GO INTERNATIONAL

COMPENSATED DENSITY LOG

FILING NO. ______

COMPANY AMOCO PRODUCTION COMPANY

WELL SCHNEIDER GAS COM B NO1

FIELD BLANCO PICTURED CLIFF

COUNTY SAN JUAN STATE NEW MEXICO

Location: 1110'FSL& 1185'FWL

Sec. 28 Twp. 32N Rge. 10W

Other Services: IEE

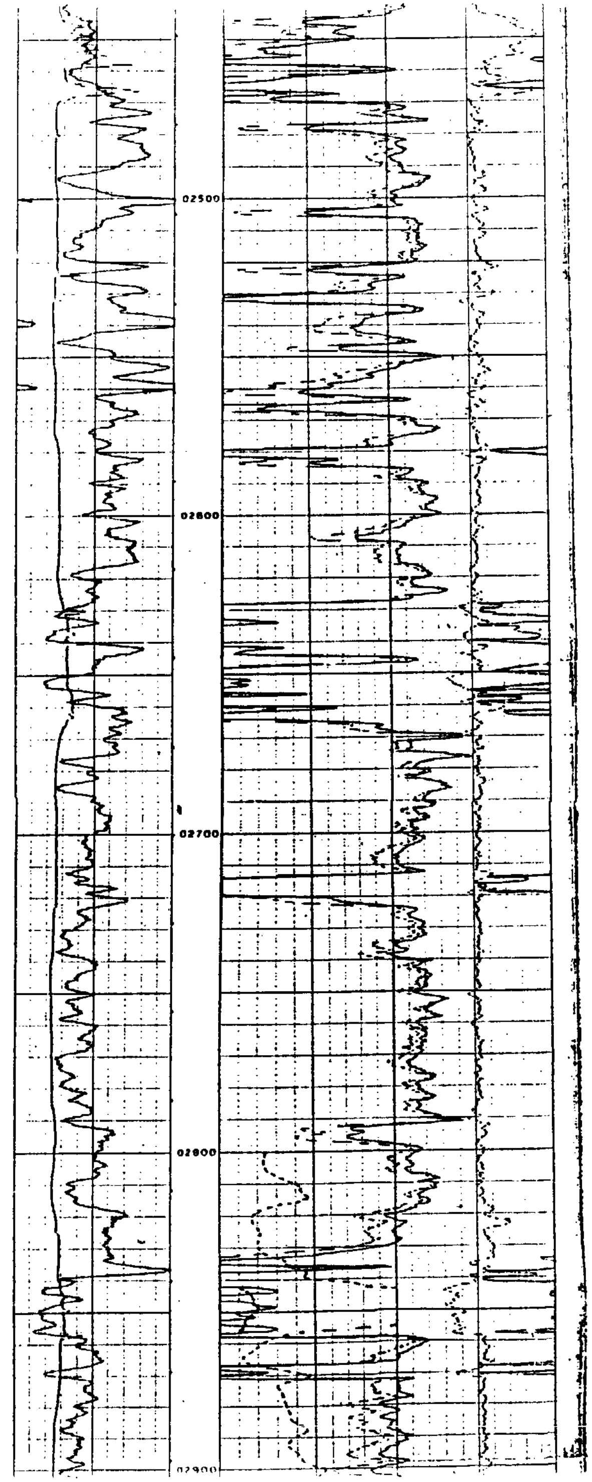
Permanent Datum: Ground Level ; Elev.: 6059
Log Measured From KB 11 Ft. Above Perm. Datum
Drilling Measured From KB

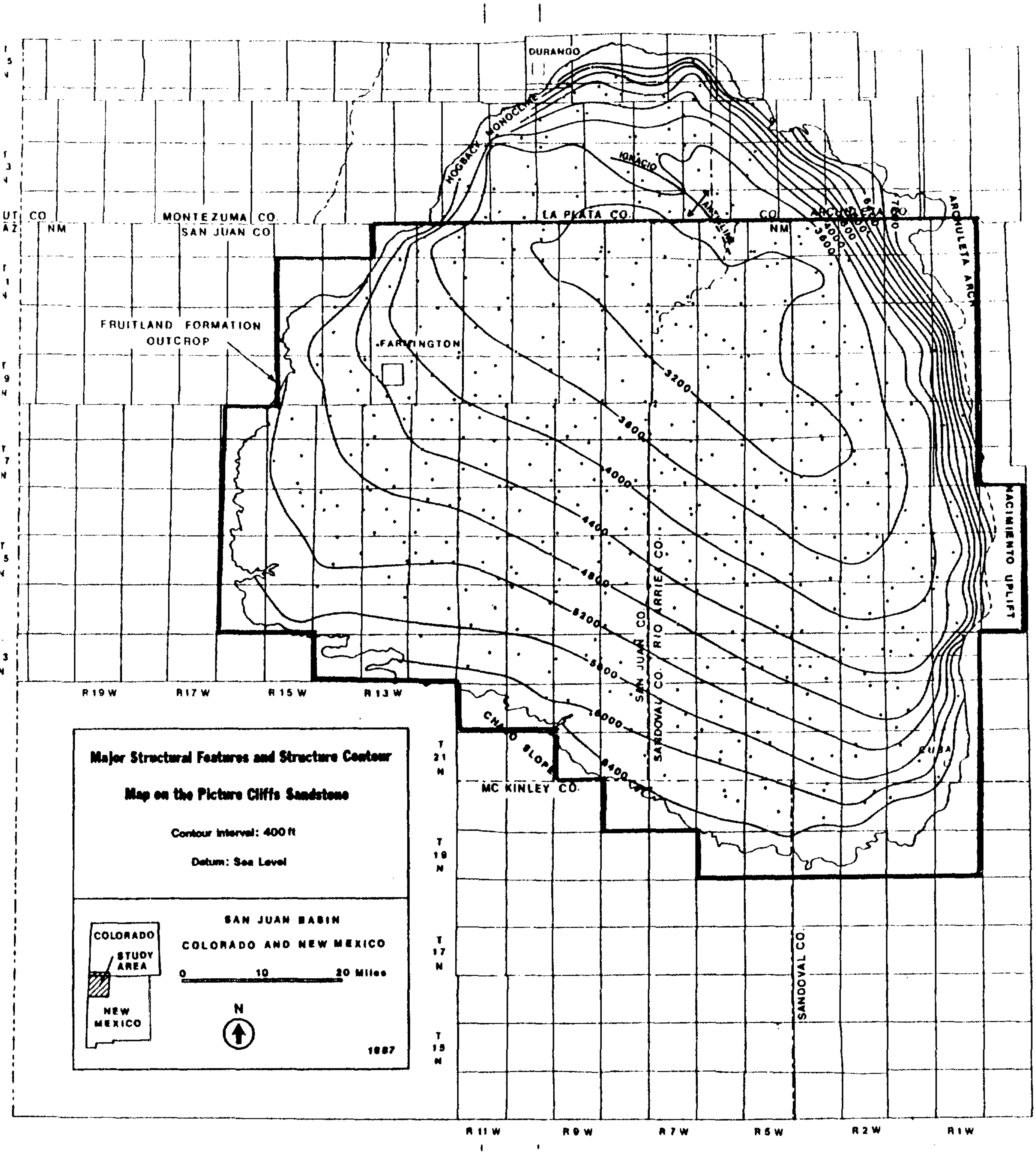
Elev.: K.B. 6070
D.F. 6069
G.L. 6059

Date	1-8-77
Run No.	One
Type Log	Gamma-Gamma
Depth—Driller	3050
Depth—Logger	3053
Bottom logged interval	3052
Top logged interval	2200
Type fluid in hole	Fresh Gel
Salinity, PPM Cl.	3600
Density	10.6
Level	Full
Max rec. temp., deg F.	110
Operating rig time	1 1/2 Hours
Recorded by	Hamilton, Villa
Witnessed by	Bloom

RECEIVED
MAR 15 1977
OIL CON. COM.
DIST. 3

Run	Bore-Hole Record			Casing Record			
No.	Bit	From	To	Size	Wgt.	From	To
One	7 7/8	257	3050	8 5/8		Surface	257




Major Structural Features and Structure Contour Map on the Picture Cliffs Sandstone
Contour Interval: 400 ft
Datum: Sea Level
SAN JUAN BASIN
COLORADO AND NEW MEXICO
0 10 20 Miles
N
COLORADO
STUDY AREA
NEW MEXICO
1987
DURANGO
HOGBACK MONOCLINE
IGNACIO
LA PLATA CO.
MONTEZUMA CO.
SAN JUAN CO
UT CO
AZ NM
CO NM
ARCHULETA ARCH
FRUITLAND FORMATION OUTCROP
FARMINGTON
NACIMIENTO UPLIFT
SAN JUAN CO.
RIO ARRIBA CO.
SANDOVAL CO.
MC KINLEY CO.
CHACO SLOPE
CUBA
3200
3600
4000
4400
4800
5200
5600
6000
6400
R 19 W
R 17 W
R 15 W
R 13 W
R 11 W
R 9 W
R 7 W
R 5 W
R 2 W
R 1 W
T 21 N
T 19 N
T 17 N
T 15 N

IT IS THEREFORE ORDERED:

(A) That, effective ________________, a new pool in all or parts of San Juan, Rio Arriba, McKinley and Sandoval Counties, New Mexico, classified as a gas pool for production from the Fruitland Coalbed Seams, is hereby created and designated the San Juan Basin Fruitland Coalbed Methane Gas Pool, with the vertical limits comprising all coal seams within the stratigraphic interval from approximately 2450 feet to 2880 feet on the Gamma Ray/Bulk Density log of the Amoco Production Company Schneider Gas Com "B" Well No. 1, located 1110 feet from the South line and 1185 feet from the West line of Section 28, Township 32 North, Range 10 West, NMPM, San Juan County, New Mexico, which for the purpose of this order shall include all stratigraphically equivalent coal seams which by virtue of intertonguing or other geological events may be found within the upper Pictured Cliffs Formation. The horizontal limits shall consist of the following described lands:

Township 19 North, Ranges 1 West through 6 West, NMPM
Township 20 North, Ranges 1 West through 8 West, NMPM
Township 21 North, Ranges 1 West through 9 West, NMPM
Township 22 North, Ranges 1 West through 11 West, NMPM
Township 23 North, Ranges 1 West through 14 West, NMPM
Township 24 North, Ranges 1 East through 16 West, NMPM
Township 25 North, Ranges 1 East through 16 West, NMPM
Township 26 North, Ranges 1 East through 16 West, NMPM
Township 27 North, Ranges 1 West through 16 West, NMPM
Township 28 North, Ranges 1 West through 16 West, NMPM
Township 29 North, Ranges 1 West through 15 West, NMPM
Township 30 North, Ranges 1 West through 15 West, NMPM
Township 31 North, Ranges 1 West through 15 West, NMPM
Township 32 North, Ranges 1 West through 13 West, NMPM

(B) That for the purpose of this order a San Juan Basin Fruitland Coalbed Methane Gas Well is a well that is producing from the Fruitland Coalbed Seams as demonstrated by a preponderence of data which could include the following data sources:

a) Electric Log Data

b) Drilling Time

c) Drill Cutting or Log Cores

d) Mud Logs

e) Completion Data

f) Gas Analysis

g) Water Analysis

h) Reservoir Performance

i) Other evidence that indicates the production is predominately coalbed methane.

No one characteristic of lithology, performance or sampling will either qualify or disqualify a well from being classified as a Fruitland Coalbed Methane Gas Well.

SPECIAL RULES AND REGULATIONS FOR THE

SAN JUAN BASIN FRUITLAND COALBED METHANE GAS POOL

SAN JUAN, RIO ARRIBA, MCKINLEY AND SANDOVAL COUNTIES, NEW MEXICO

RULE 1. GENERAL

Each well completed or recompleted in the San Juan Fruitland Coalbed Methane Gas Pool shall be spaced, drilled, operated and produced in accordance with the Special Rules and Regulations hereinafter set forth.

RULE 2. POOL ESTABLISHMENT

That the Director may require the operator of a San Juan Basin Fruitland Coalbed Methane Gas Well, a Fruitland Sand Well or Pictured Cliffs Sand Well, which is proposed in the lands described in (A) above, furnish information and data that would demonstrate to the satisfaction of the Director that the existing wells are producing and the proposed well will produce from the appropriate common source of supply.

RULE 3 (a). WELL SPACING & LOCATION

A standard drilling unit for a San Juan Basin Fruitland Coalbed Methane Gas Well shall consist of 320 acres, plus or minus 25%, substantially in the form of a rectangle, consisting of a half section, being a legal subdivision of the U.S. Public Land Surveys, and shall be located no closer than 790 feet to any outer boundary of the tract, nor closer than 130 feet to any interior quarter section line.

Ask preferential 1st qtr. to be drilled

In the absence of a standard 320 acre drilling unit, an application for administrative approval of a non-standard unit may be made to the Division Director provided that the acreage to be dedicated to the non-standard unit is contiguous, and the non-standard unit lies wholly within a single governmental half section, and further provided that the operator seeking the non-standard unit obtains a written waiver from all offset operators of drilled tracts or owners of undrilled tracts adjacent to any point common to the proposed non-standard unit. In lieu of the waiver requirements the applicant may furnish proof of the fact that all of the aforesaid were notified by registered or certified mail (return receipt requested) of the intent to form such non-standard unit. The Director may approve the application if no objection has been received to the formation of such non-standard unit within 20 working days after the Director has received the application.

The drilling unit orientation will be determined by the first well permitted to be drilled in any one particular standard section.

RULE 3 (b). UNORTHODOX WELL LOCATION

The Director shall have authority to grant an exception to the well location requirements of Rule 3 (a) above without notice and hearing when the necessity for such unorthodox location is based upon topographic conditions or the recompletion of a well previously drilled into a deeper horizon, provided said well was drilled at an orthodox or approved unorthodox location for such original horizon.

Applications for administrative approval of unorthodox locations shall be filed in duplicate (original to Santa Fe and one copy to the appropriate District Office) and shall be accompanied by plats showing the ownership of all leases offsetting the spacing unit for which the unorthodox location is sought, and also all wells completed thereon. If the proposed unorthodox location is based on topography, the plat shall also show and describe the existent topographic conditions.

If the proposed location is unorthodox by virtue of being located closer to the outer boundary of the spacing unit than permitted by rule, actual notice shall be given to any operator of a spacing unit or owner of any undrilled lease toward which the proposed location is being moved.

All such notices shall be given by certified mail (return receipt requested) and the application shall state that such notification has been given. The Director may approve the unorthodox location upon receipt of waivers from all such offset operators or if no offset operator has entered an objection to the unorthodox location within 20 working days after the Director has received the application.

The Director may at his discretion, set any application for administrative approval of an unorthodox location for public hearing.

RULE 4. INCREASED WELL DENSITY

The Director shall have the authority to administratively approve one (1) additional San Juan Basin Fruitland Coalbed Methane Gas Well provided the following conditions are met:

(a) The increased density well must conform to the spacing and boundary footage requirements set forth in Rule 3 (a). and the increased density well cannot be located in the same quarter section as the existing well.

(b) The operator must notify by certified mail (return receipt requested) all: offset operators located in contiguous standup or laydown drilling units; and in the case that the offsetting units are not developed, then notice shall be provided to the owners of contiguous lands.

(c) If no objection is received within 20 working days from receipt of notice, then the application will be administratively approved by the Director. If any objection is received within the time limit, then the Director will set the application for increased well density for public hearing.

RULE 5. HORIZONTALLY DRILLED WELLS

The Director shall have the authority to administratively approve an intentionally deviated well in the San Juan Basin Fruitland Coalbed Methane Gas Pool for the purpose of penetrating the coalbed seams by means of a wellbore drilled horizontally, at any angle deviated from vertical, through such coalbed seams provided the following conditions are met:

(a) The surface location of the well is within the permitted drilling unit area of the proposed well.

(b) The bore hole must not enter or exit the coalbed seams outside of a drilling window which is in accordance with the setback requirements of Rule 3 (a).

If the operator applies for a permit to drill a horizontal well in which the wellbore is intended to cross the interior quarter section line, the operator must notify by certified mail (return receipt requested) all: offset operators located in contiguous standup or laydown developed drilling units; and in the case that the offsetting units are not developed, then notice shall be provided to the owners of contiguous lands.

If no objection is received within 20 working days from receipt of notice, then the application may be administratively approved by the Director. If any objection is received within the time limit, then the Director will set the application for horizontally drilled wells for public hearing.

RULE 6 (a) TESTING.

In lieu of the gas well testing requirements of Order No. R-8170, testing for the San Juan Basin Fruitland Coalbed Methane Gas Pool shall consist of: a minimum twenty-four (24) hour shut-in period, unless otherwise specified by the Director, and a three (3) hour production test. The following information from this initial production test must be reported:

(1) the surface shut in tubing and/or casing pressure and date these pressures were recorded;

(2) the length of the shut-in period;

(3) the final flowing casing and flowing tubing pressures and the duration and date of the flow period;

(4) the individual fluid flow rate of gas, water and oil which must be determined by use of separator; and

(5) the method of production, e.g. - flowing, pumping, etc., and disposition of gas.

