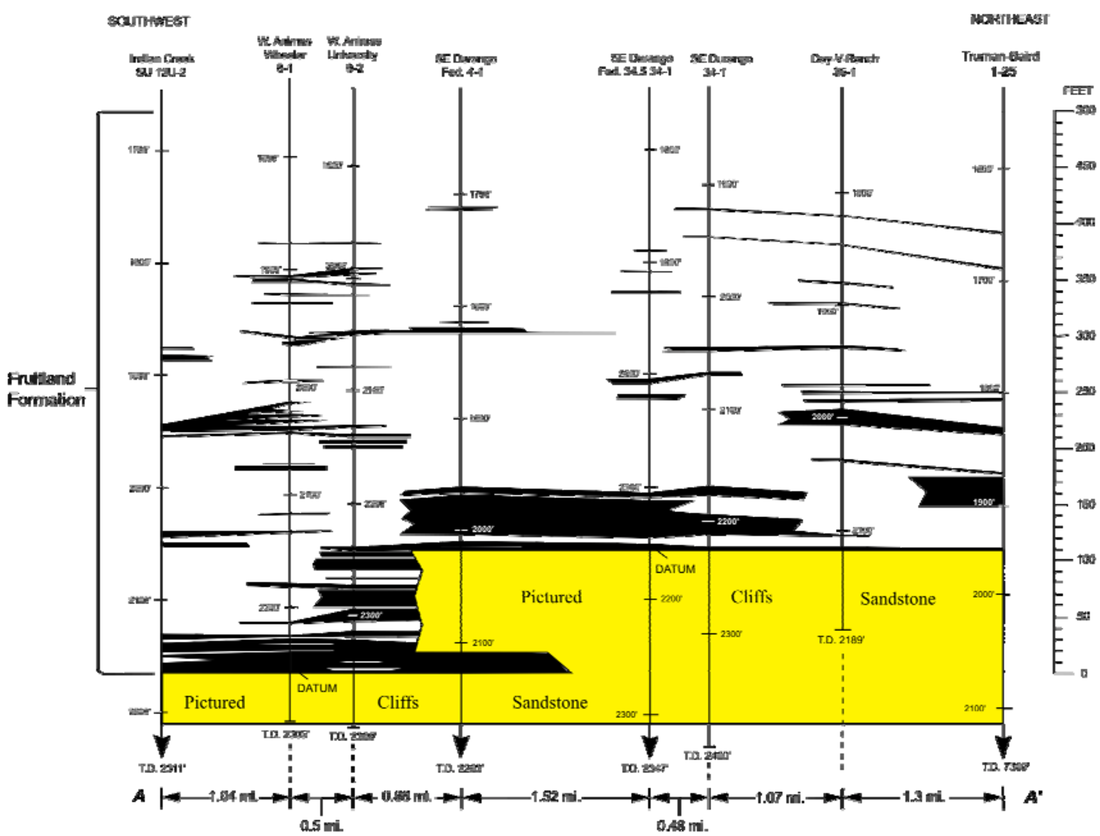

Figure 23 Cross-Section Showing the Fruitland Formation Constructed Using Subsurface Data From Wells Adjacent to the Carbon Junction and Basin Creek Seeps Near Durango, Colorado. This cross-section shows similar relationships between the Pictured Cliff and Fruitland tongues, indicating the continuation of those units from the outcrop into the subsurface. (From Fassett, 2000).

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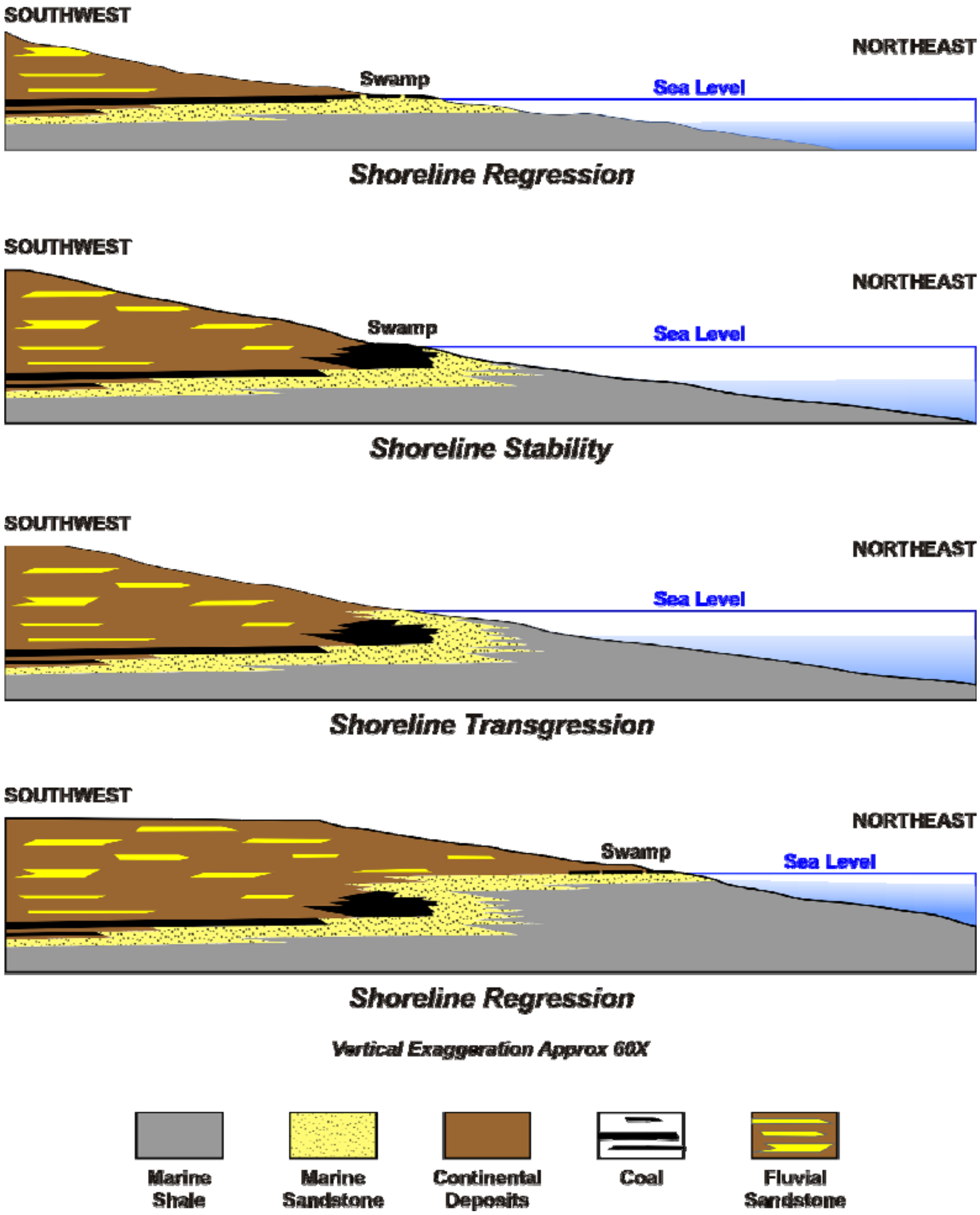

Figure 24 Diagrammatic Cross-Section of Pictured Cliffs/Fruitland Formation Deposition.

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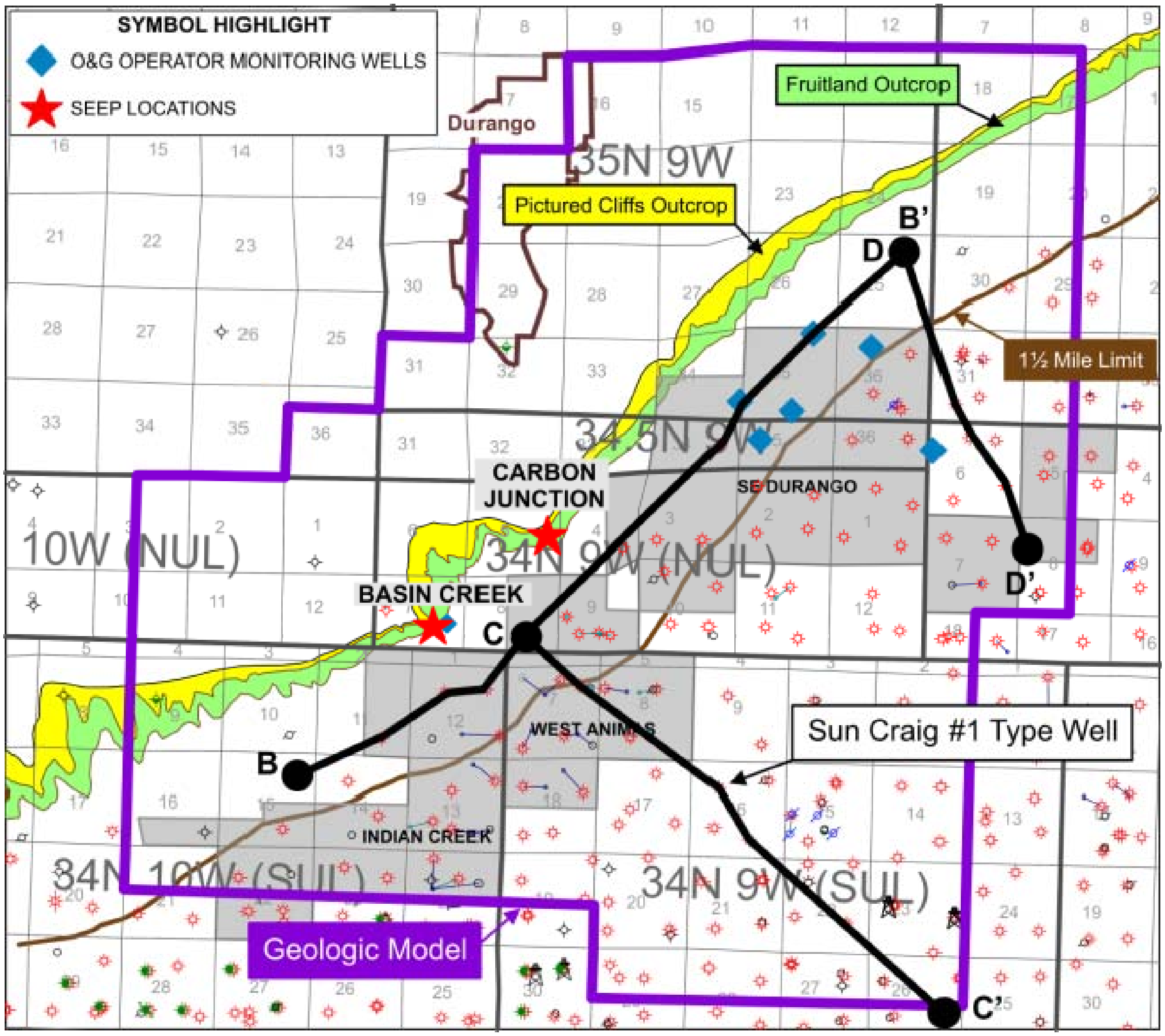

Figure 25 Locations of cross sections B-B', C-C', and D-D' in the Chevron study area, and the outcrop trends of the Pictured Cliff Sandstone and Fruitland Formation relative to the cross sections.

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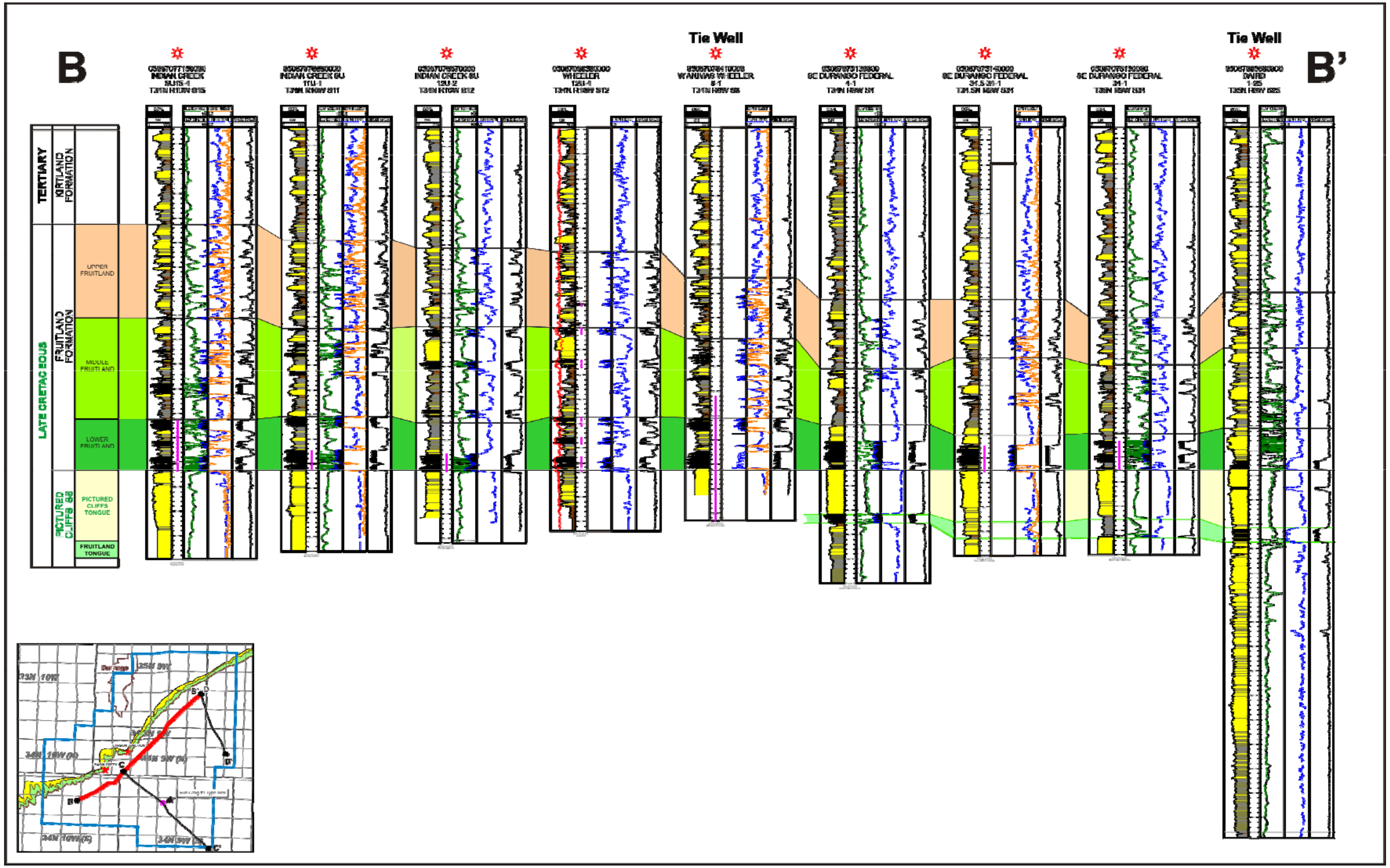

Figure 26 Stratigraphic Cross Section B –B'

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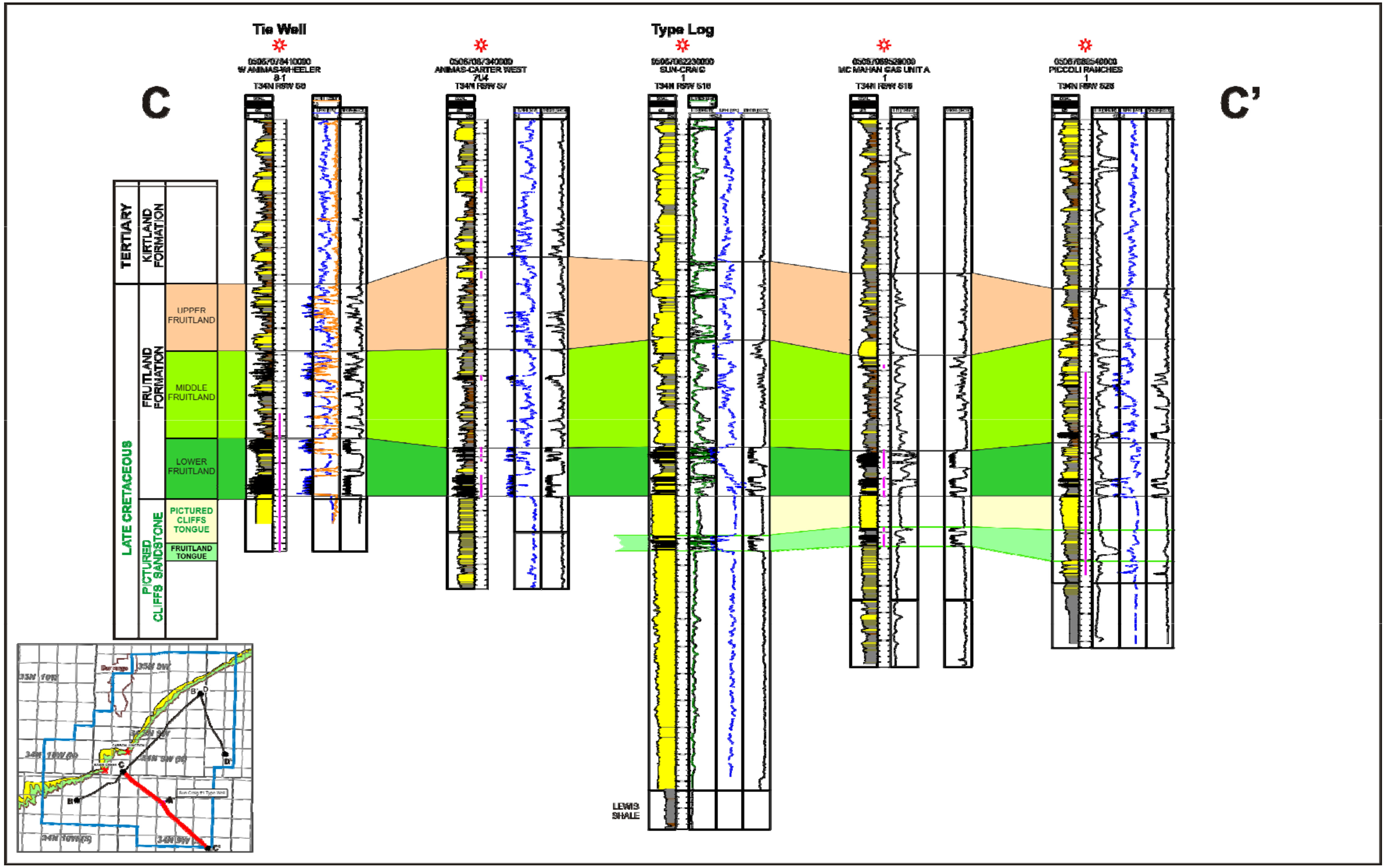

Figure 27 Stratigraphic Cross Section C-C'

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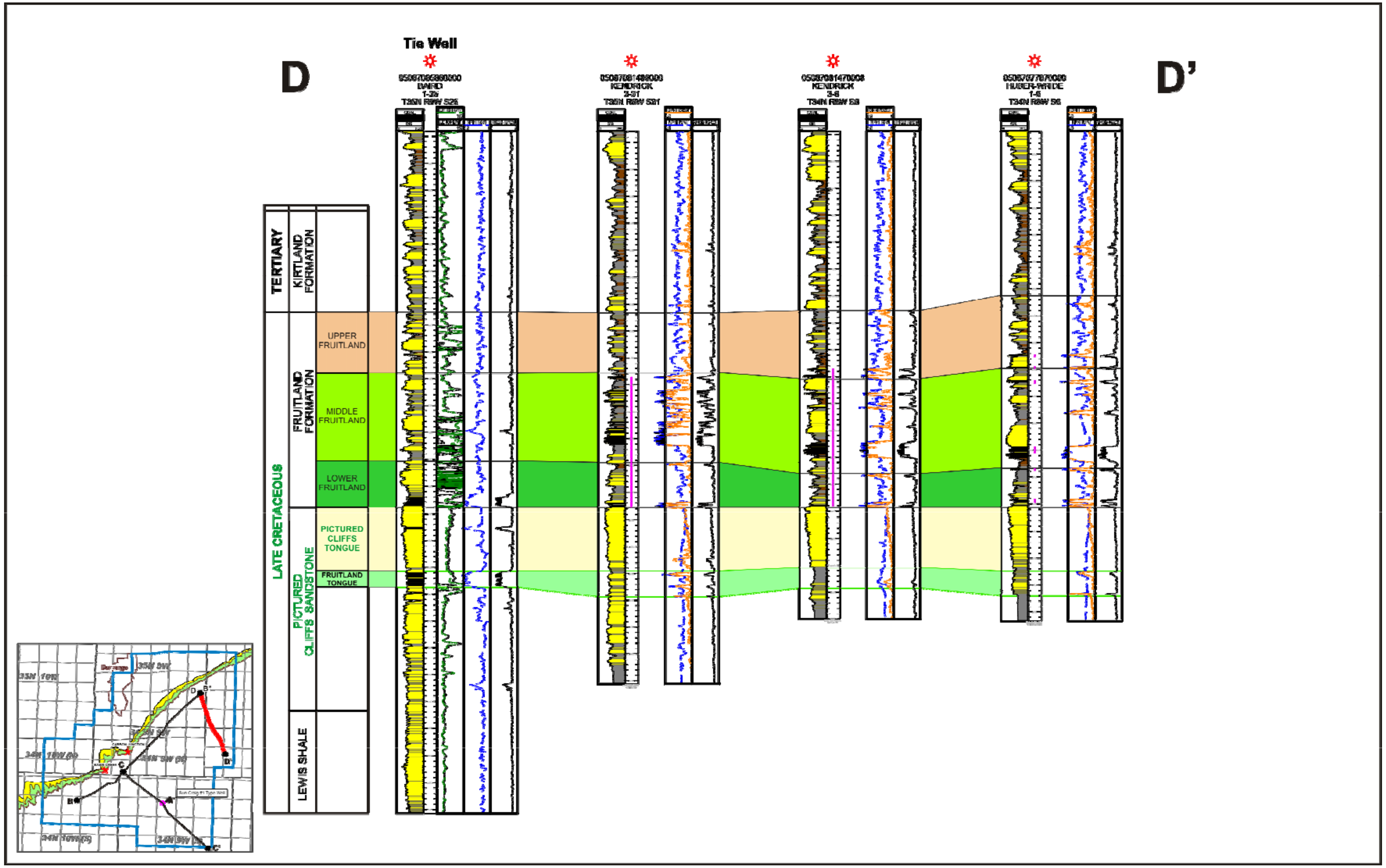

Figure 28 Stratigraphic Cross Section D-D'

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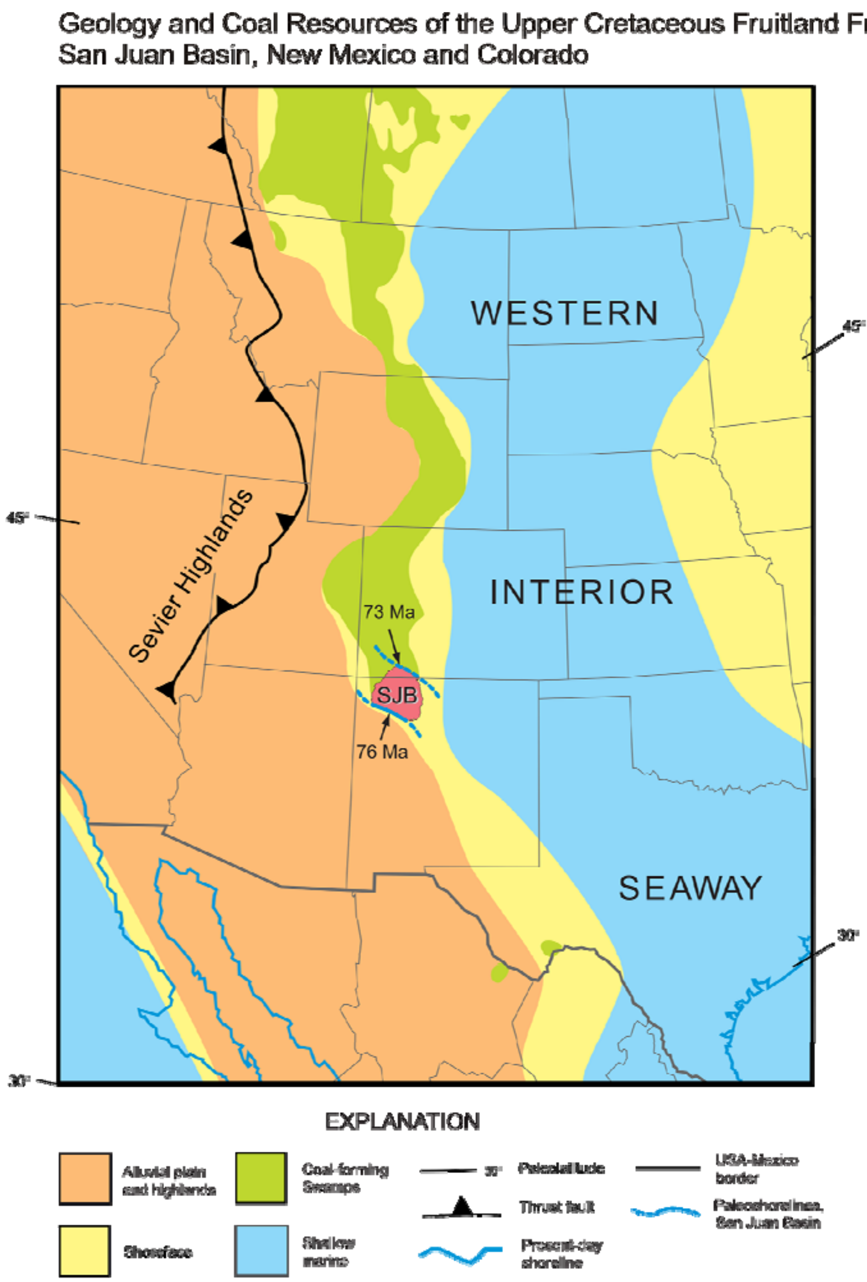

Figure 29 Paleogeographic Map of The Western United States During the Campanian Epoch of the Late Cretaceous.

