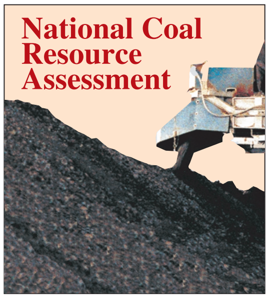

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Chapter L

Coal-Bed Methane Gas-In-Place Resource Estimates Using Sorption Isotherms and Burial History Reconstruction: An Example from the Ferron Sandstone Member of the Mancos Shale, Utah

By Todd A. Dallegge[1] *and* Charles E. Barker[1]

Chapter L *of*

Geologic Assessment of Coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah

Edited by M.A. Kirschbaum, L.N.R. Roberts, *and* L.R.H. Biewick

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Coal-Bed Methane Gas-In-Place Estimates Using Sorption Isotherms and Burial History Reconstruction: An Example from the Ferron Sandstone Member of the Mancos Shale, Utah

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Overview

This chapter describes coal-bed methane resource assessment and production practices to non-specialists. The chapter takes the reader through the basics of coal-bed methane (CBM). A glossary of technical terms follows the References Cited section.

After a brief overview of coal-bed methane, a comparison is made between gas-in-place (GIP) estimates derived from direct gas-content measurement with those estimates made from experimentally determined and modeled theoretical values. This comparison uses the exposed and buried coal-bearing Ferron Sandstone Member of the Mancos Shale. The Ferron coals offer a unique field laboratory where analysis of exposed coals are used to estimate GIP and model CBM productivity trends in subsurface coals.

Figure 2. Photograph of coal-bearing Ferron Sandstone Member of the Mancos Shale (foreground) and the Marysvale volcanic field (background).

What is Coal-Bed Methane?

Coal-bed methane (CBM) is an economic source of pipeline-quality methane that is generated and stored in coal beds. It is a widely occurring, exploitable resource that can be easily recovered and used near the well or where any gas-pipeline infrastructure currently exists.

Importance of Coal-Bed Methane Production

Coal-bed methane production started as a way to keep coal mining safe from explosions. Not only does it provide the same service now, it also decreases emissions of greenhouse gasses from mines, decreases air pollution because it is a clean-burning fuel, decreases the need for "conventional" fossil fuels, and further utilizes the vast coal resources that are already known. CBM potential could double our natural gas reserves in the United States (Rogers, 1994). Figure 3 shows the major areas and amounts of U.S. coal-bed methane resources as of 1996. CBM is of particular interest to regions without a pipeline infrastructure because the gas is usable at the wellhead or through a local pipeline for domestic or industrial use.

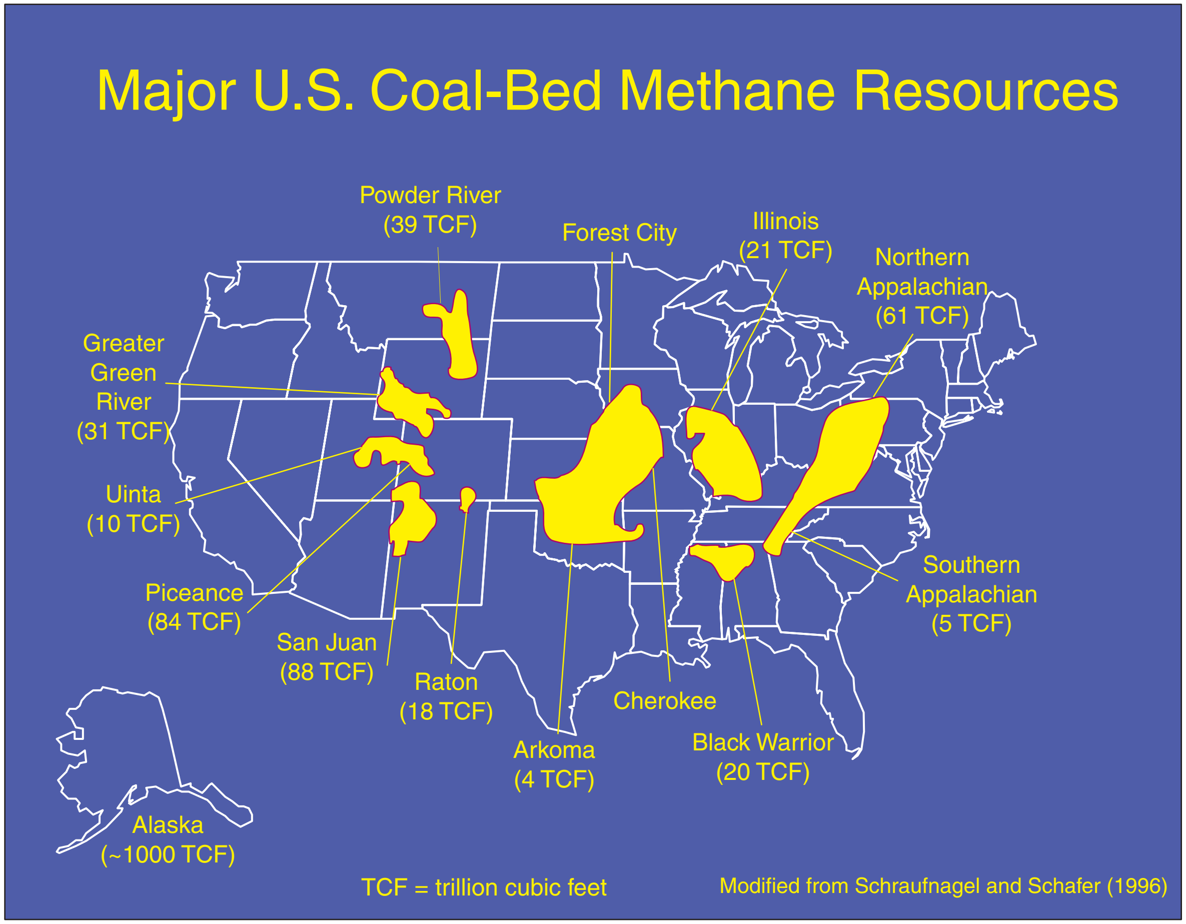


Figure 3. Map showing major U.S. coal-bed methane resources.

How Much Coal-Bed Methane is Available?

- Prior to 1982, there was little coal-bed methane production in the United States.
- Between 1983 and 1993, industry drilled ~ 6,600 coal-bed methane wells (Schraufnagel and Schafer, 1996).
- By 1994, annual production had grown to 858 BCF (billion cubic feet) (Schraufnagel and Schafer, 1996).
- In 1995, coal-bed gas supplied 5 percent of U.S. natural gas production. CBM is thought to be an important potential resource available anywhere coal is found worldwide.
- CBM for the top 20 coal-bearing countries is estimated at 51×10^{12} m^3 (1,800 TCF—trillion cubic feet) (Kuuskraa and others, 1992).
- Figure 4 shows the estimated future availability of U.S. coal-bed methane.

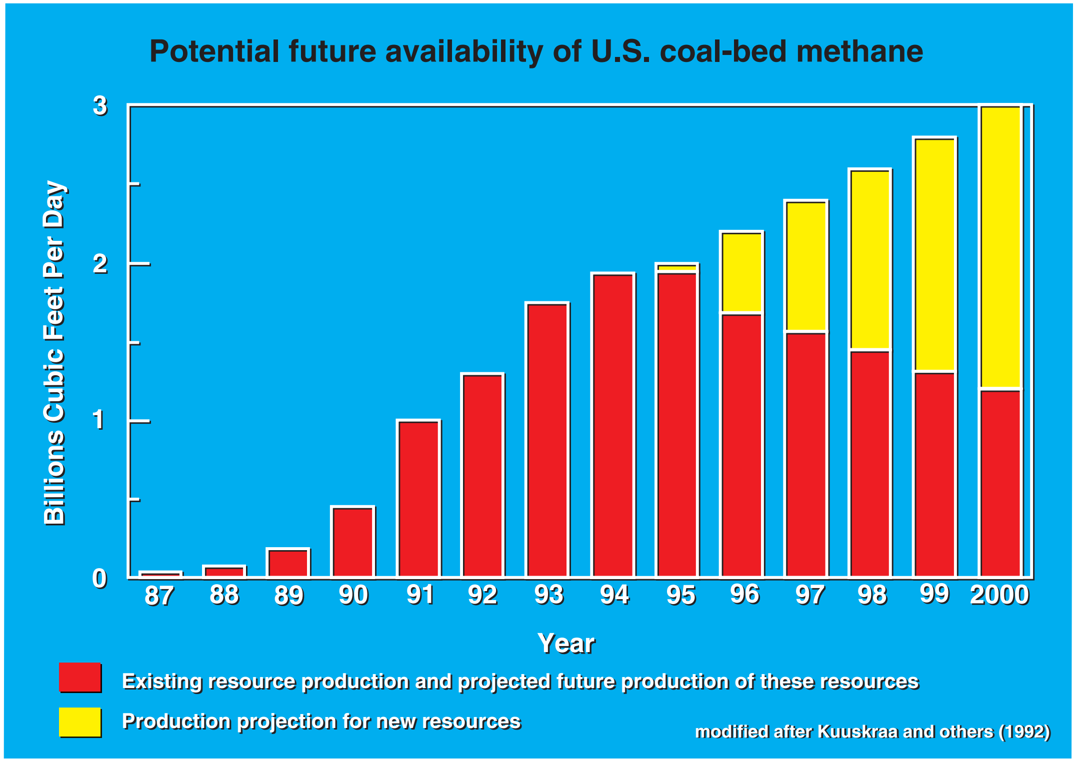


Figure 4. Graph showing potential future availability of U.S. coal-bed methane.

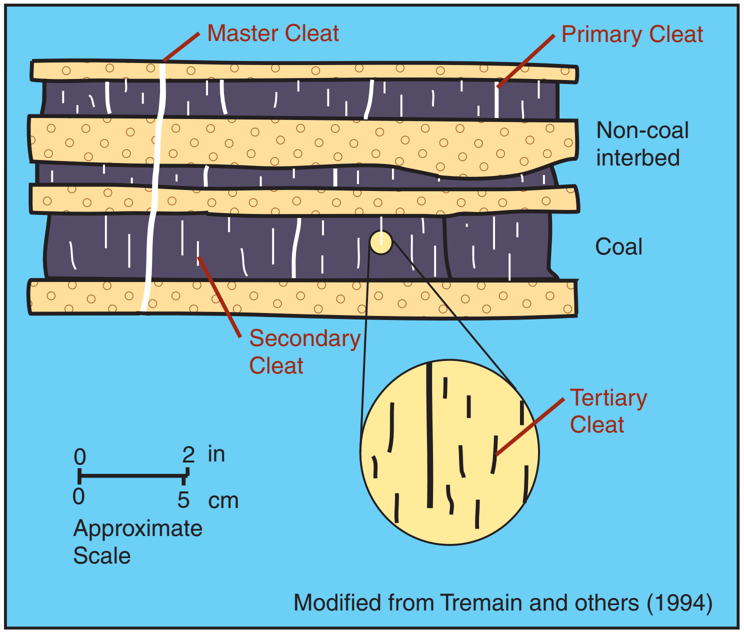
How Do Coal Beds Generate and Store Methane?

Coal acts as both source rock and reservoir rock for methane.

Methane is generated by microbial (biogenic) or thermal (thermogenic) processes shortly after burial and throughout the diagenetic cycle resulting from further burial.

Much of this gas is physically sorbed on coal surfaces in areas with coal microporosity.