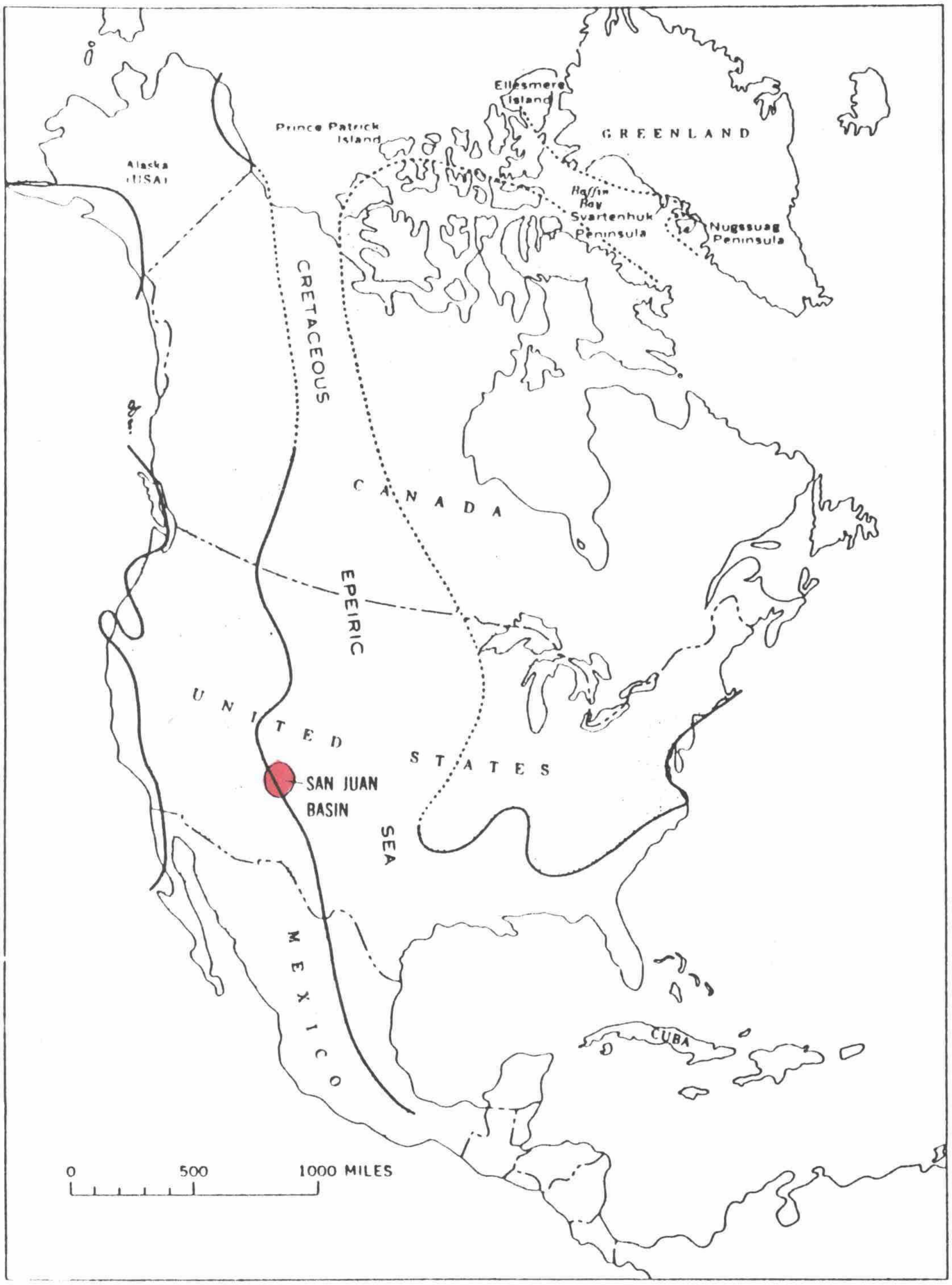
RULE 6 (b). VENTING OR FLARING

Venting or flaring for extended well testing will be permitted for completed San Juan Basin Fruitland Coalbed Methane Gas Wells for a test period of not more than thirty (30) days or a cumulative produced volume of 50 MMCF of vented gas, whichever occurs first, the operator will notify the Director of this testing period.

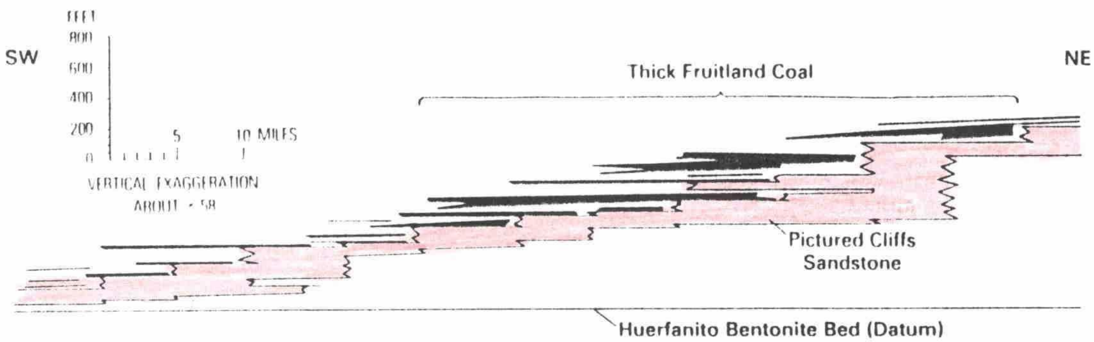
If an operator has cause to perform further testing of a well, then administrative approval may be made by the Director to permit an additional period time and volume limit, set by the Director after sufficient evidence to justify this request has been submitted. In no case shall a well be administratively authorized to vent for a period greater than twelve (12) months.

RULE 7. EXISTING WELLS

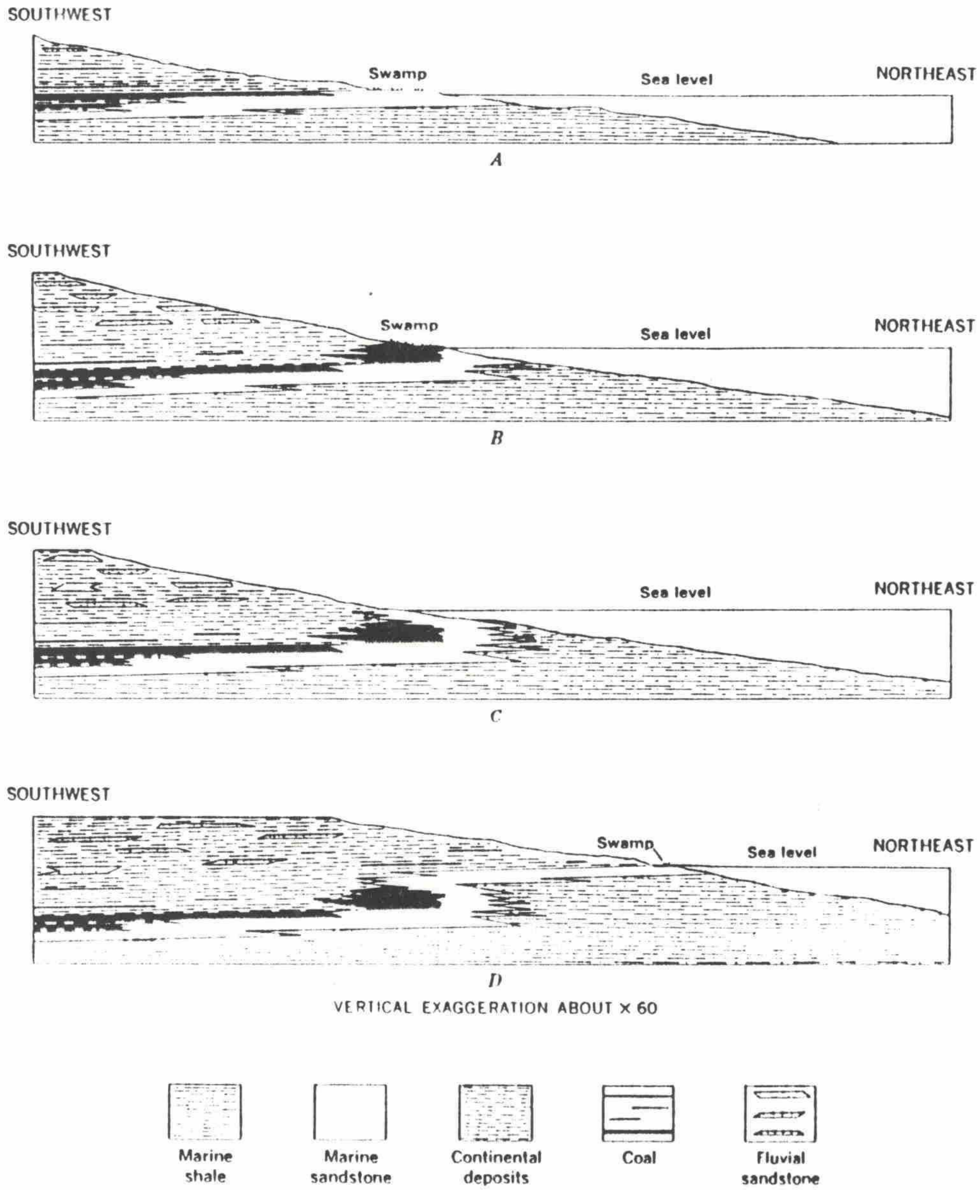
That the operator of an existing Fruitland, Pictured Cliffs or commingled Fruitland/Pictured Cliffs well, which is in conformance with Paragraphs (A) and (B) of this order and is drilling to, completed, or has an approved APD for which the actual or intended completed interval is the San Juan Basin Fruitland Coalbed Methane Gas Pool, may request such well be reclassified as a San Juan Basin Fruitland Coalbed Methane Gas Well by the submittal of a new Form C-102 and C-104 within 90 days of the effective date of this order; this well may be so designated with its original spacing unit size as a non-standard San Juan Basin Fruitland Coalbed Methane Gas Well or may be enlarged to be in conformance with Rule 3 (a).



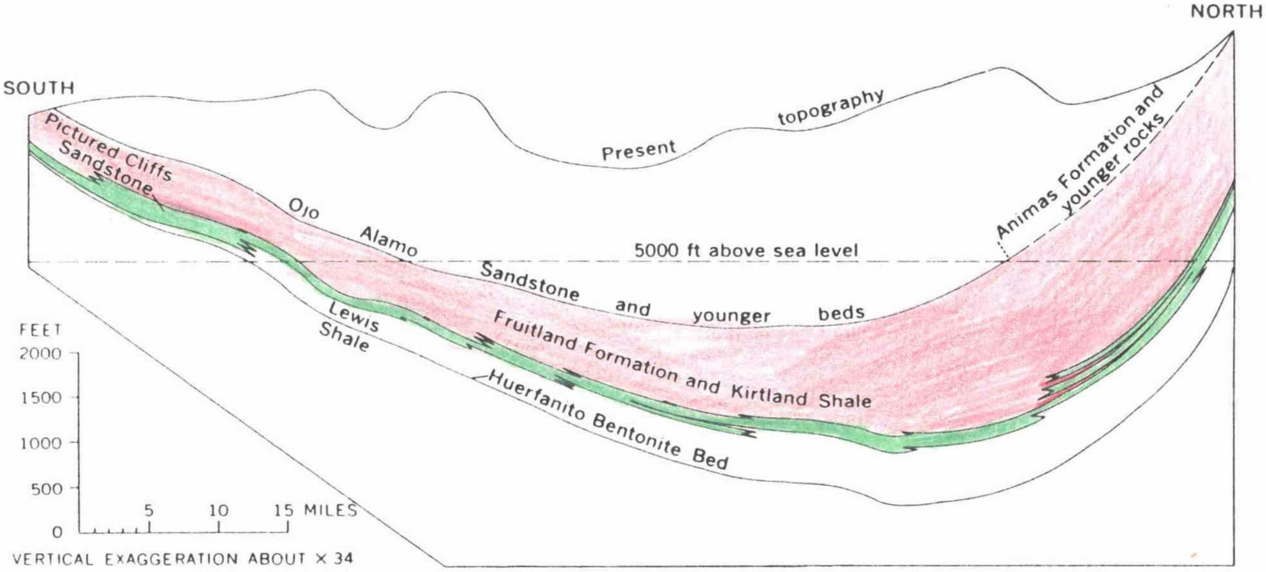
Probable configuration of the North American epeiric seaway at the time that the Upper Cretaceous rocks of the San Juan Basin were being deposited.



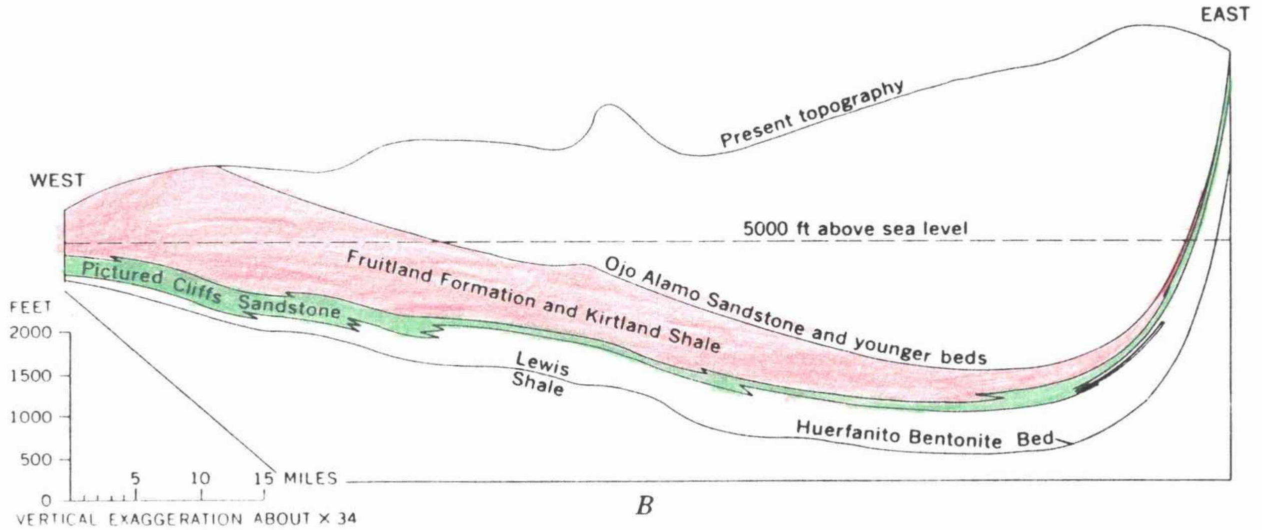
Northeast-trending stratigraphic cross-section showing Fruitland Formation coal beds and underlying Pictured Cliffs Sandstone. This cross section is modified from section B-B' of figure 8; coal bed thicknesses are from plate 3 of Fassett and Hinds (1971)



Diagrammatic cross sections showing the relations of the continental, beach, and marine deposits of Pictured Cliffs time after (A) shoreline regression, (B) shoreline stability, (C) shoreline transgression, and (D) shoreline regression.



A



B

North-trending (A) and east-trending (B) structural cross sections across the San Juan Basin showing the present basin structure. (From Fassett, 1985 [15].

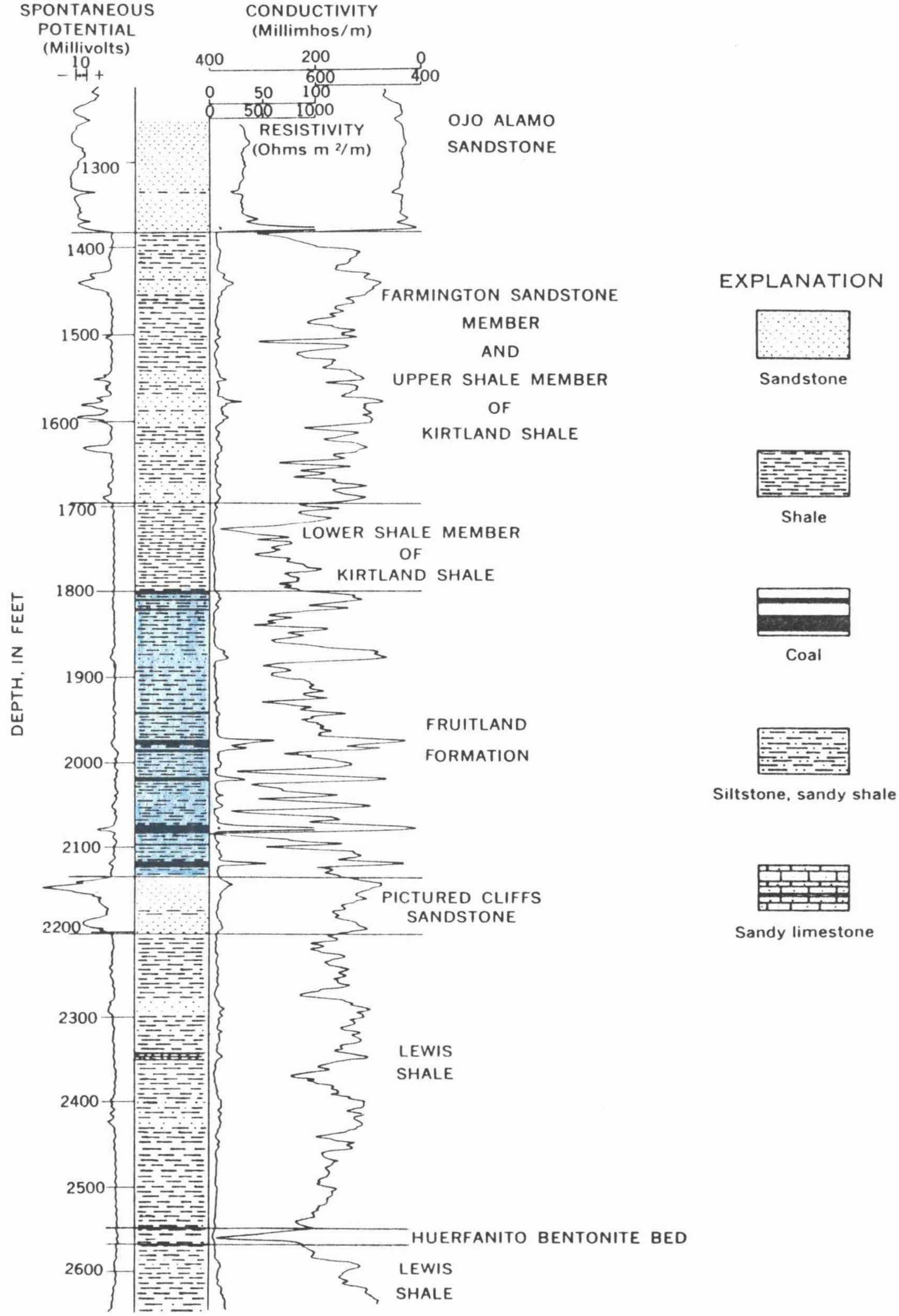


Figure 4 -- Induction-electric log and lithologic column of the type well of the Huerfanito Bentonite Bed of the Lewis Shale showing the interval from below the Huerfanito through the lower part of the Ojo Alamo Sandstone. Lithologies are based on an interpretation of the three geophysical logs shown.

THE 1987 COALBED
METHANE SYMPOSIUM

8711 Influence of Coal Composition on the Generation and Retention of Coalbed Natural Gas

J.R. Levine (University of Alabama, School of Mines & Energy Development)

INTRODUCTION

In terms of composition, coal is classified according to three distinct characteristics: 1) "grade", which represents the relative proportion of organic vs. inorganic constituents, 2) "type", which represents the natural variability of the organic constituents initially deposited in the coal, and 3) "rank", which represents the physico-chemical changes imparted to the coal by elevated temperatures and pressures during burial. Grade, type, and rank influence every aspect of coal bed natural gas reservoirs either directly or indirectly. The present paper focuses on two distinct, but related topics:
1) the influence of type and rank on the the composition and quantities of volatile substances formed during coalification, and 2) the influence of grade and type on the retention of gas in the subsurface.