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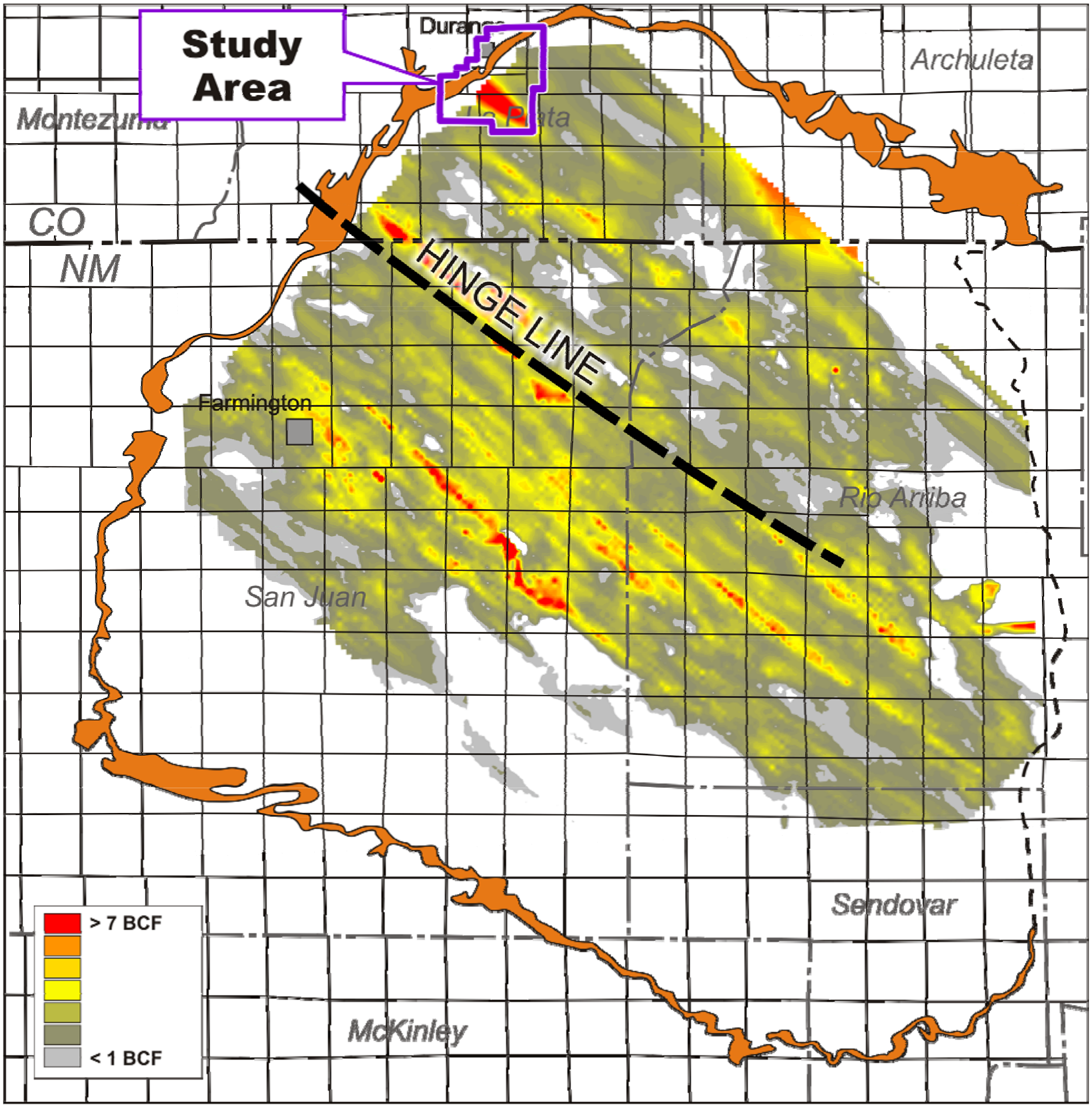

Figure 30 Pictured Cliffs Estimated Ultimate Recovery (EUR).

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Figure 31 Areal Photograph of a Modern Wave-Dominated Shoreline Along the South Carolina Coast.

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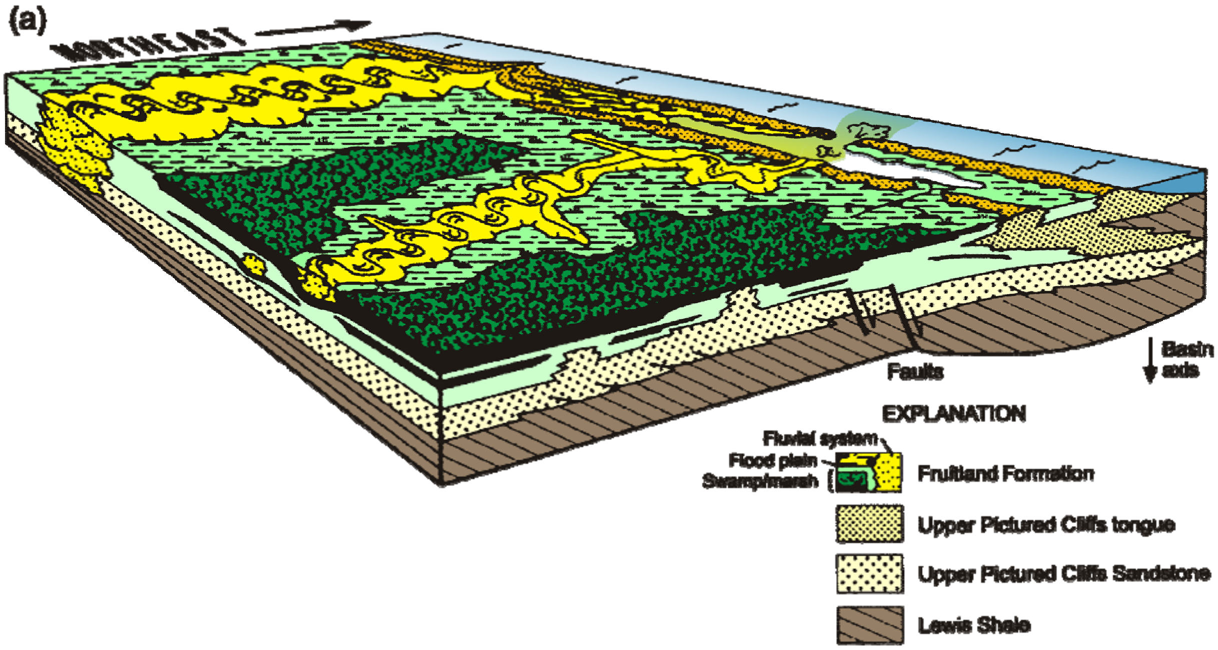

Figure 32 Depositional Model for the Lewis Shale, Fruitland Formation, and Pictured Cliffs Sandstone.

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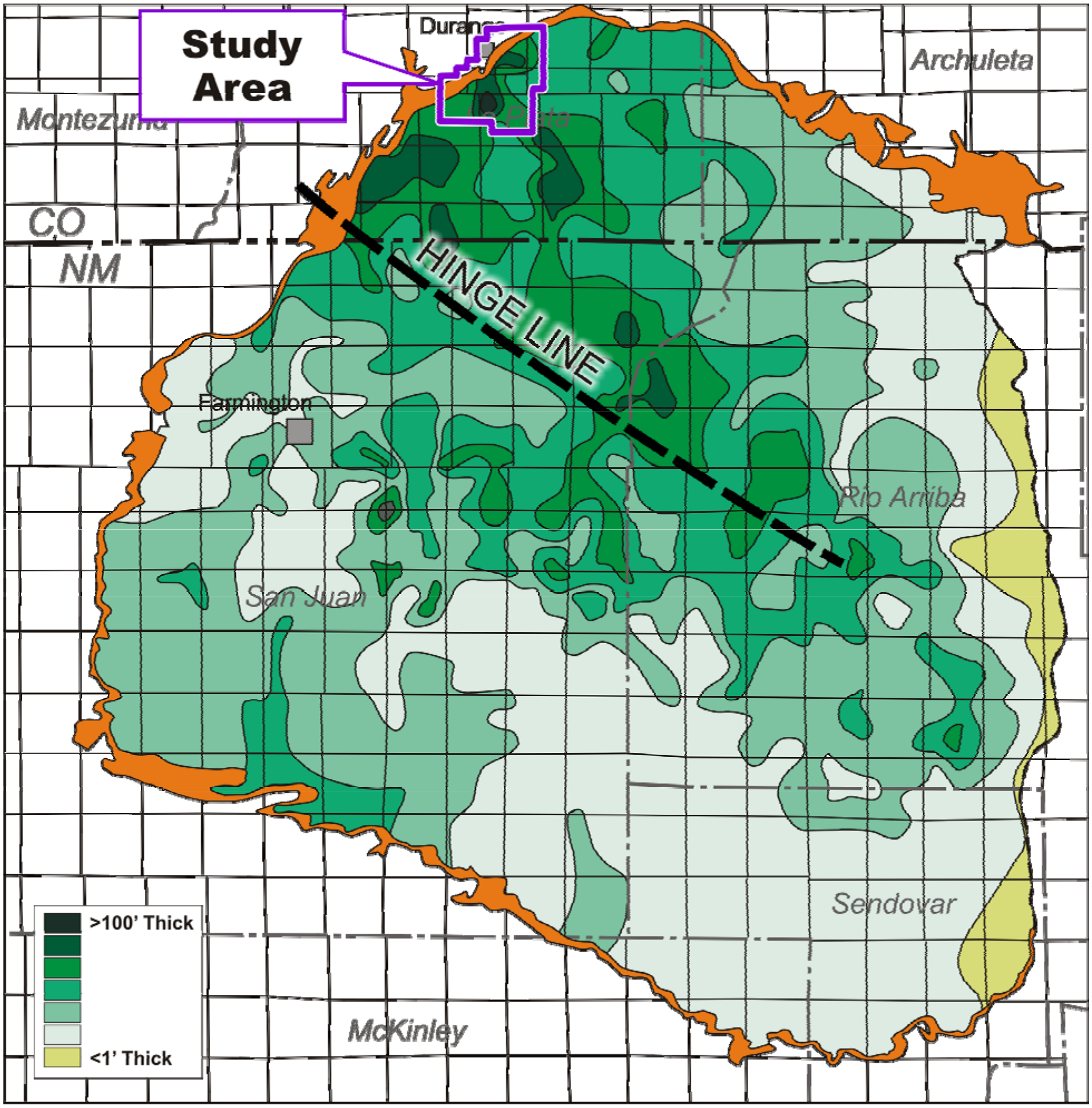

Figure 33 Fruitland Formation Net Coal Isopach

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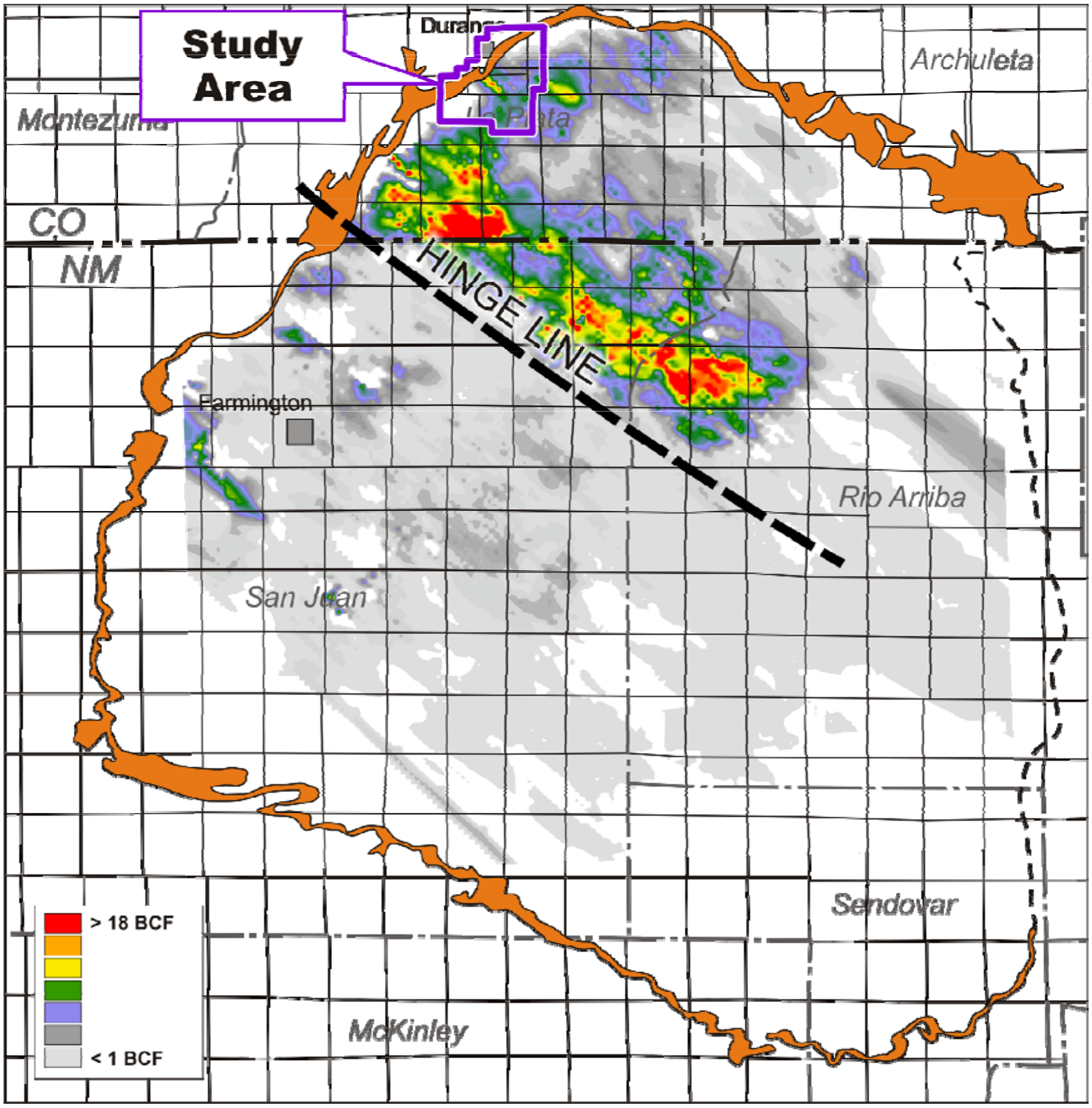

Figure 34 Fruitland Formation Estimated Ultimate Recovery (EUR)

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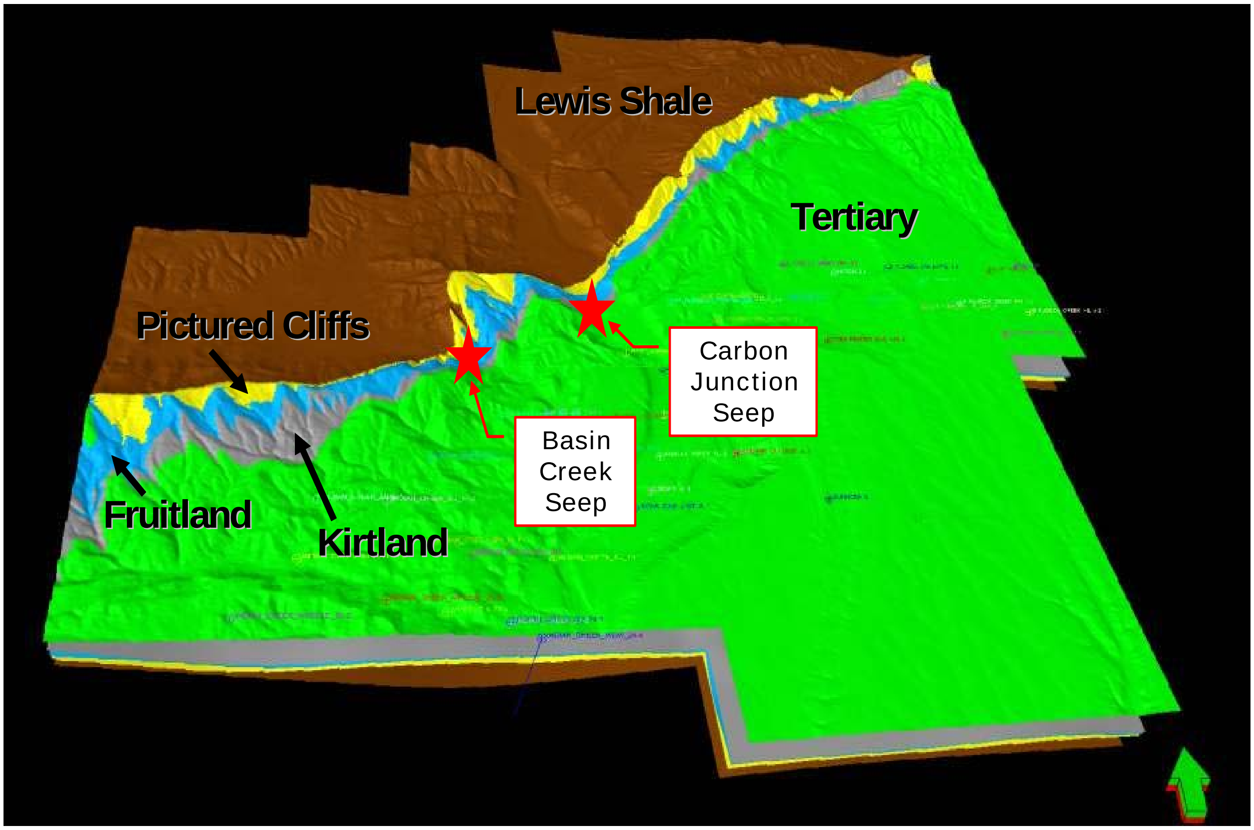

Figure 35 General Outcrop Description

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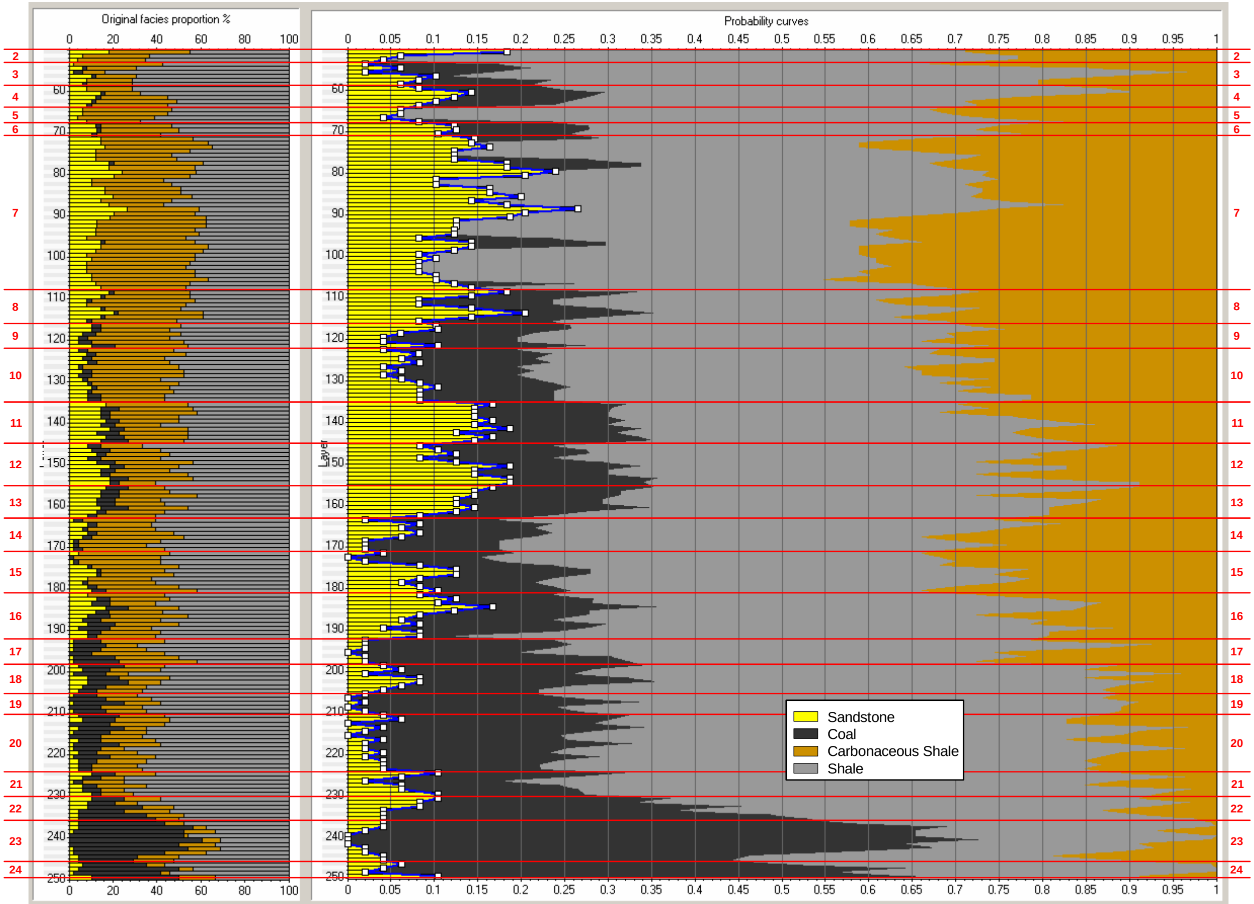

Figure 36 Initial Rock Type Proportion

The left side is the original facies proportion, and the right side shows the probability curves for each rock type. The left side curve is the default probability curve. From this basic data analysis, the initial facies model is generated. This involves the creation of a set of variograms to describe the geographical and vertical variation for each rock type. By applying this statistical process, the initial facies distribution for all cells in the 3D geologic model is defined.