One gram of coal can contain as much surface area as several football fields and therefore is capable of sorbing large quantities of methane. One short ton of coal can produce ~1,300 m^3 of methane.



Modified from Tremain and others (1994)

Figure 5. Coal cleat terminology.

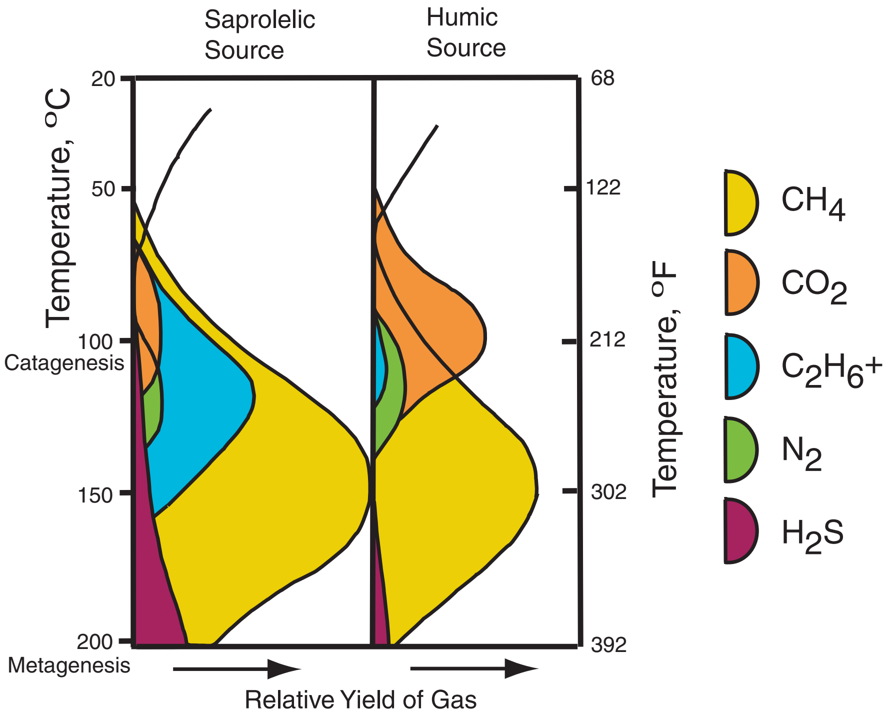
Hydraulic pressure, rather than a pressure seal or closed structure (common for conventional oil and gas fields), is the major trapping force for CBM.

Coal is extremely porous (openings), but has low permeability (connected openings).

Most coals contain methane, but much of it cannot be economically produced without the presence of natural fractures (cleats) to connect the pores.

Cleats allow the desorbed gas to flow to the well.

CH_4 (methane) and CO_2 (carbon dioxide) are the major components of CBM.



From Hunt (1996)

Figure 6. Gas generation from sapropelic and humic coals.

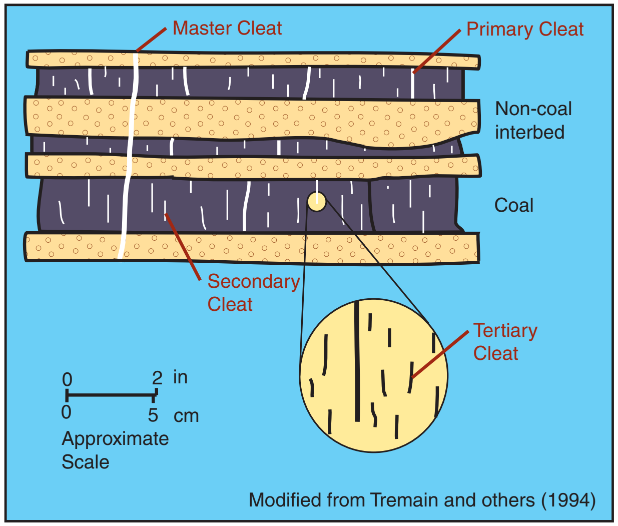
Details About Coal Cleat

Cleat develops in a coal from devolatilization occurring during coalification, as well as during regional and local structural events.

Cleat patterns are placed in a hierarchy of sizes. Secondary and tertiary cleats are the small-scale microfractures that develop within the coal seam. Primary cleat develops across coal layers and provide connections with non-coal interbeds. Master cleat crosses both coals and non-coal interbeds.

These cleat patterns are crucial for gas production because they allow for the release of sorbed gas within coal beds and migration to the well.

Cleat can be destroyed by further burial in a process called healing or filled by secondary mineralization.



Modified from Tremain and others (1994)

Figure 7. Photograph of outcrop showing pyrite filling cleat fracture.

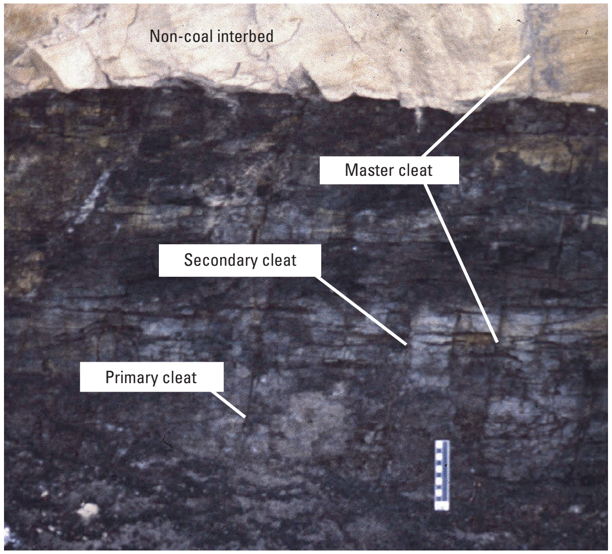


Figure 8. Photograph of cleat in the A coal horizon at the I-70 roadcut south of Emery, Utah.

Production of Coal-Bed Methane

Methane sorbed within coal beds is regulated by the hydrodynamic pressure gradient.

Methane is maintained within the coal bed as long as the water table remains above the gas-saturated coal. If the water table is lowered by basin or climatic changes, then methane stored within the coal is reduced by release to the atmosphere.

Coal-bed gas content must have reached near-saturation either by biogenic or thermogenic gas-generation processes to be economically viable.

Cleats must be present to allow for connectivity between sorption sites. If the coal-bed horizons are buried deeply (~2 or more km), cleats are closed because of overburden pressure acting on the structurally weak coal bed.

To initiate gas production, water must be pumped out of the saturated coal zone. Dewatering reduces the cleat pressure allowing gas to desorb from the coal matrix and diffuse to the cleat.

Some wells may not be economical if too much water has to be pumped. Pumping requires energy and the net gain from burning the gas may be too low to be profitable. Some coal beds may never be dewatered, depending on the hydrology.

If CBM fields are associated with a conventional gas trap, like the Drunkards Wash area in Price, Utah (Burns and Lamarre, 1997), gas flows freely upon completion of the well without the need for dewatering.

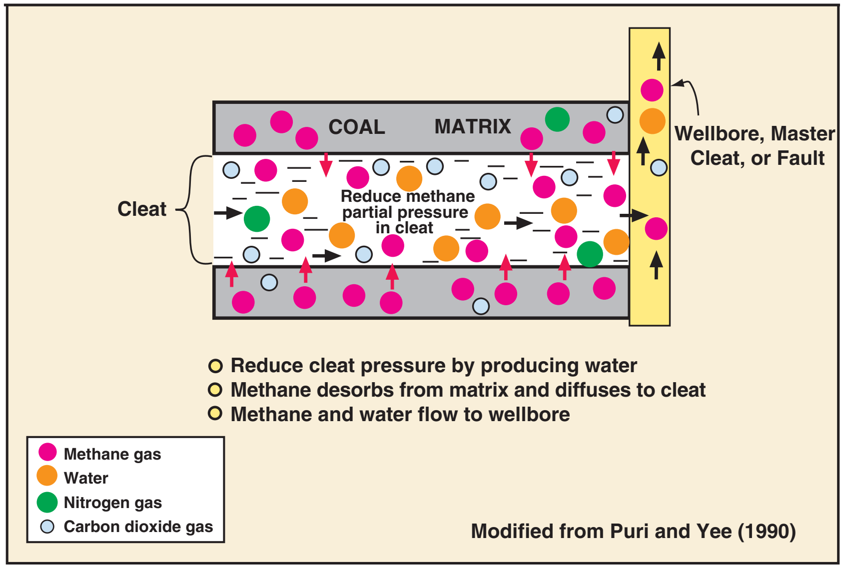
CBM, unlike conventional oil and gas production, usually shows an increase in the amount of production at first, then steadily declines. See figure 10.

Normal gas production is pressure driven and shows a decline in production from the initial tapping of the reservoir.

In the case of CBM, gas is sorbed within the microporosity of the coal matrix. As the partial pressure within the coal bed is reduced, methane is produced as the gas desorbs the microporosity of the matrix and flows through the cleat to the well.

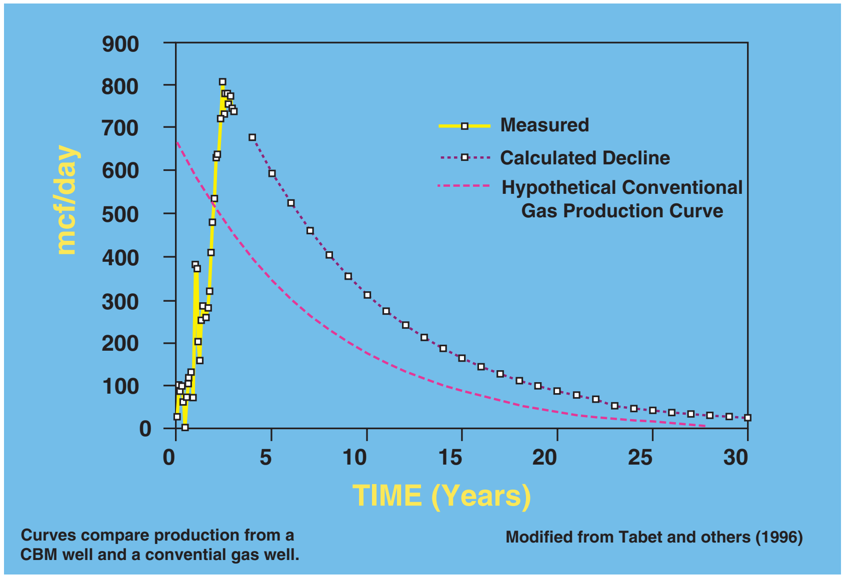
As a coal is dewatered, the cleat system progressively opens farther and farther away from the well. As this process continues, gas flow increases from the expanding volume of dewatered coal. Water production decreases with time, which makes gas production from the well more economical.

In 1997, production at Drunkards Wash was 43.7 MMCF/d (million cubic feet per day—1.245×10^6 m^3/d) of gas from 89 wells (Burns and Lamarre, 1997). Methane concentrations are from 95.8 percent to 98.3 percent (Burns and Lamarre, 1997). CO$_2$ makes up the other fraction.



Modified from Puri and Yee (1990)

Figure 9. Coal-bed methane release process.



Curves compare production from a CBM well and a convential gas well.

Modified from Tabet and others (1996)

Figure 10. Measured, calculated, and hypothetical gas production curves for River Gas Corp. 25-7-6 well.