EVOLUTION OF VOLATILE SUBSTANCES DURING COALIFICATION

The most fundamental change taking place in coal during coalification is the progressive enrichment of elemental carbon, accompanied by the elimination and release of large volumes of "volatile" substances relatively rich in hydrogen and oxygen. As these volatile substances are produced, the H/C and O/C atomic ratios of the residual solid coal progressively decrease. The three principal maceral groups, vitrinite, liptinite, and inertinite, differ substantially in their initial H/C - O/C ratios, hence they also differ in the quantity and type of gases formed during coalification.

The coalification process occurs much too slowly to be observed on a human time scale. Consequently, we are constrained to examining the end product and inferring as best we can the processes that led to it. Inasmuch as only a small portion of the volatile substances formed during coalification remain in the coal today, their volume and composition is largely problematical. However, providing a number of reasonable assumptions are made, then the quantities of CH_4, CO_2, and H_2O liberated during coalification can be estimated within a fairly narrow range, based on the major element (C H O) composition. The model requires: 1) that the organic microconstituents of coal evolve compositionally along the four generalized maturation pathways depicted in Figure 1 (Tissot and Welte, 1978), 2) that (for the most part) CH_4, CO_2, and H_2O represent the only forms in which carbon, hydrogen, and oxygen can escape from the coal bed, and 3) that once they are formed, CH_4, CO_2, and H_2O cannot recombine with the solid matrix of the coal.

The elemental compositions of coalification "products" and "reactants" can be plotted on a Van Krevelen diagram (Figure 1) which depicts both the rank and type of the organic constituents. Coalification paths for the four principal kerogen types are labeled I, II, III and IV. Kerogen type II is roughly equivalent to the liptinite (a.k.a. exinite) maceral group in coal. Kerogen type III is equivalent to vitrinite, by far the most common microscopic constituent of coal, and kerogen type IV is equivalent to the inertinite maceral group in coal. At low rank the maceral groups differ substantially in composition, but progressively converge upon one another they approach the origin. For example points A and B represent, respectively, the elemental compositions of liptinite and vitrinite macerals coexisting in a coal of vitrinite reflectance 0.5%, but by the time they have been coalified to 2.0% reflectance, they have virtually identical compositions.

A vector connecting any pair of starting and end points can be used to represent the compositional evolution of a particular coal or coal constituent. This vector can be resolved into 1,2, or 3 components, parallel to the dehydration, decarboxylation, and/or demethanation pathways plotted on the diagram. These devolatilization paths represent the change in composition brought about by the progressive removal of H_2O, CO_2, or CH_4 from the coal structure. Applying the constraints of the model, it is possible to reach an end point by a variety of pathways--but only within a limited range--or else condition (3) may be violated. For example, a liptinite maceral of initial composition A on the liptinite curve is coalified to composition C. There are two limiting end member paths to get from point A to point C. In the first, all oxygen is eliminated as CO_2 and none as H_2O while in the second the reverse is true. In the first case, the decarboxylation vector intersects the demethanation path at A', from which point all subsequent compositional changes can be accounted for by progressively removing CH_4, plus CH_4 (Path A-A"-C). Any other evolutionary pathways will include both decarboxylation and dehydration components and, consequently, and must fall between A-A' and A-A". (Note that the "head-to-tail" construction of the vectors in these examples does not necessarily imply a time sequence in volatile evolution. Volatile evolution occurs concurrently, with either one or the other substance predominating. However, the vectors do imply an explicit quantity of gases evolved.

To quantify this model and determine the precise composition and quantity of gases for each path, a set of equations is formulated whereby the total number of atoms of C, H, and O are equated between reactants (subscript r) and products (subscript p), and the H/C and O/C ratios of the reactants and products are adhered to:

$$Cp = Cr - CH_4 - CO_2 \quad (1)$$
$$Hp = Hr - 4*CH_4 - 2*H_2O \quad (2)$$
$$Op = Or - 2*CO_2 - H_2O \quad (3)$$
$$Hp = Cp * 0.50 \quad (4)$$
$$Op = Cp * 0.06 \quad (5)$$

where Cp, Hp, and Op are the number of atoms or moles of carbon, hydrogen, and oxygen per unit of the product. Cr, Hr, and Or are the number of atoms or moles of carbon, hydrogen, and oxygen in the starting (reactant) mixture; and CH_4, CO_2, and H_2O are the number of molecules or moles of methane, carbon dioxide, and water formed from the reactants during coalification.

The composition of the starting material can be determined by solving the following set of 3 equations with 3 unknowns:

$$Hr/Cr = 1.25 \quad (6)$$
$$Or/Cr = 0.07 \quad (7)$$
$$Cr + Hr + Or = 1000, \quad (8)$$

the solution to which is:

$$Cr = 431 \quad (9)$$
$$Hr = 539 \quad (10)$$
$$Or = 30 \quad (11)$$

The value of 1000 in equation (8) is arbitrary. It can be thought of as representing an imaginary coal "molecule" comprised of 1000 atoms. In subsequent calculations these 1000 atoms shall be partitioned among the various volatile products and coal.

Substituting equations (9-11) into equations (1-5) we are left with 5 equations and 6 unknowns. Hence, in order to derive a unique solution, one additional relationship must be defined. For end member case A-A'-C, $H_2O = 0$; and for case A-A"-C, $CO_2 = 0$. For intermediate paths, some ratio of CO_2 to H_2O must be selected. This needn't be an arbitrary choice, but may be based on knowledge of the functional group composition. For example Van Krevelen (1963) indicates that throughout most of the coal ranks under consideration, approximately half of the oxygen in coal is bound to hydrogen, and about half to carbon. We can propose then that CO_2 an H_2O leave the coal in roughly equal amounts; hence $CO_2 = H_2O$.

Depending on the path chosen, the relative proportions and total weight percentages of the volatile products vary considerably. Table 1 lists the yields of CH_4, CO_2, and H_2O and volatile matter produced along the various maturation pathways depicted in Figure 1. For example, as coal increases from R_o(vit) = 0.5 to R_o = 2.0, vitrinite can evolve anywhere from 24 to 173 cm^3 CH_4(stp)/g coal, depending upon whether B-B'-C or B-B"-C is followed. Assuming a ratio of 1:1 $H_2O:CO_2$ production, vitrinite will cumulatively generate around 116 $cm^3 CH_4$(stp)/g. Over this same rank range, and within the constraints of the model, liptinite macerals generate between 421 and 466 cm^3 CH_4(stp)/g; however, in reality, liptinites probably lose a significant proportion of their hydrogen as longer chain hydrocarbons rather than as methane. The devolatilization model can be modified or expanded to accommodate other hydrocarbon gases, however, a new functional relationship must be added for each new unknown.

This method of quantitatively estimating the volatile yield using simultaneous equation.is similar to a widely cited coal devolatilization model proposed by Juntgen and Karweil (1966) but differs in that it does not require that the coal liberate specific quantities of volatile substances. Juntgen and Karweil speculated that the proximate analysis volatile matter content (measured by pyrolysis at 950°C) could be used as an estimate of the total weight of material evolved as volatile products during coalification. However, this assumption is unwarranted and thermodynamically unsound. Moreover, by requiring that their coals produce such a large volume of volatile substances, Juntgen and Karweil's equations yielded negative values for water production--in other words, it was required that water be added to the coal structure to maintain the proper elemental ratios. Thus, the estimates of gas volumes based on this model are exaggerated. A subsequent article by Juntgen and Klein (1975), however, published a lower revised estimate, discussed subsequently, that is in close agreement with the one calculated herein.

Table 2 shows the progressive devolatilization path to Ro(vit) = 2.0% of an hypothetical coal, comprised of 80% vitrinite, 10% liptinite, and 10% inertinite. The total CH_4 production is 107 cm^3/g (Table 1, Path D-D'-C), almost identical to the quantity calculated by Juntgen and Klein (1975) based on experimental pyrolysis. The older estimate by Juntgen and Karweil (1966) for a whole coal was more than 200 cm^3. Unfortunately, the older figure seems to be used more commonly than the more recent one, (e.g. Meissner, 1984)

INFLUENCE OF COAL COMPOSITION ON IN SITU METHANE CONTENTS

With increasing rank coal loses its capacity to retain H_2O; hence, assuming that the beds remain fully water saturated, any water formed during coalification must be produced. Coal has a relatively strong affinity for CO_2 (as opposed to

CH_4, for example), but CO_2 is readily soluble in water; hence, its abundance will tend to diminish over time. Consequently, in comparison with other volatile substances formed during coalification CH_4 tends to become progressively enriched in the coal bed reservoir .

Coal has an attractive affinity for methane that enables it to absorb or adsorb more CH_4 under pressure than would be the case if the methane were a free gas. During the course of coalification coals generate much more methane than they have the capacity to retain (Juntgen and Karweil, 1966), so in a natural setting, most coals should be at or near their maximum methane capacity (at P,T), provided that the coals were not exposed to abnormally low fluid pressures in the past. Bearing this model in mind, the gas content of coal in situ should be proportional to the pressure, temperature, and whatever compositional parameters limit the coal's capacity to sorb gas.

A suite of 57 samples was recently collected from a 3000 ft deep coal bed methane exploration core hole in the Cahaba basin, central Alabama. The gas contents of the samples were measured using the Bureau of Mines canister desorption test. Then the coals were subjected to a comprehensive suite of analyses, including proximate, ultimate, BTU, and petrography. These data were then normalized and used to develop a multiple linear regression model to predict the gas contents of the samples. The resulting linear model was very successful, explaining 88.5% of the variability in gas content. A large component of the remaining 11.5% variability is probably due to measurement error.

Multiple Linear Regression Model
<u>Gas Contents of Cahaba Core Samples</u>

$$
\begin{aligned}
\text{Gas Content } (cm^3/g) = \; & 6.822 \\
& + 0.0025 * \text{Depth (ft)} \\
& - 0.0957 * \text{ParrMM} \\
r^2 = .885 \quad & + 0.1112 * (\%\text{Fusinite} + \%\text{Semifusinite} + \%\text{Macrinite}) \\
& - 5.449 * \text{H/C (daf)}
\end{aligned}
$$

This regression model indicates that for the suite of coals examined, gas content increases linearly with depth. In laboratory sorption isotherm studies, the gas capacity of coal increases at a less than linear rate, so the anomalously high gas contents at depth may be due to increasing rank (W. Telle, personal communication). There was not, however, enough of a systematic rank variation in the samples to produce a measurable effect in the regression model. The third term, ParrMM, is an estimate of the mineral matter content of the coal using Parr's equation based on ash and sulfur content. Once again the correlation is linear, but with a negative coefficient. The predicted gas content using the model is very close to 0.0 at 100% ParrMM, showing that for these samples, the mineral matter does not participate measurably in the gas sorption process. The fourth term is a indication of the influence of coal petrography on gas sorption capacity. This composite variable, comprised of members of the inertinite maceral group, indicates that while inertinite does not contribute significantly to gas generation, it has a positive influence on the gas content. The fifth term, the hydrogen to carbon ratio (dry, ash-free basis) does not contribute strongly toward the model, but indicates that an increasing H/C ratio has a negative influence on the gas capacity. It is uncertain whether this is related to decreasing rank, or increasing liptinite content. Neither standard rank parameters nor the liptinite percentages showed a significant effect.

It remains to be seen whether this model can be applied to coals in other basins as well. As additional data become available the model will be tested and refined.

REFERENCES CITED

Jüntgen, H. and Karweil, J., 1966, Gasbildung und Gasspeicherung in Steinkohlenflözen, Part I and II: Erdöl u. Kohle, Erdgas, Petrochem, v. 19, p. 251-258 and 339-344.

Jüntgen, H. and Klein, J., 1975, Entstehung von Erdgas aus kohlingen Sedimenten.: Erdöl u. Kohle, Erdgas, Petrochem., Ergänzungsband, I, 74/75, p. 52-69. Industrieverlag v. Hernhausen Leinfelden bei Stuttgart.

Krevelen, D.W. van, 1963, Geochemistry of coal, in Breger, I.A., ed., Organic Geochemistry: Oxford, Pergamon Press, p. 183-247.

Meissner, F.F., 1984, Cretaceous and Lower Tertiary coals as sources for gas accumulations in the Rocky Mountain Area: Hydrocarbon Source Rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists, Denver, CO, p. 401-432.

Tissot, B.P. and Welte, D.H., 1978, Petroleum Formation and Occurrence: Springer-Verlag, Berlin, 538 p.

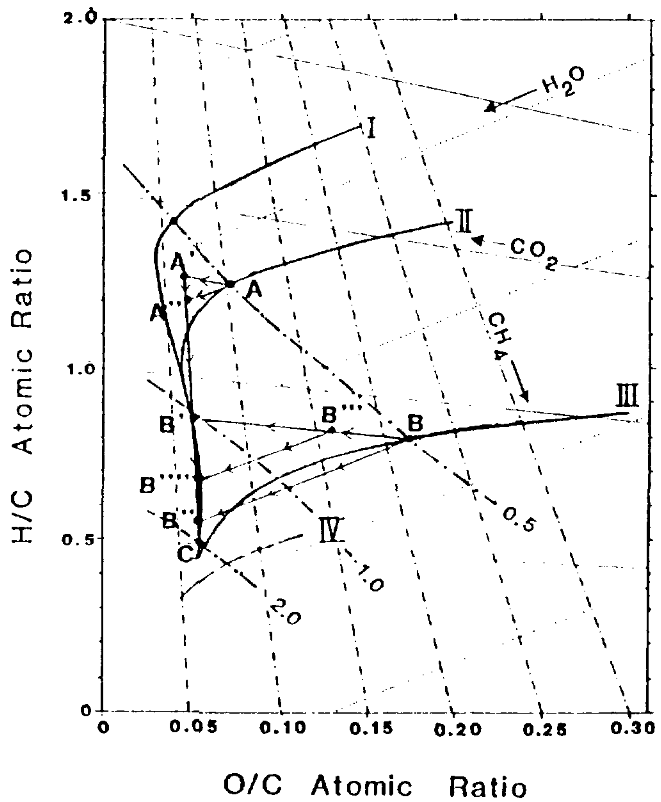


Figure 1 - Van Krevelen diagram depicting evolutionary devolatization paths. Liptinite (A) and vitrinte (B) are situated at the intersections of the Type II and Type III kerogen maturation paths and the 0.5% R_o isoreflectance line. A number of alternate devolatilization paths may be followed for each starting material, each path yielding different quantities of volatile products (see Table 1 for details).

Coalification from R_o(vit) = 0.5 to R_o(vit) = 2.0		Cumulative Grams of Volatiles per Gram of Coal			% of Original Weight Lost as Volatiles	Volume of CH_4 (stp) per Gram of Solid Coal
Path	Description	CH_4	CO_2	H_2O		
A-A'-C	Max. CH_4, Max. CO_2, Min. H_2O	0.333	0.049	0	27.6	466.
A-A"-C	Min. CH_4, Min. CO_2, Max. H_2O	0.301	0	0.036	25.2	421.
B-B'-C	Max. CH_4, Max. CO_2, Min. H_2O	0.124	0.236	0	26.5	173.
B-B"-C	Min. CH_4, Min. CO_2, Max. H_2O	0.017	0	0.156	14.7	24.
B-B"'-B""-C	Intermediate Path: H_2O = CO_2	0.083	0.146	0.059	22.4	116.
D-D'-C	Intermediate Path: H_2O ≡ CO_2	0.076	0.110	0.045	18.7	107.

TABLE 1. Volatile Products of Coalification

Step:	C	H	O	H/C	O/C
Starting Material:					
80 % Vitrinite:	4096	3192	712	0.78	0.17
+ 10 % Liptinite:	431	539	30	1.25	0.07
+ 10 % Inertinite:	746	224	30	0.30	0.04
Total:	5273	3955	772	0.75	0.15
Decarboxylation: (79 * CO_2)	-79	0	-158		
	5194	3955	614	0.76	0.12
Dehydration: (315 * H_2O)	0	-630	-315		
	5194	3325	299	0.76	0.06
Demethanation: (208 * CH_4)	-208	-832	0		
	4986	2493	299	0.50	0.06

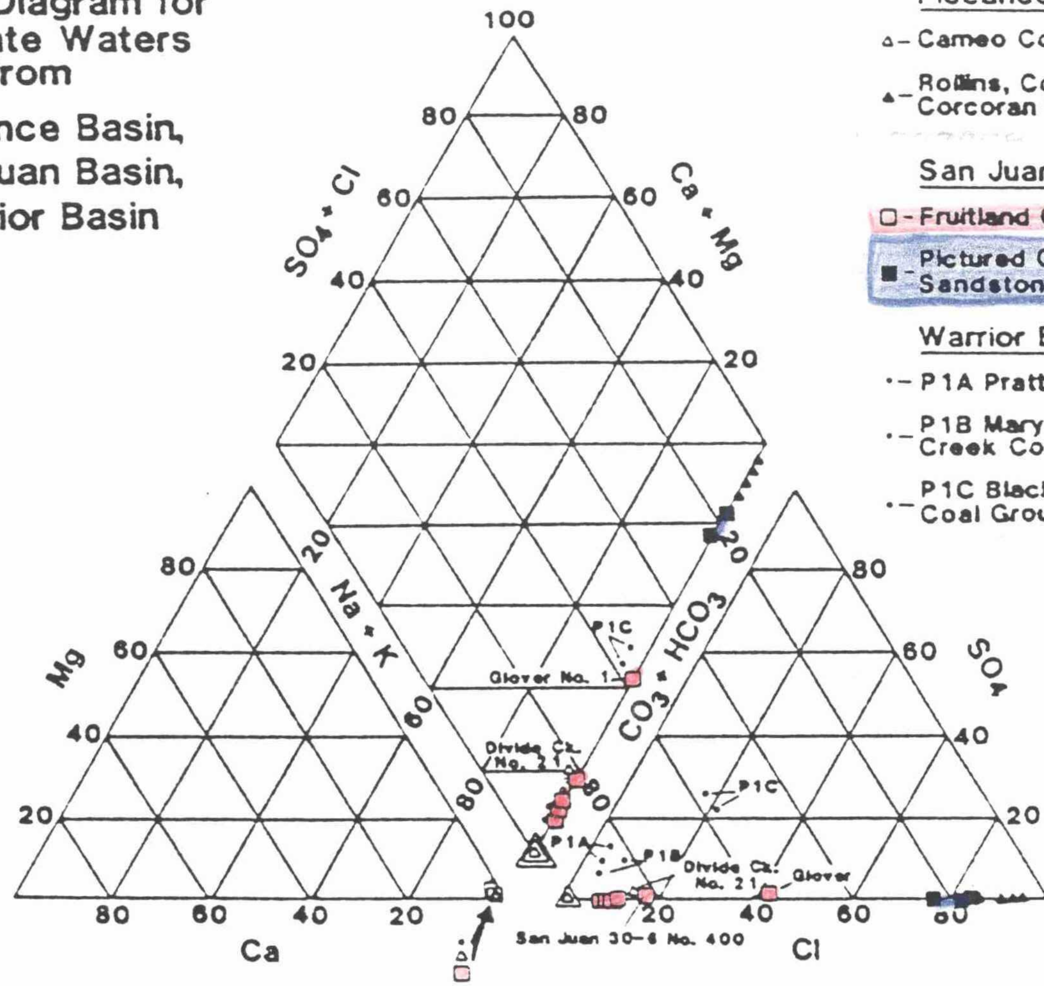
TABLE 2. Devolatilization Path for Whole Coal (D-D'-C, Table 1.)