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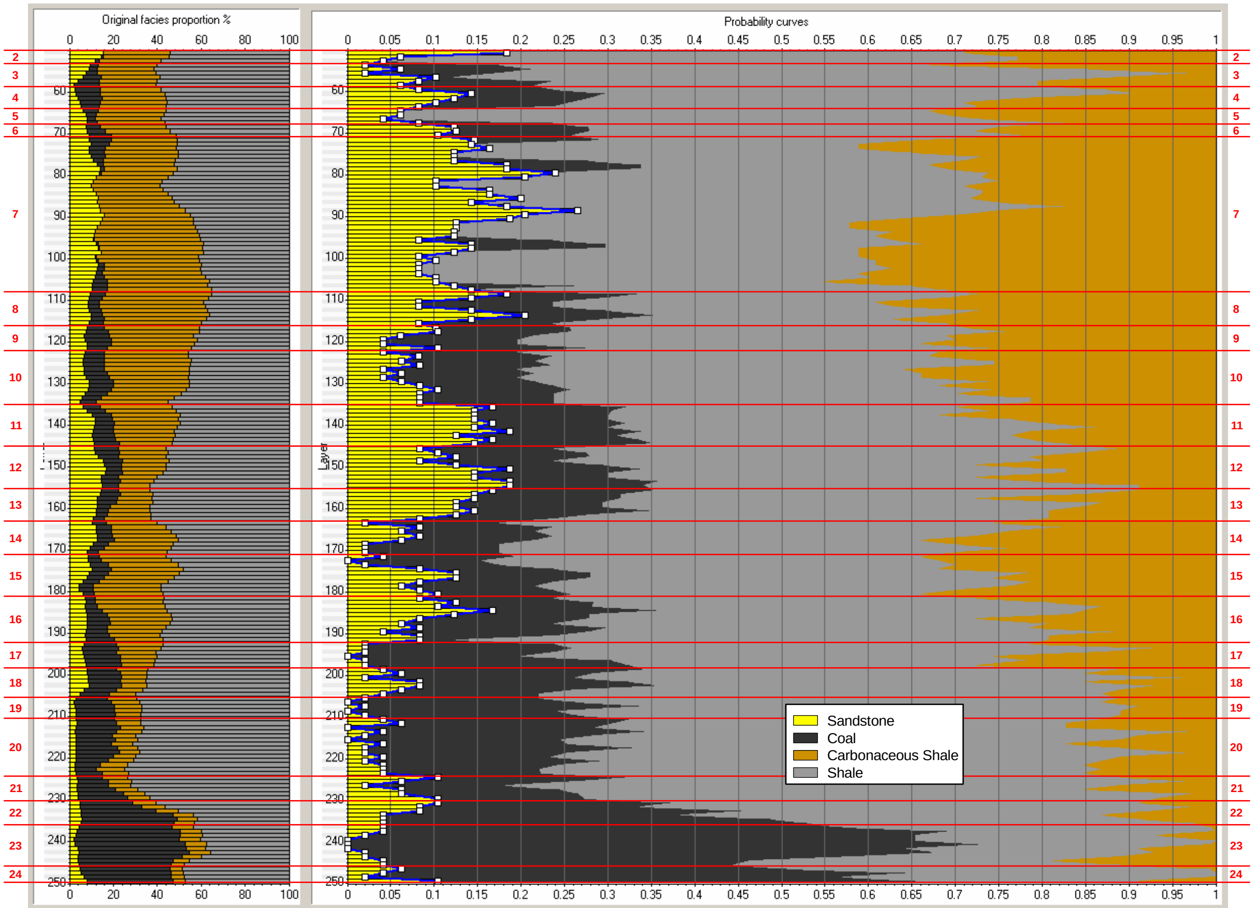

Figure 37 Upscaled Rock Type Proportion

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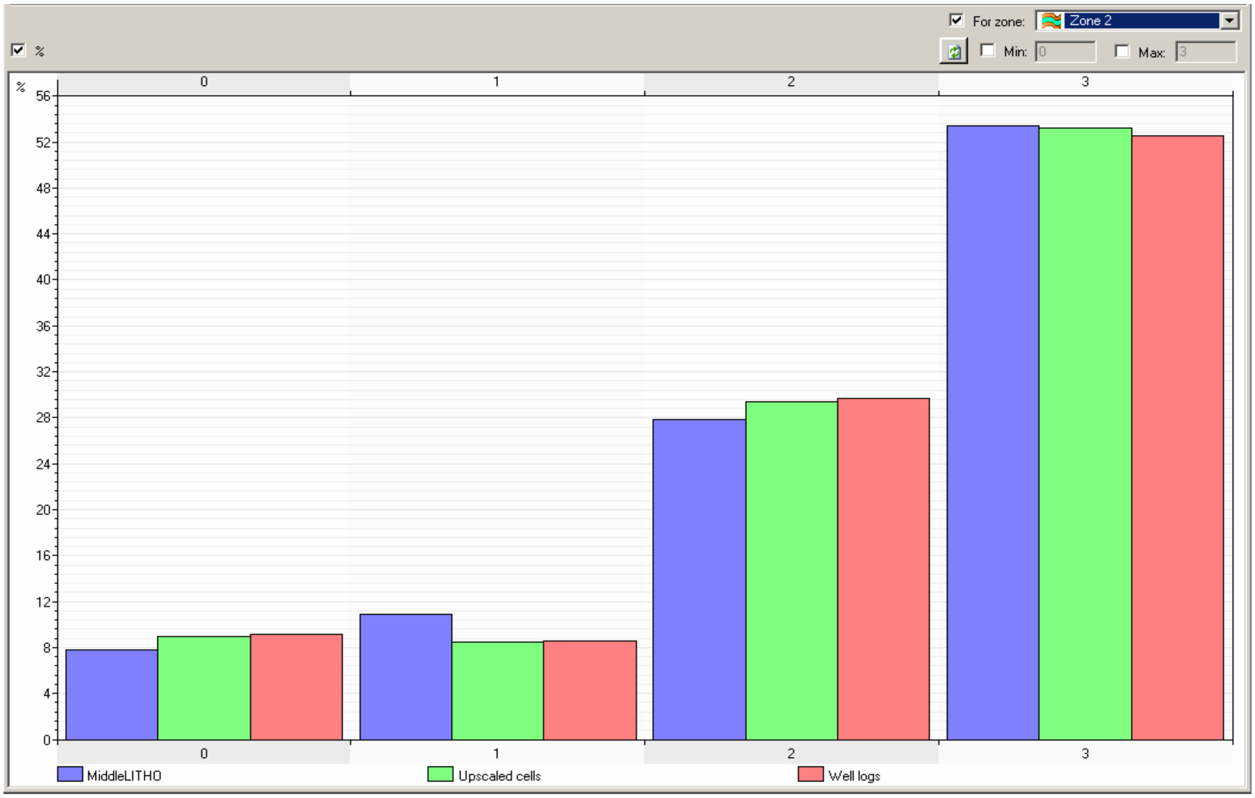

Figure 38 Rock Type Histogram

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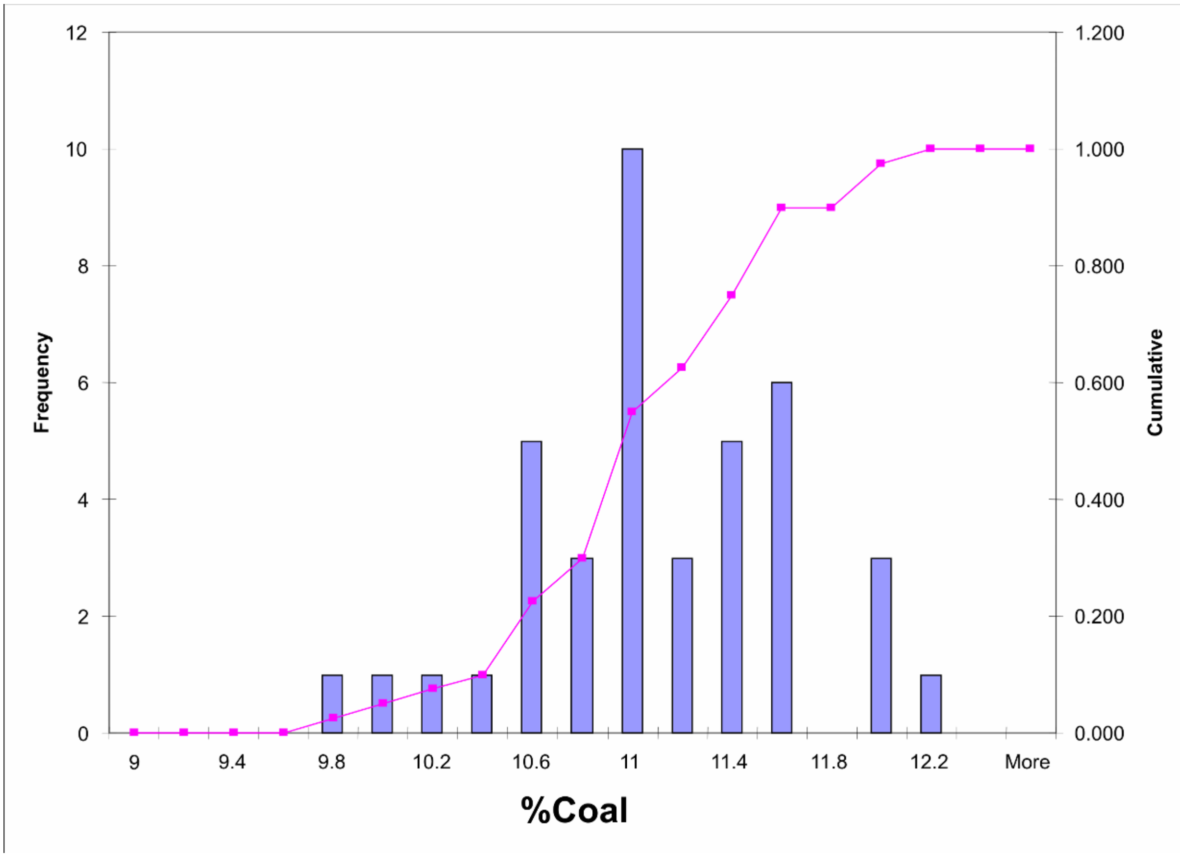

Figure 39 Forty Realization Average Coal Proportion Histogram

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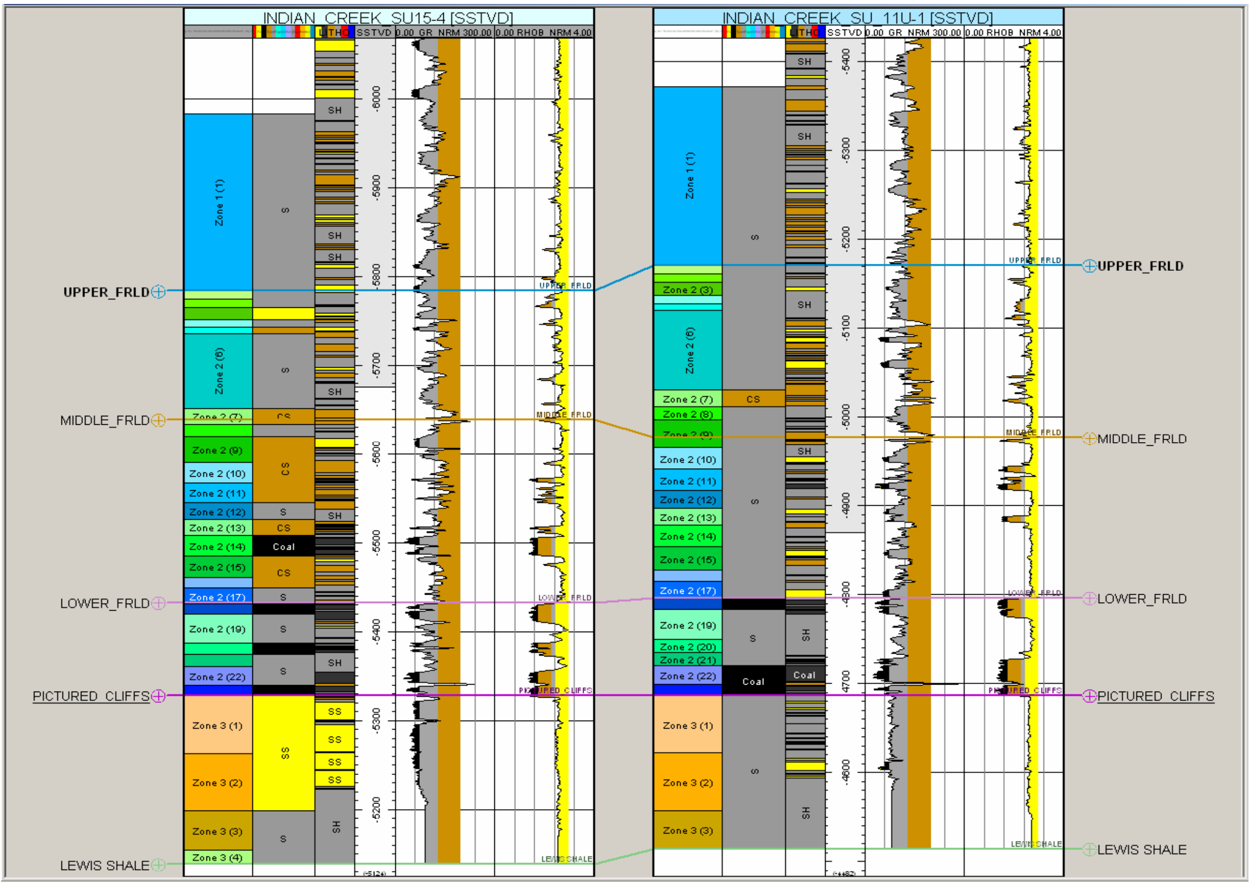

Figure 40 Rock Type Cross-Section

Track 6 is a color-filled normalized bulk density curve. Track 5 is a colored-filled normalized GR curve. Track 4 is the subsea total vertical depth scale. Track 3 is a color-filled discrete lithology that follows the layering in the 3D geologic model. Yellow is sandstone, black is coal, orange in carbonaceous shale, and grey is shale. Track 2 is also a color-filled discrete lithlogy log that follows the simulation models vertical layering. Finally, track 1 is a color-filled discrete log that indicates the simulation model layer number.

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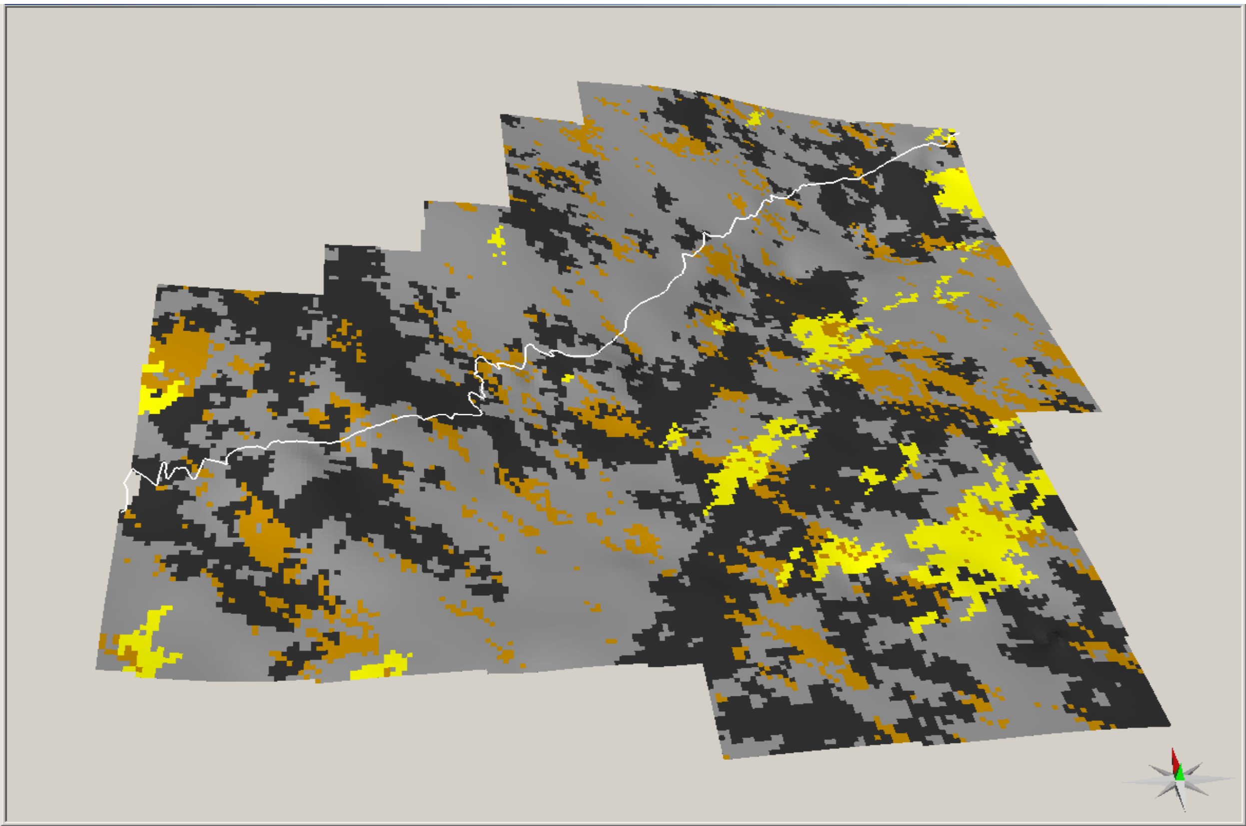

Figure 41 Statistical Body Orientation and Distribution
Note the northwest to southeast trend of the coals and shales in contrast to the southwest to northeast trend of the sandstones. This is a carry-over from the geologic description through the geo-statistics. The white line on this figure is the base of the Fruitland/Top of the Pictured Cliffs outcrop.

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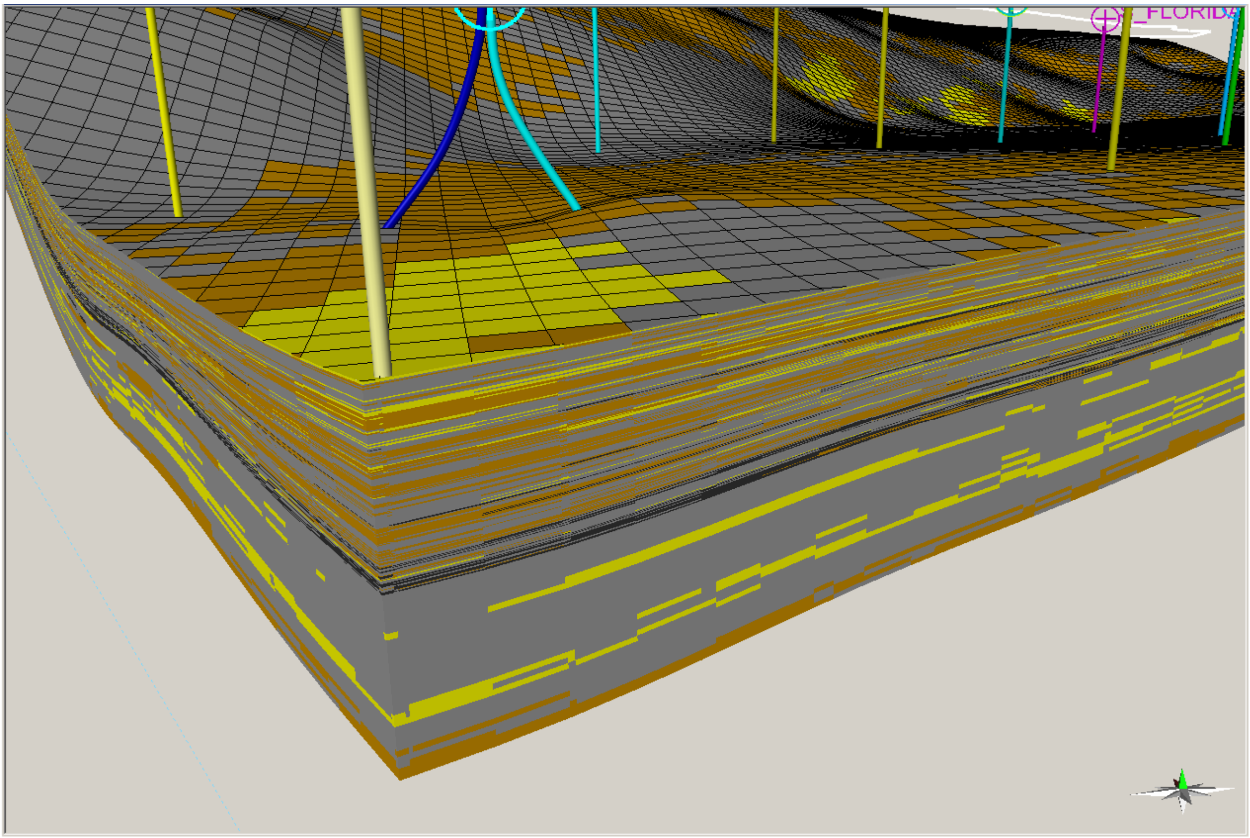

Figure 42 Geologic Model Fine Grid Granularity

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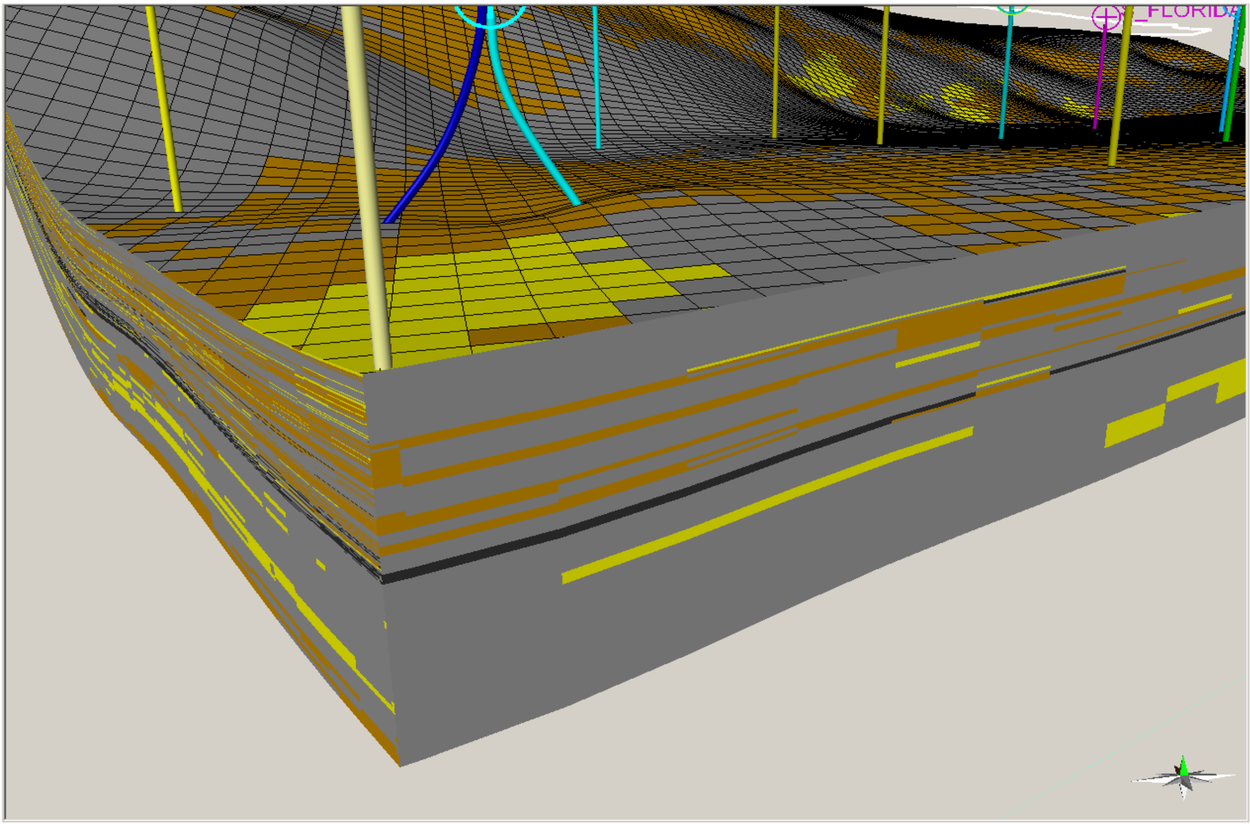