Introduction to Ferron Sandstone CBM

The U.S. Geological Survey (USGS) has been assessing coal-mass resources in the United States. This coal assessment data could also be used to make an assessment of coal-bed methane resources in the United States. To do this, a method is needed to take coal mass resource data and convert it, using estimates of gas content per unit mass, to gas-in-place (GIP) estimates. Estimates of gas content per unit mass can be made from (1) direct measurements of the gas content of fresh samples, (2) values determined experimentally, and (3) values derived from theoretical models. This study compares these three different methods and the resulting GIP estimates.

The comparison is made using data from coals of the Ferron Sandstone Member of the Mancos Shale. Near Emery, Utah, the upper Ferron coals are exposed in a 20- by 50-km outcrop band that gives a three-dimensional exposure of these deposits. The lower Ferron coals in the northern portion of the coal production trend near Price, Utah, are still buried. A portion of this production trend, located within the Drunkards Wash area, has been intensively developed for CBM, and a nearly complete grid of data is available to calculate the coal mass in-place. Further, many of the coal cores were measured directly for gas content. This situation offers an optimal setting to test various methods of estimating GIP resources.

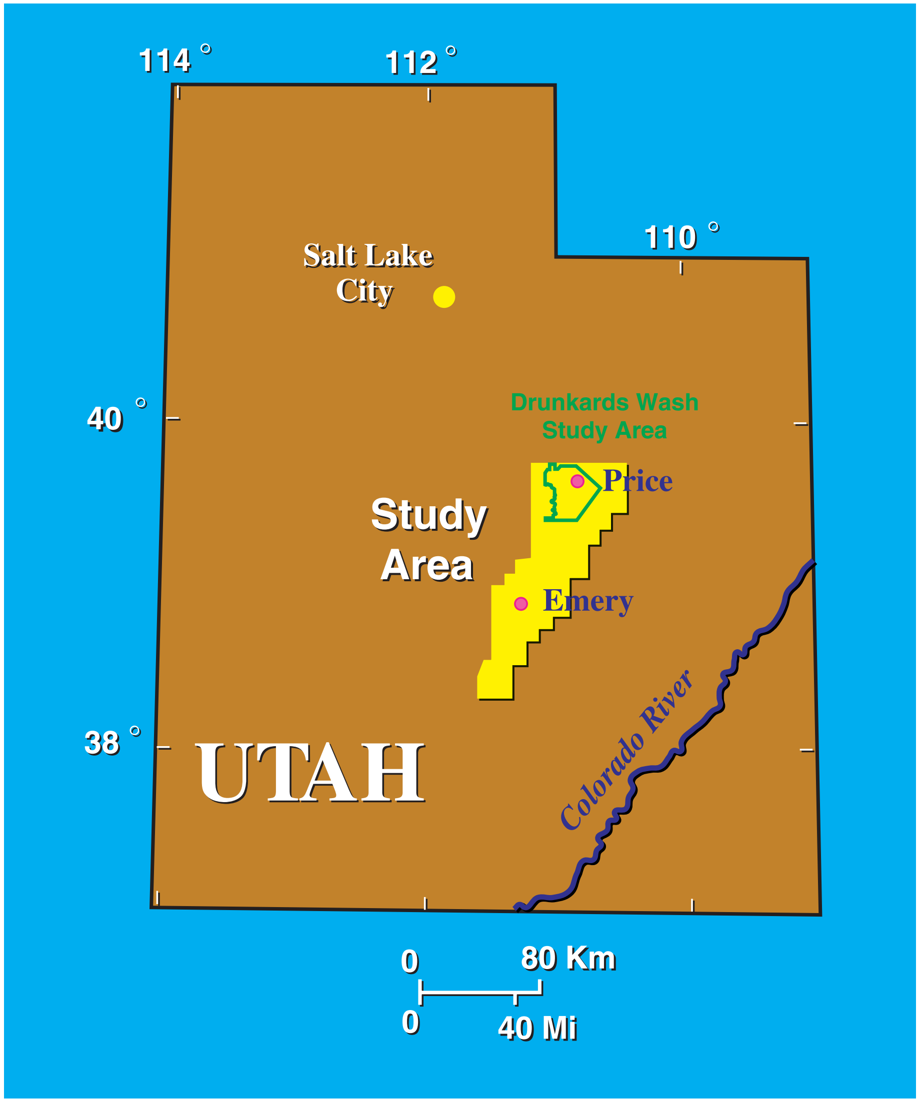
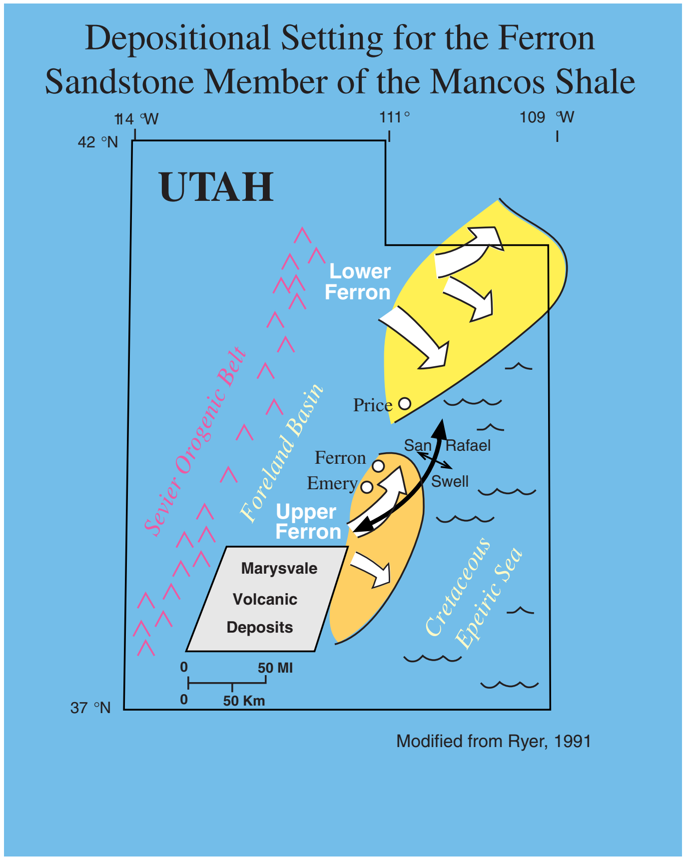


Figure 11. Map showing location of Drunkards Wash study area.

Regional Geology

The Upper Cretaceous (~ 90 million years old) sediments of the Ferron Sandstone Member of the Mancos Shale were deposited in the shallow Mancos sea.

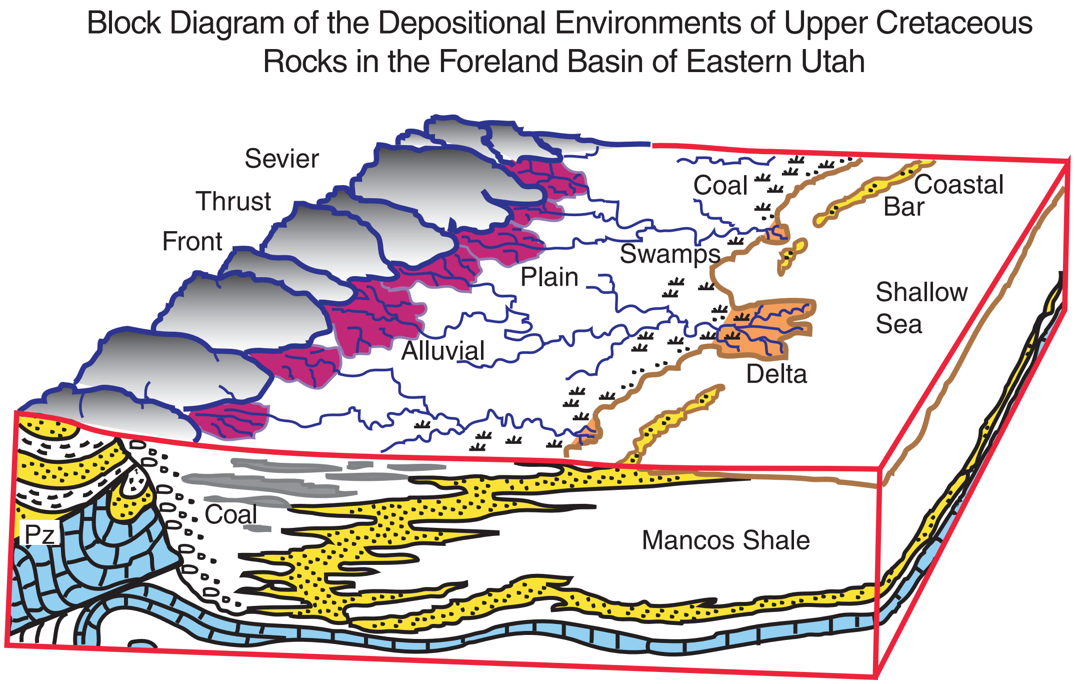
The Ferron Sandstone Member was deposited in a series of deltas along the western edge of a basin that formed when thrust faulting during the Sevier orogeny thickened the crust and caused the crustal area ahead of the faulting to sag.



Depositional Setting for the Ferron Sandstone Member of the Mancos Shale

Modified from Ryer, 1991

Figure 12. Depositional setting for Ferron Sandstone Member of the Mancos Shale.



Block Diagram of the Depositional Environments of Upper Cretaceous Rocks in the Foreland Basin of Eastern Utah

Modified from Hintze (1988)

Figure 13. Block diagram showing depositional environments of Upper Cretaceous rocks in the foreland basin of eastern Utah.

Structural Setting in the Western United States During the Late Cretaceous

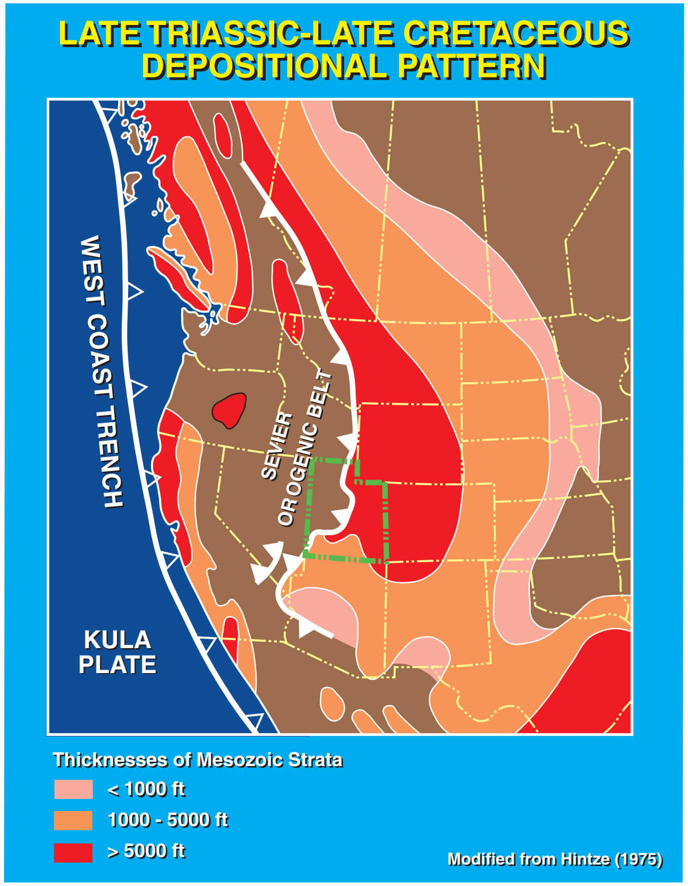
The Sevier thrust belt system formed a foreland basin in central Utah during Turonian time (~90 Ma—~90 million years ago).