COMPARISON OF GAS ANALYSES

FORMATION	WELL LOCATION	C2	CO2	BTU
Fruitland coal	A-18-32-7	94.84	4.25	976
"	O-08-32-9(CO)	95.92	2.61	997
"	D-11-33-10(CO)	95.53	2.20	1011
"	N-07-31-09	89.67	8.54	949
Fruitland sand	G-08-29-10	83.22	0.65	1235
"	E-22-28-12	85.55	1.45	1138
"	D-34-30-11	82.50	0.33	1223
"	O-28-32-11	83.41	0.42	1224
Pictured Cliffs	J-06-33-10(CO)	79.55	1.66	1234
"	O-26-32-07	85.23	0.58	1188
"	F-13-28-09	91.77	0.48	1102
"	O-18-30-08	88.20	0.94	1157

Piper Diagram for Connate Waters from

Piceance Basin, San Juan Basin, Warrior Basin



Piceance Basin

- ▵ – Cameo Coal
- ▴ – Rollins, Cozzette, Corcoran Sandstone

San Juan Basin

- □ – Fruitland Coal
- ■ – Pictured Cliffs Sandstone

Warrior Basin

- • – P1A Pratt Coal Group
- • – P1B Marylee-Blue Creek Coal Group
- • – P1C Black Creek Coal Group

ɔceedings of the 1987 Coalbed Methane Symposium, Tuscaloosa, Alabama, Nov. 16-19, 1987

THE 1987 COALBED
METHANE SYMPOSIUM

8714 Origin and Production Implications of Abnormal Coal Reservoir Pressure

A.D. Decker (Resource Enterprises, Inc.); D.M. Horner (Gas Research Institute)

ABSTRACT

The ability to produce low cost, pipeline quality gas from deep coal reservoirs depends largely on thorough integration of exploration methods with appropriate drilling, completion and production strategies. In the extreme case, areas that are not economic with current completion technologies should be avoided with adherence to prudent exploration practices. Therefore, reliable predictive geologic methods to specify coal reservoir conditions need to precede drilling and completion decisions.

Dominant coal reservoir mechanisms include: permeability, saturation, reservoir pressure and gas-in-place. Production characteristics from low permeability coal reservoirs are most sensitive to the interaction between type of saturation and reservoir pressure. The geologic processes responsible for these reservoir conditions have been examined in the Piceance Basin. This basin, known for low permeability reservoirs, was selected for geologic evaluation due to the large coalbed methane resource and large data base. Also located in the basin is the Deep Coal Seam Project, a multi-year, multi-well, field laboratory joint venture by the Gas Research Institute and Resource Enterprises, Inc., providing fully integrated reservoir and geologic engineering data on deep coal reservoirs.

Reservoir diagnostics and modeling suggests that reservoir pressure and type of saturation demonstrate an interaction between catagenesis and permeability. Thick, thermally mature coal deposits actively generate more gas and water than can be adsorbed by the coal or be diffused through a low permeability system. In these regions over-pressuring occurs. Ultimately, pore pressure will exceed in-situ stresses resulting in tensional fractures through the coal bearing sequences. While the coal seams remain in the active gas generation phase, the fractures and pore spaces become gas saturated. Eventual temperature reduction through erosion will halt the gas generating phase, resulting in an under-pressured reservoir. Imbibition of water into these reservoirs is unlikely in areas of low permeability. In contrast, coal seams that have not reached an active gas generation phase may be overpressured and water saturated due to compaction and coal dewatering in a shale bounded situation. Overpressured water saturated coal reservoirs of the Cedar Hills and San Juan 30-6 Unit in the San Juan Basin have, to date, shown the highest production capacity for coalbed methane production.

In summary, geochemical evaluation techniques have been applied to characterize and predict coal reservoir mechanisms in the Piceance and San Juan Basin.

INTRODUCTION

A portion of the extensive gas accumulations found in the San Juan Basin[1], the Green River Basin[2], and the Alberta Basin[3] have been sourced largely by coal. Despite the amount of data collected on coal reservoir characteristics and coal as a source rock, little work has been done integrating the two sciences. A coupled understanding of coal reservoir mechanisms and coal maturation will assist the explorationist in his pursuit of coalbed gas resources. This work was sponsored by the Gas Research Institute under Contract No 5083-214-0844 with Resource Enterprises, Inc.

A geologic model is presented which incorporates coal's resistance to transfer heat with its ability to generate large volumes of gas over a specific temperature and time sequence. In basins where low permeability prohibits cross formational fluid flow, gas generation can exceed the quantity of gas that can migrate through the geologic system. This results in high pore pressure within the coal reservoirs. Conversely, where migration exceeds rate of gas generation, low pore pressure will be observed. These stages of reservoir disequilibrium have been observed in other deep coal basins of the western United States.

The focus of this paper is to describe and quantify these states of pore pressure disequilibrium within some coal reservoirs of the Piceance Basin and San Juan Basin. A sequential approach is undertaken to examine the coal system in each phase of basin evolution, as follows:

1. Determination of the volumes of water and gas produced from coal at specific maturity levels during the coalification process.

2. Relate the maturity levels to specific time periods using thermal maturation models.

3. Determination of the amount of gas that cannot be retained by the coal and, therefore, which must diffuse through the geologic section for specified time interval.

This paper is directed at providing the volumetric calculations of Step 1 and the methodology (using a case study) for Steps 2 and 3.

Included in this paper are geologic observations and interpretations of areas within the Piceance Basin where underpressured and overpressured (less than and greater than hydrostatic pressure, respectively) coal seams have been identified. Also included is a section suggesting a relationship between well deliverability, permeability and reservoir pressure in coal degasification wells in the San Juan Basin. A relationship between material balance, gas/water flow and abnormal coal pore pressure is presented.

THE EVOLUTION OF COAL

In response to burial depth, time and temperature, deposits of terrestrially derived plant tissue evolves physically and chemically into thermally mature coal. Compaction and temperature increases transform the organic material into three primary coal components or macerals. (Macerals are the microscopically recognizable constituents of coal.) The vitrinite maceral represents jellified cell walls or woody material, the exinite maceral is representative of plant resin (cuticles and spores) and the inertinite maceral represents carbonized woody material.

The degree of maturation or coal rank during the coalification process is most accurately measured from the vitrinite maceral. The percentage of vitrinite optical reflectivity (Ro) increases correspondingly with increases in coal rank. The temperature necessary to increase rank as indicated by Ro and derived by Gijzel[4] is shown on Table 1. Systematic chemical and biological degradation of organic material during the coalification process yield varying amounts of water and gas. Examination of such chemical products is important in understanding the water and gas accumulations within present-day coal reservoirs.

The two most significant stages of coal maturation, diagenesis and catagenesis, are defined largely by the products of biological and thermal evolution. Water, biogenic methane and carbon dioxide are the primary coal diagenetic products. Water originates from the depositional system and organic decomposition[5]. All biogenic gas and 98 percent of the coal's water generative capacity occurs during diagenesis at maturity levels of 0.23 to 0.76 Ro[6].

Continued exposure of coal to pressure and temperature allow coal to enter the stage of catagenesis. Juntgen and Klein[7] determined that thermal methane generation commences during catagenesis for coal with a vitrinite reflectance of 0.73 Ro. As shown in Figure 1, active gas generation accelerates at 0.90 Ro and continues through 1.30 Ro, accounting for 76 percent of thermal methane generation. Water produced during catagenesis is from the hydration of inorganic minerals and clays[8]. Water and thermal methane volumetrics as a function of increasing coal maturity is summarized in Figure 2.

Coal's ability to absorb gas decreases with higher temperature[9] and pressure[10], but increases with higher coal rank[11]. Eight to ten times more gas is generated than can be retained, thereby initiating gas migration from the coal into other strata. Therefore, the development of a time framework for the coal generative episodes becomes necessary to understand the possible influence that thermal generation rates have on coal reservoir properties. Deterministic relations between time, temperature and ensuing gas generation episodes are derived from thermal maturity modeling.

<u>Thermal Maturity Modeling</u>

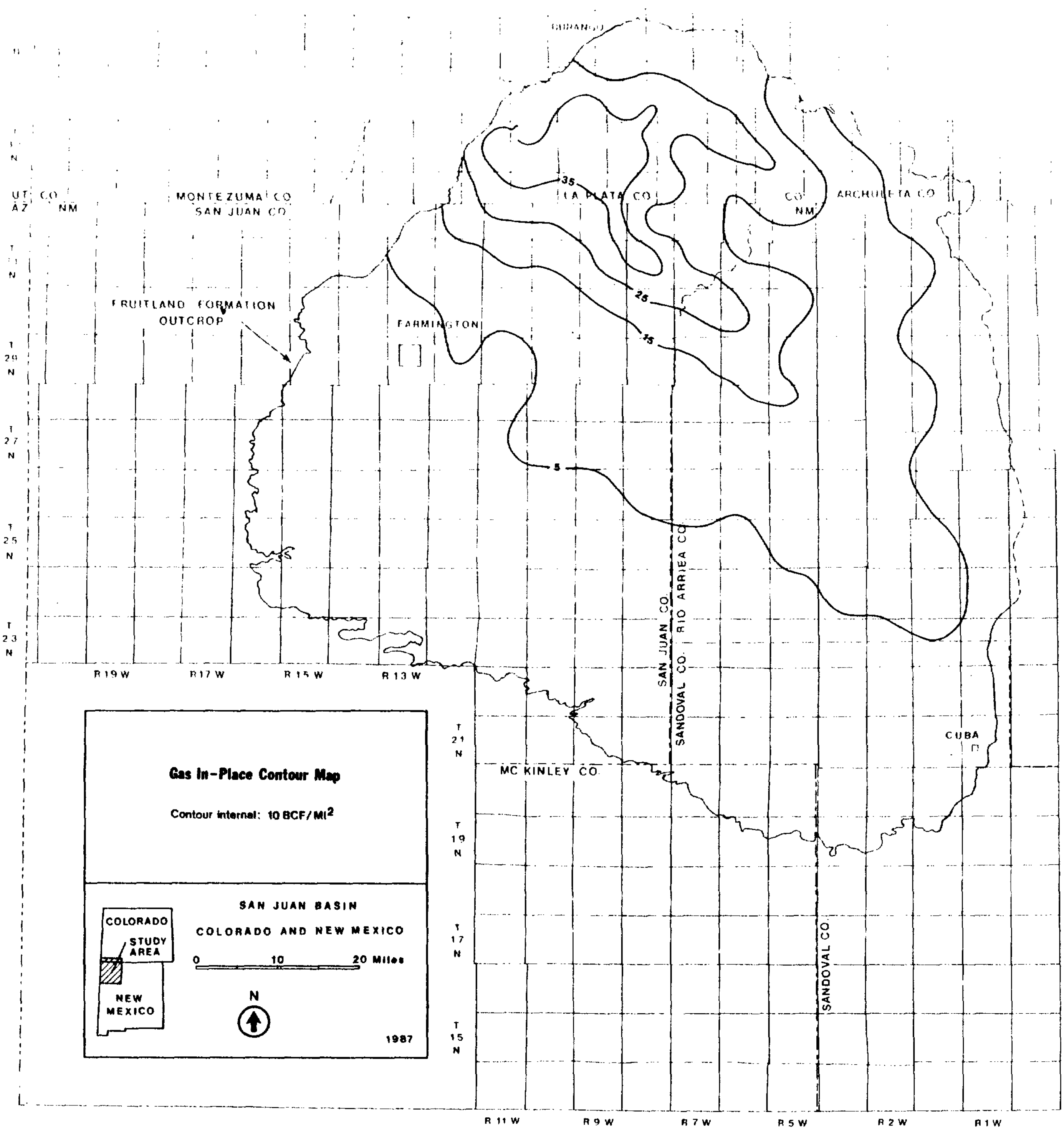
The timing of coal digenetic and catagenetic history may be identified through use of a time-dependent, three-dimensional mathematical model to simulate gas generation dependence on variables such as sedimentary burial rate, paleotemperature, paleopressure, thermal conductivity and heat flow. The simulation initially requires the computation of three-dimensional pore pressure in sediments as a function of time. The system assumes that the inflow-outflow is equal to the net accumulation due to grain and fluid compressibility plus the net accumulation to change in sediment density, rate of sedimentation and change in water depth[12]. The next step of the simulation is evaluation of the simultaneous transfer of heat by conduction and convection[13]. In this step, thermal parameters of the evolving system are particulary sensitive to pressure and temperature. The third step in thermal modeling is relating temperature to specific geologic periods. Lopatin[14] determined for coalification reactions, the reaction rate doubles with each increase of 10°C. He further related time and temperature by specifying a geologic time period with 10°C intervals as follows:

$$TTI = T_1 G_1 + T_2 G_2 + T_n G_n$$

where: TTI = Time Temperature Index
T_1 = Temperature Correction Factor
G_1 = Geologic Heating Time

Next, a correlation between vitrinite reflectance is incorporated as a maturity indicator and the TTI is established. The relationship between vitrinite reflectance (Ro) and the time-temperature index is:

$$R_o\% = 1.301 \lg TTI - 0.5282...$$



UT CO
AZ NM
MONTEZUMA CO
SAN JUAN CO
LA PLATA CO
CO
NM
ARCHULETA CO
FRUITLAND FORMATION
OUTCROP
FARMINGTON
35
25
15
5
SAN JUAN CO.
RIO ARRIBA CO.
SANDOVAL CO.
MC KINLEY CO.
CUBA
T 29 N
T 27 N
T 25 N
T 23 N
T 21 N
T 19 N
T 17 N
T 15 N
R 19 W
R 17 W
R 15 W
R 13 W
R 11 W
R 9 W
R 7 W
R 5 W
R 2 W
R 1 W
Gas In-Place Contour Map
Contour internal: 10 BCF/MI2
SAN JUAN BASIN
COLORADO AND NEW MEXICO
0
10
20 Miles
COLORADO
STUDY AREA
NEW MEXICO
N
1987

Figure 6.

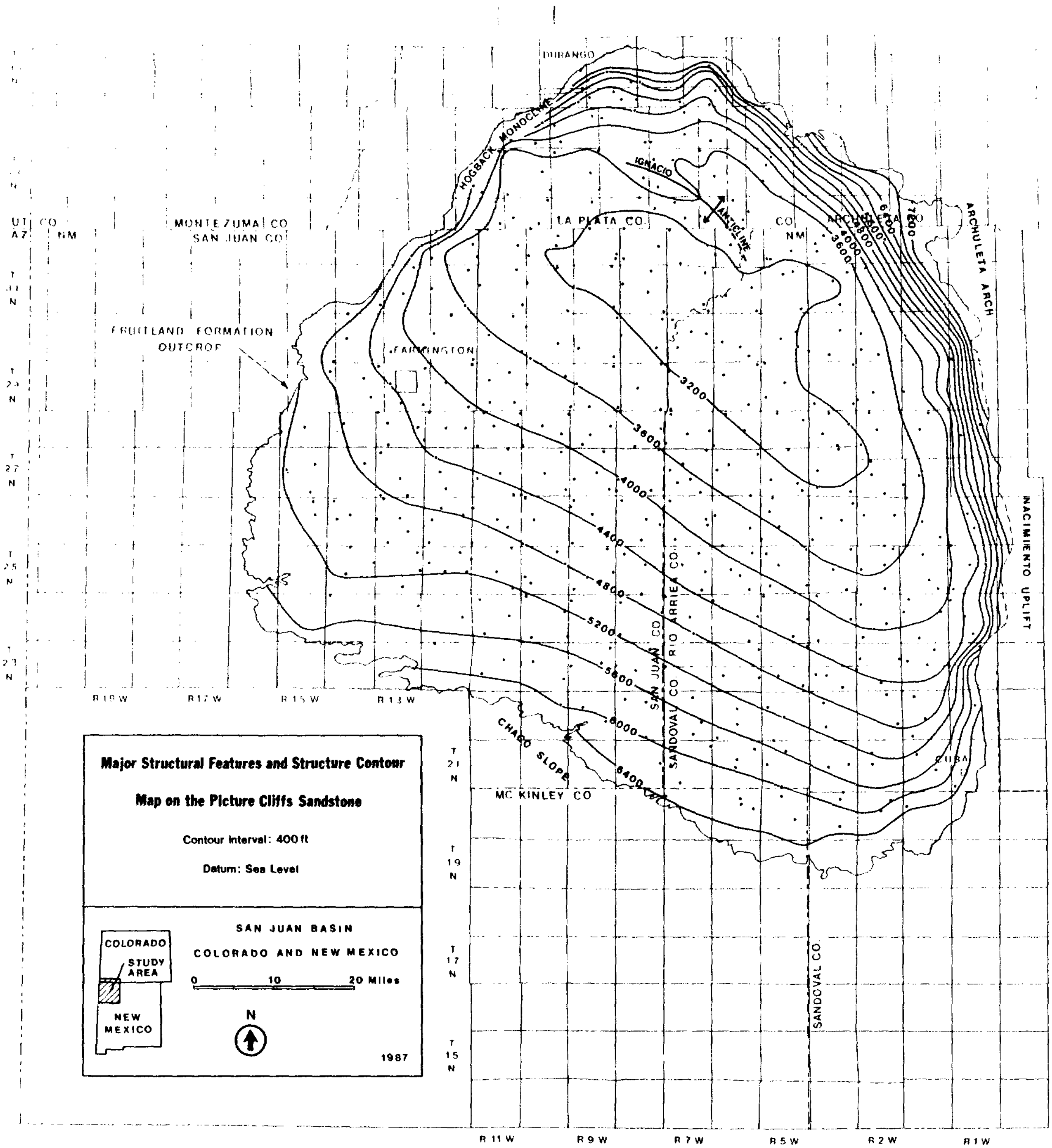

DURANGO
HOGBACK MONOCLINE
IGNACIO
ANTICLINE
LA PLATA CO.
ARCHULETA CO
ARCHULETA ARCH
NACIMIENTO UPLIFT
UT CO
AZ NM
MONTEZUMA CO
SAN JUAN CO
CO
NM
FRUITLAND FORMATION OUTCROP
FARMINGTON
3200
3600
4000
4400
4800
5200
5600
6000
6400
7600
SAN JUAN CO.
RIO ARRIBA CO.
SANDOVAL CO.
CHACO SLOPE
MC KINLEY CO
CUBA
R 19 W
R 17 W
R 15 W
R 13 W
R 11 W
R 9 W
R 7 W
R 5 W
R 2 W
R 1 W
T 21 N
T 19 N
T 17 N
T 15 N
Major Structural Features and Structure Contour Map on the Picture Cliffs Sandstone
Contour interval: 400 ft
Datum: Sea Level
SAN JUAN BASIN
COLORADO AND NEW MEXICO
0
10
20 Miles
N
COLORADO
STUDY AREA
NEW MEXICO
1987

Figure 3.