Figure 43 Simulation Model Coarse Grid

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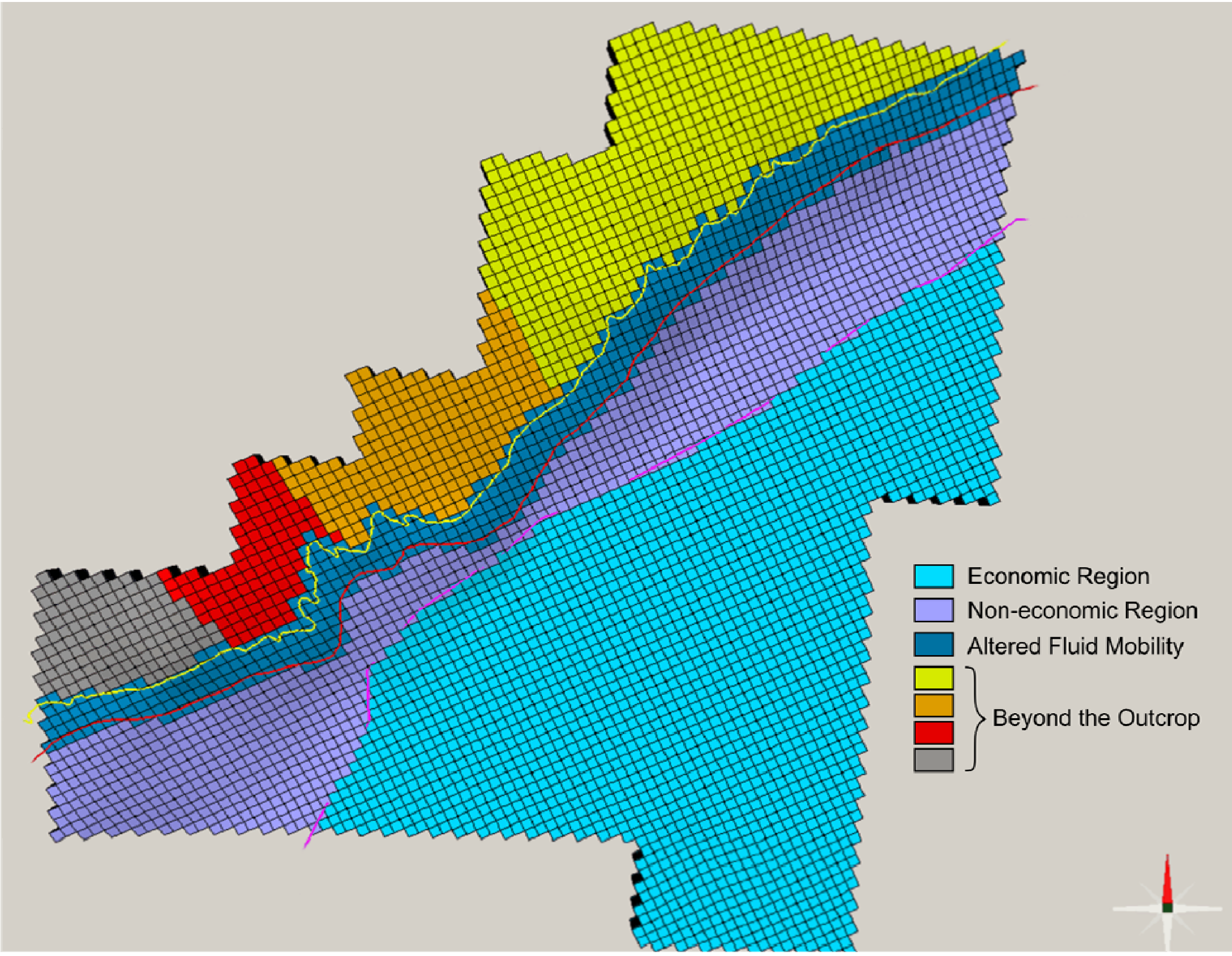

Figure 44 Region Locations
The cells that are in the atmosphere are divided into four regions to isolate the leak locations (Carbon Junction – orange and Basin Creek -red). During the simulation runs, fluid migration is tracked between these regions of interest.

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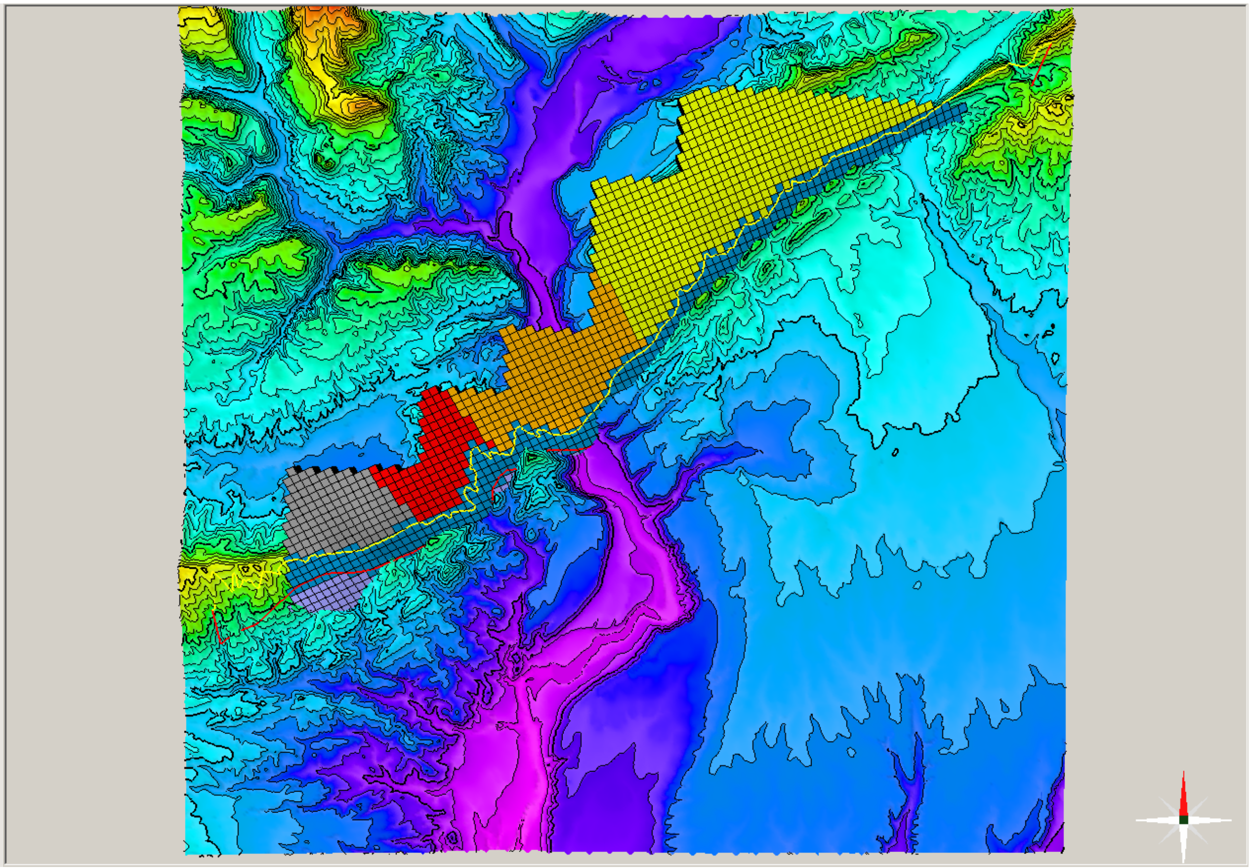

Figure 45 Areal Simulation Cells

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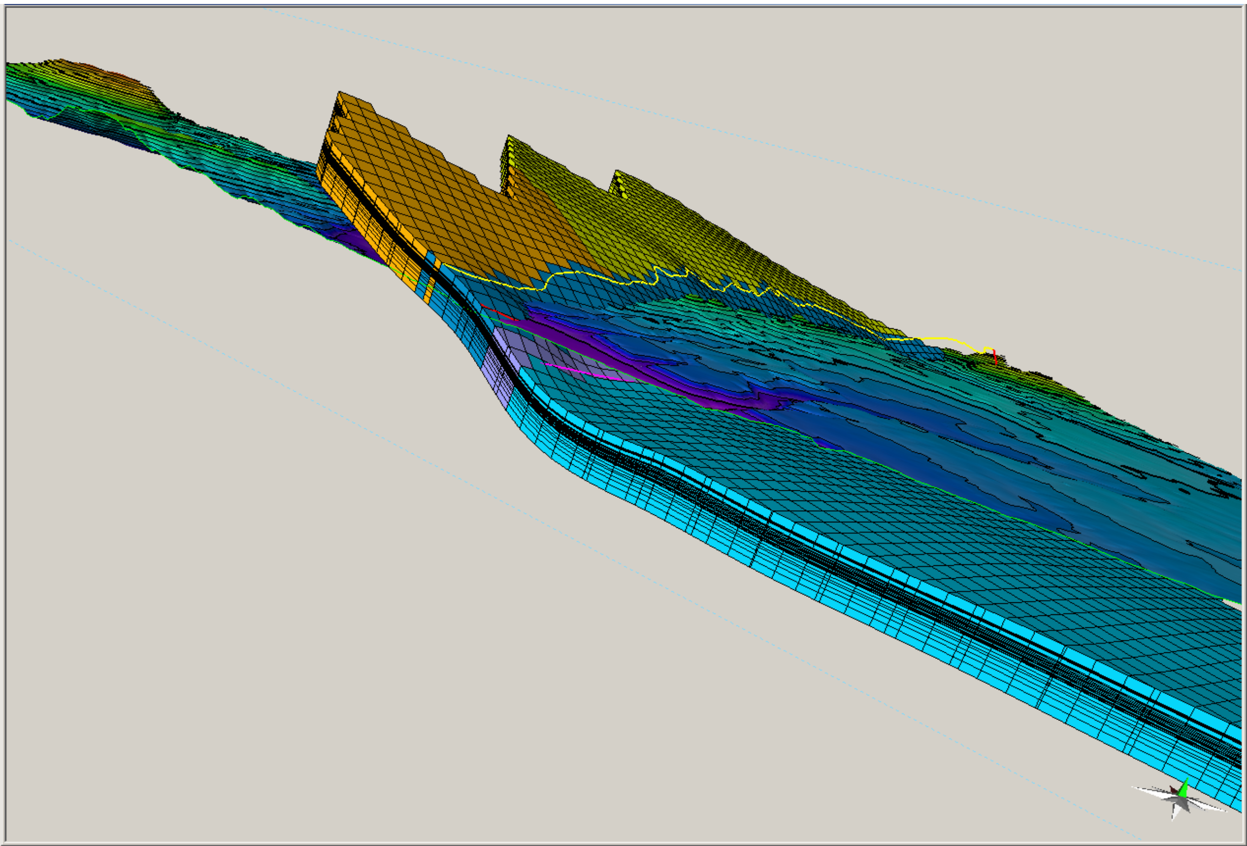

Figure 46 Region Cross-Section – View 1

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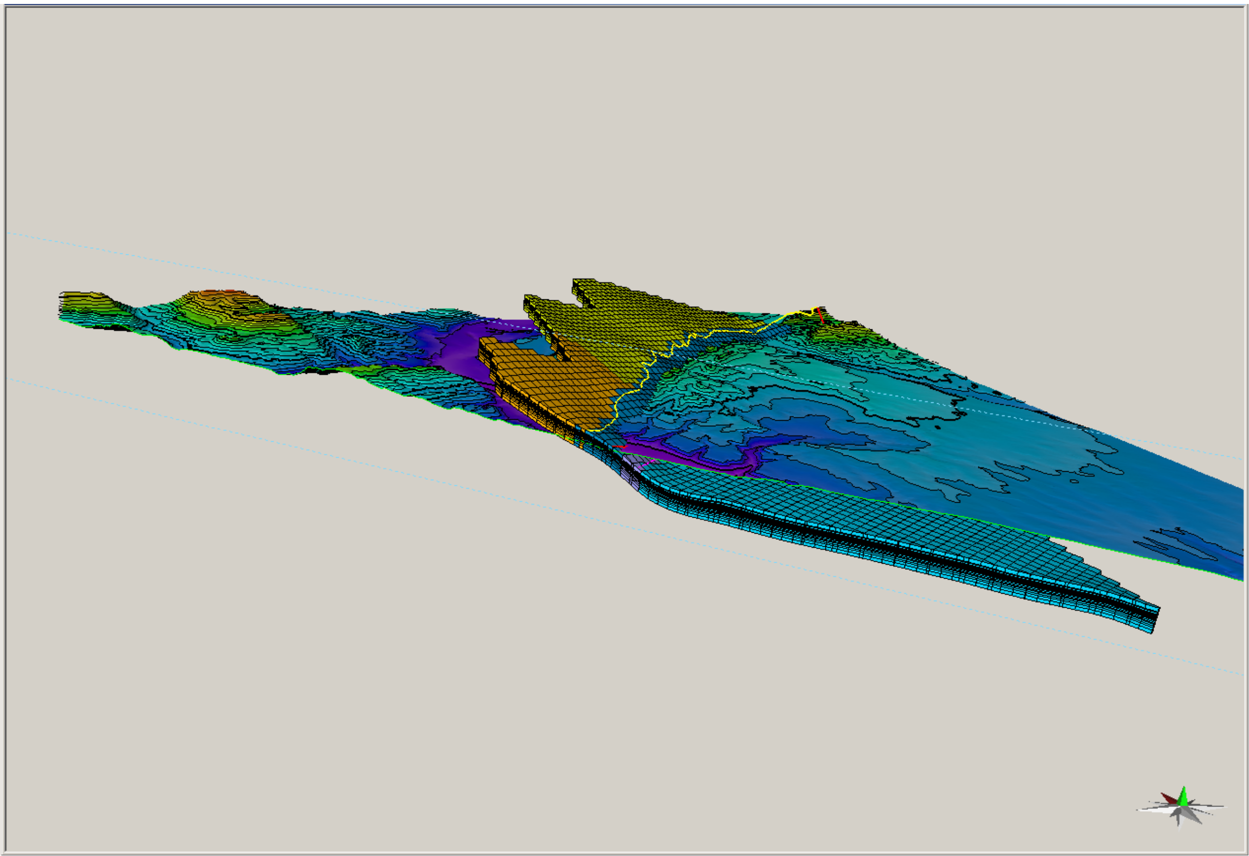

Figure 47 Region Cross-Section – View 2

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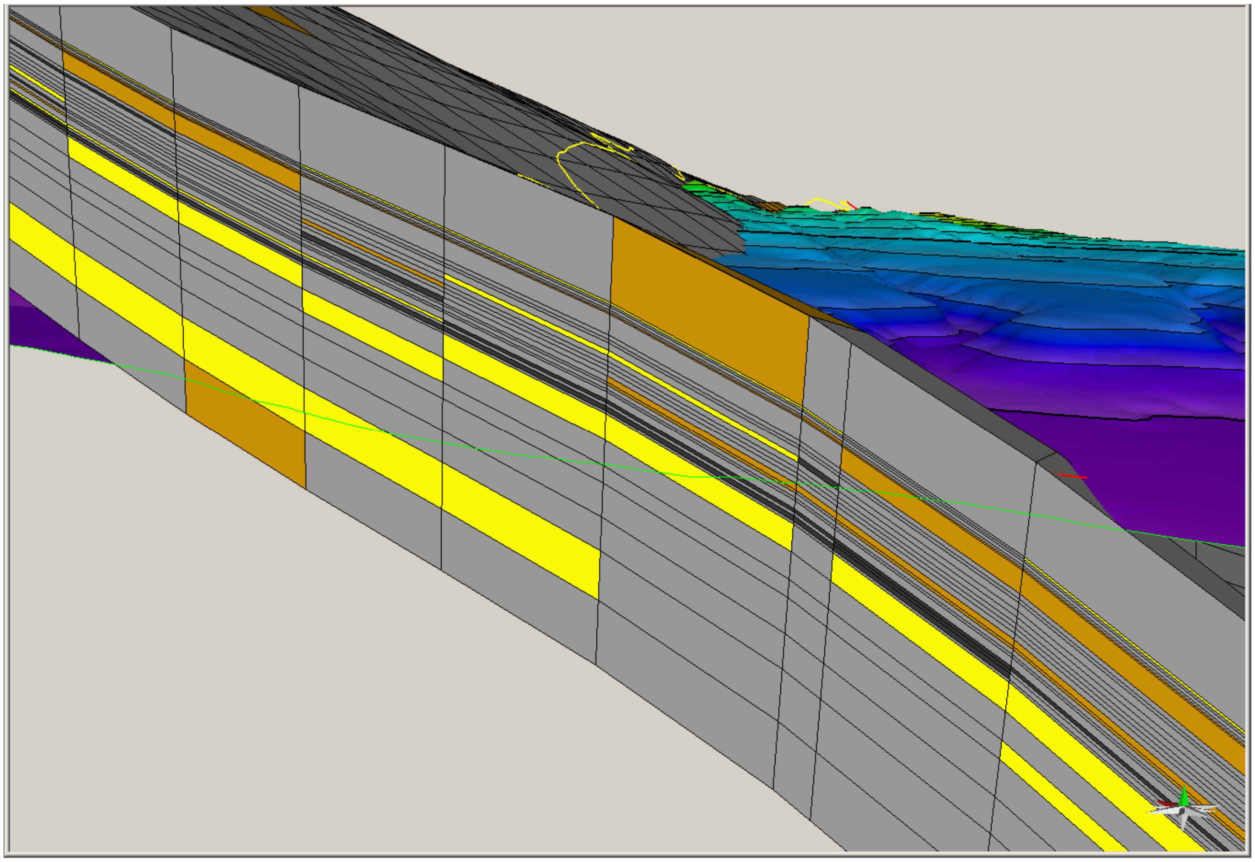

Figure 48 Rock Type Cross-Section in the Animas River Bed.

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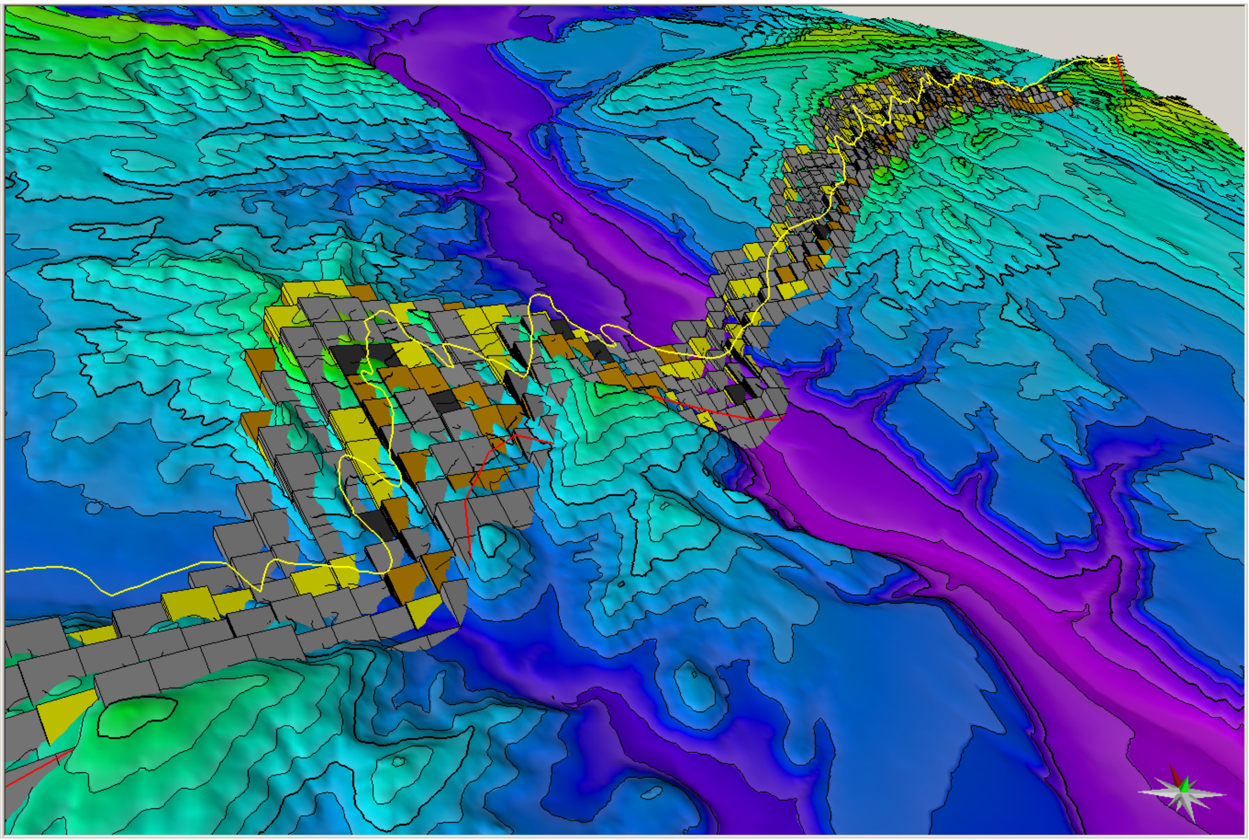

Figure 49 Eroded Simulation Model

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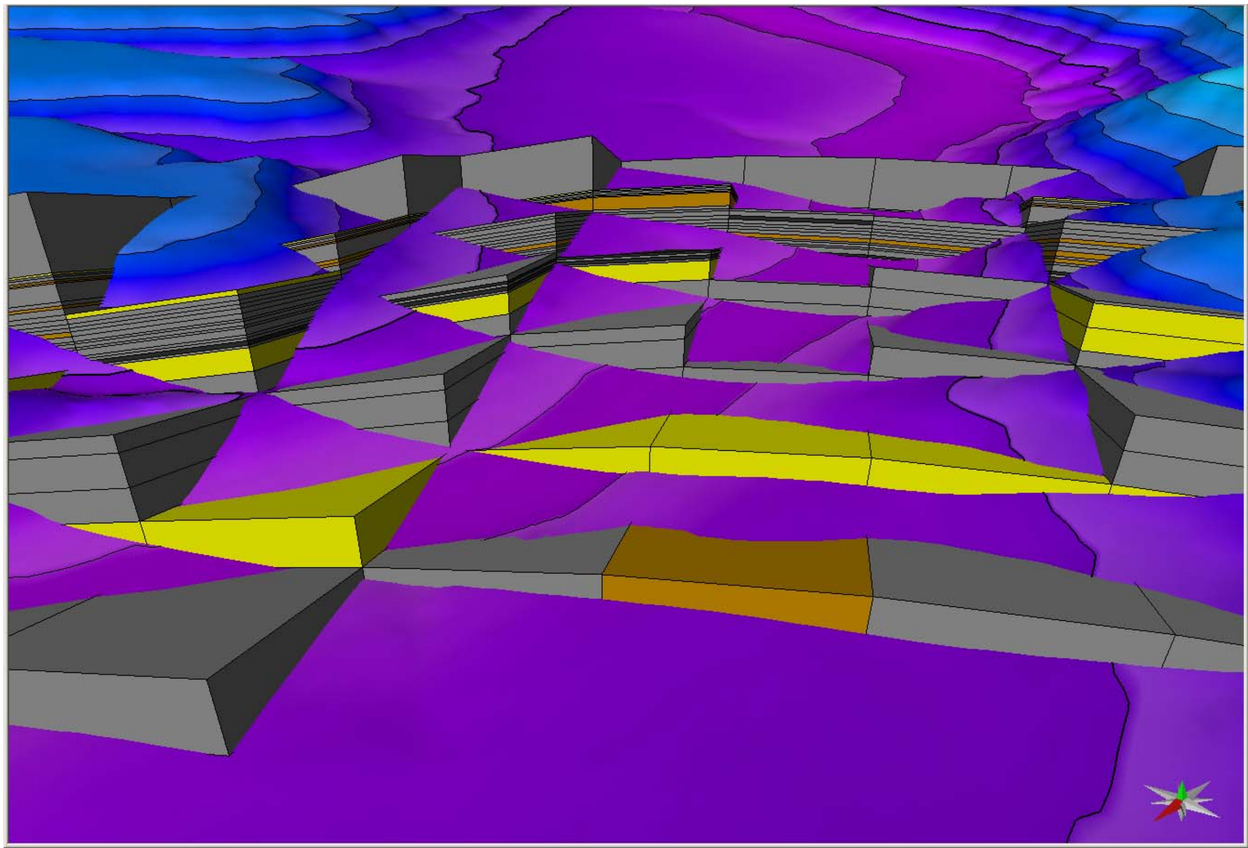