Sediments from the Sevier Highlands to the west were shed to the east and formed many clastic wedges that intertongued with marine intercontinental Mancos seaway.

As sea level rose and fell and the Sevier thrust front advanced, transgressive and regressive cycles are represented by clastic and carbonate deposition that filled the continuously subsiding foreland basin.

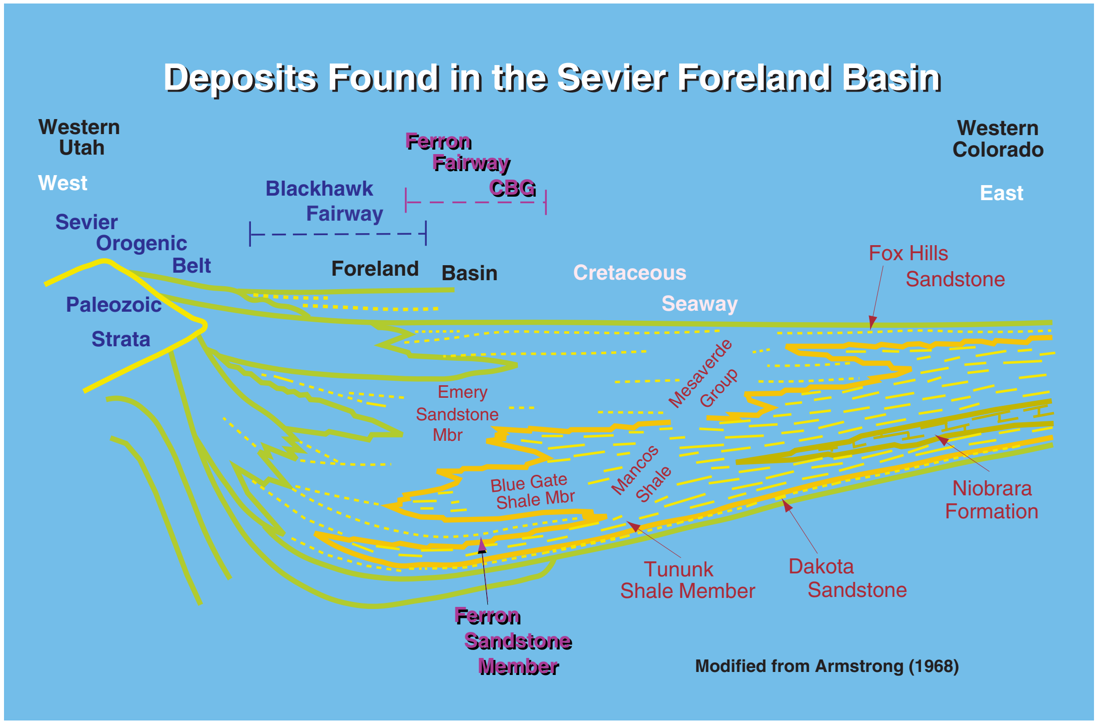
The Ferron Sandstone Member of the Mancos Shale represents one episode of deltaic sedimentation into this foreland basin.

The Ferron Sandstone Member of the Mancos Shale was deposited in the Vernal and Last Chance deltas.



Modified from Hintze (1975)

Figure 14. Late Triassic–Late Cretaceous depositional pattern in the Western United States.



Modified from Armstrong (1968)

Figure 15. Diagrammatic cross section of the Sevier foreland basin.

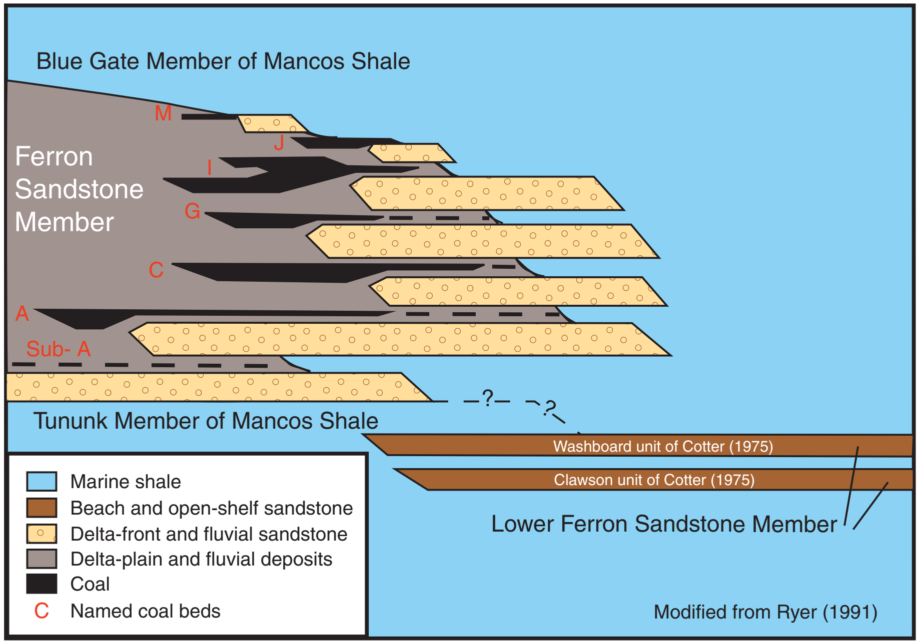
Depositional Environment for the Ferron Sandstone Member

These deltaic environments produced substantial coal deposits.

The deposits created by the Last Chance delta can be observed in surface outcrop exposures. The deposits of the Vernal delta are only found in the subsurface.

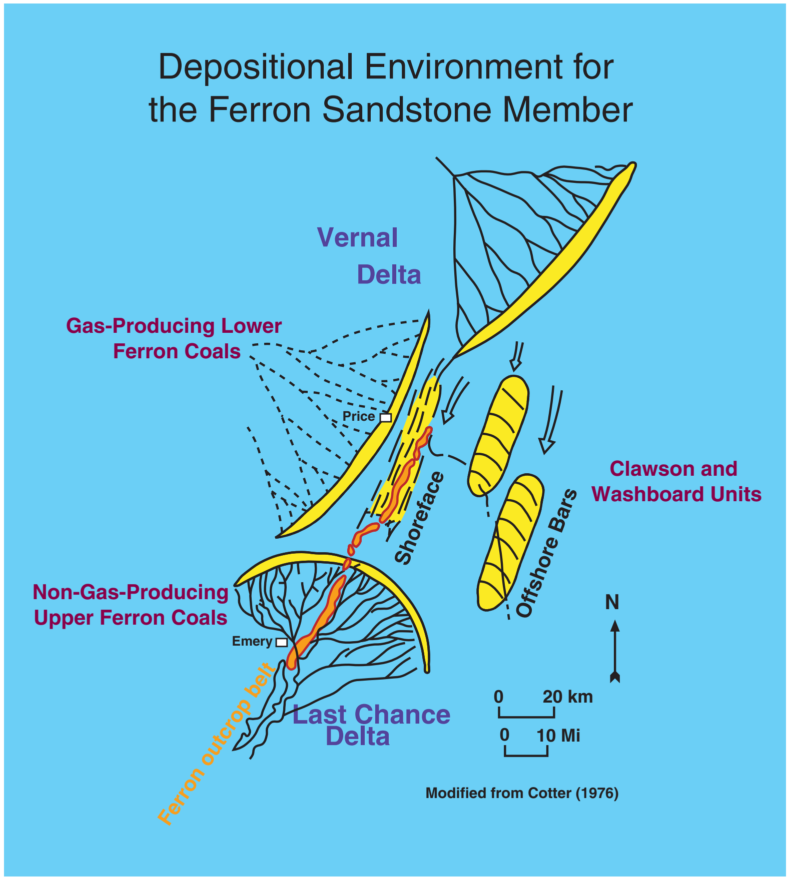
The deposits from the Ferron Sandstone Member show a series of stacked, small-scale, transgressive-regressive cycles that are defined in outcrop by cliff-forming delta-front sandstones (Ryer, 1991).

Drunkards Wash gas field, located west of Price, Utah, is currently being exploited for coal-bed methane production.



Modified from Ryer (1991)

Figure 16. Generalized cross section showing Ferron Sandstone Member stratigraphy.



Modified from Cotter (1976)

Figure 17. Diagram showing depositional environment for Ferron Sandstone Member of the Mancos Shale.

Formation of Ferron Coal

The Ferron Sandstone Member contains as many as 14 coal horizons.

These coals formed in swampy areas behind the delta-front of the prograding shoreline. They generally mark the onset of each transgressive event (Garrison and others, 1997) because peat preservation is enhanced under these conditions.

Peat forms when plant debris is preserved by a rise in the water table caused by a relative rise in sea level that occurs during a transgressive event. This preserved peat is transformed to coal by thermogenic and biogenic processes resulting from burial.

A combination of the rapidly subsiding foreland basin and sea-level changes provided accommodation space for the accumulation of relatively thick coal beds.

Many of these coal beds are laterally extensive or can be correlated to carbonaceous mudstones that were deposited on the alluvial plain (Garrison and others, 1997).

It is possible to study the upper Ferron coals across an outcrop band that is ~20 km wide and ~50 km long.

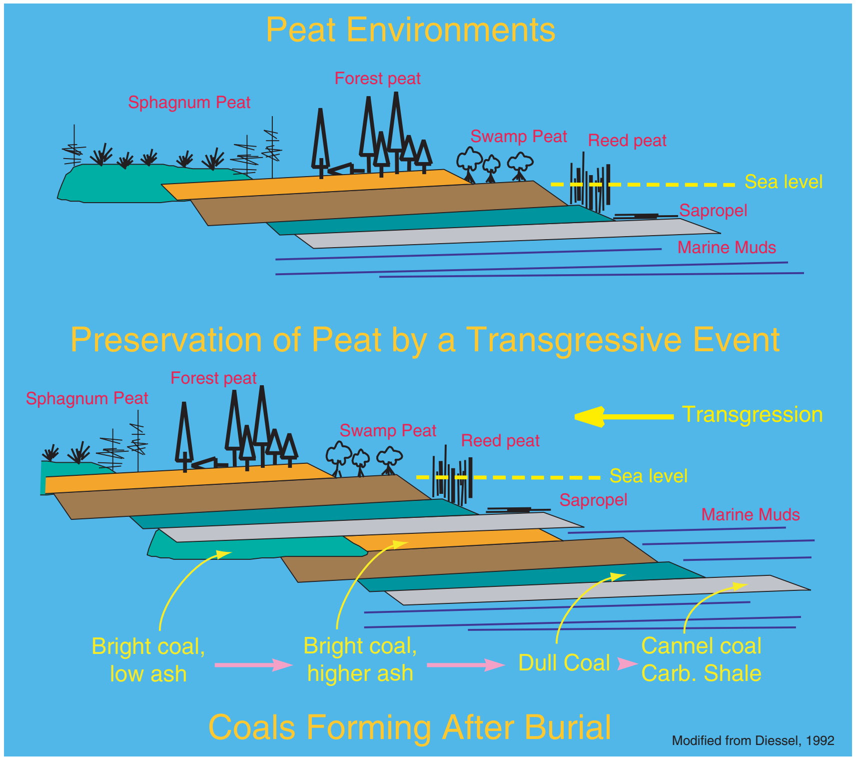


Figure 18. Diagram showing peat environments and preservation of peat by a transgressive event.