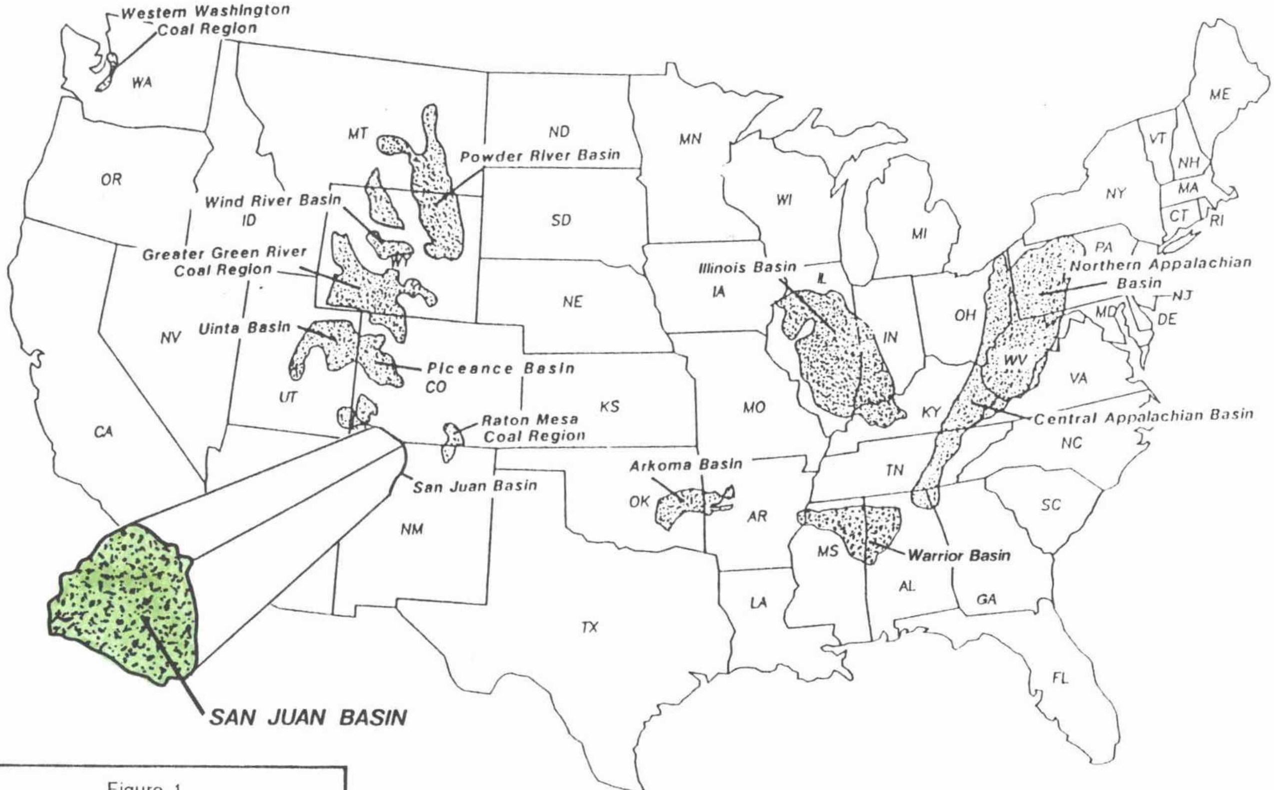
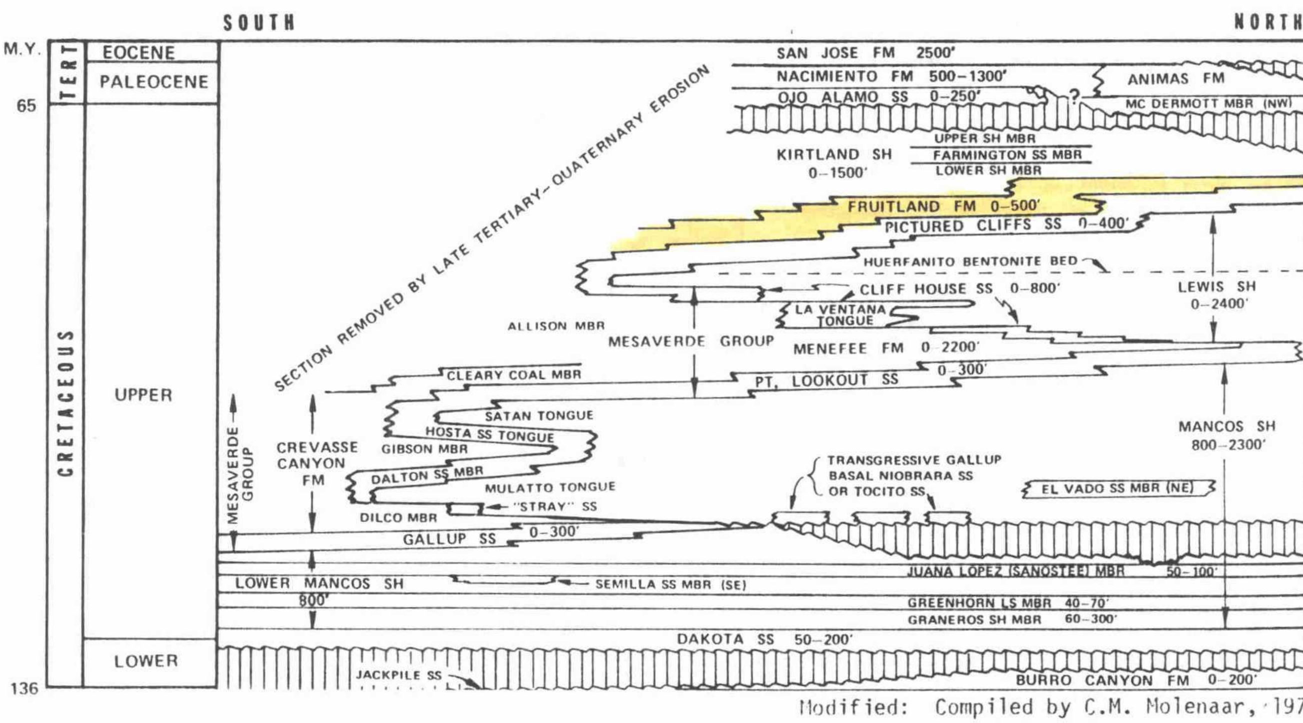


Figure 1

MAJOR COAL BASINS OF THE UNITED STATES

0 100 300
Miles

After: Rightmire, 1984.



Modified: Compiled by C.M. Molenaar, 1977.

Figure 2. San Juan Basin time - stratigraphic nomenclature chart.

9. McFall, K., Wicks, D., Kelso, B., Sedwick, K., and Brandenburg, C., "An analysis of the coal and coalbed methane resources of the Piceance Basin, Colorado", SPE/DOE Paper 16418, in Proceedings of the 1987 SPE/DOE Low Permeability Symposium, Denver, May 18-19, p. 283-295.

10. Averitt, P., "Coal resources of the United States, January 1, 1974", U.S. Geological Survey, Bulletin 1412, (1975), 131 p.

11. Koenig, Robert, In-situ, Inc., (1987) personal communication.

12. Jones, A.H., "Methane production characteristics of deeply buried coalbed reservoirs", Gas Research Institute Topical Report No. 85/0033, (March 1985), 176 p.

ranges from 20 to 68 feet, with the thickest individual coal seam being 42 feet. Coal rank is medium volatile bituminous and the area has an average measured gas content of 380 cubic feet/ton.

A research project was conducted at the Tiffany Gas, Glover #1 well in section 2, T32N, R6W, by Terra Tek, Inc., under GRI contract. The purpose of the project was to identify the resource potential and characteristics at a site, and provide the operator with a completion technique that would lead to economical production of Fruitland coalbed methane. Extensive work on reservoir characteristics was conducted and reported by Jones, 1985 [12]. A static reservoir pressure of 1483 psi or gradient of 0.48 psi/foot was measured at the site by In-Situ, Inc. This indicates an overpressured reservoir, at least in the southeastern corner of the study area. A measured permeability value of 3.5 md was obtained from coal samples and 1/4 inch cleat spacing was measured on recovered coal cores. As in Area 1 of the Ignacio Blanco Field, most of the wells in Area 2 produce significant volumes of water. Gas-in-place estimates for this area range from 14 to 45 BCF/section.

Completions of the 28 wells in this area are similar to those discussed in Area 1 of the Ignacio Blanco Field. Amoco has attempted recompletion on a number of the Perlman wells, but production data is not yet available. A variety of completion and stimulation methods have been applied to wells in this area and no single method provides better results than another.

CONCLUSION

The following conclusions have been drawn from the regional geologic analysis and detailed field site investigations of this coalbed methane resource study:

- This extensive subsurface geologic analysis provides a foundation for additional research and development of the Fruitland Formation coalbed methane resource.
- Additional measured gas content data is needed for assessment of the resource.
- It is estimated that the Fruitland Formation coals contain 56 trillion cubic feet of natural gas.
- Lower Fruitland coals at the four field investigation sites are overpressured.
- Permeability measurements at two locations in the Ignacio Blanco Field are low and measurements are not available for the Cedar Hill and the Undesignated Fruitland Fields. Structural enhancement of permeability may exist within all four fields. Fracture and lineament studies are needed for possible identification of enhanced areas.
- Numerous well completion and stimulation methods have been utilized with varying degrees of success.

ACKNOWLEDGEMENTS

The Gas Research Institute (GRI) has sponsored a geologic and economic analysis of the Fruitland Formation coalbed methane resource under its Natural Gas Supply Program. This effort is part of a much larger economic evaluation of recoverable coalbed methane in the San Juan Basin and other U.S. coal basins. The scope of the program is in support of GRI's goal of adding low cost gas to the United States gas supply reserves through research and development. The authors of this paper wish to thank the Gas Research Institute for their support of this project and for their permission to publish the findings.

References

1. Fassett, J., "The non-transferability of a Cretaceous coal model in the San Juan Basin of New Mexico and Colorado", in Paleoenvironmental and Tectonic Control of Coal-Forming Basins of the United States, Geological Society of America Special Paper 210, (1986), p. 155-171.
2. Kelly, V.C., "Tectonics of the San Juan Basin", in Guidebook of the south and west sides of the San Juan Basin, New Mexico and Arizona, New Mexico Geological Society, 2nd Field Conference, (1951), p. 124-131.
3. Woodward, L. and Callender J., "Tectonic framework of the San Juan Basin", in Guidebook to the San Juan Basin III, New Mexico Geological Society, 28th Field Conference, (1977), p. 209-212.
4. Fassett, J.E. and Hinds, J.S., "Geology and fuel resources of the Fruitland Formation and Kirtland Shale, of the San Juan Basin, New Mexico and Colorado", U.S. Geological Survey Professional Paper 676, (1971), 76 p.
5. Choate, R., Lent, J., and Rightmire, C.T., "Upper Cretaceous geology, coal, and the potential for methane recovery from coalbeds in the San Juan Basin-Colorado and New Mexico", in Coalbed Methane Resources of the United States, Am. Assoc. of Petroleum Geologist Studies in Geology Series #17, (1984), p. 185-222.
6. Kelso, B., Goolsby, S., and Tremain, C., "Deep coalbed methane potential of the San Juan River Region, southwestern Colorado", Colorado Geological Survey Open-File Report 80-2, (1980), 56 p.
7. Rice, D., "Relation of natural gas composition to thermal maturity and source rock type in San Juan Basin, northwestern New Mexico and southwestern Colorado", Am. Assoc. Petroleum Geologists Bull., v. 67 no. 8, (August 1983), p. 1199-1218.
8. Diamond, W.P. and Levine, J.R., "Direct method determination of the gas content of coal: Procedures and results", U.S. Bureau of Mines, Report of Investigation No. 8515, (1981), 36 p.

initial wells. No permeability data was available for any of the coal seams in the field. A gas-in-place estimate of 5 to 35 billion cubic feet/section (BCF/sec.) was calculated for the Cedar Hill Field.

Analysis of the completion histories of eight Amoco Production Company wells in the field showed that five were completed open-hole and three were completed through pipe with stimulation. Both completion techniques have proven successful and a conclusion can not be drawn on the best method of completion. Five of the eight wells are completed in a single seam and the remaining three are multiple seam completions. One conclusion drawn from this geologic and reservoir study is that the Cedar Hill Field area is overpressured.

Undesignated Fruitland Field

The Undesignated Fruitland Field is located in Township 30 North, Range 7 West. The field contains four coalbed methane wells with production histories dating from early 1986. This field, much like the Cedar Hill Field, shows very little structural relief on the Pictured Cliffs Sandstone. Structural relief does not exceed 80 feet across the area and a northwest-southeast structural trend is present. Structural closures of small magnitude exist along the trend. Net coal thickness ranges from 36 to 75 feet and approximately 95 percent of the coal occurs within 100 feet of the Pictured Cliffs. The thickest single seam in the area is 30 feet and the coal is ranked high volatile A bituminous. There are no measured gas contents in the study area. Therefore, data from the Cedar Hill Field, based on similar coal rank and depths, were used for this parameter.

Reservoir pressure data in the area range from 1332 to 1521 psi which converts to gradients of 0.45 to 0.50 psi/foot. Based on this data, the area is overpressured. Reservoir temperatures range from 93 to 112 degrees Fahrenheit in the lower Fruitland interval. This field appears to contain both gas and water saturated coal seams. One well in the area exhibits a predominantly gas-saturated coal seam, as shown by recent decreases in gas production and unchanged water production rates. There is no permeability data available for the coal reservoirs in the study area. The gas-in-place resource estimate for the Undesignated Fruitland Field, assuming similar gas content data for the Cedar Hill Field, ranges from 16 to 38 BCF/sec.

The four coalbed methane wells in the field were drilled by Meridian Oil Company. Two are completed open-hole with production liners and two are completed through casing. Three of the four wells have been stimulated. All of the wells have multiple coal seam completions and net coal thickness ranges from 43 to 63 feet per well. One of the open-hole completion wells has had tremendous gas production rates, at times exceeding 4 million cubic feet per day (MMCF/d). The worst well in the field only averages 150 thousand cubic feet per day (MCF/d). The remaining two wells have production rates ranging between 1 and 2 MMCF/day.

Ignacio Blanco Field

The Ignacio Blanco Field encompasses most of the Colorado portion of the basin. Two areas within the field were selected for detailed site investigations. It should be noted that the majority of the coalbed methane wells in the two areas were initially drilled and completed by William Perlman between 1982 and 1984. Amoco Production Company recently took over the Perlman acreage and recompleted a number of the wells in 1986 and 1987. Preliminary production statistics from recompleted wells indicate improvement over past production.

<u>Area 1 - Township 34 North, Range 8 West.</u> Area 1 contains 18 Fruitland coalbed methane wells with erratic production histories dating back to 1982. There is 1100 feet of structural relief across the area with structural lows and possible closures located in the southern half. A stratigraphic rise of the Pictured Cliffs Sandstone and intertonguing with the Fruitland Formation is located in the north and west portions of the study area. Net coal thickness throughout the area ranges from 26 to 76 feet with the thickest individual seam being 35 feet. The coal is ranked medium and low volatile bituminous and gas contents from five samples average 315 cubic feet/ton.

This area contains the two Southern Ute Indian, Oxford wells in section 25, which were part of a Department of Energy (DOE) coalbed methane research project. The coring of these wells revealed 1/4 to 1/2 inch cleat spacing. The Oxford #2 well was used in 1985 by In-situ, Inc., a GRI contractor, for reservoir data analysis. In-situ, Inc. determined a static reservoir pressure of 1490 psi or a gradient of 0.52 psi/ft and a calculated permeability of 5 md [11]. Reservoir temperature data across the area, for the lower Fruitland Formation ranges from 100 to 128 degrees Fahrenheit. The pressure data from In-situ's research and from additional Fruitland Formation drill-stem test data indicate that the southern region of the study area is overpressured. All of the coalbed methane wells produced significant volumes of water in the field. A gas-in-place estimate of 18 to 52 BCF/section is estimated for this area.

Completion methods of the 18 wells in the area included cased and open-hole, with stimulated and unstimulated examples of each. No one method has proven more successful than another and erratic production histories from the wells make it difficult to draw a completion/production history conclusion. As noted before, Amoco has recompleted 6 of the 18 wells in the area with small to moderate size sand/water stimulations. Production data from the recompleted wells is not yet available, but will be valuable for additional analysis.

<u>Area 2 - Township 32 and 33 North, Range 6 West.</u> Area 2 of the Ignacio Blanco Field contains 28 coalbed methane wells. A maximum of 350 feet of structural relief is found in the area and a structural nose is located in the northwest portion of the area. A north-south trend of structural depressions is located along the western edge of the area. Net coal thickness

analog curves were founded on the results of similar analyses in a Piceance Basin study [9]. The mathematical relationship that resulted from the analysis is:

$$GC = m * (\ln d) + b \quad \text{.......... } 2$$

Where: GC = Gas content (cubic feet/ton)
m = Scaling coefficient
ln d = Natural log of depth (feet)
b = y intercept

GAS IN-PLACE OF THE FRUITLAND COALS

The regional geologic evaluation of the Fruitland Formation coals, San Juan Basin, concluded with a gas-in-place resource estimate. The unit of analysis is a township and range and a gas-in-place value was calculated for each of the 210 units in the study area. Elements of the gas-in-place calculation are gas content, net coal thickness, drillable area, and coal density.