Figure 50 Eroded Simulation Model at Carbon Junction – View 1

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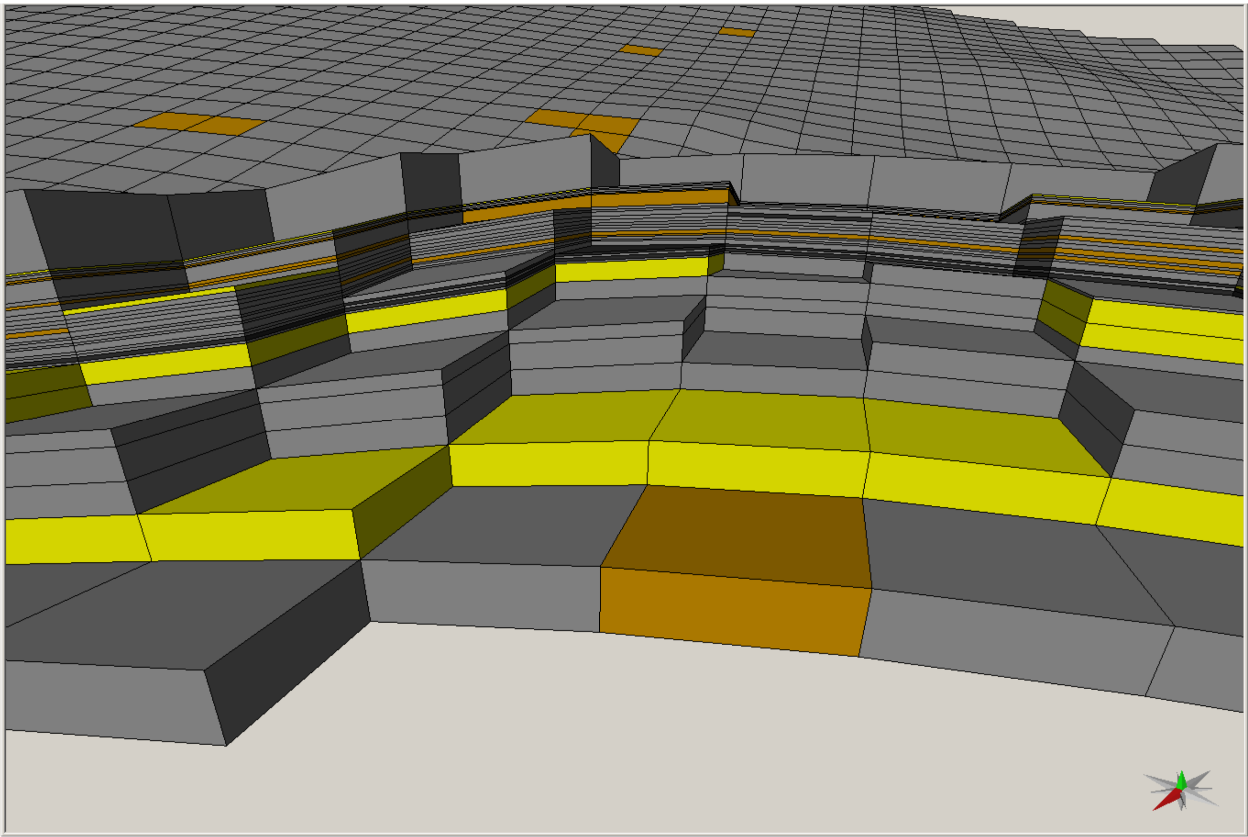

Figure 51 Eroded Simulation Model at Carbon Junction – View 2

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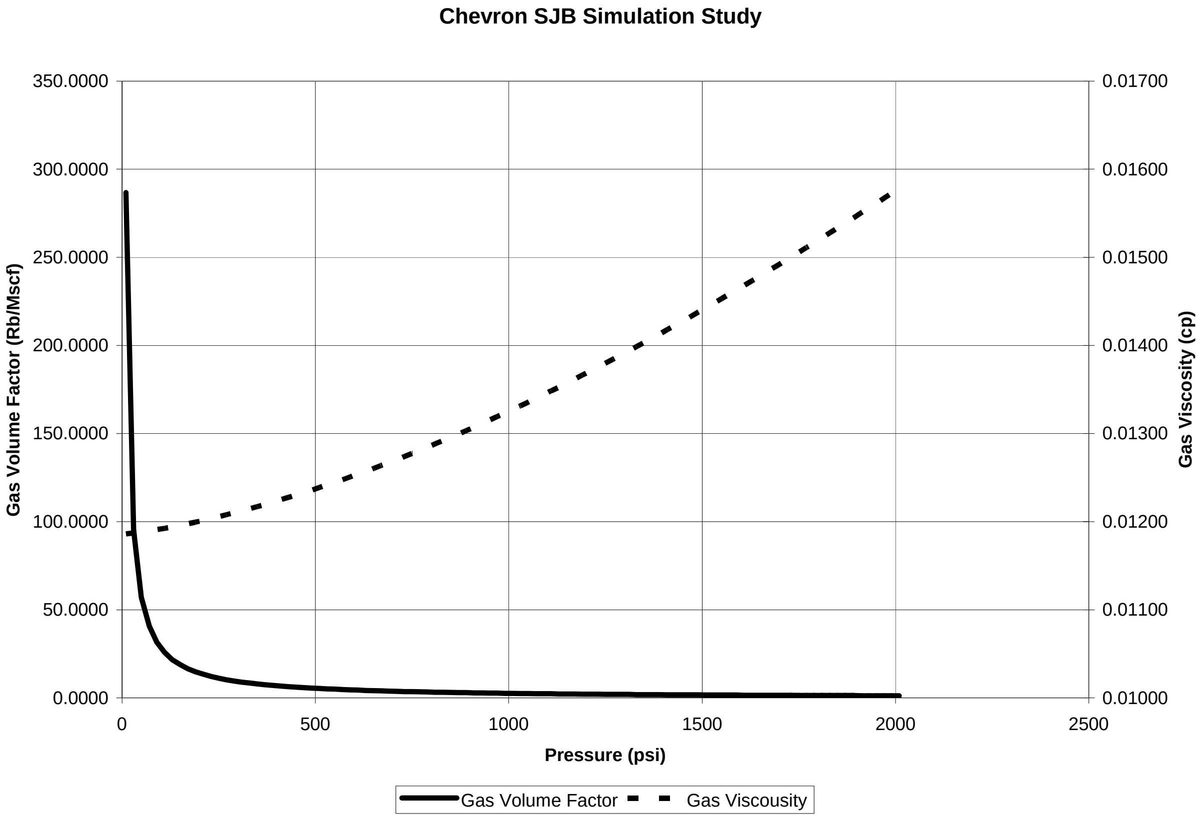

Figure 52 Gas PVT Properties used in Simulation

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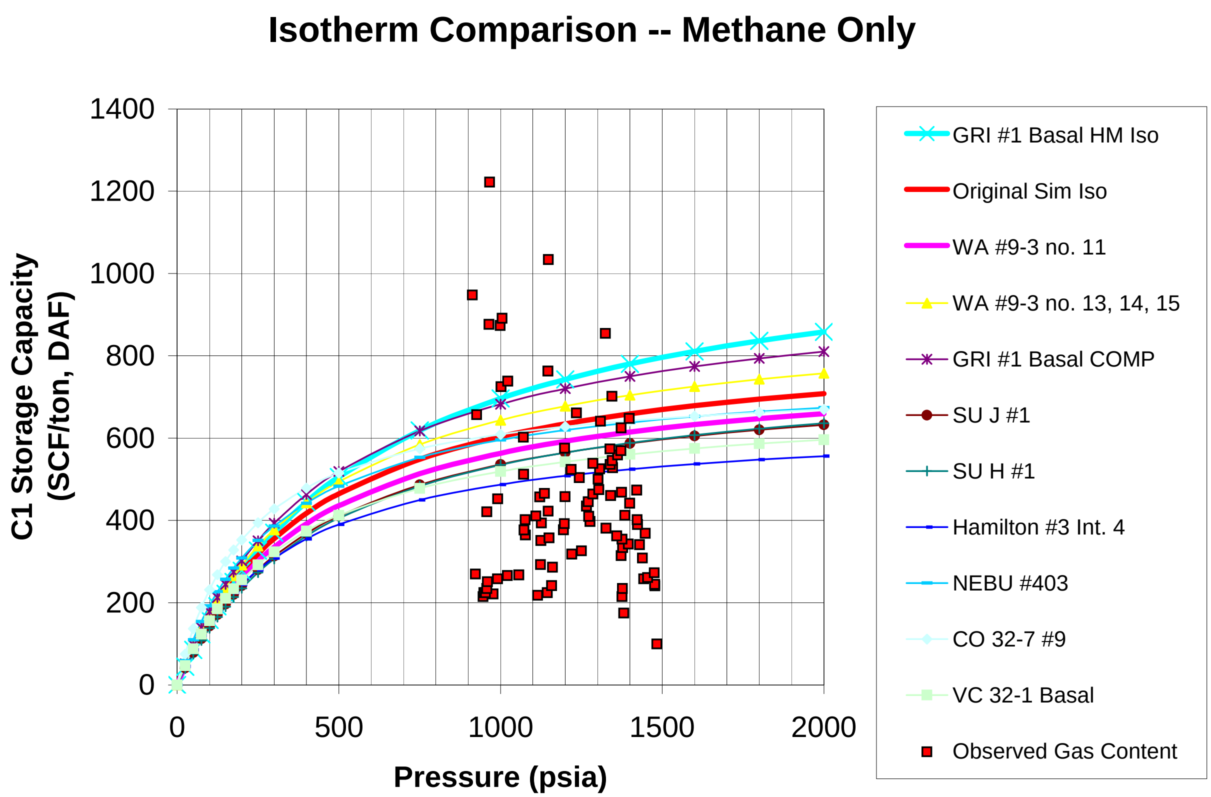

Figure 53 Methane Isotherms and Gas Content

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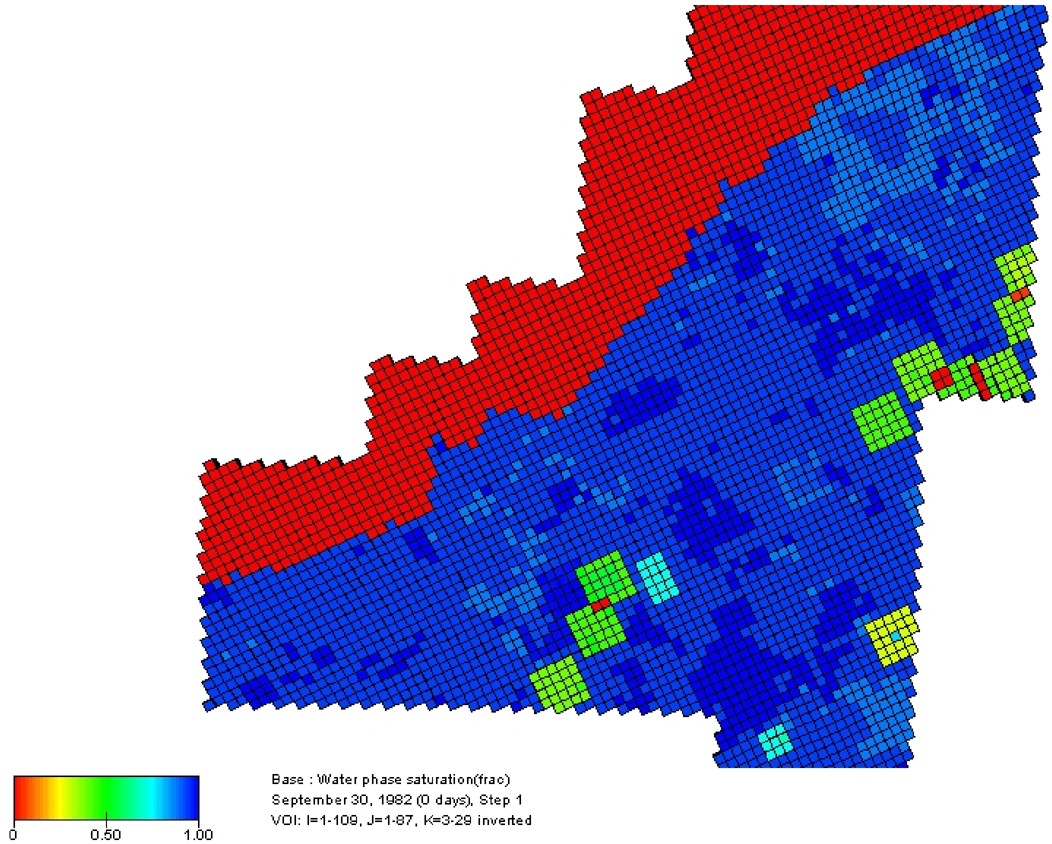

Figure 54 Initial Water Saturations used in Simulation

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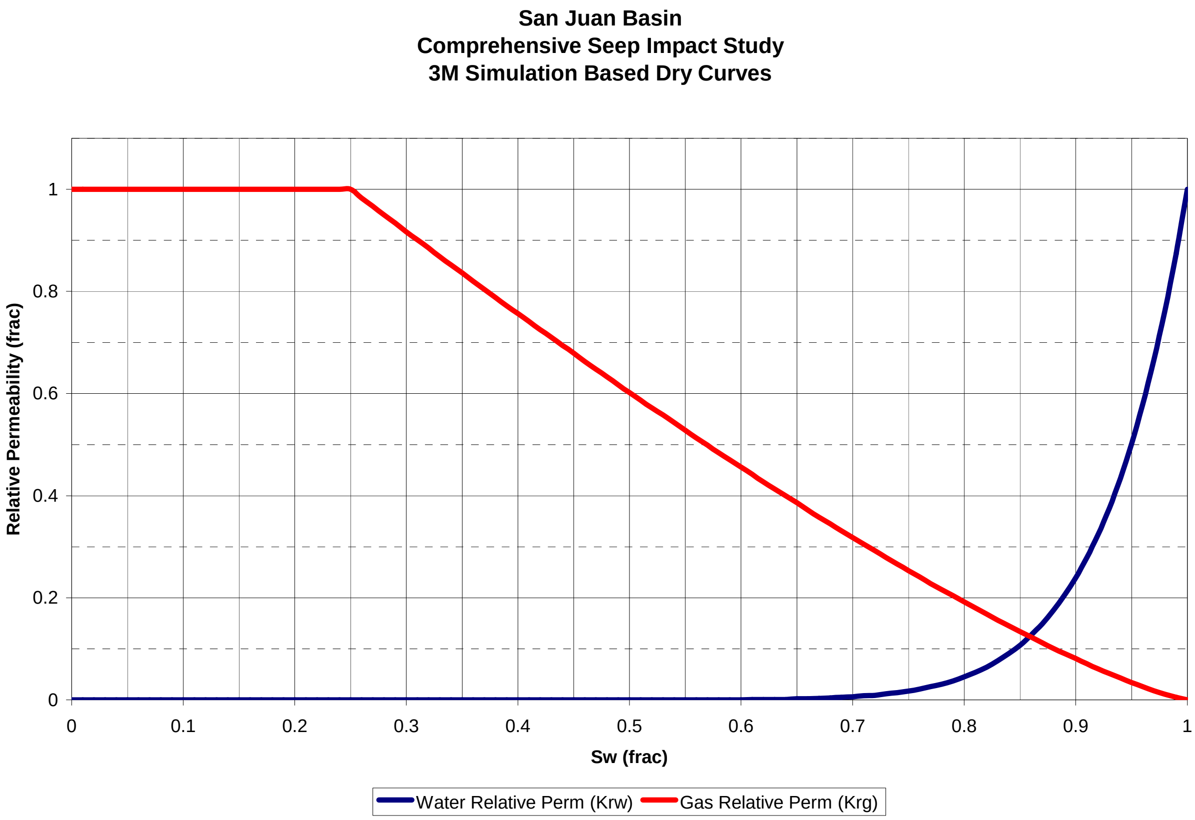

Figure 55 Relative Permeability Curves used for History Match in Regions 1 -4

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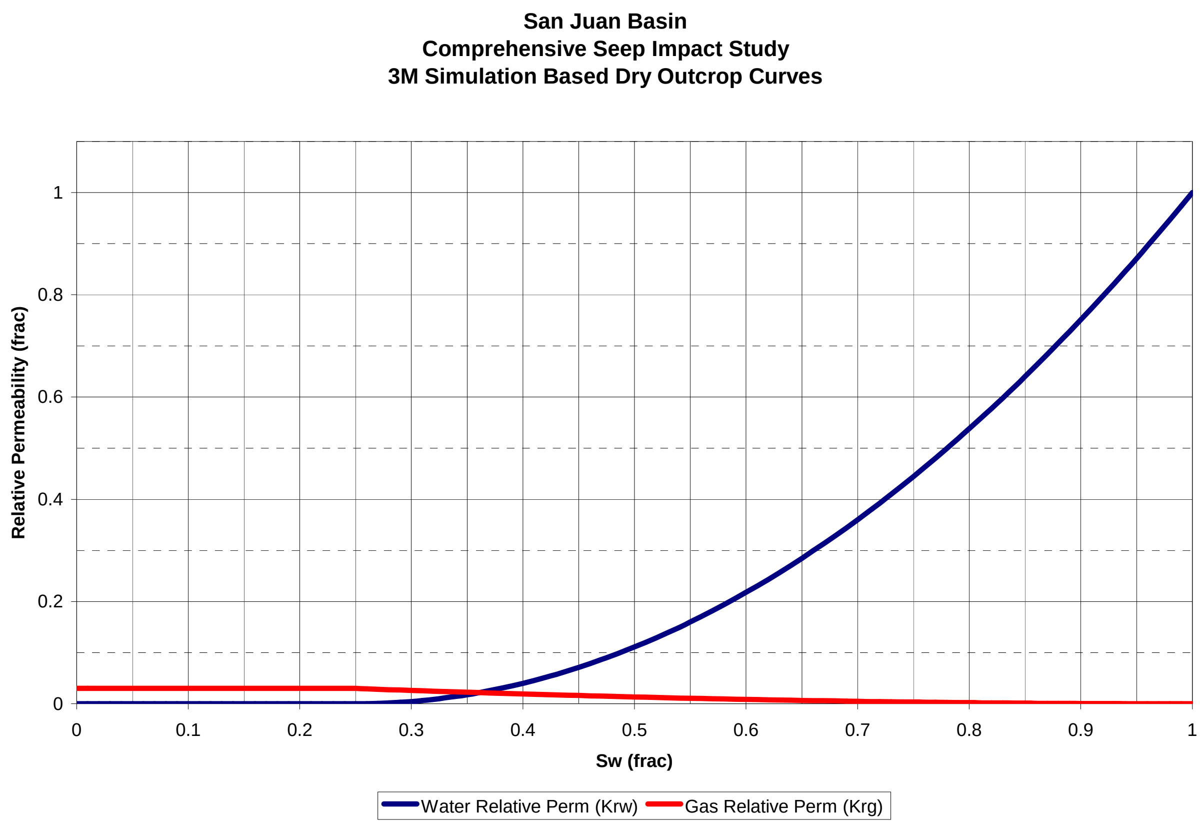

Figure 56 Relative Permeability Curves used for History Match in Regions 5 -8

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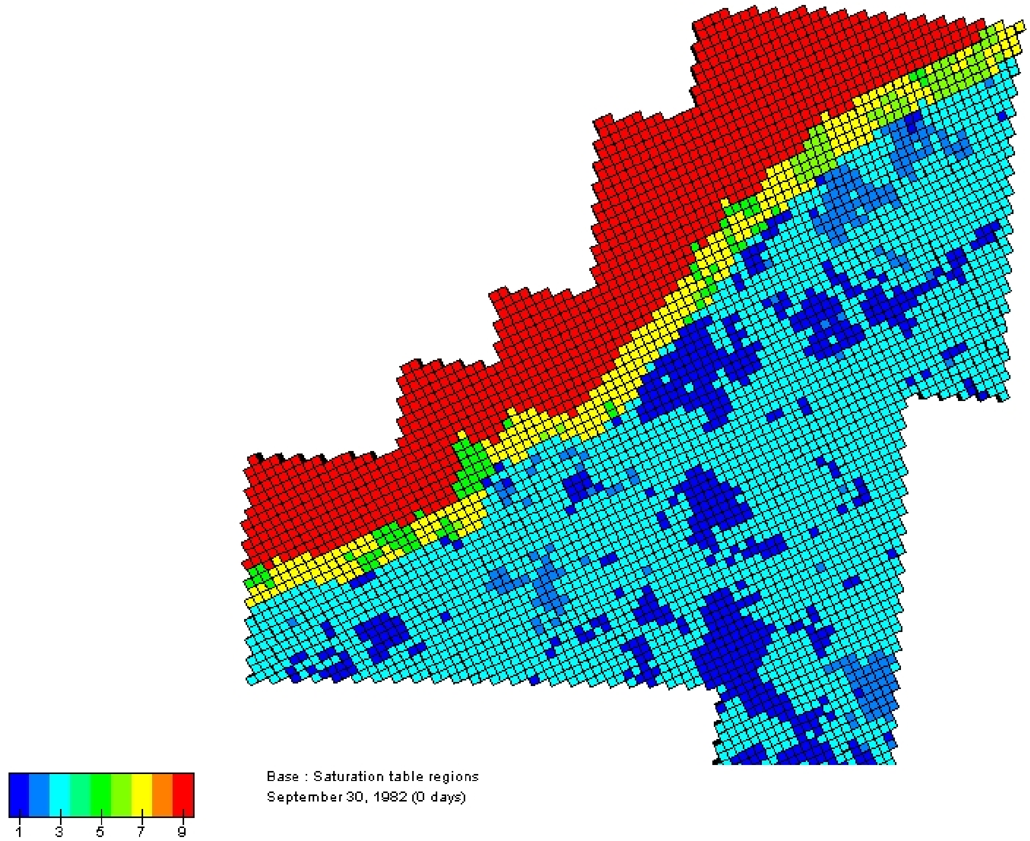

Figure 57 Saturation Regions used in Simulation to Set Relative Permeability Curves