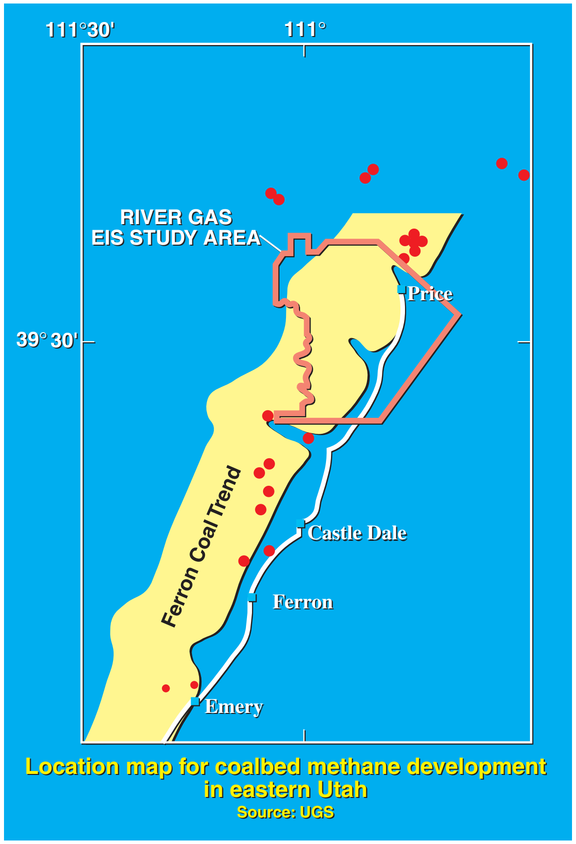
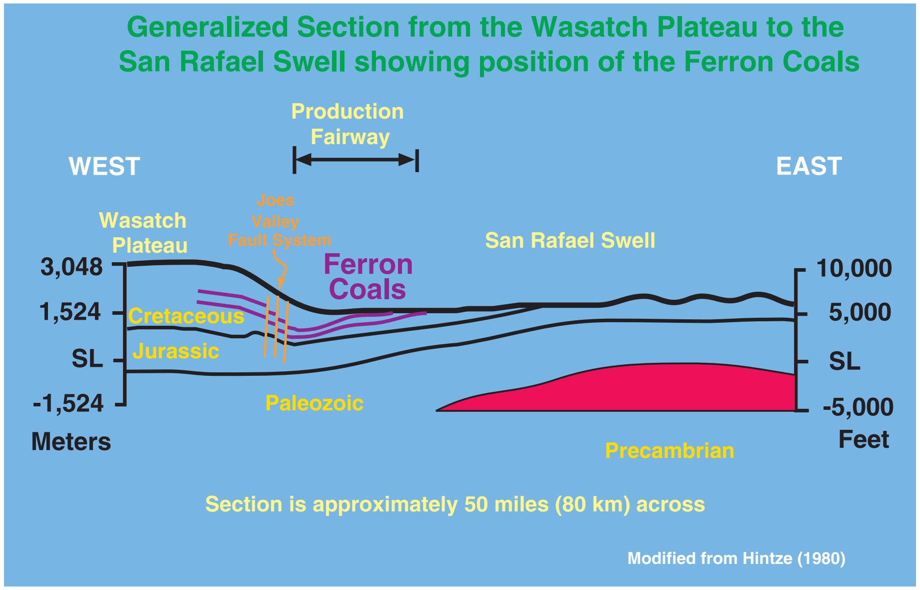


Figure 19. Location map for coal-bed methane development in eastern Utah.

Ferron Coals

Near Emery, Utah, Ferron coals are exposed on the western flank of the San Rafael Swell. Along the eastern front of the Wasatch Plateau near Emery, Utah, the Ferron coals are deeply buried and form a production fairway (fig. 20). To the north, near Price, Utah, Ferron coals are only found in the subsurface.

Average depth to the Ferron coals in Drunkards Wash, west of Price, is 732 m (2,400 ft) with an average net-coal thickness of 7.3 m (24 ft) (Burns and Lamarre, 1997).



Modified from Hintze (1980)

Figure 20. Generalized cross section from the Wasatch Plateau to the San Rafael Swell showing position of Ferron coals.

From Tabet and others, 1995

Figure 21. Surface outcrop pattern of the Ferron Sandstone Member.

Characteristics of Lower Ferron Coal at Drunkards Wash

At Drunkards Wash, the lower Ferron coals have a mean random vitrinite reflectance value (R_o) of 0.7 percent. This classifies them as high-volatile B bituminous coal (Burns and Lamarre, 1997).

Proximate analyses of the coals indicated the following averages; ash yield 14.6 weight percent (basis not reported), volatile matter content 42 weight percent (dry, ash-free basis [d.a.f.]), fixed carbon content 48.6 weight percent (basis not reported) (Burns and Lamarre, 1997).

Permeability in Ferron coals is estimated between 5 and 20 millidarcies (mD) (Burns and Lamarre, 1997).

Characteristics of Upper Ferron Coal at Emery

Near Emery, Utah, the upper Ferron coals generally have a lower rank, R_o values of 0.4 percent to 0.6 percent, than the lower Ferron coals at Drunkards Wash.

Our proximate analyses indicate the following averages: ash yield 35.0 weight percent (dry basis), volatile matter content 48.7 weight percent (d.a.f.), fixed carbon content 51.3 weight percent (d.a.f.).

Burial and gas-generation models with identical heat-flow histories indicate that the upper Ferron coals have generated about 0.1 cm^3 gas/g carbon, whereas the lower Ferron coals have generated about 8 cm^3 gas/g coal (256 standard cubic feet per short ton [scf/short t]).

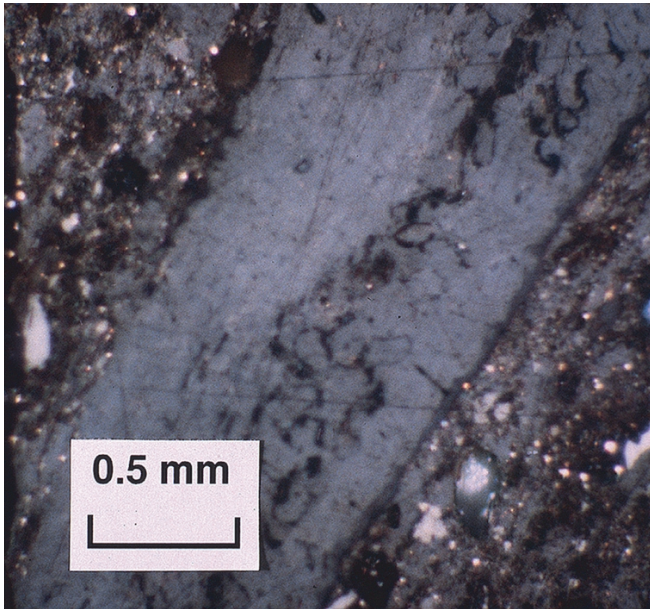
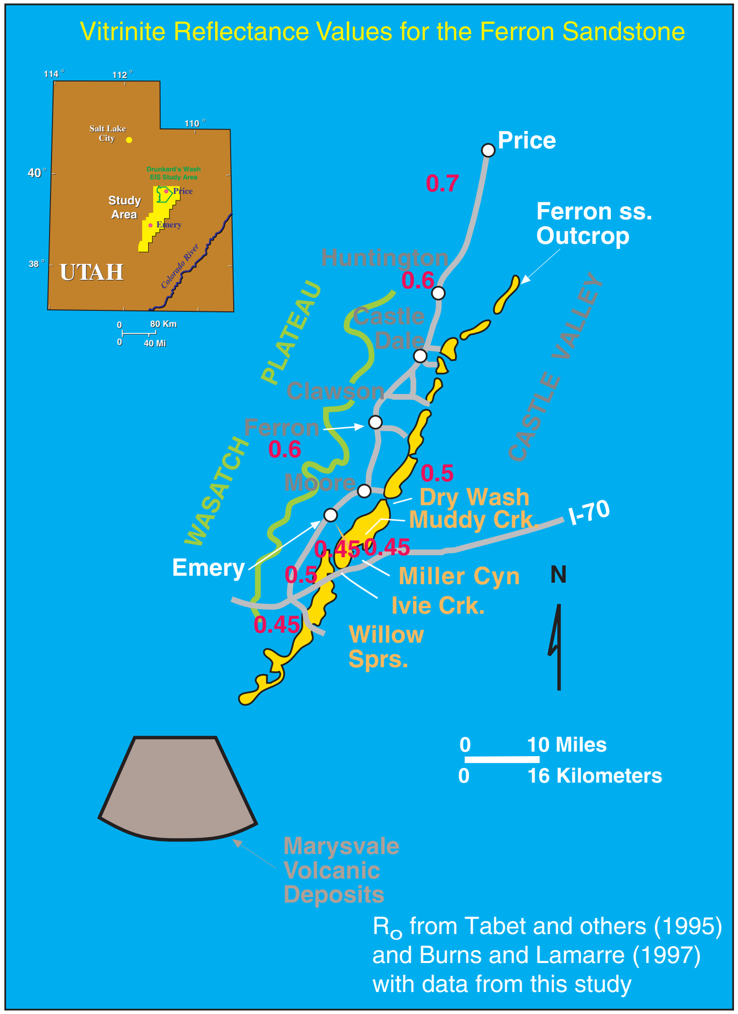


Figure 22. Photomicrograph of an upper Ferron coal showing vitrinite, the major gas-sorbing component of a coal.



R_o from Tabet and others (1995) and Burns and Lamarre (1997) with data from this study

Figure 23. Map showing vitrinite reflectance values for the Ferron Sandstone Member.

Similarities of Upper and Lower Ferron Coals

The upper and lower Ferron coals were deposited in a similar geologic setting. Consequently, the coals had similar starting compositions, but changes occurred because of burial history (rank) and grade (syndepositional mineral matter).

The coals near Emery have a higher ash content (lower grade) and lower rank indicated by higher moisture and generally lower vitrinite reflectance values. This would account for much of the difference in the chemical properties between lower and upper Ferron coals.

Because the lower and upper Ferron coals are similar, we used average-gas-content estimates from different methods and applied them to both lower and upper Ferron coals. These gas-content estimates were used with coal-mass estimates to compute GIP for the lower Ferron coals at the Drunkards Wash area.

Table 1. Average analyses of Ferron coals.

[ar, as-received; d.a.f., dry, ash-free; mmmf, moist, mineral-matter-free. Modified from Doelling and Smith (1982)]

Analysis	Location		Basis
	Price	Emery	
Moisture (wt. %)	5.6	14.6	ar
Volatile matter (wt. %)	38.9	33.5	d.a.f.
Fixed carbon (wt. %)	46.1	38.5	d.a.f.
Ash (wt. %)	7.5	11.4	ar
Sulfur (wt. %)	0.82	1.78	d.a.f.
Btu/lb	12,322	9,453	mmmf
R_o (%)	0.5 to 0.7	0.4 to 0.6	mean random

Procedures for Estimating Gas-In-Place

Direct Method

Direct measurements of gas content of the lower Ferron coal at the Drunkards Wash area have been reported by Burns and Lamarre (1997). The other parameters necessary for this method are proximate analyses and total coal mass. We produced an estimate of the total coal mass from coal-thickness maps of the Drunkards Wash area. The GIP estimate for the Drunkards Wash area was calculated by multiplying the desorption data (gas content) by the total coal mass of the lower Ferron coals.