Each of the 210 units was assigned an estimated gas content value using the mathematical relationship discussed previously. Depths used in the calculation were average maximum overburden on the Pictured Cliffs Sandstone. Analysis of the vertical distribution of Fruitland coals showed more than 85 percent of the net coal thickness is within 200 feet of the Pictured Cliffs. Insignificant differences result in gas content values when depth values are varied within this 200 foot range.

Net coal thickness and coal density are factors in the coal resource portion of the gas-in-place calculation. An average net coal thickness was determined for each unit from the coal isopach map constructed in the geologic evaluation. The coal rank map was used to assign coal density to the unit. Densities increase with rank as documented by Averitt, 1975 [10]. The following table shows the variation of coal density with rank used in this study.

Rank	Density (Tons/acre-foot)
High Volatile Bituminous (A, B, and C)	1800
Medium Volatile Bituminous	1850
Low Volatile Bituminous	1900

The drillable area of a unit is determined by totaling the number of acres in the unit and subtracting undevelopable acreage. Undevelopable acreage includes areas with urban development; abandoned, active or permitted coal mining operations; acreage already containing coalbed methane wells; and areas of insufficient coal overburden (gas containment) or coal thickness.

Gas-In-Place Estimate

The total gas-in-place resource estimate for the Fruitland Formation coals is 56 trillion cubic feet (TCF). This is only a resource estimate, not a reserve estimate and no recovery factor has been applied. It must be pointed out that up to this point, we have only been discussing gas in the micro-pore system of the coals and not dealt with "free" gas or gas in the cleat system of the coals. Calculation of the gas in the cleat system will be based on the results from history matching work and is expected to increase the current gas-in-place estimate by 2 to 3 percent. Figure 6 is a gas-in-place contour map for the Fruitland Formation coals.

The 56 TCF gas-in-place estimate is nearly twice the estimate previously reported by Choate and others, 1984 [5]. A comparison of the two estimates revealed that coal resource values used for each were within 10 percent. The conclusion was drawn that gas content data in the two studies were drastically different. Analysis of the data set used by Choate showed the use of fewer core desorption data and a large percentage of chip desorption samples. This explains the increase in the gas-in-place estimate resulting from this study.

DETAILED FIELD INVESTIGATIONS

Four sites located in three coalbed methane production fields were selected for detailed geologic and reservoir analysis. The number of completed wells in each area and their production histories aided in site selection. Figure 4 shows the location of the four sites studied. They are the Cedar Hill Field, New Mexico; an Undesignated Fruitland Field, New Mexico; and two sub-areas of the Ignacio Blanco Field, Colorado. The primary purpose of the field site investigations was to validate the regional geologic study at a field level. In addition, the field investigations incorporated production data into the geologic analysis and established the stratigraphic intervals contributing to the Fruitland coalbed methane production.

Cedar Hill Field

The Cedar Hill Field is located in portions of Townships 31 and 32 North, Range 10 West. Development of the coalbed methane resource in this area was initiated more than ten years ago and presently, the field contains 12 coalbed methane wells. A structure map on the Pictured Cliffs Sandstone for the area shows a maximum of 100 feet structural relief with a series of subtle northeast-southwest trends. Most of the structures in these trends exhibit relief of 20 feet or less. Net coal thickness across the area ranges from 9 to 55 feet. A coal in the basal section of the Fruitland Formation has been the primary production target and thickness ranges from 5 to 27 feet. This seam thins and splits to the southeast. The coal rank in the area is high volatile A bituminous and gas contents average 358 to 521 cubic feet/ton from four samples.

The reservoir parameters assessed in this evaluation are pressure, temperature, saturation, permeability and a gas-in-place estimate. Three bottom hole pressures were available from public records. They range from 1362 psi to 1590 psi or 0.49 to 0.56 psi/foot and indicate an overpressured coal reservoir. Reservoir temperatures of the basal coal ranged from 95 to 114 degrees Fahrenheit. Reservoir saturation status for this area is unknown and based on production histories of the earliest wells, 100 percent water saturation was assumed. Wells drilled at later dates were probably less than 100 percent water saturated and were partially dewatered by the

Stratigraphic Cross-Sections

Two regional, basin-wide, geologic cross-sections were constructed with density-porosity or gamma-density geophysical logs. (Figure 4). Both were segmented due to the length of the sections and the number of logs used. Section A-A", trending northwest to southeast, is parallel to the depositional strike of the Pictured Cliffs strandline. Section B-B" is constructed perpendicular to depositional strike, or southwest to northeast. Orientation of the cross-sections was designed to support the concept that coals parallel to depositional strike can be followed for greater distances than those perpendicular to strike. Interpretations of the cross-sections were used to understand the lateral continuity of the Fruitland coals and to determine if the Fruitland Formation could be divided into zones, based on vertical coal distribution.

In cross-section A-A", the Fruitland Formation thins from the northwest to the southeast. Maximum thickness is greater than 450 feet. Thinning of the Fruitland in the southeast to less than 100 feet is the result of erosion and a stratigraphic rise of the Pictured Cliffs [4], as seen on the cross-section. Coals are found at depths ranging from 2400 to 4200 feet, with the deeper coals along the southeast extension of A-A". Maximum net coal thickness and thicker individual seams are located on the northwest extension of this cross-section with net coal thickness ranging from 4 to 95 feet, and frequent 20 foot individual seams. The spacing between control points averages 5 miles and correlation of individual beds was not possible at this scale. No grouping or zone determination was established due to the lack of traceable markers.

The cross-section B-B" trends southwest to northeast and shows minor thickness variations in the Fruitland ranging from 200 to 350 feet. A stratigraphic rise is present to the northeast, approximately 10 miles south of the Colorado-New Mexico state line. Coals on the southeast end of the cross-section are located at 1100 foot depths and gradually deepen towards the basin's center, with the deepest coals found at 4000 feet. Net coal thickness ranges from 19 to 67 feet with a single seam of 40 feet found near the northeast limit of the cross-section. Most wells used in this cross-section have a well developed coal in close proximity to the Pictured Cliffs. These basal coals range from 8 to 40 feet in thickness and are sometimes correlative over many miles. The average spacing between wells on section B-B" is 5 miles and no correlation of individual beds was attempted. As with A-A", no division of the Fruitland Formation into coal groups or zones was made.

Net Coal Thickness and Overburden

A Fruitland Formation net coal isopach map was constructed using data from gamma-density, density-porosity, and a limited number of gamma ray-neutron geophysical logs (Figure 5). Net coal values do not include coals thinner than 2 feet with efforts made to exclude partings and shaley units within individual coals. Net coal thickness values ranged from 0 to greater than 100 feet. An eastern area of the basin exhibits 0 net coal values which are the results of non-desposition and erosion of the Fruitland. The maximum net coal values are found in the northwest part of the basin with net thickness exceeding 100 feet. An approximate 10 mile wide, northwest trend is observed in the north central portion of the basin. This trend is parallel to the structural axis of the basin with average net coal thicknesses of 70 to 80 feet. It can be generally stated that the southern end of the basin has less than 30 feet of net coal, with the exception of a small area in the southwest. Net coal values and the geologic cross-sections were used to determine the lateral and vertical distribution of coals in the Fruitland.

The overburden map or depth parameter of the Fruitland coals in the regional geologic analysis was utilized as part of the gas content and containment evaluation. Depths of coals range from 0 feet at the basin's outcrop to more than 4200 feet along the basin's structural axis. Depths change rapidly along the north, northeastern, and northwestern margins of the basin due to the structural monoclines. In the southern part of the basin, coal depths gradually increase as the structural slope increases to the northeast. The deepest coals are found in the northeastern quarter of the basin.

Coal Rank

Fassett and Hinds, 1971 [4] reported the coals of the Fruitland Formation as subbituminous. Support for their conclusion comes from an observation of the weathering nature of the coals when mined and stockpiled. Viewing the coals as a reservoir for natural gas requires a different approach to rank assessment. The approach used in this study was based on the thermal maturity of the coals, which is measured by the vitrinite reflectance. This approach is applicable to all coal basins. Rank generally increases from south to north, with the highest ranks found in the north central portion of the basin. A vitrinite reflectance rank map of the San Juan Basin (Rice, 1983) [7] was modified with additional data and used to establish the various Fruitland coal ranks, ranging from high volatile C bituminous to low volatile bituminous with 0.46 to 1.51 reflectance values.

GAS CONTENTS OF FRUITLAND COALS

A moderately small public domain database of measured gas contents exists for the Fruitland Formation coals. The primary source of the data was the U.S. Bureau of Mines (USBM) gas content measurement database for samples from around the United States. A description of the desorption process and a partial list of samples is found in Diamond and Levine, 1981 [8]. Additional desorption data were acquired from the Colorado Geological Survey.

Twenty-eight data points were standardized for ash content, temperature, and pressure. The data was sorted by coal rank and sample depth to develop correlations relating gas content to depth and rank. Curves were established for high volatile A bituminous and high volatile B and C bituminous coals combined. Insufficient data was available for medium and low volatile coals and lagoons, marshes, swamps and abandoned channels and are overlain by fluvial shales and sandstones. The coals are the most correlative units of the fluvial Fruitland sediments.

The underlying Pictured Cliffs is a regressive, coastal-barrier sandstone. Formation thickness varies from 125 to 400 feet due to minor transgressive episodes, which locally intertongue the Fruitland and Pictured Cliffs. The lower portion of the Pictured Cliffs is primarily interbedded sandstone and shales, with the upper unit a quartzitic, fine-to-medium grained sandstone.

Structure

The San Juan Basin's arcuate structural axis lies just south of the Colorado-New Mexico state line. The U-shaped Hogback Monocline forms the western and northern rims of the basin. To the east, the Nacimiento Uplift and Archuleta Arch bound the basin. The south and southwestern boundaries of the basin are not structurally defined and sediments gently dip northward from the Chaco Slope (Figure 3).

There are few major structural elements within the San Juan Basin and most are of Laramide age. The Ignacio Anticline, located in the north central portion of the basin, is the largest and best documented structure. Minor northwest trending en echelon folds and northeast-trending, high angle, low displacement faults are found on the eastern and southeastern edges of the basin. Radial folds, which plunge toward the basin's center, can be found around the perimeter. Minor structures resulting from Tertiary intrusive activity are located in the basin. Kelly, 1951 [2] and Woodward and Callender, 1977, [3] provide complete structural and tectonic descriptions of the San Juan Basin.

Detailed Field Investigation Settings

The four field investigation sites are located in the northern end of the basin where operator activity levels have been concentrated (Figure 4). The sites selected provide wells with production histories over extensive time periods and all four sites lack major structural features. Two sites are located in the Colorado Ignacio Blanco Field and one each in the New Mexico Cedar Hill and Undesignated Fruitland Fields. Site 1 of the Ignacio Blanco Field and the Undesignated Fruitland Field are in areas of a Pictured Cliffs stratigraphic rise, that is, an area of intertonguing with the Fruitland. The other two sites are stratigraphically less complex.

METHODOLOGY

The geologic evaluation of coal bearing formations is a key element in an economic appraisal of any coalbed methane resource. The San Juan Basin provided an opportunity for detailed geologic field investigations as well as a regional scale study, because of the large number of exploration control points and Fruitland coalbed methane tests. The purpose of the regional geologic investigation was to determine a gas-in-place resource estimate for the Fruitland Formation coals. The detailed geologic field studies were performed to analyze the geology and reservoir properties associated with producing coalbed methane wells, and for use in the regional economic evaluation of the basin.

The regional geologic evaluation consisted of the construction of two geologic cross-sections and the interpretation of several thousand geophysical logs for subsurface geologic data. The cross-sections provided insight into the lateral and vertical distribution of the Fruitland coals. The subsurface geophysical log data were used to construct structure, overburden, and net coal thickness maps associated with the Fruitland Formation and underlying Pictured Cliffs Sandstone.

The geology and coal resources of the Fruitland Formation have previously been documented [4] and other coalbed methane resource estimates have been based upon this work [5,6]. In order to independently evaluate the Fruitland coalbed methane resource, an original investigation of Fruitland coal resources was conducted.

After the resource and distribution of Fruitland coals was determined, an emperical formula was derived using measured gas contents, depth, and coal rank. The formula allowed projection of gas contents into areas lacking measured data. Gas-in- place estimates were then calculated on a township and range basis using the following equation.

$$GIP = GC * h * A * p \quad (1)$$

Where: GIP = Gas in-place (trillion cubic feet)
GC = Gas content (cubic feet/ton)
h = Net coal thickness (feet)
A = Drillable area (acres)
p = Coal density (tons/acre-foot)

The gas-in-place values for 210 townships with sufficient coal thickness and depth of cover were summed to derive the Fruitland Formation gas-in-place resource estimate.

Four detailed field investigation sites in three producing fields were chosen in areas with sufficient coalbed methane well populations for analysis. Detailed geologic cross-sections and subsurface structure and net coal thickness maps were prepared for each area. In addition to the geologic data, reservoir data including pressure, temperature, permeability (very little data), and cleat spacing were collected. Drilling, completion and production history data for each coalbed methane well in the four areas were also compiled. An analysis of the geologic, reservoir and completion data is being performed in an attempt to establish trends between the reservoir data and production histories.

REGIONAL GEOLOGIC ANALYSIS

The primary products of the regional geological analysis are two cross-sections, a net coal isopach map, an overburden map of the Fruitland-Pictured Cliffs contact, and a thermal maturity rank map. All of the products were used to evaluate the geology and properties of the coals necessary to determine a gas-in-place estimate.

Proceedings of the 1987 Coalbed Methane Symposium, Tuscaloosa, Alabama, Nov. 16-19, 1987

THE 1987 COALBED
METHANE SYMPOSIUM

8731 GRI Geologic and Economic Appraisal of Coalbed Methane in the San Juan Basin

B.S. Kelso (Colorado Geological Survey); A.D. Decker (Resource Enterprises, Inc.); D.E. Wicks (Lewin & Associates, Inc.); D.M. Horner (Gas Research Institute)

ABSTRACT

A regional geologic assessment of the Fruitland Formation coals in the San Juan Basin indicates that this formation has a high potential for natural gas production from coal seams. This study, sponsored by the Gas Research Institute, includes subsurface structure, depth, thickness, and geometry interpretations. Coal ranks were assessed using vitrinite reflectance data and gas contents were compiled from public databases.

In addition to the regional geologic investigation, four sites were chosen for detailed field-level geologic and reservoir analyses. The geologic assessment employed cross-sections, net coal isopachs, and structure maps. Reservoir analyses included pressure, temperature, and permeability, in conjunction with coalbed methane well completion and production histories.

The regional geologic analysis concluded that the Fruitland Formation coals have an estimated in-place methane resource of 56 trillion cubic feet (TCF) - nearly double the previous estimate of 31 (TCF). Field-level investigations concluded that no single completion practice provided better production results than any other and overpressured reservoirs are significant contributing factors in the better producing wells.

An economic evaluation of the coalbed methane resource is due to be completed in early 1988.

INTRODUCTION

Activity of coalbed methane development is greater in the San Juan Basin than in other western coal basins. Production of the vast coalbed methane resource of the Fruitland Formation dates back to 1953, with the Phillips Petroleum Co., No. 6-17, San Juan 32-7 Unit well. More recent activity, specifically directed at resource development, started in the mid-1970's. To date, more than 200 wells have been documented as Fruitland Formation coalbed methane tests. Several pools or fields have been designated in the basin reporting Fruitland coal seams, or the "basal" Fruitland as the producing horizons.

The geologic analysis of the Fruitland Formation coalbed methane resource is part of a larger economic evaluation to determine recoverable coalbed methane in the San Juan and other U.S. coal basins. The San Juan Basin evaluation is divided into three phases: 1) a geologic appraisal of the Fruitland Formation coals, concluding with a gas-in-place resource estimate; 2) case history studies and history matching of Fruitland coalbed methane wells; and 3) an economic appraisal of the resource, using various technology cases. At this time, the regional geologic appraisal and four detailed field investigations have been completed. History matching of wells is underway and the economic evaluation has not been initiated. All three phases of the project will be completed by early 1988.

GEOLOGIC SETTING OF THE SAN JUAN BASIN

Regional Setting

The San Juan Basin is located in northwestern New Mexico and southwestern Colorado, with the study area of this project defined by the Pictured Cliffs Sandstone outcrop (Figure 1). It is approximately 90 miles wide, west to east, and 100 miles long, north to south and covers 7500 square miles.

Stratigraphy and Depositional Environments

The coals of the San Juan Basin are Cretaceous age and located in the Dakota, Mesaverde, and Fruitland formations (Figure 2). The Fruitland, the youngest of these, contains the largest coal resource. Deposition of the Fruitland coals occurred predominantly in lagoons, landward of the Pictured Cliffs barrier strandline. The thickest and most continuous seams are located in the lowermost 70 feet of the formation and are often associated with stratigraphic rises in the Pictured Cliffs. A detailed discussion of the Fruitland-Pictured Cliffs depositional environment is presented in Fassett, 1987 [1] and in the Fassett paper in this proceeding.