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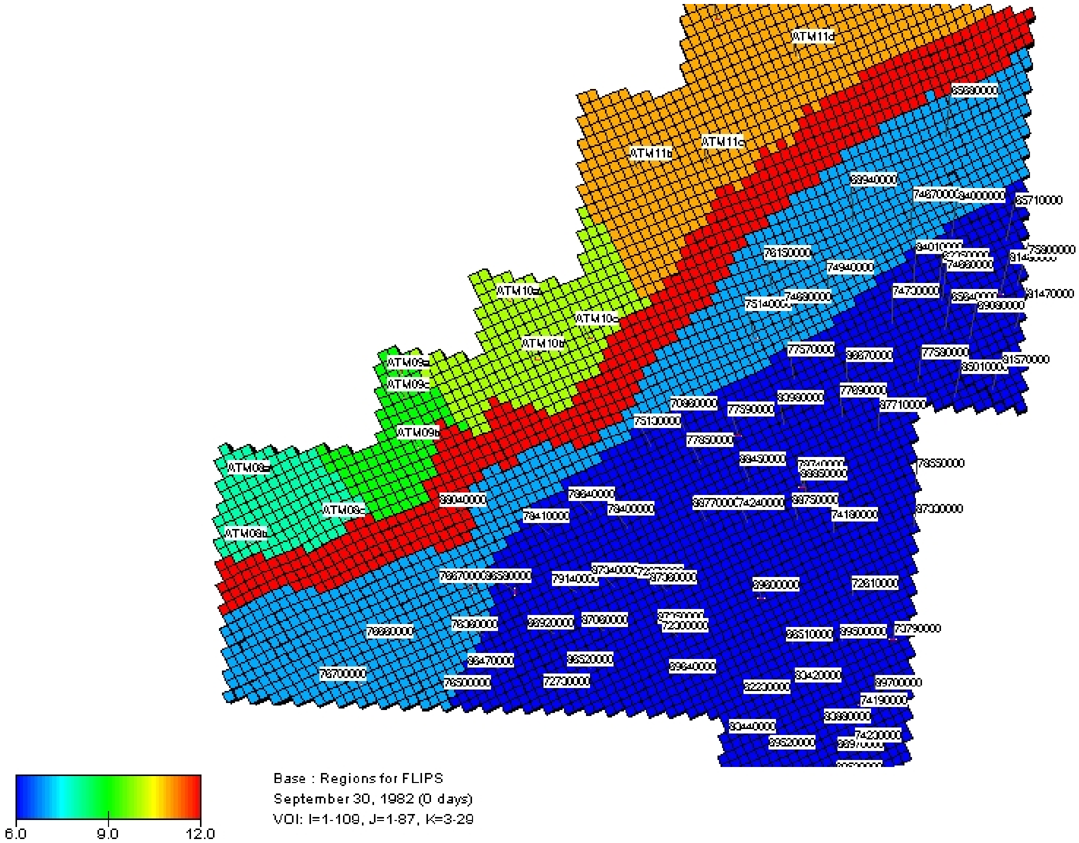

Figure 58 Fluid-in-Place Regions used in Simulation

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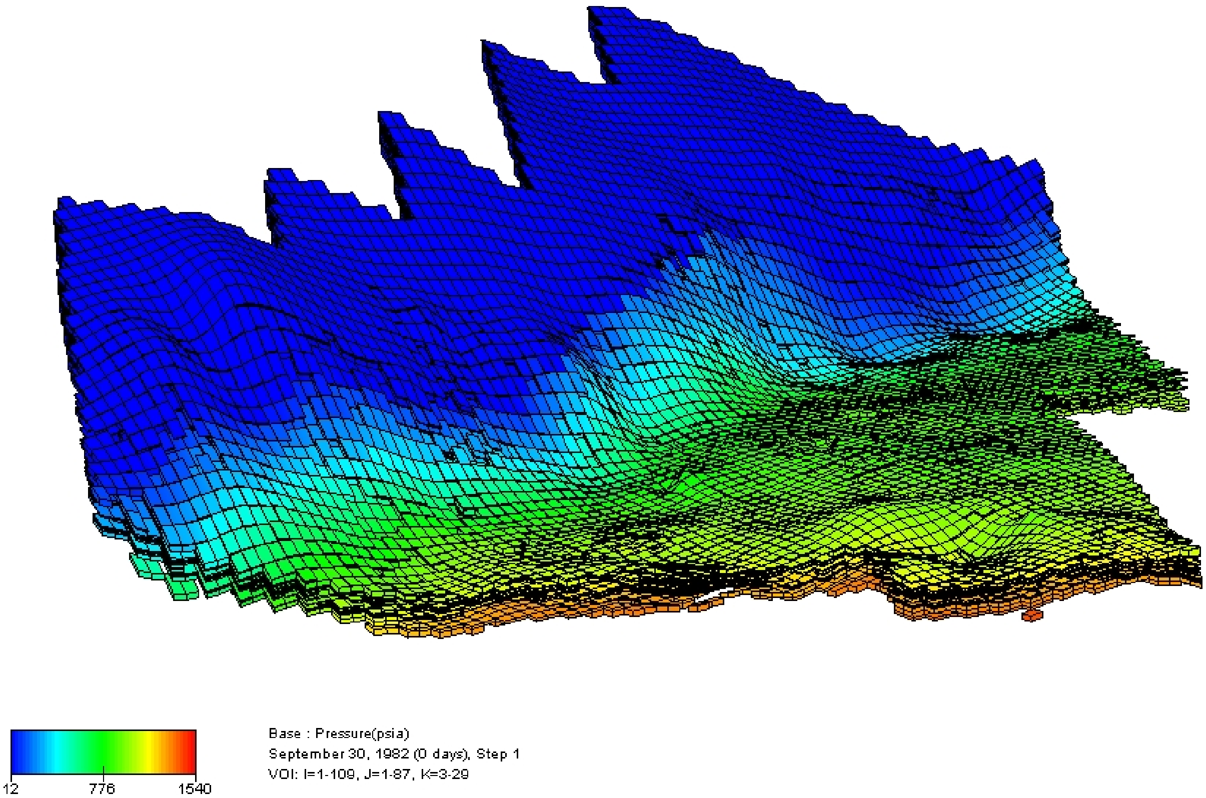

Figure 59 Initial Pressure from 3M Study which was used in Simulation

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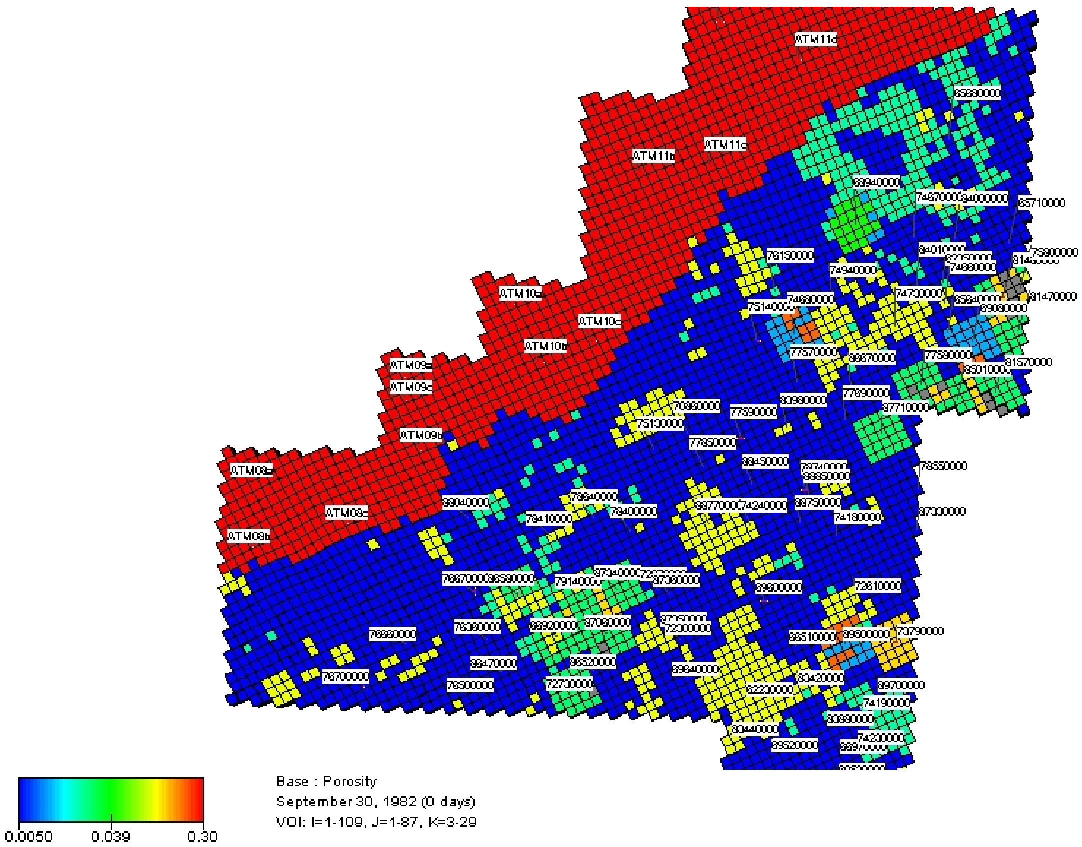

Figure 60 History Match Modifications to Porosity to Increase Gas Availability to Select Wells

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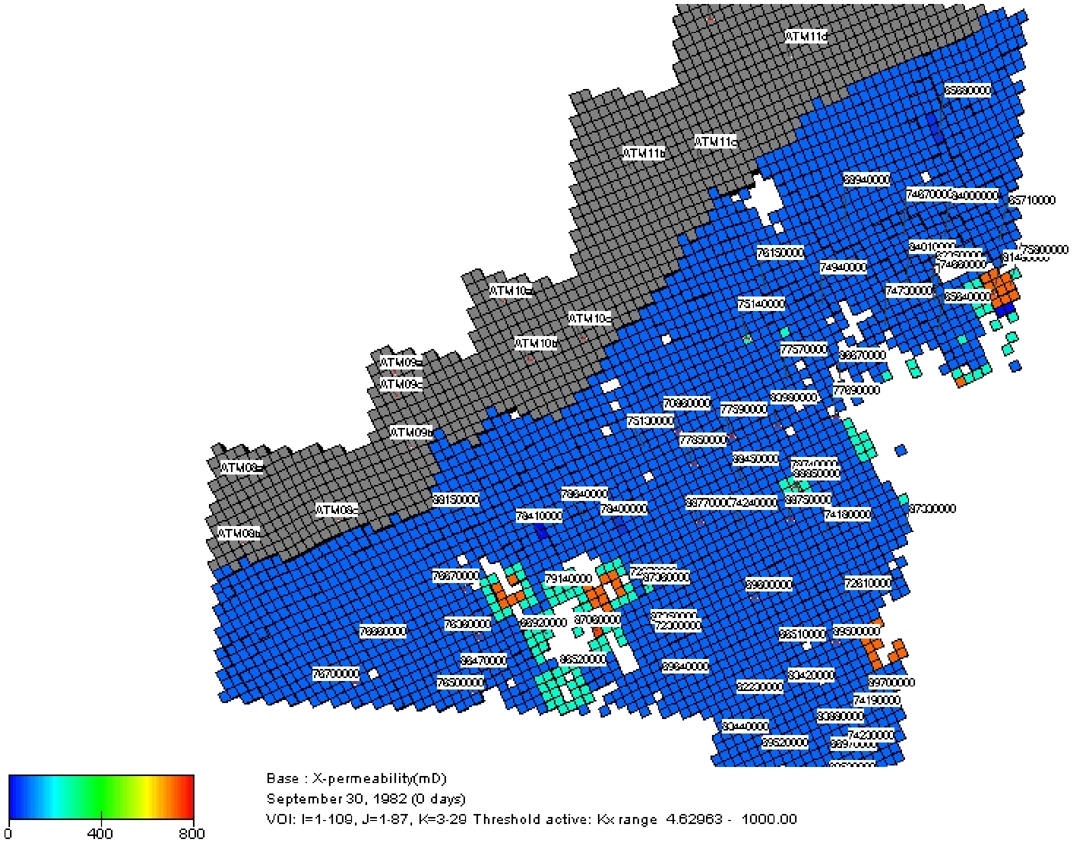

Figure 61 Illustration of History Match Modifications to Permeability to Increase Gas Availability to Select Wells And Areas

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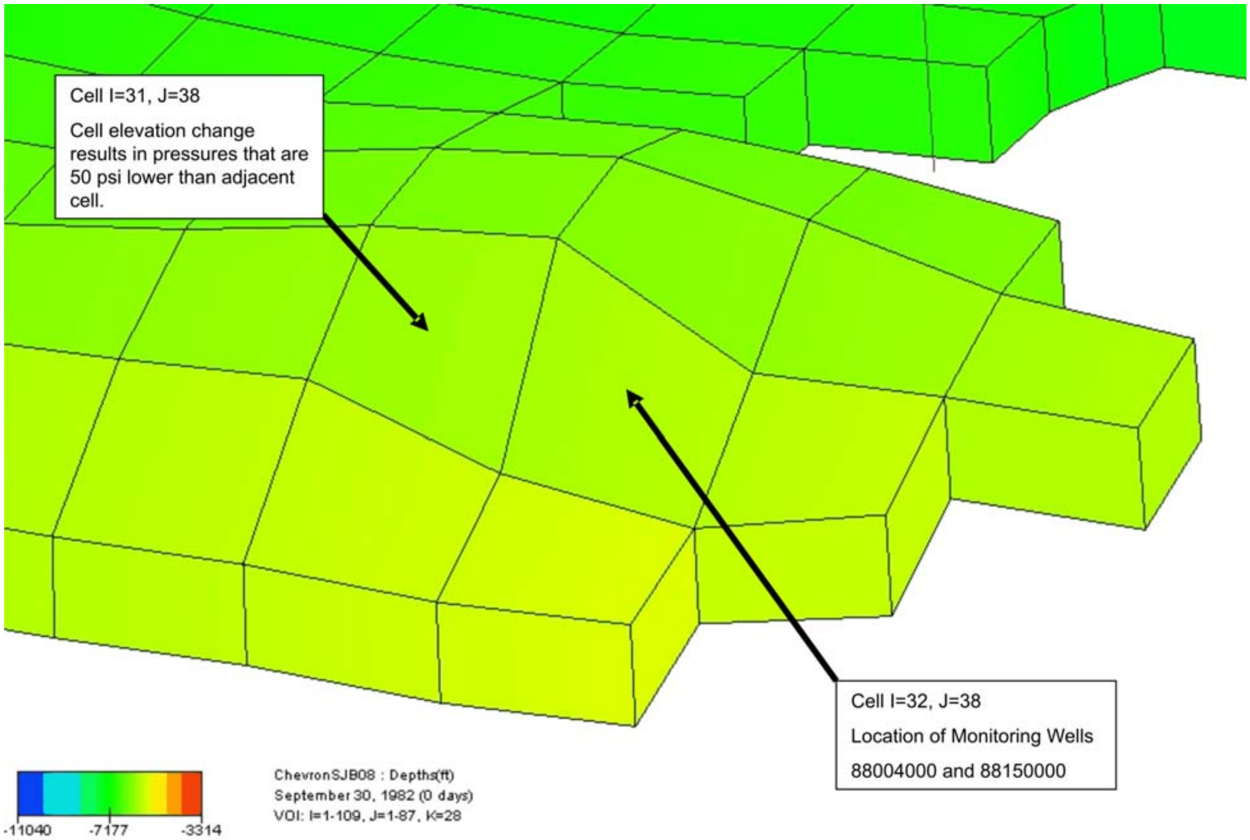

Figure 62 Illustration Of Well Location Impact On Simulation Pressure Due To Cell Elevation.

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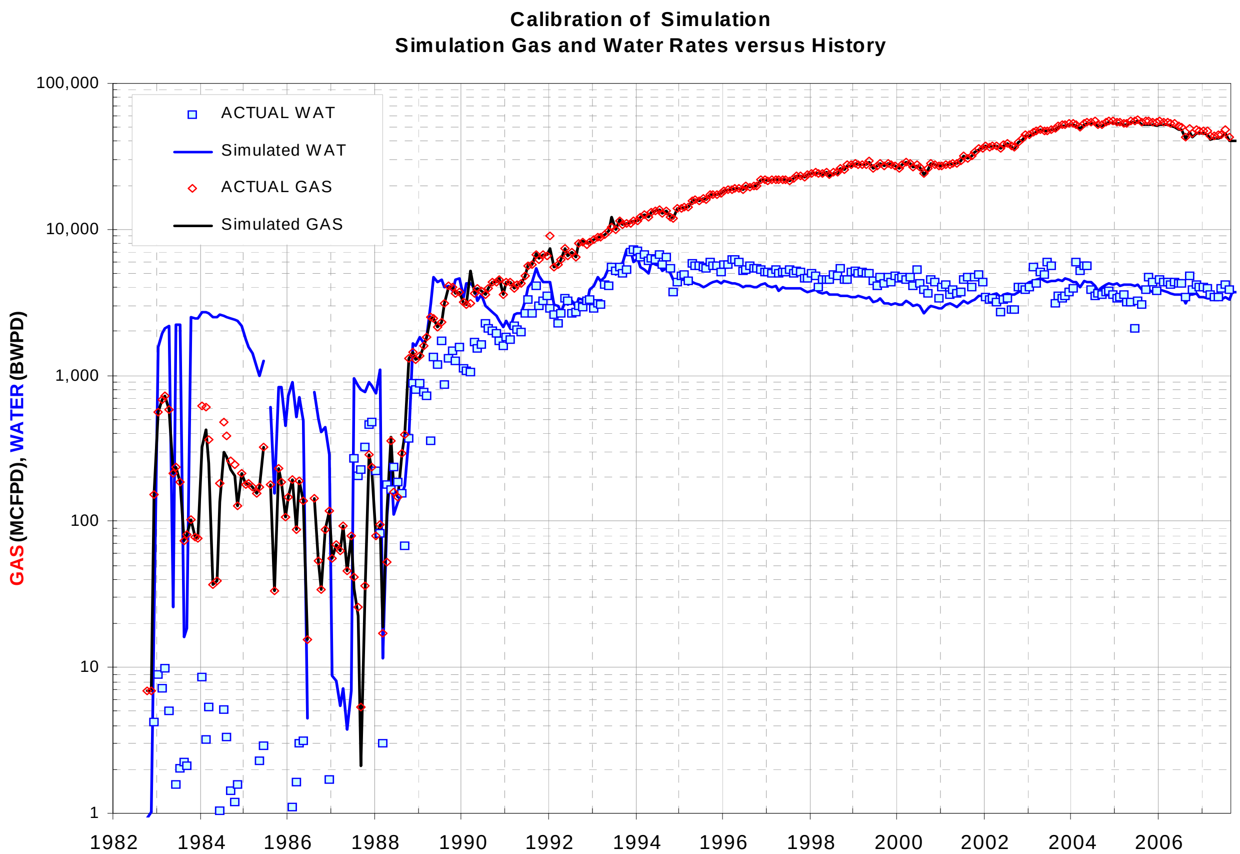

Figure 63 Field Production Rate History Match, Gas and Water

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HISTORY MATCH CASE-31
March 13, 2008 (HMRun031)

Total Gas Production and History

Cumulative Gas Production

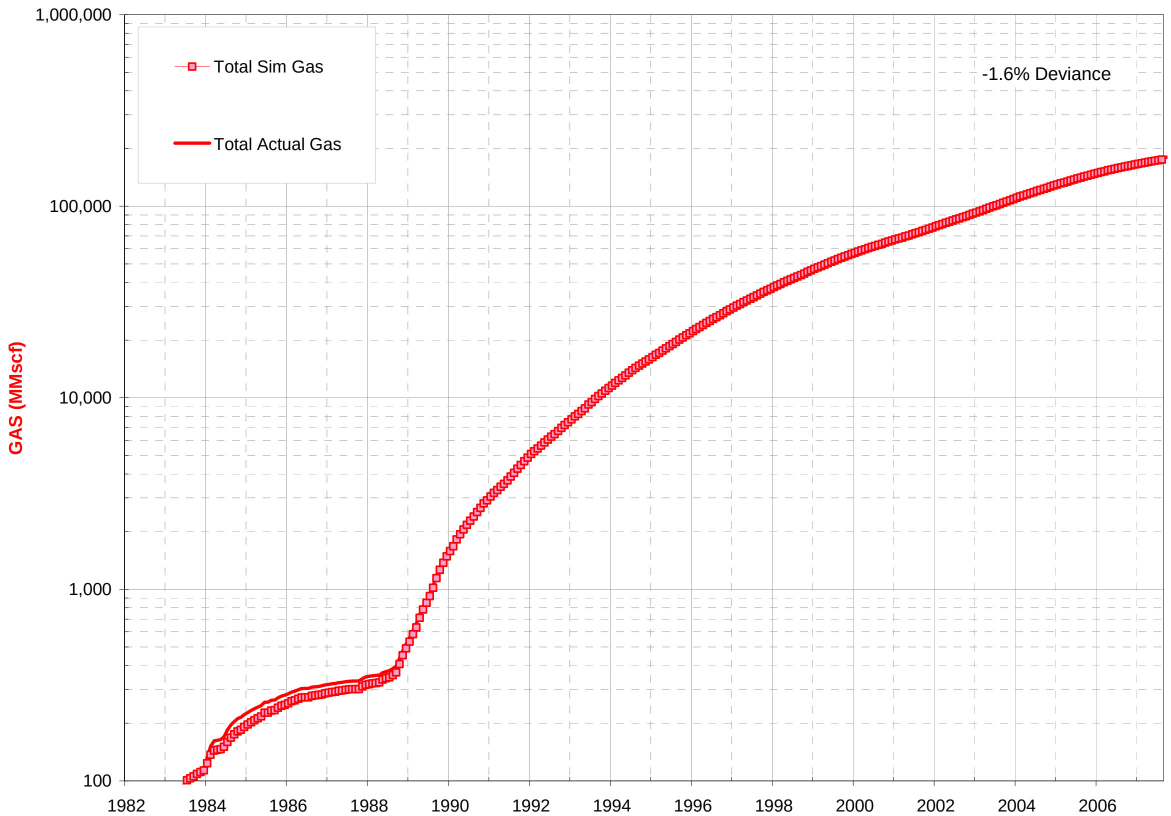

Figure 64 Field Cumulative Gas History Match Scales

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HISTORY MATCH CASE-31
March 13, 2008 (HMRun031)