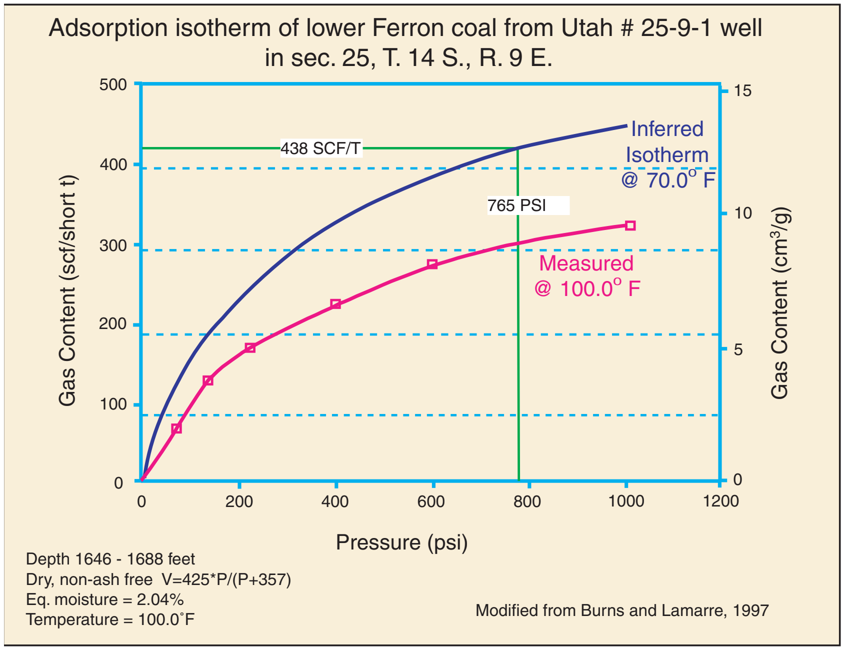
Direct Measurements of Coal-Bed Methane Content

The direct method for measuring CBM content involves coring the coal, immediately placing the coal in a gas-tight container, and then measuring the gas evolved over time. The gas evolved, when corrected for gas lost after core drilling and before placement in canister, is a direct measurement of gas content.

Figure 24 shows the adsorption isotherm for coals at Drunkards Wash EIS area. The red curve indicates the maximum amount of gas (at saturation) that the coal can hold at a given pressure. These measurements were made at equilibrium moisture conditions and at 38°C (100°F), the apparent reservoir temperature. The curve predicts a maximum gas content for the lower Ferron coals of ~9.4 cm^3/g (~300 scf/short t) for a pressure of 5,275 kPa (765 psi).

The average total gas content from desorption tests at Drunkards Wash is 13.67 m^3/g (438 scf/short t). The measured experimental isotherm (red curve) at the reservoir temperature (38°C, 765 psi) should intersect at the measured desorption content. Burns and Lamarre (1997) interpreted this condition as oversaturation of the coals. CBM gas content of coals is not considered to reach oversaturated conditions. We believe the discrepancy is due to conducting the experimental sorption isotherm tests at an excessively high temperature, thus depressing the isotherm.

The adsorption isotherm generated at a reservoir temperature of 21°C (70°F) would yield a curve (blue line) near that indicated by the measured gas content of the lower Ferron coals at the Drunkards Wash EIS area.


Adsorption isotherm of lower Ferron coal from Utah # 25-9-1 well in sec. 25, T. 14 S., R. 9 E.

Depth 1646 - 1688 feet
Dry, non-ash free $V=425*P/(P+357)$
Eq. moisture = 2.04%
Temperature = 100.0°F
Modified from Burns and Lamarre, 1997

Figure 24. Adsorption isotherm of lower Ferron coal from Utah 25-9-1 well.

Methods for Determining Sorption Isotherms

Sorption iostherms indicate the maximum volume of methane that a coal can store under equilibrium conditions at a given pressure and temperature.

The direct method of determining sorption isotherms involves drilling and cutting core that is immediately placed in canisters followed by measurements of the volume of gas evolved from the coal over time.

The indirect method takes advantage of core or cuttings that have been stored and does not require fresh core, thus making this method more economical.

Sorption isotherms are experimentally measured using a powdered coal sample whose saturated methane content at a single temperature is measured at about six pressure points (Mavor and others, 1990).

Moisture content in a coal decreases the sorption capacity of a coal. Because coal loses moisture at a variable rate subsequent to removal from the bore hole, a standard moisture content is used when measuring sorption isotherms.

Sorption isotherm data are useful in predicting theoretical gas-production characteristics. For example, desorption of gas will not occur at pressures above the critical desorption pressure in a coal that is undersaturated with gas. The reservoir pressure must be reduced by pumping and dewatering the coal until the critical sorption pressure is reached. In a case where the coal is saturated with gas, the reservoir pressure is equal to the critical desorption pressure, and dewatering causes immediate onset of gas production.

Experimental Method

We used adsorption isotherm analyses of coal-seam samples from the upper Ferron coals near Emery, Utah, to estimate the gas content of the coals and applied this value to the coal mass estimate of the lower Ferron coals within the Drunkards Wash EIS area. The experimental maximum gas content was derived from adsorption isotherm data by computing the gas content at present reservoir temperature and pressure conditions. Our experimental GIP estimate for the Drunkards Wash EIS area was calculated by multiplying the estimated gas content of the upper Ferron coals by the total coal mass (from the direct method above) of the lower Ferron coals.

Experimental Method of Estimating CBM Content

Six channel samples from various exposures of the upper Ferron coals were used to estimate the experimental saturated gas content from sorption isotherm analyses.

The six samples were analyzed for adsorption capacity at 25°C (77°F) over a range of pressures from 0 to 12 MPa (0 to 1,740 psi). Adsorption isotherms were plotted from these experimental runs.

A maximum burial depth of 730 m (2,395 ft) was determined from vitrinite reflectance values and burial history analysis. A hydrostatic gradient of 10.4 kPa/m (0.46 psi/ft) was used to calculate a pressure of 7.6 MPa (1,100 psi) at maximum burial depth.

The maximum burial pressure of 7.6 MPa was used in each adsorption isotherm plot to determine the experimental gas content at saturation (cm^3/g [scf/short t]) for that sample.

Proximate analyses of the six samples determined ash and moisture content.

The ash + moisture fraction was plotted against the adsorbed values (at 7.6 MPa) to determine the average pure coal (at 0 percent ash + moisture). The gas content of the pure coal is 5 cm^3/g (160 scf/short t).

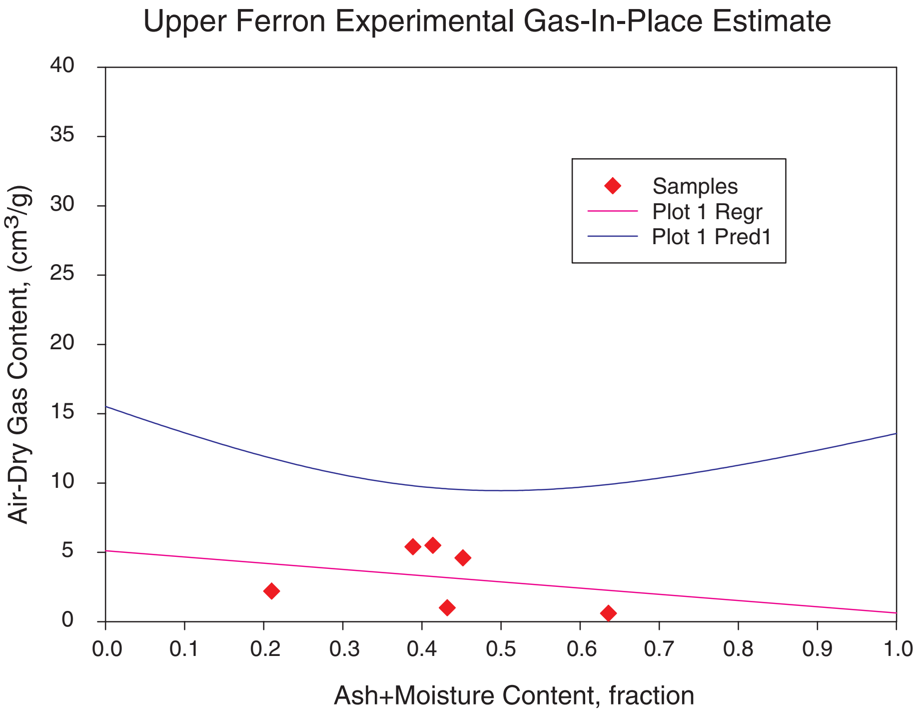


Figure 25. Diagram of upper Ferron experimental gas-in-place estimate.

Theoretical Method

Burial history and kinetic models of gas generation (using BasinMod 5.0 software) were used to reconstruct the generated gas volume. For this method we assume complete sorption of generated gas by the source coal. Our theoretical GIP estimate for the Drunkards Wash area was calculated by multiplying the computed theoretical gas content for the lower Ferron coal by the total coal mass (from the direct method above).

Theoretical Method of Estimating CBM Content: Burial History Reconstruction

The upper Ferron coals to the south and west of Emery contain little CBM even though they are buried at depths comparable to those of the gas-productive lower Ferron coals at Drunkards Wash. Because hydraulic pressure, roughly related to depth of burial, is a primary trapping agent of CBM, the lack of CBM suggests significant differences in gas generation and (or) retention. The upper Ferron coals, relative to lower Ferron coals, generally have a lower mean random vitrinite reflectance, about 0.4 percent to 0.6 percent versus 0.5 to 0.7 percent. This suggests a difference in burial heating. Burial and gas-generation models (figs. 26 and 27) based on two stratigraphic sections, one near Price and one near Emery, with identical heat-flow histories, indicate that the upper Ferron coals have generated less than 1 cm^3 gas/g carbon whereas the lower Ferron coals generated about 6 cm^3 gas/g carbon.

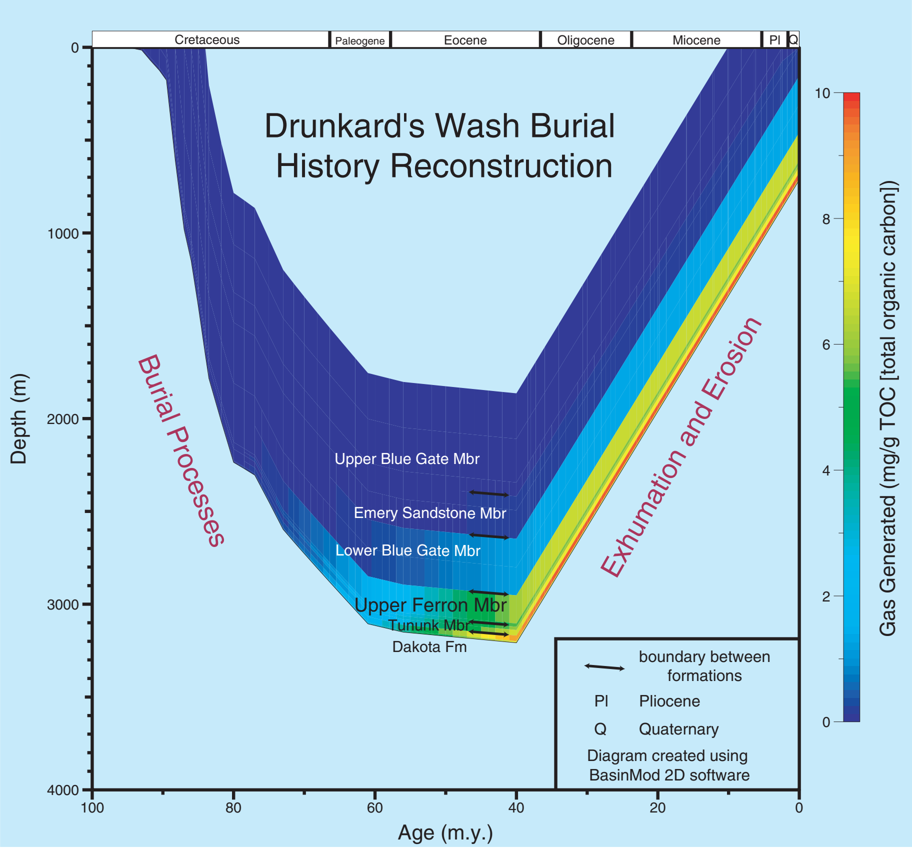


Figure 26. Drunkards Wash burial history reconstruction.