The Fruitland Formation is a coastal plain deposit of paludal carbonaceous shales, siltstones, sandstones and coals deposited behind the regressing Pictured Cliffs strandline. Formation thickness ranges from less than 100 to greater than 600 feet and contains evidence of fresh and brackish water environments. The sandstones are soft to hard and grey-white to brown in color. The shales are firm and grey to black in color. The coals were deposited in

FIGURE 9

PRESSURE - TEMPERATURE RELATIONSHIP

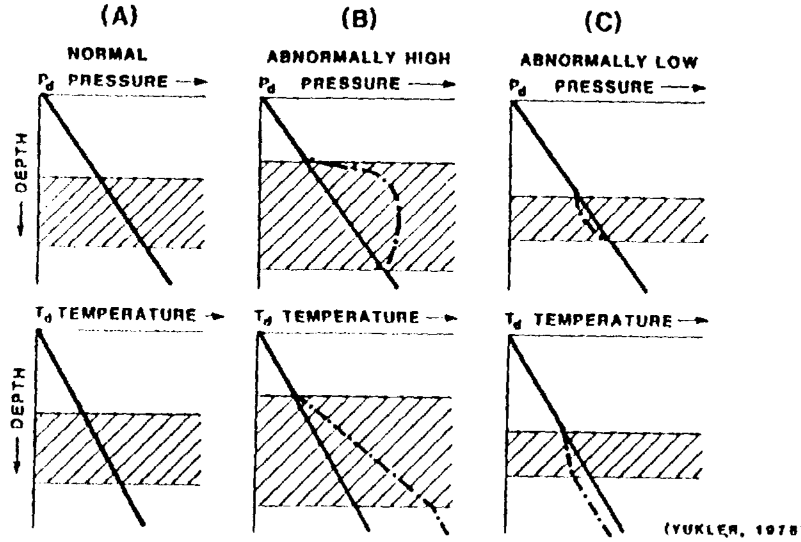
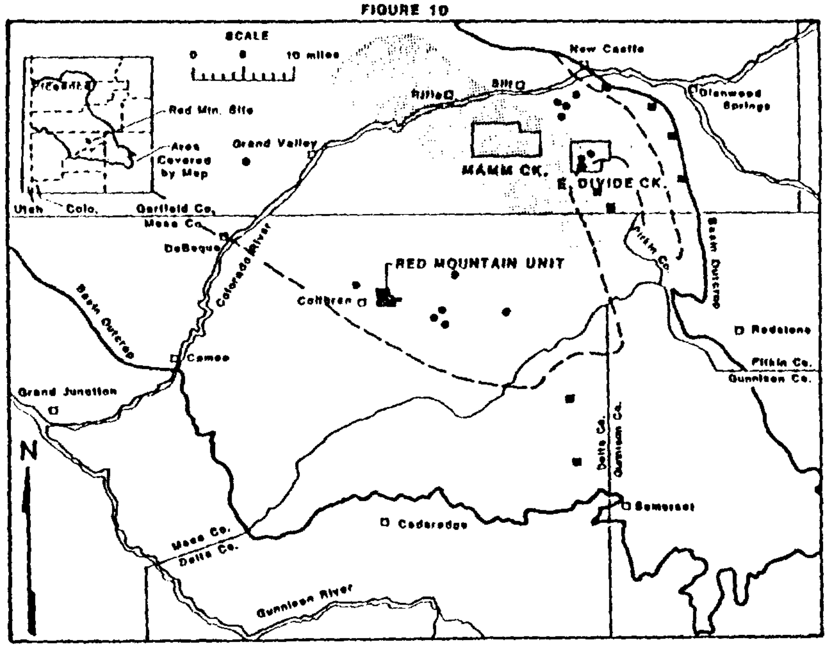


FIGURE 10



■ WATER SATURATED
• GAS SATURATED

GAS & WATER SATURATED
COALBED METHANE WELLS

OVERPRESSURED AREA

FIGURE 7

MATURITY vs. DEPTH

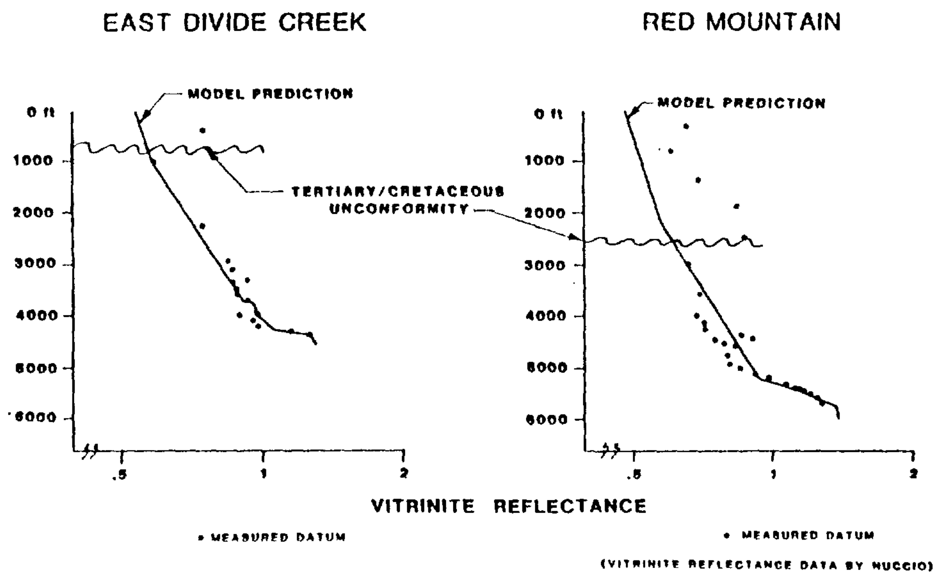


FIGURE 8

STATIC TEMPERATURE LOGS

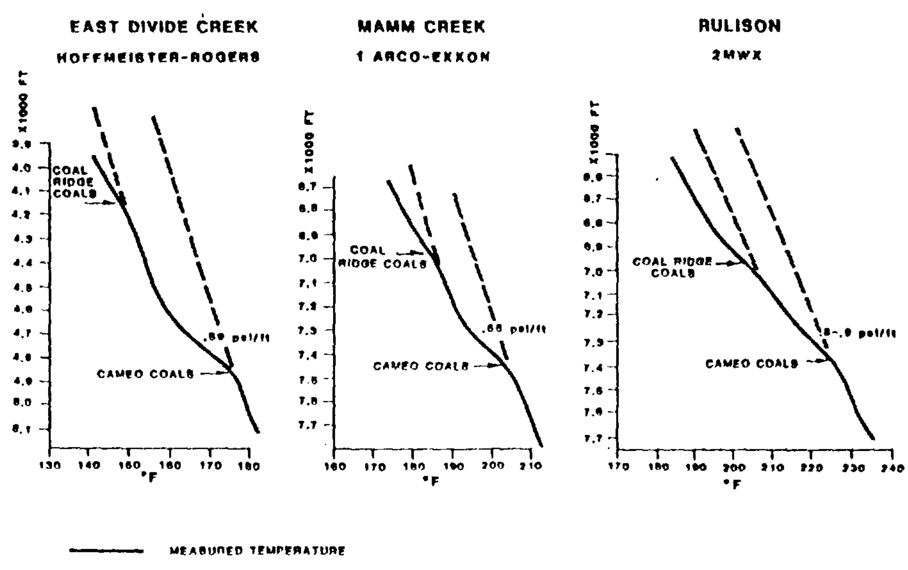
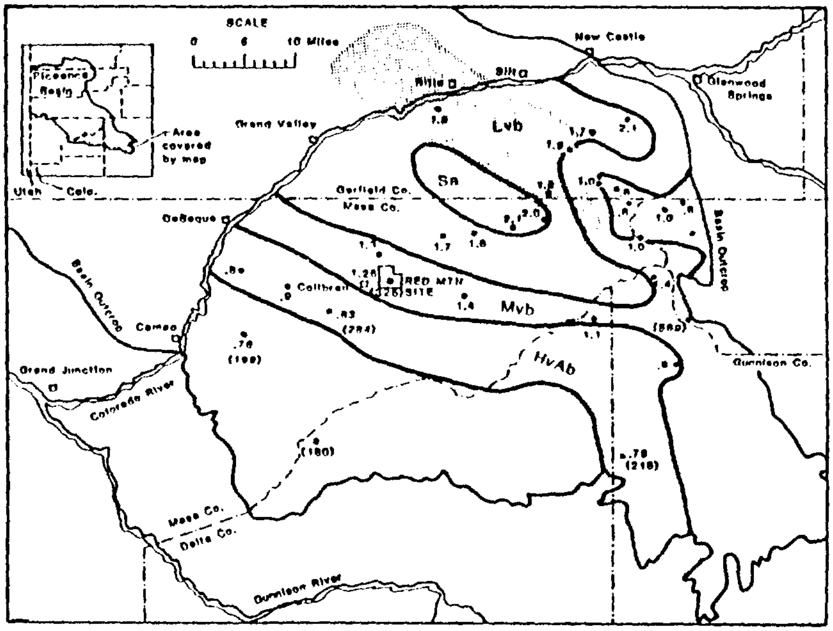


FIGURE 5



PICEANCE BASIN

• ISOREFLECTANCE CONTOURS ☐ OVERPRESSURED AREA

FIGURE 6

WATER AND THERMAL METHANE GENERATION AS A FUNCTION OF TIME AND COAL MATURATION

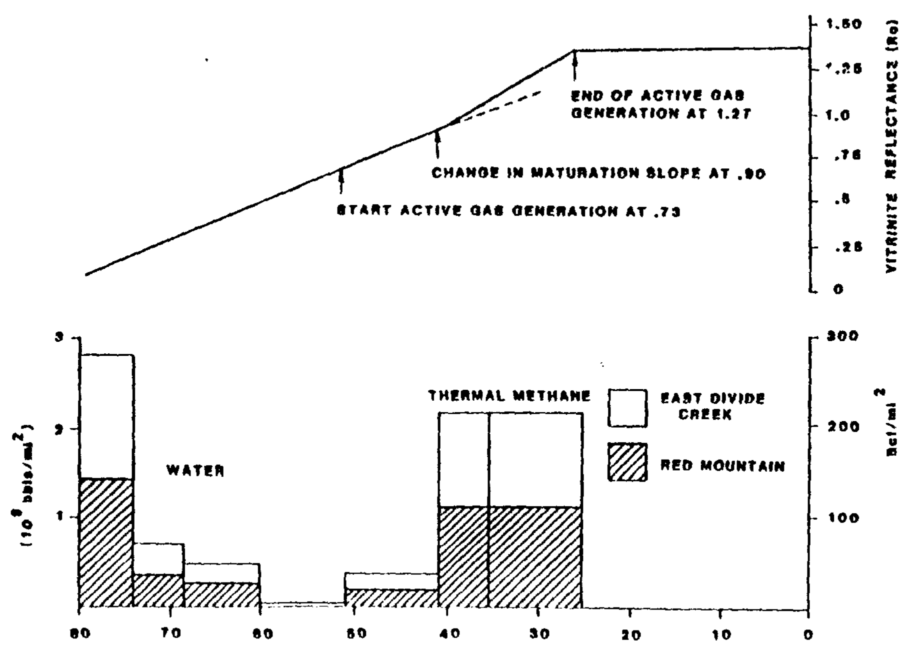
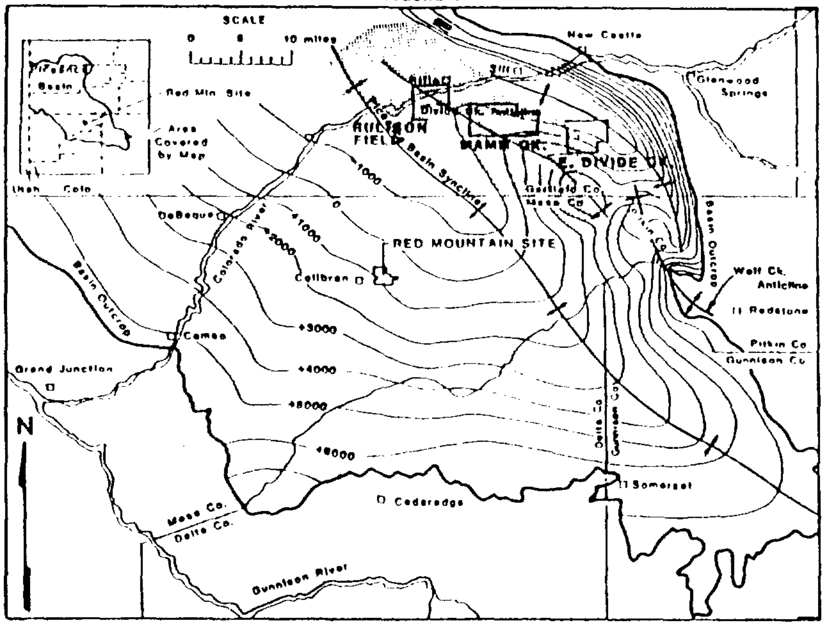


FIGURE 3

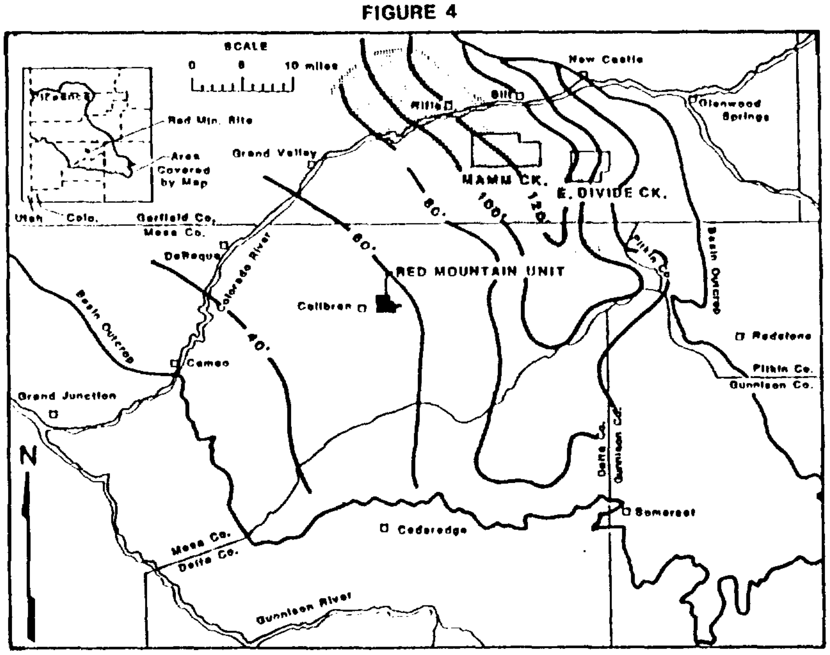


C.I.=1000'
SUBSEA ELEVATIONS

STRUCTURE CONTOUR MAP
TOP OF ROLLINS SANDSTONE
PICEANCE BASIN, COLORADO

☐ OVERPRESSURED AREA

FIGURE 4

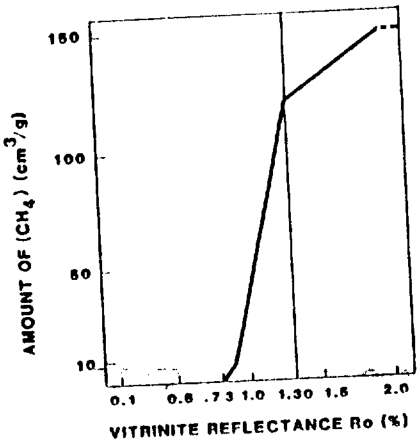


TOTAL COAL ISOPACH TREND MAP

☐ OVERPRESSURED AREA

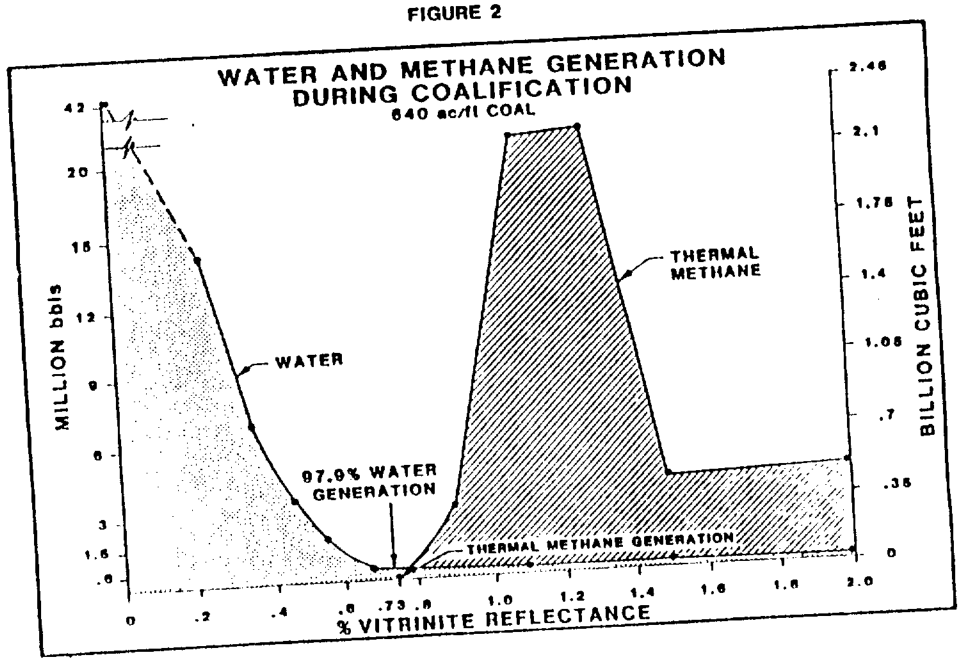
FIGURE 1

METHANE GENERATION



(AFTER WELTE, 1984)

FIGURE 2



23. Decker, A.D., et al.; 1987, Geochemical Techniqiues Applied to the Identification and Disposal of Connate Coal Water. The 1987 Coalbed Methane Symposium Proceedings, held at the University of Alabama, Tuscaloosa, Alabama, November 16-19, 1987.

21. Decker, A.D. and J.C. Seccombe, 1986, Geologic Parameters Controlling Natural Gas Production from a Single Deeply Buried Coal Reservoir in the Piceance Basin, Mesa County, Colorado: SPE Paper #15221, presented at Unconventional Gas Technology Symposium, May 1986.

22. McKee, C.R. et al., 1986, Using permeability vs-depth correlations to assess the potential for producing gas from coal seam: Quarterly Review of Methane from Coal Seams Technology, vol, 4, no. 1, p. 15-26.

TABLE 1

COAL VOLUMETRICS

Ro%	% F	COAL RANK	THERMAL METHANE (Bcf/Mi²)	WATER (10^6 bbl/mi²)	THICKNESS (FEET)	
		EARLY PEAT	-	42.0	7.0	DIAGENESIS
		PEAT	-	14.0	3.5	
.23	95					
		LIGNITE	-	6.8	2.4	
.36	122					
		SUB-C	-	3.6	1.8	
.43						
		SUB-B	-	2.3	1.4	
.47						
		SUB-A	-	1.6	1.4	
.51	158					
		HvBb	-	.56	1.2	
.76	196					
		HvAb	.37	.50	1.2	CATAGENESIS
.90						
		HbAb	2.14			
1.11	248					
		Mvb	2.16	.45	1.0	
1.30						
		Mvb	.47			
1.50	302					
		Lvb	.49	.34	1.0	
2.04	356					
		Sa	-	.25	1.0	META-GENESIS
2.7	392					
		TOTAL	5.63	72.42		

AFTER LAW, 1983

TABLE 2

COAL RESERVOIR AND GEOLOGIC PROPERTIES

RED MOUNTAIN UNIT AND EAST DIVIDE CREEK

	COAL THICKNESS (FT)	RANK (Ro)	GAS GENERATED (BCF/mi²)	IN PLACE (BCF/mi²)	EXPELLED (BCF/mi²)	DEPTH (FT)	TEMP °F	PRESSURE GRADIENT (PSI/ft)	PERMEA-BILITY (md)
RED MOUNTAIN 1 DEEP SEAM 32-2	51'	.90-1.27	238	18	220	5600'	164'	.33	<.01
EAST DIVIDE CK 1 CAMEO 20-4	100'	.90-1.27	467	35	432	4460'	176'	.59	>10.0

REFERENCES

1. Meissner, F.E., 1984, Cretaceous and Lower Tertiary Coals as Sources for Gas Accumulations in the Rocky Mountain Area: Hydrocarbon Source Rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists, Denver, Colorado, p. 401-432.