Total Water Production and History

Cumulative Water Production

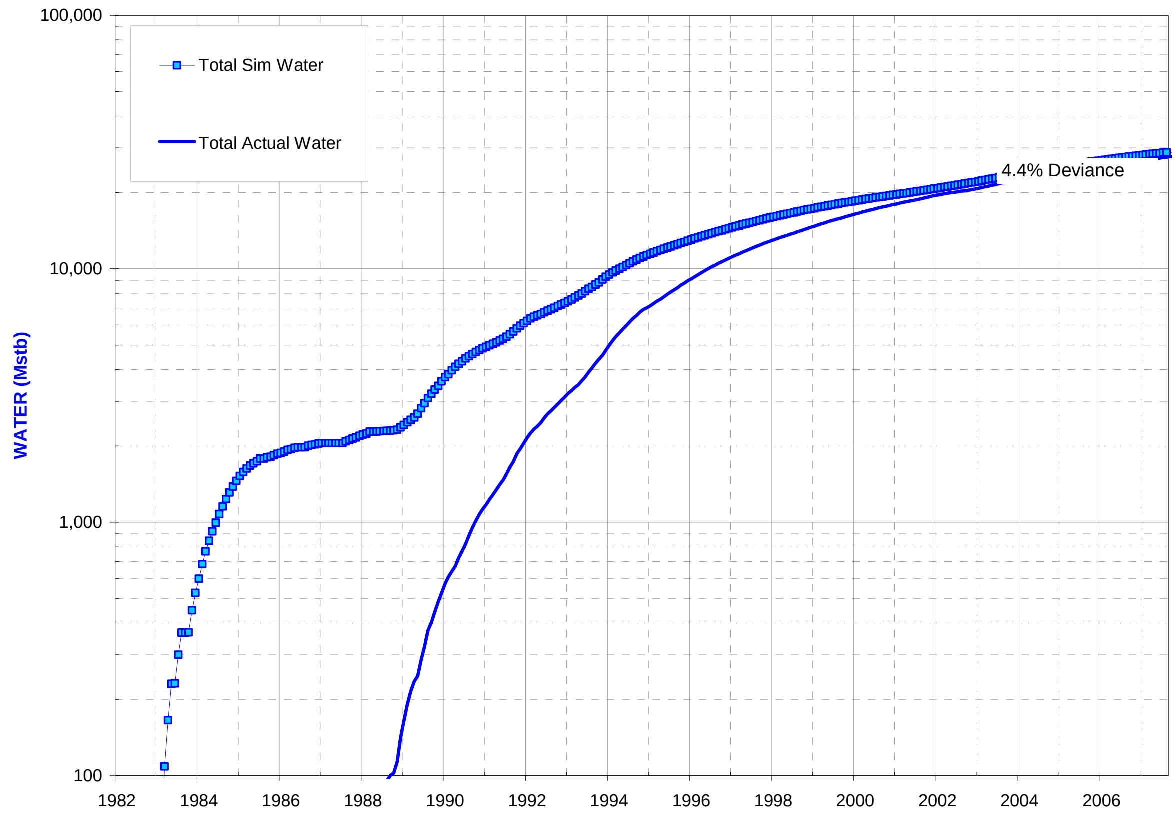

Figure 65 Field Cumulative Water History Match Scales

Back to Text

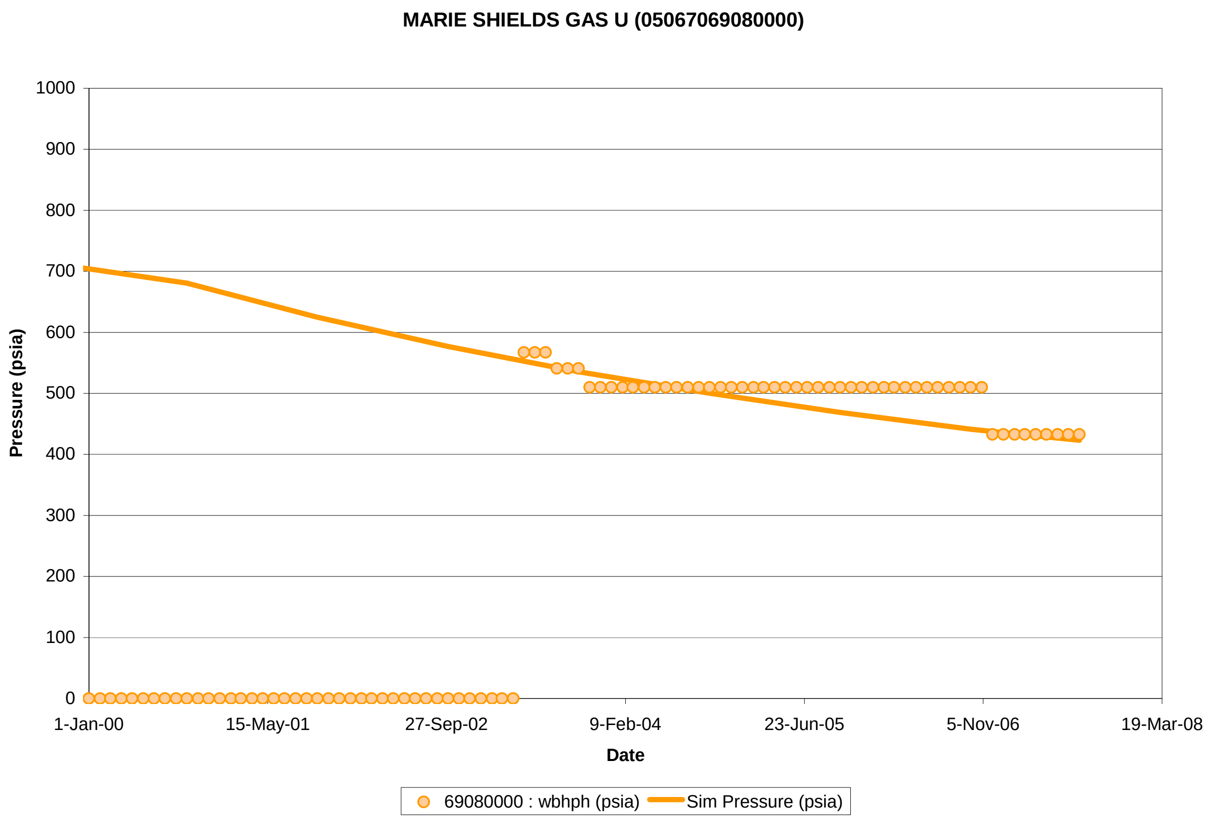

Figure 66 History Matched Pressure Plot, Marie Shields Gas Unit No. 1 Well

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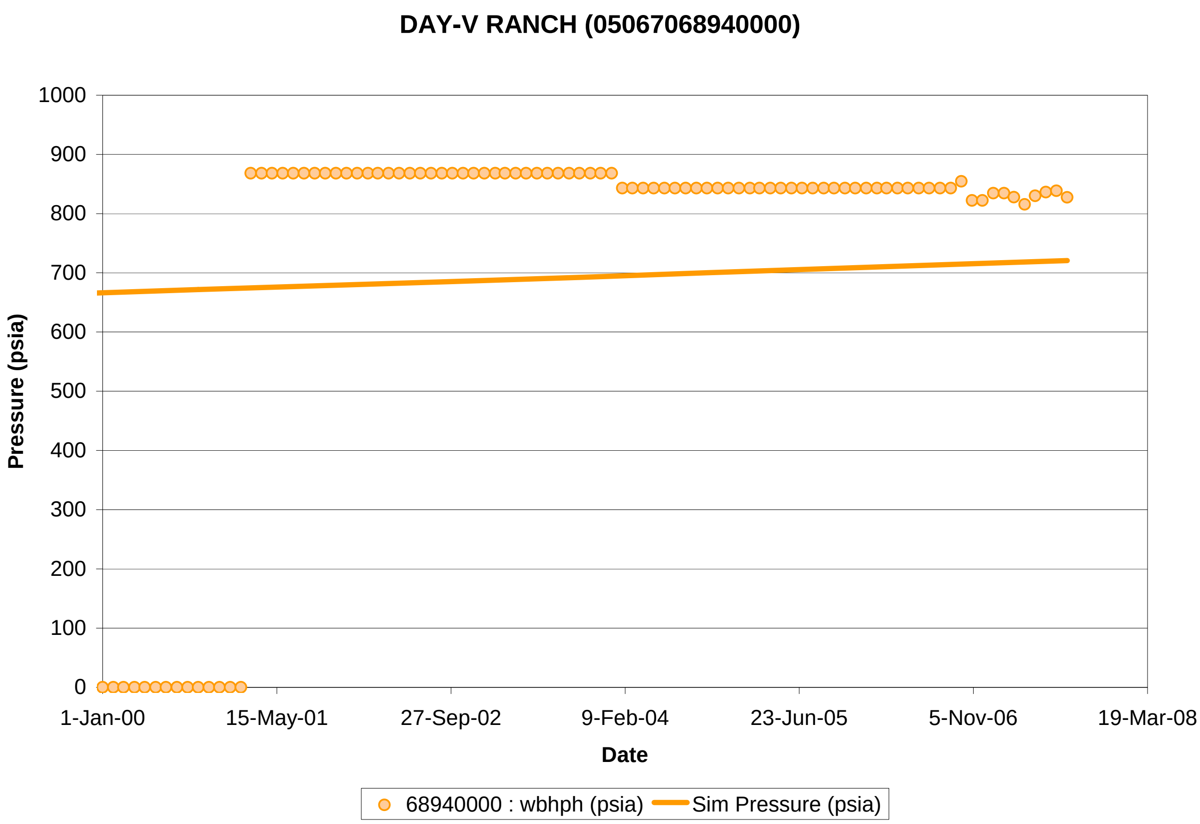

Figure 67 History Matched Pressure Plot, Day-V Ranch 1-35 Well

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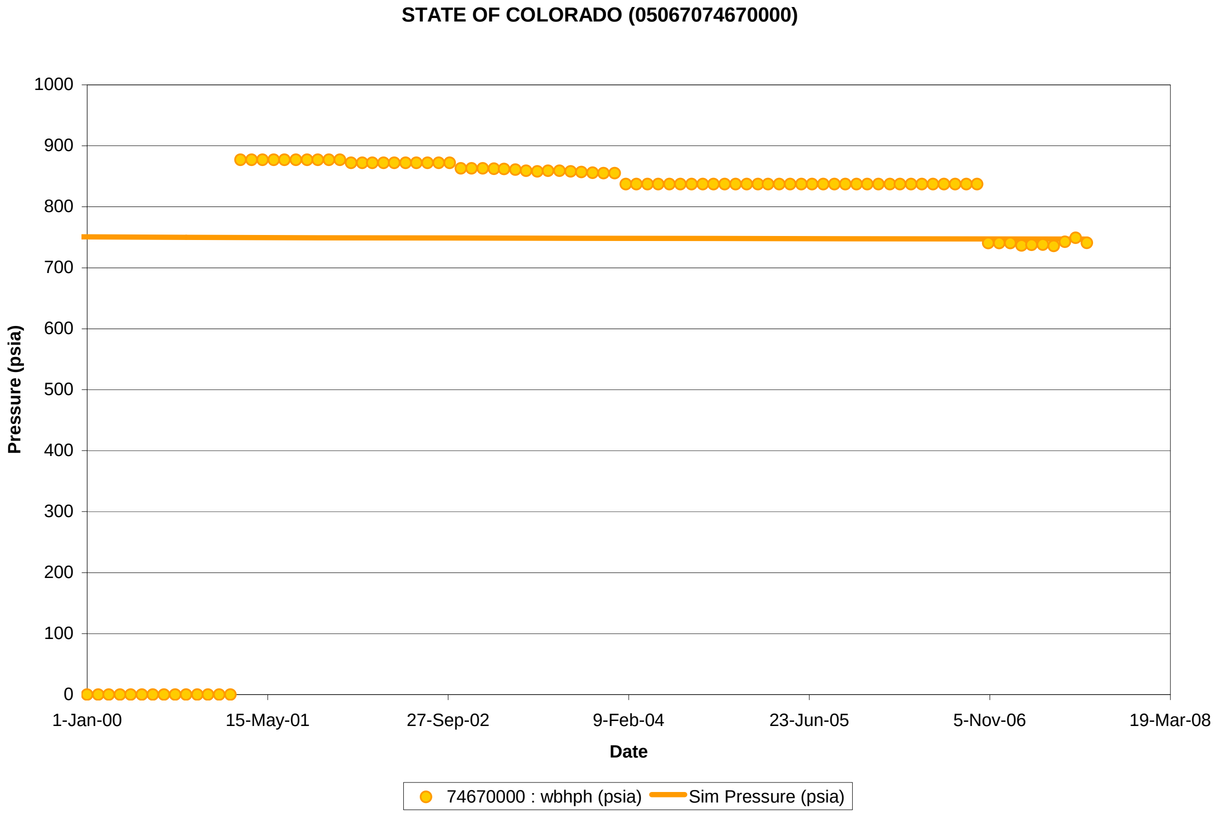

Figure 68 History Matched Pressure Plot, State of Colorado 36-3 Well

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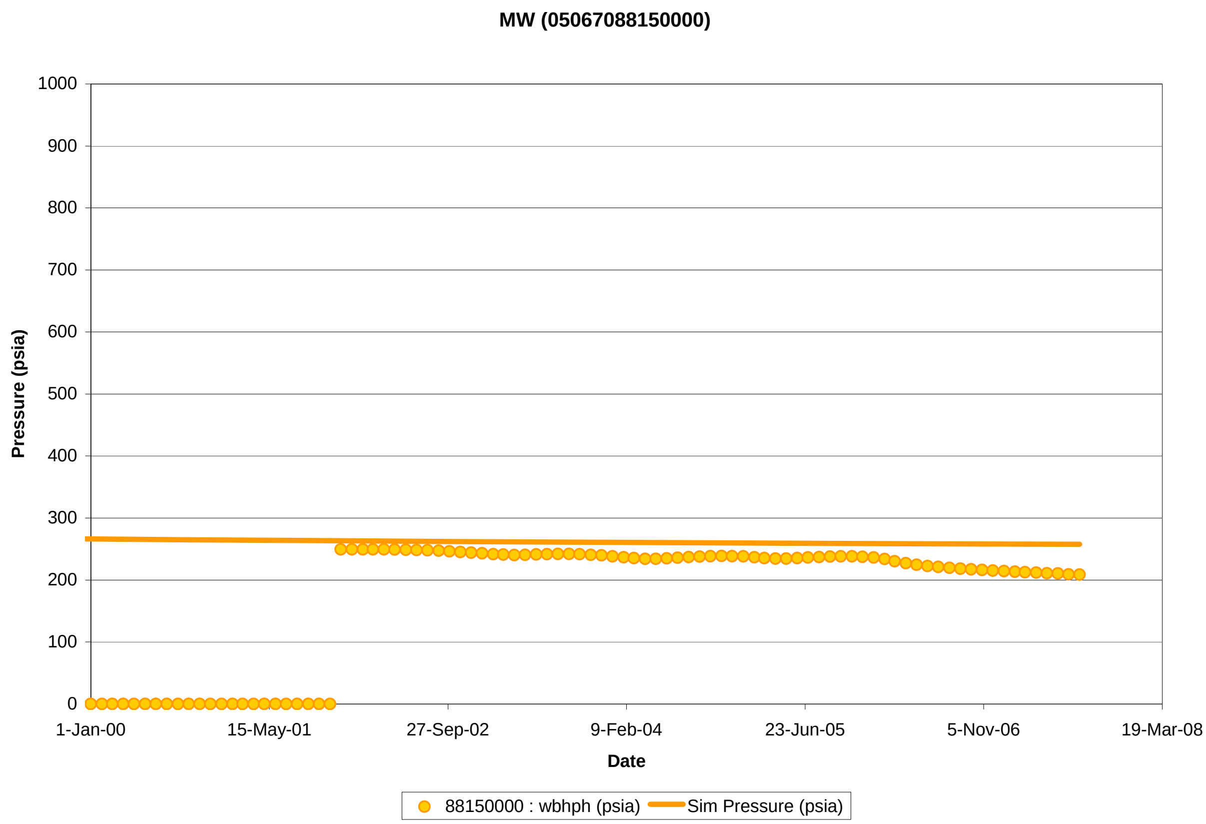

Figure 69 History Matched Pressure Plot, COGCC Monitor Well 34-9-7-1

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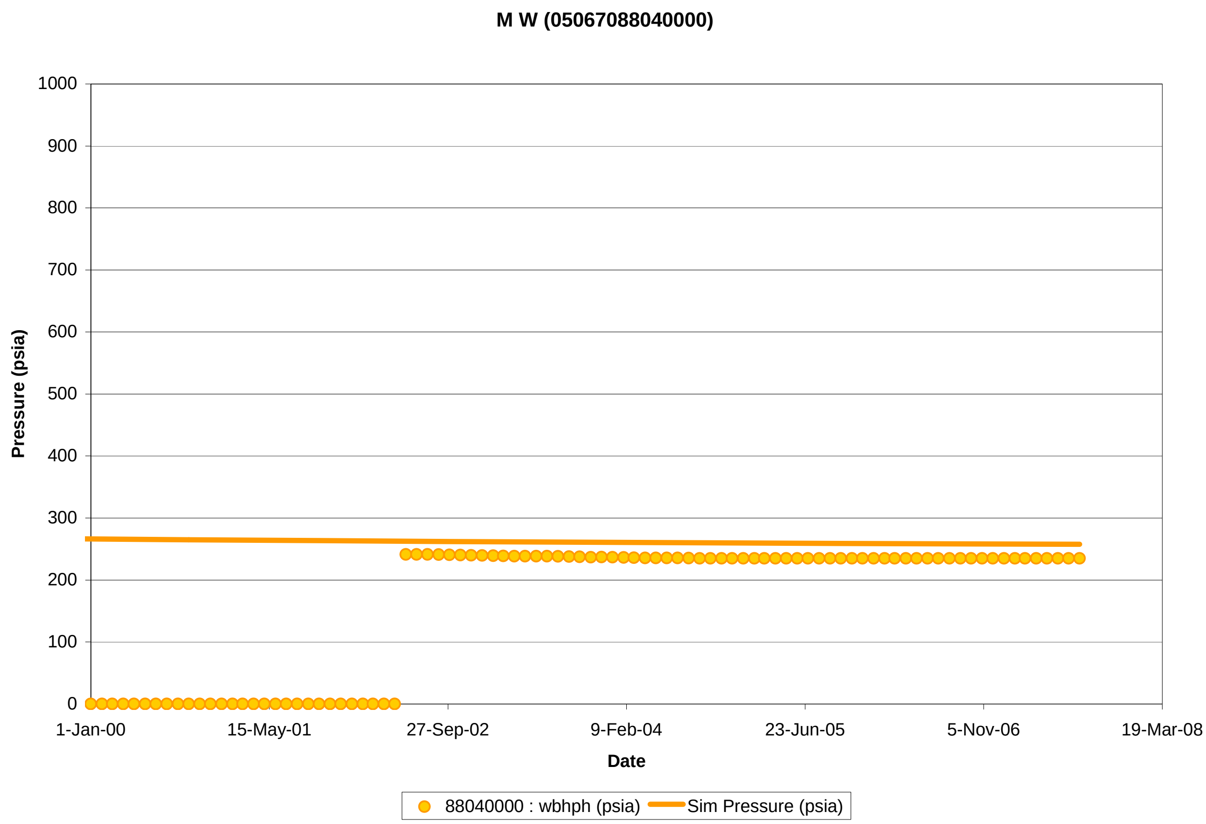

Figure 70 History Matched Pressure Plot, COGCC Monitor Well 34-9-7-2

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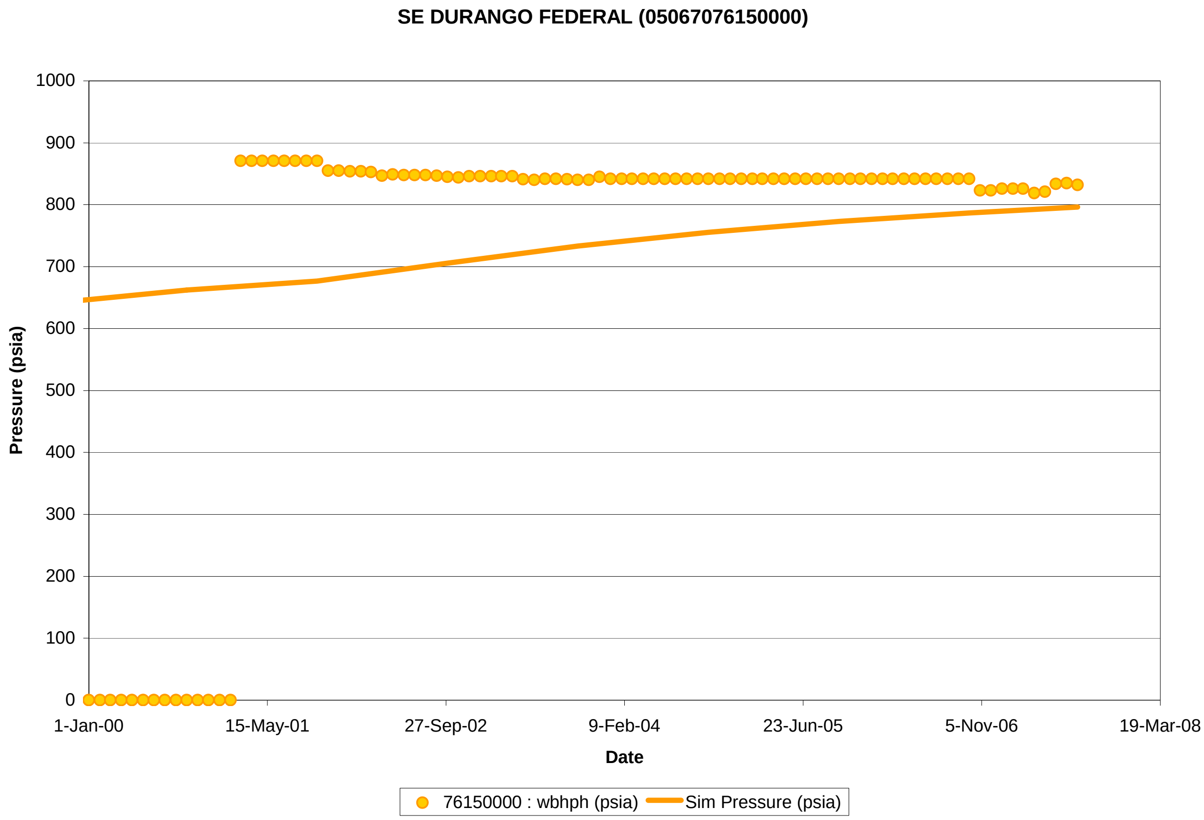

Figure 71 History Matched Pressure Plot, SE Durango Federal 34-1 Well

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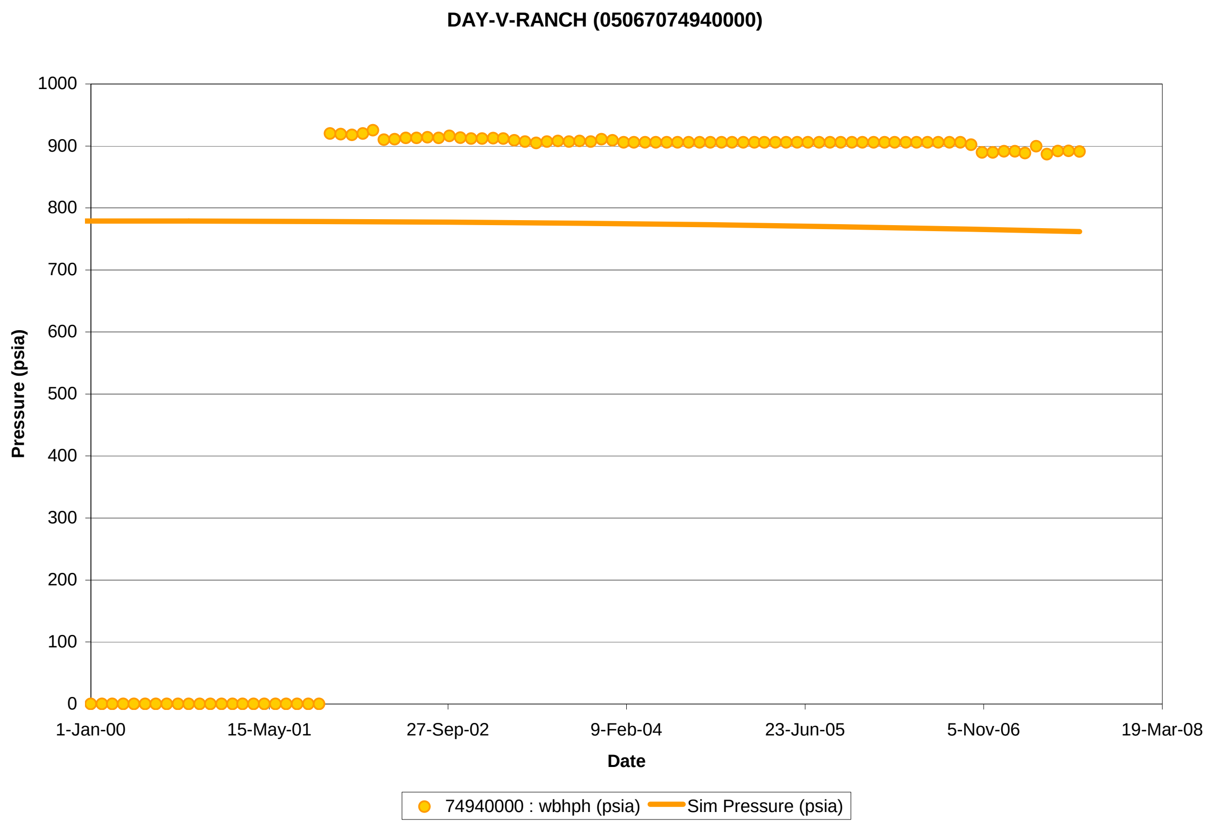