Theoretical Method of Estimating CBM Content: Burial History Reconstruction—*Continued*

Ultimate analyses of lower Ferron coals indicate they contain about 80 weight percent carbon d.a.f. The inferred isotherm suggests that these coals, at saturation, hold about 12 cm^3/g (384 scf/short t) gas at the present reservoir pressure. Adjusting this inferred isotherm value from a d.a.f. coal to a carbon basis indicates the coals can hold as much as 9.6 cm^3/g carbon. Sorption analysis and gas-generation models of the lower Ferron coals show that they can hold all of the gas generated. We use 6 cm^3 gas/g carbon (equivalent to 8 cm^3/g coal) as the theoretical gas content value (from Drunkards Wash burial history reconstruction on previous page) and assume all the indicated generated gas has remained in the coal.

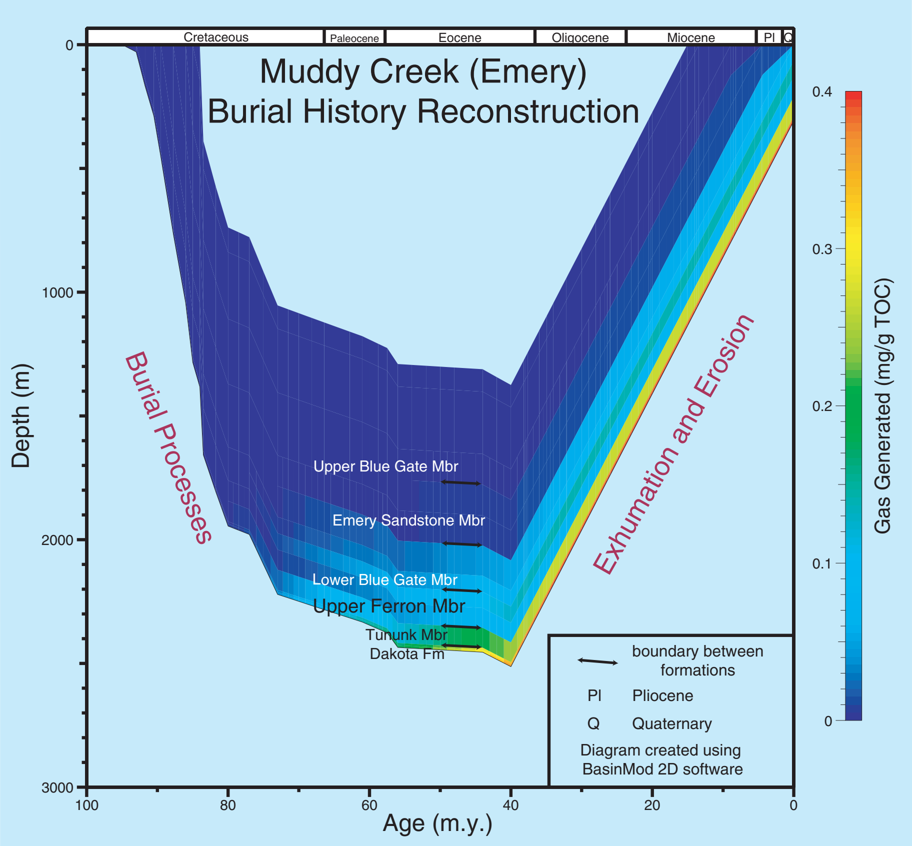


Figure 27. Muddy Creek (Emery) burial history reconstruction.

Biogenic Gas—An Unknown Quantity

Whereas thermal and burial history analysis provides a quantitative measure of thermogenic gas generated for the coals and associated marine rocks that appear to have petroleum source-rock potential, biogenic gas is much more difficult to model. The quantity of biogenic gas produced in a basin is related to how fast the rocks were buried and reached temperatures beyond which microbial activity was impossible, and when the rocks were exhumed to a level where microbial activity resumed. The level of microbial activity within these thermal constraints is controlled by the species present in the subsurface, nutrient supply, living conditions, and waste-product removal. Microbial activity starts to decrease near 50°C (Clayton, 1998) and ceases at about 100°C when the rocks become sterilized. These temperature constraints are easily evaluated from the thermochronology data derived from the burial model. In the northern portion of the Ferron production trend, vitrinite reflectance values suggests temperatures reached 80° to 110°C by the Late Cretaceous (Barker and Pierce, 1997). In the southern portion of the Ferron production trend, vitrinite reflectance data were somewhat lower but reached 60° to 95°C by the Late Cretaceous. The upper range of these temperatures is sufficient to sterilize the Ferron coals. These temperatures persisted until late Oligocene. After the initial biogenic gas generation during early diagenesis in the Cretaceous, there was also a possible late diagenic window commencing at about 25 Ma for additional biogenic gas generation. In particular, the fresh water and nutrient recharge into the Ferron coals caused by movement on the Joes Valley fault system in the Miocene may mark the time of resurgence of significant microbial activity in the Ferron coals.

The nutritional controls on microbial activity are far more difficult to evaluate. At the present state of science, these variables are difficult to quantify. Clayton (1998) indicates gas-generation levels from humic sources of as much as 10 cm^3/g of coal may be possible given that adequate living conditions are present.

Modeling the contribution of biogenic gas to the GIP in the Ferron is not possible at this time. Isotopic data from the northern portion of the Ferron suggests some biogenic contribution to the total gas content. This apparent biogenic contribution, plus that indicated from kinetic modeling of the thermogenic gas generation, account for the total gas content of the Ferron coals without invoking gas migration to the Ferron production trend from deeply buried gas sources to the west under the Wasatch Plateau or to the northwest from the Uinta Basin.

Estimates of Total Coal Mass for Drunkards Wash Area

The total coal mass for Drunkards Wash area was estimated from coal isopach maps and average coal density to be 1.3×10^{15} g of coal.

Between isopach lines, the total thickness used in the calculations was the midpoint thickness for that interval.

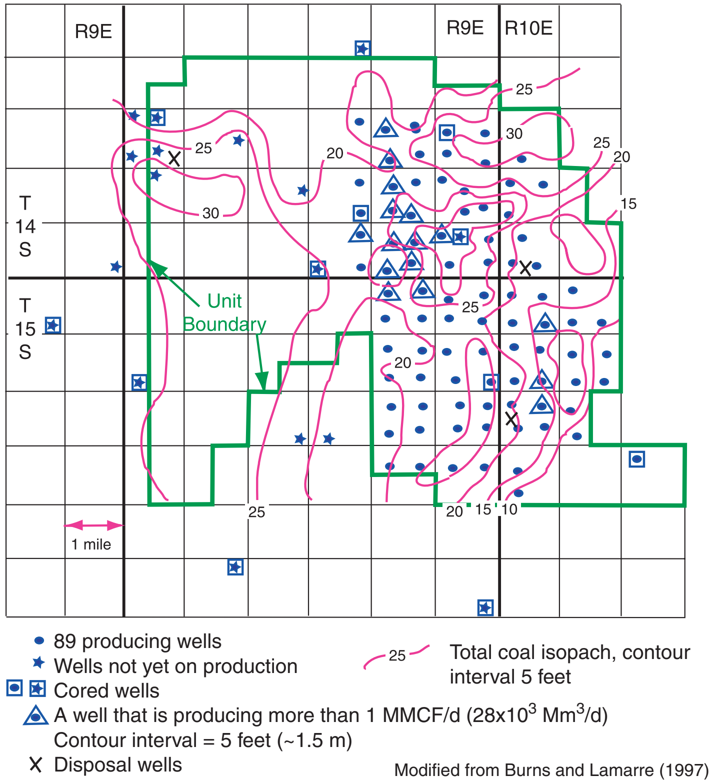
Each township was divided into quarter-quarter sections. The midpoint isopach thickness and area for each 1/16 of a square mile was used to calculate total coal volume.

This resulted in a total coal volume estimate of 8.9×10^{8} m^3 (31.4×10^{9} ft^3) for the Drunkards Wash area.

An average coal density of 1.43 g/cm^3 (89.2 lb/ft^3), which is also a midrange value (Williamson, 1967) based on coal rank for the Drunkards Wash area, was used to calculate total grams of coal.

$$(8.9\times10^{8}\ \text{m}^3)\times(1.43\ \text{g/cm}^3)\times(1\times10^{6}\ \text{cm}^3/\text{m}^3) = 1.3\times10^{15}\ \text{g of coal}\ [2.9\times10^{12}\ \text{lb}]$$

Map showing isopachs of total coal, Drunkard's Wash: Wells cored for, producing, and not yet on production for coal-bed methane are included.



Modified from Burns and Lamarre (1997)

Figure 28. Map showing isopachs of total coal for Drunkards Wash area.

Method for Determining Gas-In-Place

Gas-in-place (GIP) determination is complex and requires (1) the area of coal beds, (2) the thickness of the coal and carbonaceous shale, (3) average coal-bed interval density, (4) and in-situ gas content.

The first three values are used to estimate coal mass in-place and can be determined from well log data and analysis of core or cuttings. The fourth parameter, in-situ gas content, varies widely and is most accurate if measured directly on fresh core. The direct method is not applicable to frontier areas without actually drilling them.

Therefore, to estimate in-situ gas content, this study used burial history reconstruction and gas-generation models to compute a theoretical value. The experimental method uses adsorption isotherms to give a value.

It is very important that the gas-in-place is corrected for moisture and ash content of the coals. These non-coal components sorb negligible amounts of gas. Higher quantities of moisture and ash reduce the amount of gas present in the coal. Our experimental method accounts for non-coal components by including them in the analyses. The theoretical method accounts for non-coal components by computing a gas content adjusted for the carbon content of a coal zone.

The gas content determined from these analyses and methods can then be calculated from the coal mass to determine the GIP.

$$\mathrm{GIP} = \mathrm{CM}_{\text{coal mass}} \times \mathrm{G}_{\text{as content}}$$

$$\mathrm{CM}_{\text{coal mass}} = \mathrm{Z}_{\text{coal zone thickness}} \times \mathrm{A}_{\text{rea}} \times \mathrm{D}_{\text{ensity}}$$

Estimating the GIP for Drunkards Wash

The estimates for coal (reservoir rock) density, total coal volume, and gas content can be used to calculate the gas-in-place for the Drunkards Wash area.

Direct Method

Using the direct experimental adsorption value of 13.7 cm^3/g (438.4 scf/short t) coal from the lower Ferron coals at Drunkards Wash, the maximum (from highly productive coal seams) GIP was estimated to be:

$$(1.3\times10^{15}\text{ g coal})\times(13.7\text{ cm}^3/\text{g coal}) = 17.8\times10^{15}\text{ cm}^3\text{ of gas [630 BCF]}$$

Experimental Method

Using the experimental adsorption value of 5 cm^3/g (160 scf/short t) for coal from the upper Ferron, the minimum GIP was estimated to be:

$$(1.3\times10^{15}\text{ g coal})\times(5\text{ cm}^3/\text{g coal}) = 6.5\times10^{15}\text{ cm}^3\text{ of gas [230 BCF]}$$

Theoretical Method

Using the theoretical adsorption value of 8 cm^3/g (256 scf/short t) coal from the upper Ferron coals, the GIP was estimated to be:

$$(1.3\times10^{15}\text{ g coal})\times(8\text{ cm}^3/\text{g coal}) = 10.4\times10^{15}\text{ cm}^3\text{ of gas [370 BCF]}$$

Previously reported estimates for the GIP of the northern Emery coal field are between 56.6×10^{15} and 70.8×10^{15} cm^3 (2,000 and 2,500 BCF) (Sommer and Gloyn, 1993). The Drunkards Wash area accounts for ~ 30 percent of the northern Emery coal field area. Therefore, our methods for estimating the GIP at Drunkards Wash are within the same magnitude as previously reported GIP estimates.

Summary

Our study uses existing mining industry information for coal mass and three methods of estimating coal gas content to calculate gas-in-place (GIP). The direct method is the most accurate but requires drilling and coring throughout the area of interest. Our experimental and theoretical coal-gas-content methods are applicable to frontier areas without drilling as long as coal mass estimates are available. Because CBM exploration often occurs in areas of existing coal and oil and gas exploration, coal mass data is widely available although desorption data is not. The experimental method overcomes this limitation by using adsorption isotherm analysis and assuming the coals are saturated with gas. The theoretical method can be applied in any basin as long as some stratigraphic data are available for burial history reconstruction. The theoretical method overcomes the lack of direct desorption data by computing the cumulative gas generation from the burial history and gas generation kinetics (BasinMod 5.0).

Compared to the direct-method estimates, the experimental method is thought to give a minimum value for GIP. The reason is because it involves using weathered coal samples from either coal outcrops or aged well core, which reduces sorption capacity. The theoretical method gives a moderate GIP value in these low-rank coals because the modeled volume of gas generated has not exceeded the sorption capacity of the coal.

Our method of studying exposed coal beds related to those that produce gas at depth appears to be a useful method of estimating resources, given the following caveats.

Caveats

1. A major limitation of our method is that we are comparing data gathered from relatively unweathered buried coals with weathered surface coals. Coals are commonly altered by atmospheric contact, thus hindering the collection of unweathered surface samples. Surface weathering may have caused the low to extremely low sorption values found in the upper Ferron coals. Alternately, because these values are measured on whole-seam channel samples, which include carbonaceous mudstone partings, the values may be lower than those found by the direct method.
   The direct method tends to measure only coal, rather than coals and partings. The partings were included in our sampling technique because they can contain considerable methane. Perhaps a better technique would be to run sorption isotherms on a suite of samples ranging from low-ash coal to carbonaceous mudrocks and apply the method of Mavor and Nelson (1997) to estimate gas content for the coal seam.
2. The coal mass and depth to coal (for pressure estimates) within the area of interest is required to estimate GIP. Whether estimated or measured, the applicable gas content value for a given coal mass is required.
3. Gas-generation kinetics for the coal of interest should probably be directly measured for more accurate results in the theoretical method.

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Glossary

Adsorption.—The process whereby gas adheres to the internal surfaces of a coal. At low to moderate pressures—typically found at normal exploration depths of less than 2 km—this layer of gas is one molecule thick. At low pressure, there is little difference between total and adsorbed gas.

Adsorption isotherm.—The gas retention capacity of a powdered coal sample at a constant temperature but at different pressures. Usually measured under equilibrium moisture conditions.

Alluvial plain.—A level or gently sloping land surface that is covered by extensive deposition of alluvium.

Ash yield.—Non-combustible inorganic residue remaining after a coal has been completely combusted. It represents the bulk of mineral matter in a coal after carbonates, sulfides, and clays are broken down during heating. Therefore, ash yield is less than the total mineral-matter content.

Biogenic gas.—Gases produced from coal by the metabolic activities of microbes.

Bituminous coal.—An intermediate rank humic coal whose rank as measured by vitrinite reflectance that exceeds 0.5% R_o.

Canister.—A gas-tight container for holding a sample as it is being desorbed.

Carbonaceous mudstone (carbonaceous shale).—A dark-gray or black rock that contains an abundant amount of carbon in the form of small particles of organic mater; it is commonly associated with coal seams.

Channel sample.—A channel of consistent volume is cut across a seam and all coal within the cut is collected for analysis.

Clastic wedge.—A concave asymmetrical layer of sediments that forms from a domination of sediment input form one side of the basin, generally due to a topographic high or increased sediment input.

Cleats.—Orthogonal sets of fractures in coal caused by shrinkage related to desiccation, devolatization, and structural processes. Somewhat analogous to joints in other rocks.

Coal.—A rock dominantly composed of sedimentary organic matter. A coal contains more than 50 percent by weight and more than 70 percent by volume of sedimentary organic matter.

Coal-bed gas.—Gas produced from the desorption of coal. It is usually composed of methane, but carbon dioxide, nitrogen, and light alkane hydrocarbons are also commonly found.

Coal-bed methane (CBM).—Strictly referring to the methane produced from coal-bed gas.

Coal matrix.—Solid unfractured pieces of coal that are bounded by cleats.

Coalification.—The diagenetic process whereby plant debris is altered to coal during burial heating.

Coal seam.—A single bed of coal including partings within that one coaly interval.

Critical desorption pressure.—The pressure at which gas begins desorbing from coal beds.

Delta-front.—The frontal area of a delta where sediment is transported and deposited. On a prograding delta, a thick continuous sandstone is produced that displays abundant high-angle crossbedding.

Delta-plain.—The landward portion of the delta where a river channel bifurcates and forms abundant distributary channels. This area is characterized by swampy lowlands.

Desorption.—The process of removing gas from sorption sites by reducing the partial pressure in the coal.

Dewatering.—The removal of water from the subsurface. In the case of coal, the removal of water reduces the cleat pressure and causes the onset of methane production.

Dry, ash-free basis.—Coal-analysis data recalculated to mathematically remove ash yield and moisture content from the data.

Equilibrium moisture.—Moisture content after saturating a coal sample with water at 96–97 percent relative humidity at 30°C. The humidity is maintained by placing the sample in a humidor containing a saturated solution of potassium sulfate.

Fixed carbon.—The carbon remaining after the volatile matter has been expelled during combustion.

Foreland basin.—A flexural sag in the Earth's crust that forms from loading by thrust-sheet faulting. These basins are major sediment-accumulation sites for material being transported off of the thrust sheet and being deposited in coeval depositional systems outbound from the thrust front (i.e., shallow-sea, lake, or fluvial sedimentation)

Gas reserves.—The amount or recoverable gas determined by exploration that, under current economical and technological conditions, represents a fraction of the total gas in a reservoir.

GIP.—Acronym for gas-in-place. GIP includes all gas producible by complete desorption of coal to atmospheric pressure levels. GIP overestimates the gas resource because, realistically, a coal bed can only be depressurized to the regional pressure level, not to atmospheric pressure.

Humic coal.—A coal dominantly composed of the debris from terrestrial plants.

Hydrostatic gradient.—The pressure increase with depth of a liquid in contact with the surface. The hydrostatic gradient for most petroleum basins is 10.4 kPa/m (Hunt, 1979). This varies from the lithostatic gradient (pressure with depth due to overlying rock) of 24.4 kPa/m (Hunt, 1979).

Isopach map.—A contour map showing the variation of a component across a geographical area. Generally these maps show thickness of a rock unit or interval, but they can be used for other components, e.g., facies, rock type, fossil distribution, sedimentary environment.

Macerals.—Microscopically identifiable plant debris in coal and kerogen.

Methane.—A colorless, odorless, inflammable gas which is the simplest paraffin hydrocarbon. Formula CH_4. It is the principle component of natural gas.

Microporosity.—Storage areas within a rock, usually on the scale of 1/1,000th of a millimeter.

Mineral matter.—The proportion of inorganic components in a coal before combustion analysis.

Natural gas.—Any of the gaseous hydrocarbons generated below the Earth's surface.

Net-coal thickness.—Total thickness of coal in a coal-bearing interval. The coal seams may be separated by meters of inorganic strata.

Overburden.—The layers of rock above a specific point or rock layer.

Partings.—Thin beds within a coal zone dominantly composed of mineral matter

Peat.—A humic coal whose rank as measured by vitrinite reflectance is greater than 0.2 and less than 0.3 percent R_o.

Permeability.—The interconnectivity of pores and micropores within a rock through which fluids or gas can be transported; measured in millidarcies (mD).

Photomicrograph.—Photograph taken on an image from a petrographic microscope of a mounted rock sample.

Production fairways.—Areas of enhanced coal-bed gas (CBG) production relative to adjacent portions of a coal bed.

Proximate analysis.—The determination of moisture, volatile matter, fixed carbon, and ash in coals.

Rank.—Stage of thermal alteration in coal and dispersed organic matter.

Reservoir rock.—Any rock with adequate porosity, fracture or joints, or sorption potential that can store liquid or gas hydrocarbons.

Reverse fault.—A fault in which the hanging wall has moved upward relative to the footwall. A reverse fault with a fault-plane angle of less than 45° is termed a thrust fault.

Sedimentary organic matter.—Plant- and microbial-derived organic matter deposited in sedimentary and diagenetic environments.

Sorbed gas.—Gas held in a coal by sorption.

Sorption.—A physical process where molecules of gas adhere to the surfaces of a microporous substance by weak intermolecular attraction due to van der Waals or electrostatic forces. After sorption, gas forms a liquid-like condensate in a coal, which is a microporous substance. See also Absorption or Adsorption.

Source rock.—Any rock that contains or originally contained significant organic material that is currently or has undergone thermogenic or biogenic maturation. Rocks in which oil and (or) gas have been generated.

Swamps.—A wooded wetland that is ground-water and occasionally surface-water dominated.

Thermogenic gas.—Gases produced from heating a coal, usually occurring during burial but may also occur during contact metamorphism.

Thrust front.—The leading edge of a thrust sheet.

Thrust sheet.—One or more rock slabs that are thrust up a low-angle reverse fault. A thrust sheet generally implies the emplacement of older over younger rocks.

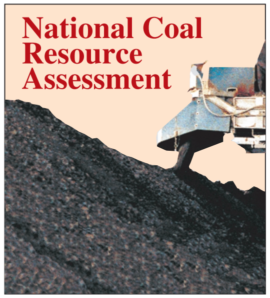
Transgressive-regressive cycle.—The raising and lowering of sea level through time with respect to a given geographic point. Various recognizable sedimentation and erosional events occur during these cycles.

Vitrinite.—The group of macerals composed of woody plant matter, mostly lignin and cellulose.

Vitrinite reflectance.—The proportion of light reflected back from a normally incident light beam of known intensity from a planar polished surface of the coal maceral vitrinite. Expressed as a percentage of the incident light returned. Abbreviated R_o.

Volatile matter.—The mass lost from a coal by heating to high temperatures in the absence of air after removal of moisture from the sample.

Water table.—A layer of water below the ground surface. It is generally used to infer the depth below the surface to which the sediments are saturated with ground water.



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