Figure 72 History Matched Pressure Plot, Day-V Ranch 35-2 Well

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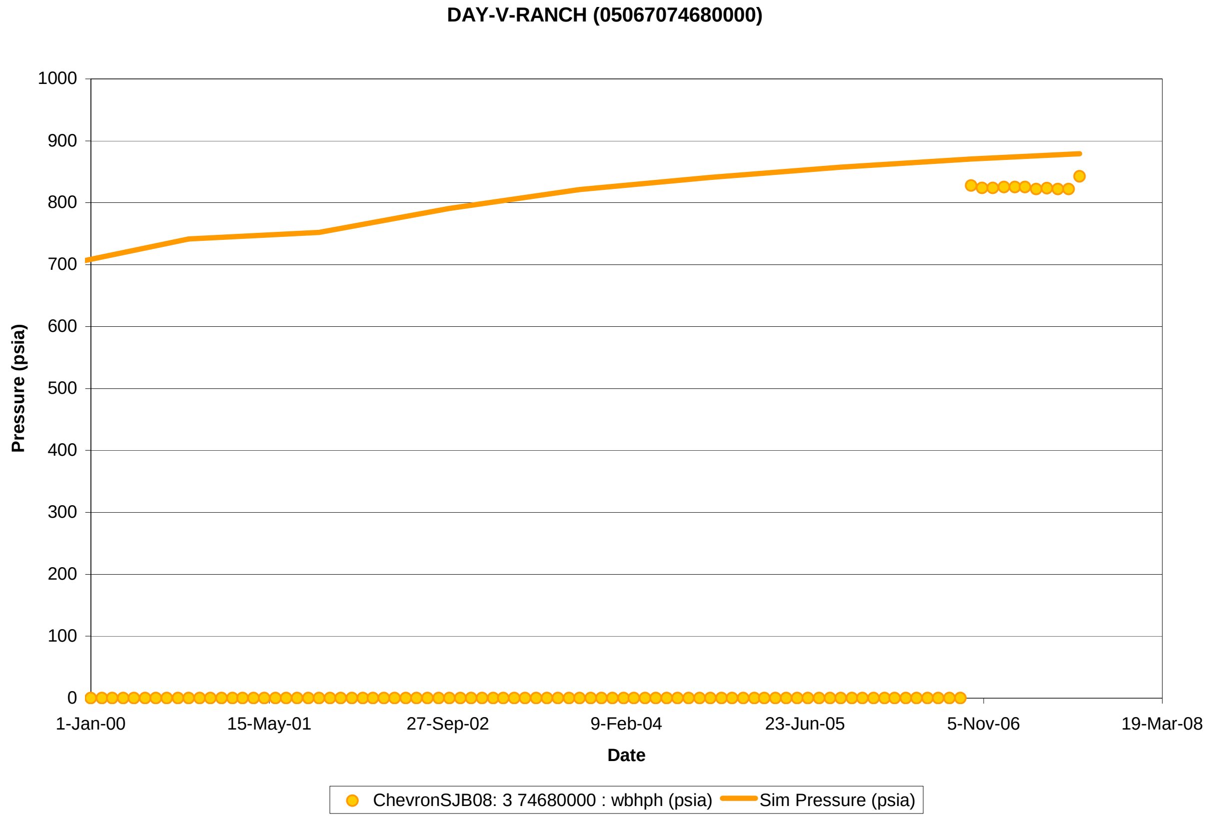

Figure 73 History Matched Pressure Plot, Day-V Ranch 34 ½ -35-1 Well

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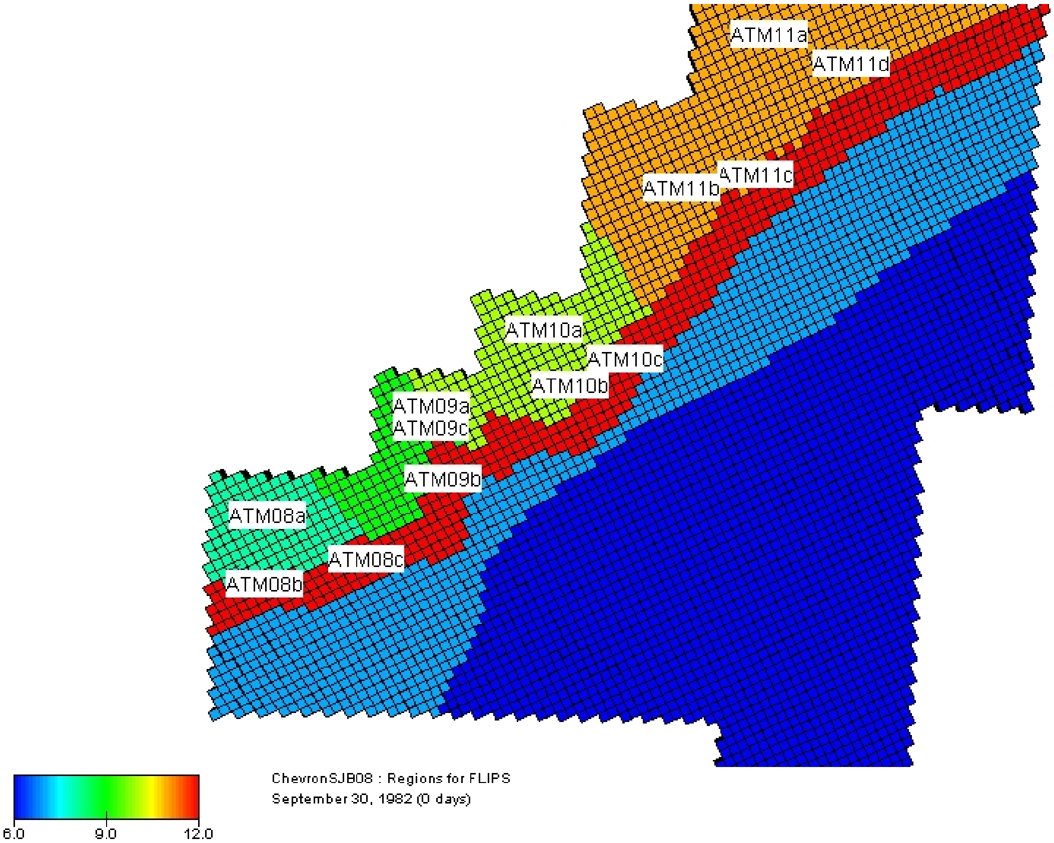

Figure 74 Location of Atmospheric (ATM) Wells in the Air FLIPS 8 -11

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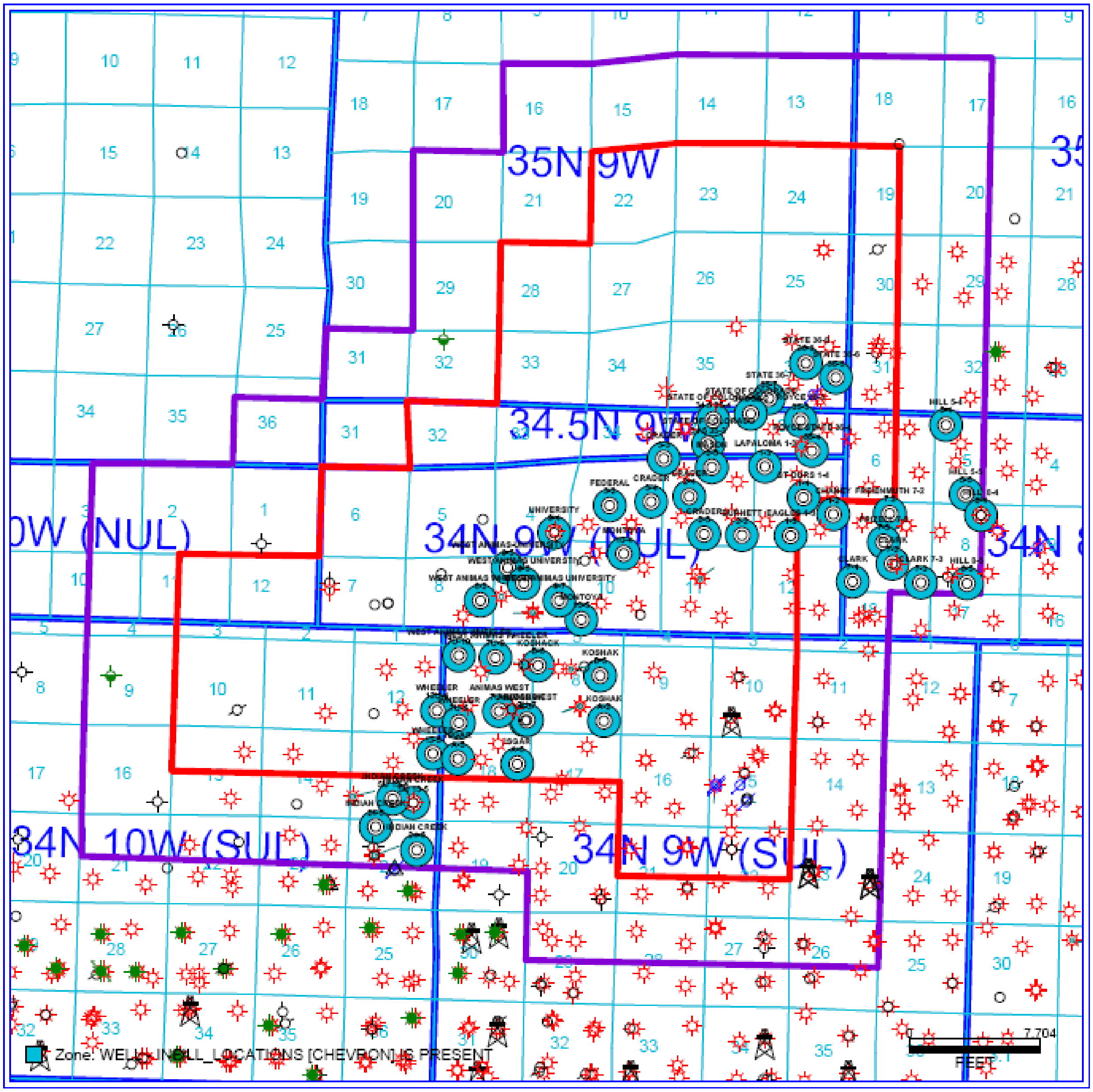

Figure 75 Infill Well Locations, Red Polygon is Simulation Area of Interest

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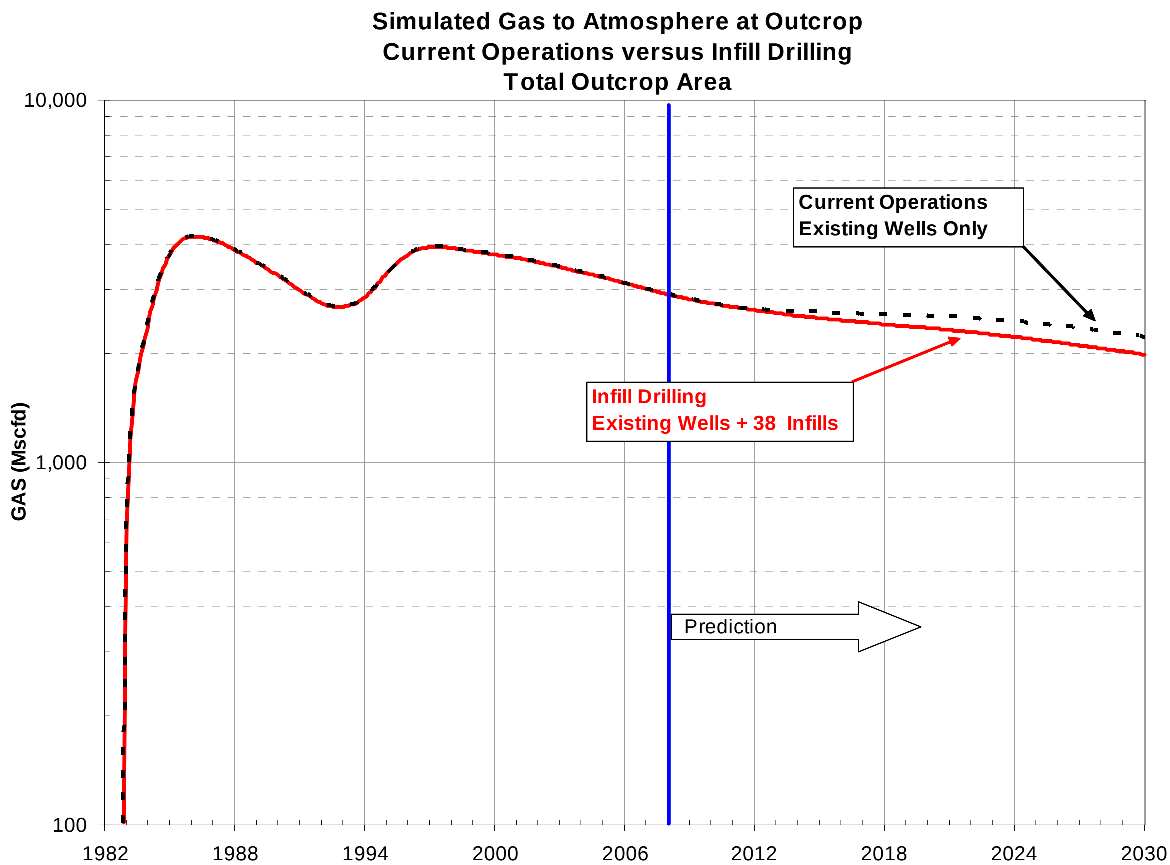

Figure 76 Atmospheric Wells Total Gas Production, Base Case vs. Infill Case

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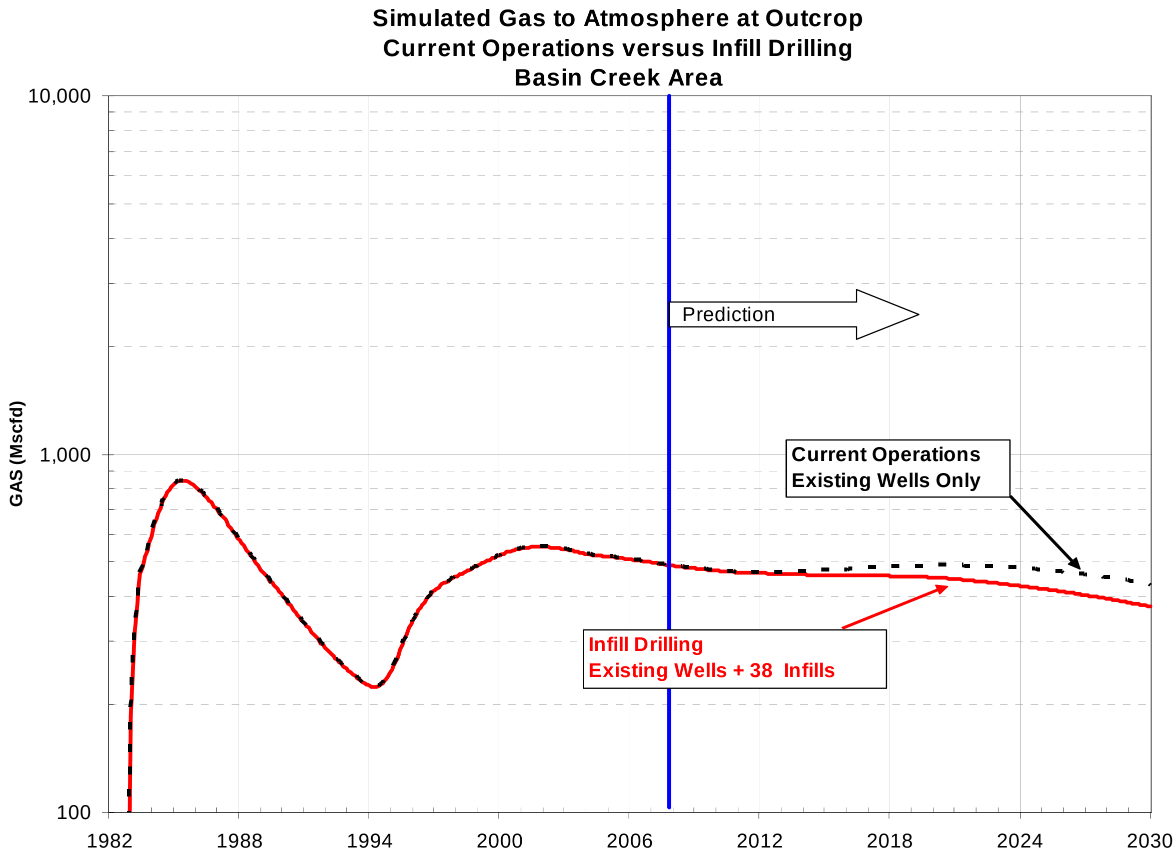

Figure 77 Atmospheric Wells Total Gas Production for the Basin Creek Outcrop Area

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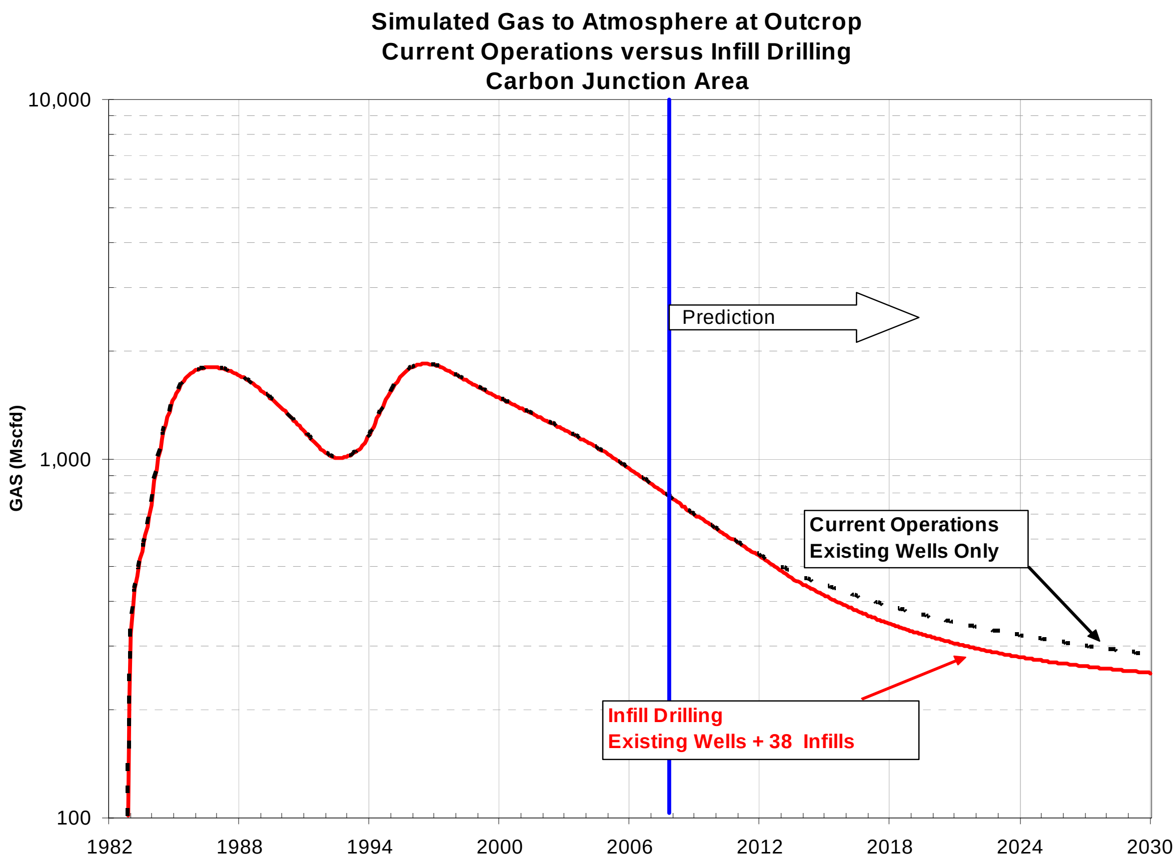

Figure 78 Atmospheric Wells Total Gas Production for the Carbon Junction Area

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TABLES

Table 1 3M CBM MODEL Seepage Rate Predictions, December 2000

Area	Peak Rate MMSCFPD	Peak Rate Year-Existing wells	Peak Rate Year-Existing & Infill Wells
A	5	2011	2007
B	1-1.5	2017-2020	2015
Total	6-6.5		

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Table 2 Comparison of Rock Type Proportions

Rock Type	%	N	Intervals	Min	Mean	Max	Std Dev
UpScale Cells							
SS	8.93	863	320	1.60	5.70	45.40	5.522
Coal	8.48	820	357	1.60	4.90	26.60	4.039
Carb-Shale	29.41	2843	1034	1.60	5.90	68.90	5.535
Shale	53.18	5140	1467	1.60	7.50	79.50	8.092
Geo-Model							
SS	7.79	519128	269123	0.10	3.70	47.50	3.000
Coal	10.92	727888	309811	0.10	4.30	71.70	4.157
Carb-Shale	27.89	1858387	655631	0.10	5.50	98.60	5.469
Shale	53.40	3558815	898408	0.10	7.60	134.90	8.889
Simulation Model							
SS	5.81	5995	5207	3.00	144.00	105.70	9.455
Coal	9.47	9775	7132	3.00	17.70	65.30	9.614
Carb-Shale	23.08	23815	14509	2.90	32.00	223.10	30.890
Shale	61.63	63593	22065	2.80	47.60	409.00	42.040

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Table 3 Forty Realization Statistical Comparison

Fruitland - Geo-Model

	SS	Coal	Carb-Shale	Shale
Mean	7.75425	11.00325	27.60375	53.63925
Standard Error	0.068559246	0.084535979	0.076893772	0.076471368
Median	7.82	10.91	27.62	53.595
Mode	8.19	10.84	27.62	53.4
Standard Deviation	0.433606743	0.534652475	0.486318918	0.4836474
Sample Variance	0.188014808	0.285853269	0.23650609	0.233914808
Kurtosis	-0.56450316	-0.013171618	0.573089749	0.518308445
Skewness	0.137615627	-0.143953015	-0.813573691	0.045281813
Range	1.79	2.36	2.04	2.4
Minimum	6.93	9.71	26.29	52.34
Maximum	8.72	12.07	28.33	54.74
Sum	310.17	440.13	1104.15	2145.57
Count	40	40	40	40
Largest(1)	8.72	12.07	28.33	54.74
Smallest(1)	6.93	9.71	26.29	52.34
Confidence Level(95.0%)	0.138674028	0.170989989	0.155532182	0.154677791
LOG Average	8.93	8.48	29.4	53.18

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Table 4 Forty Realization Coal Proportion Ranking

Coal			
Case Number	Coal Volume %	*Rank*	*Percent*
34	12.07	1	100.00%
28	11.91	2	97.40%
22	11.9	3	94.80%
38	11.83	4	92.30%
10	11.59	5	87.10%
39	11.59	5	87.10%
26	11.56	7	84.60%
23	11.46	8	82.00%
1	11.44	9	79.40%
2	11.42	10	76.90%
18	11.37	11	74.30%
13	11.35	12	69.20%
27	11.35	12	69.20%
12	11.24	14	66.60%
31	11.22	15	64.10%
30	11.16	16	61.50%
9	11.07	17	58.90%
4	11.02	18	56.40%
25	10.94	19	53.80%
8	10.92	20	51.20%
20	10.9	21	48.70%
7	10.87	22	46.10%
19	10.85	23	43.50%
6	10.84	24	38.40%
15	10.84	24	38.40%
24	10.83	26	35.80%
29	10.81	27	30.70%
32	10.81	27	30.70%
5	10.75	29	28.20%
36	10.74	30	25.60%
37	10.73	31	23.00%
17	10.59	32	20.50%
33	10.58	33	17.90%
14	10.51	34	12.80%
16	10.51	34	12.80%
21	10.49	36	10.20%
11	10.34	37	7.60%
3	10.07	38	5.10%
35	9.95	39	2.50%
40	9.71	40	0.00%
Log Average	8.48		

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Table 5 Initial Global Rock Properties

Rock Type	Sand	Coal	Carbonaceous Shale	Shale
Porosity	10%	2%	0.5%	0%
Permeability	0.024 -0.02	80	0.25	NA
Compressibility	6e-6	200 e-6	6e-6	NA
Ash + Moisture	100%	30%	70%	NA

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