2. McPeek, L.A., 1981, Eastern Green River Basin: A Developing Giant Gas Supply from Deep, Overpressured Upper Cretaceous Sandstones: AAPG Bull., Vol. 65, p. 1078-1098.

3. Wyman, R.E., Gas Resources in Elmworth Coal Seams: Elmworth - Case Study of a Deep Basin Gas Field, AAPG Memoir 38, p. 173-189.

4. van Gijzel, P., 1982, Characterization and Identification of Kerogen and Bitumen and Determination of Thermal Maturation by Means of Qualitative Microscopical Techniques, in How to Assess Maturation and Paleotemperatures: SEPM Short Courses No. 7, p. 159-216.

5. Law, B.F. et al., 1983, Geologic Implications of Coal Dewatering: AAPG Bull., Vol. 67, p. 2255-2260.

6. Allardice, D.J., and D.G. Evans, 1971, The Brown Coal/Water System: Part 2; Water Sorption Isotherms on Bed Moist Yallourn Brown Coal: Fuel, V. 50, p. 236-253.

7. Juntgen, H. and J. Klein, 1975, Enstehung Von Erdgas Aus Kohligen Sedimenten: Erdol und Kohle, Erdgas, Petrochemie, Erganzungsband, V. 1, p. 52-69.

8. Allardice, D.J. and D.G. Evans, 1978, Moisture in Coal, in C. Karr, Jr., ed., Analytical Methods for Coal and Coal Products, V. I: New York. Academic Press.

9. Kim, A.G., 1977, Estimating Methane Content of Bituminous Coalbeds From Adsorption Data: U.S. Bureau of Mines Report of Investigations 8245, p. 22.

10. Kissev, F.N., C.M. McCulloch, and C.H. Elder, 1973, The Direct Method of Determining Methane Content of Coalbeds for Ventilation Design: U.S. Bureau of Mines Report.

11. Eddy, G.E., Rightmire, C.T., and C. Byrer, 1982, Relationship of Methane Content of Coal, Rank and Depth: Proceedings of the SPE/DOE Unconventional Gas Recovery Symposium, Pittsburgh, Penn., SPE/DOE 10800, p. 117-122.

12. Welte, D.H., et al., 1981, Application of Organic Geochemistry and Quantitative Analysis to Petroleum Origin and Accumulation - An approach for a Quantitative Basin Study, in G. Atkinson and J.J. Zuckerman, eds., Origin and Chemistry of Petroleum: Elmsford, NY, Pergamon Press, p. 67-88.

13. Stallman, R.W., 1963, Computation of Ground-Water Velocity from Temperature Data, in Methods of Collecting and Interpreting Ground-Water Data: U.S. Geological Survey Water - Supply Paper 1544-H. p.36-46.

14. Lopatin, N.V., 1971, Temperature and Geologic Time as Factors in Coalification: Akademiya Nauk, Uzb. SSSR, Ser. geologicheskaya, Izvestiya, No. 3, p. 95-106. (Translation by N.H. Bostick, Illirois State Geological Survey, February 1972).

15. Decker, D., 1985, Appropriate Stratigraphic Nomenclature for Coal Reservoirs in the Piceance Basin, Abstract Presented at the Rocky Mountain AAPG Convention, Denver, Colorado (June 1985).

16. Hanson, J.M., 1987, Evaluation and analysis of the response of "Cameo" and "Hoffmeister-Rogers" wells to solid earth tides and barometric pressure. Unpublished paper submitted to Resource Enterprises, Inc. under contract to GRI #5083-214-0844.

17. Waples, D.W., 1987, Maturity Modeling of the 1 Cameo 20-4 Well, Unpublished report submitted to Resource Enterprises, Inc.

18. Kappelmeyer, O., Haenel, R.: Geothermics--with Special Reference to Application. Berline-Stuttgart: Borntraeger, 1974.

19. Law, B.E., and V.F. Nuccio, "Segmented Vitrinite Reflectance Profile from the Deep Seam Project, Piceance Basin, Colorado--Evidence of Previous High Pore Pressure". Abstract presented at the Rocky Mountain AAPG Convention, Casper, Wyoming (Sept. 1986).

20. Yukler, M.A., 1976, Analysis of Groundwater Flow Systems and an Application to a Real Case, in D. Gill and D.F. Merriam, eds., Geomathematical and Petrophysical Studies in Sedimentology, Computery and Geology, V. 3: Elmsford, NY, Pergamon Press, p. 33-49.

21. Kelso, B.S. and A.D. Decker, et al., 1987, GRI Geologic Appraisal of Coalbed Methane in the San Juan Basin. The 1987 Coalbed Methane Symposium Proceedings, held at the University of Alabama, Tuscaloosa, Alabama, November 16-19, 1987.

22. Hays, J.B., 1979, Sandstone diagenesis- The hole truth. In: Aspects of Diagenesis. P.A. Scholle adn P.R. Schluger, eds., Soc. Econ. Paleontologists and Mineralogists, Spec. Publ. No. 26, pp. 127-139.

well documented[22] in detrital sequences. Coal seams bounded by impermeable shales would similarly develop high pore pressure due to the inhibited ability to expel water during compaction. Produced waters from both field contain 12,000 to 14,000 ppm sodium bicarbonate type coal water which is suggestive of sluggish or isolated reservoirs conditions. Coal derived should be a sodium bicarbonate water[23], however, the high levels measured at the Cedar Hill and San Juan 30-6 Unit indicates little dilution of connate water over time, supporting bounded reservoir conditions. In theory, incompressible water under high pressure could be acting as a hydraulic proping mechanisms in coal cleats limiting porosity and permeability reduction effects from lithostatic loading.

Overpressured coal reservoirs are a product of shale bounded coal seams during diagenetic compaction during water expulsion. The process is similar to the origin of overpressured shales and sandstone in the Gulf Coast region. To date, coalbed methane wells producing from deeply buried coal seams with high permeability and deliverability occurring in overpressured, water saturated areas of the San Juan and Piceance Basins. The simultaneous occurrence of overpressuring, water saturation and high permeability in coal seams is not thought to be coincidental but rather suggestive of a common relationship. That relationship could be quantified through integration of geologic and reservoir modelling using data collected from laboratory core measurements in conjunction with field level reservoir tests.

SUMMARY

Recognition of the geologic and resulting reservoir processes controlling gas production from deeply buried coals is the first steps in the formulation of an exploration strategy for coalbed gas. The dominant coal reservoir mechanisms affecting production include: permeability, reservoir pressure, saturation and gas-in-place[24]. The relationship between decreasing coal permeability with increasing depth has been described by McKee[25]. In order to overcome the inherent low coal permeability at depth, permeability enhancement through structural deformation should be sought. Utilizing fundamental relationships including Darcy's Law and equation of state, at a given permeability, overpressured coal reservoirs will have better deliverabilities and, therefore, are a preferred exploration target over underpressured and normally pressured coal seams.

Based on observations resulting from drill stem tests, blowouts from intercepted coal seams, gas flares while drilling through coal seams and coalbed gas production, inferences may be made regarding areas in the Piceance Basin that are either water productive or predominantly flow gas with little or no mobile water (reference Figure 10). The pattern shown in Figure 10 coincides with : (i) an area within an vitrinite isoreflectance contour of 1.1 Ro (Figure 5), and (ii) proximity to the basin outcrop. A relationship is suggested where active gas generation has occurred in coals at depths greater than 4500 feet from the surface and isolated from the outcrop will result in little or no mobile water from coal reservoirs. Large volumes of gas generated from the coals and redistributed laterally and vertically throughout the geologic section is a possible mechanism for relocation of water from the coal reservoirs. Imbibition of water back into the system may be precluded by the absence of cross-formational fluid flow in low permeability basins.

Thermal modeling of geologic evolution has been used to describe and quantify existing reservoir conditions for deep coal seams within the Piceance Basin. Various conclusions and observations regarding coal reservoir conditions as a function of time, temperature and cross-formational fluid migration include:

1. Gas occluded in coal seams with maturities less than .73 Ro vitrinite reflectance may have largely originated from a deeper source or are a biogenic origin.

2. The unusual vitrinite reflectance profile observed in the Piceance Basin (and other deep coal basins) is caused by the low thermal conductivity of the coal.

3. Simplistic and commonly used geothermal gradient maturation models that do not account for heat transfer will fail to predict the accelerated phase of coal maturation and resulting hydrocarbon generation.

4. Active gas generation from coal seams in the Piceance Basin discontinued approximately twenty-five million years ago.

5. In the Piceance Basin, underpressured and overpressured coal reservoirs are part of a single hydrocarbon generation cycle, differing by the volume of hydrocarbons generated and a post-laramide uplift.

6. To date, overpressured coal reservoirs in the San Juan Basin are water saturated and highly permeable. These reservoir conditions may be related to coal water generative cycle under shale bounded conditions.

7. Water and gas generated during the coalification process may have fractured overlying sediments during expulsive cycles.

8. High permeability overpressured coals with high gas-in-place represent attractive coal reservoir conditions. For low permeability basins (such as the Piceance Basin), these reservoir parameters are most likely to occur along positive structural features that overlap thick, thermally mature coal seams.

Mountain Unit), at the 1 Cameo 20-4 (East Divide Creek Area), and other areas of the Piceance Basin as reported by Law[19]. All wells examined displayed an increased maturation profile occurring at approximately 0.90 Ro. The unusual vitrinite reflectance profiles measured at the 1 Deep Seam 32-2 and 1 Cameo 20-4 were closely matched by Waples[18] maturation modeling (Figure 7) indicating that maturity modeling in coal-bearing basins must take heat transfer through coalbeds into consideration. Poor thermal conductors, such as coal, result in a heat buildup under the low conductive section. This phenomenon is well documented by a static, cased hole temperature log from the East Divide Creek Area, Mamm Creek and Rullison Field (Figure 8). Note the repeated thermal anomalies at the base of the Cameo and Coal Ridge groups.

Yukler[20] first described the temperature and pressure interrelationship with abnormally pressured reservoirs. He observed a sharp increase in the temperature gradient on top of a high pressure medium and a sharp decrease in the temperature gradient on top of a low-pressure medium (Figure 9). These findings are consistent with temperature profiles for overpressured coal sections as shown in Figure 8. The abnormally high pressured sedimentary unit resulted from an insulation effect caused by a zone of low thermal conductivity. A barrier to heat flow is created in the areas of thick, laterally continuous coal seams found in the overpressured region of the Piceance Basin due to the low thermal conductivity of coal. This results in high temperatures and pressures which accelerate coal maturation as noted in vitrinite profiles from wells at the Red Mountain Area and East Divide Creek (Figure 7). The sequential results of thermal maturation events in the Piceance Basin may be summarized as follows:

1. The coal's insulating property which exists from deposition results in heat buildup and accelerates both the initiation and degree of coal maturation. Therefore, increasing temperature initiates increasing gas generation.

2. The rapid decay of the gas generative system is caused by reduced temperatures resulting from erosion of the stratigraphic section.

3. Once in the passive gas generation stage, the migration of gas from the coal seam to achieve equilibrium will result in decreasing pore pressure.

From the perspective of the Piceance Basin evolution, the coal seams underlying the Red Mountain and East Divide Creek Unit have similar thermal histories and generally evolved as a single system. However, thermal maturation and gas generation events alone fail to explain the different reservoir pressure gradients measured within the coal seams at the two areas. (e.g. Red Mountain Area = 0.33 psi/ft, East Divide Creek Area = 0.59 psi/ft). Distinguishing factors between the two areas include the post-laramide uplift paralleling the overpressured, East Divide Creek region, and absent at the Red Mountain Area and nearly twice the gas generation in the overpressured area due to increased coal thickness (Table 2).

The following thermal maturation events are presented as mechanisms for high coal pore pressure. During active gas generation, coal seams in the overpressured region were located in the deepest portion of the basin. Therefore, coalbed gas adsorption reached peak levels due to high formation pressures and temperatures from burial. The gas retention capacity was reduced during rapid post-laramide uplift and erosion. As a result of the uplift, the coal seams are currently at elevated maturation and temperature levels relative to laterally equivalent coal sections (Table 2). High pore pressure may then be related to coalbed gas retention in excess of equilibrium temperatures and pressures. Disequilibrium may have been accentuated by the large concentration of coal volume in the overpressured area (Figure 4).

OVERPRESSURED COAL RESERVOIRS

Gas is produced from overpressured, water saturated Fruitland coal reservoirs at the Cedar Hill Field and San Juan 30-6 Unit in the San Juan Basin. The two fields have been examined in detail[21] in an effort to: (i) determine geologic processes responsible for reservoir characteristics, and (ii) establish reservoir parameters controlling production.

The fields were selected because of their high productivity. The Cedar Hill Field has produced a cumulative of 7.1 Bcf from 7 wells since 1979 and is still producing at a rate of 1.3 Bcf/year. The Fruitland coal discovery was made in the San Juan Unit 30-6 during 1985. Three wells in that field have produced 2.3 Bcf during the first 15 months of production and continue to flow at a rate of 2.2 Bcf/year.

A detailed geologic study of both fields failed to detect significant geologic anomalies that might explain favorable production characteristics. Similarly investigation of drilling and completion techniques failed to yield technological reasons for high productivity. The only obvious factor that both fields share which is lacking in approximately 200 less successful coalbed completions in the San Juan Basin is overpressured coal reservoir conditions over a large lateral area. From the stand point of decreasing formation pressure below gas desorption pressure, over pressure, water saturated coals should have negative production implications. However, the overpressuring condition maybe indicative of a permeability enhancement process resulting in highly permeable coal reservoirs.

Based on regional isoreflectance maps, coal reservoirs in both fields fall in the maturation range of .80 - .90 Ro. According to Figure 2 this maturity level falls below peak gas generation phase. Therefore, sufficient volumes of gas have not been generated to cause high pore pressure. However, coal rank and age are appropriate for relict overpressuring conditions during the coal dewatering phase. Overpressuring during shale compaction and dewatering has been

The final output of the thermal model reveals the type of depositional basin, tectonic (structural histories, sediment accumulation erosion) through time, thermal history of the basin and its effect on coal maturation and compactional history. A comparison of measured vitrinite reflectance and bottomhole temperatures with that predicted by the model indicates the accuracy of modeled events.

ABNORMALLY PRESSURED COAL RESERVOIRS, PICEANCE BASIN

The preceding coal volumetrics and thermal modeling may be used to study the implications of abnormally pressured coal reservoirs within the Piceance Basin of northwestern Colorado. The Basin was selected due to the availability of reservoir and geologic data collected for the Cretaceous coal reservoirs as are dominate in the western U.S. and which contain significant coalbed accumulations.

To date, the thick coal seams of the laterally continuous Cameo Coal Group, (Williams Fork Formation, Mesaverde Group) have been the objective for coalbed gas exploration within the Piceance Basin. A significant coalbed methane resource also exists within the Coal Ridge Coal Group[15], stratigraphically 200 to 400 feet above the top of the Cameo Coal Group, laterally confined to the eastern margin of the basin.

The primary questions to address are: i) what is the origin and implications of abnormally ssured coal reservoirs?, and ii) why atigraphically equivalent coal seams with milar coal ranks and burial depths have such diverse coal reservoir conditions.

The integration of drill stem test data, bottomhole pressure, buildup tests and drilling mud weights have resulted in identification of a regional northeastern overpressured trend approximately 25 miles in length and eight miles in width (Figure 3). The East Divide Creek Area (which has a reservoir pressure gradient in the Cameo coal seam of 0.59 psi/ft) is located on the southern-most extension of the regional trend. In contrast, the reservoir pressure gradient at the Red Mountain Area is .33 psi/ft. The overpressured region coincides with: i) maximum total coal development in the Basin (Figure 4), ii) thermally mature coals (Figure 5), and iii) northern plunging nose of the Divide Creek Anticline (Figure 3). These coal characteristics are interrelated and result in dynamic reservoir conditions.

The Divide Creek anticline has brought deeply buried, mature coal seams 4,000 - 5,000 feet closer to the surface than laterally equivalent coal seams. The abrupt post-laramide uplift appears to have contributed to the coal disequilibrium state along the axis of the anticline. The timing of coalbed gas and water generative events and material balance calculations may be determined using thermal m ation modeling.

Material Balance

An examination of regional maps (Figure 4 and 5) indicate that up to 100 feet of low-volatile bituminous coal exists in the over-pressured region. Following lithification and compaction, 9.18×10^8 barrels of water and 4.27×10^{11} cubic feet of gas are calculated to have been displaced by the coal seams per square mile. To determine the coal's fluid retention capability, earth strain analysis was conducted at the East Divide Creek Site. The upper bound interpretation for coal porosity was calculated to be 6.0 percent[16]. Therefore, if all pore space in the coal was saturated with water, the coal could only contain $.41 \times 10^{-3}$ percent of generated water. If completely gas filled, at equivalent pressure and temperature, the coal could retain roughly 12 percent of the generated gas. Clearly the volumetric difference between the gas and water generated and that which may be stored in the coal system is large and suggests a reason for overpressuring in this region.

Determination of Sequential Thermal Events

The timing of coal generative events at the East Divide Creek Area and Red Mountain Unit was determined by Waples using computer-aided thermal modeling[18]. In order to best match present-day calculated subsurface temperatures of 164°F at Red Mountain and 176°F at East Divide Creek, and to obtain good agreement between measured maturity data and calculated maturity levels, paleo heat flow was varied. This facilitates simultaneous corrections for a nearby late Eocene intrusive event and post-Eocene uplift and erosion. Pre-Eocene heat flows were held constant at 1.5 heat flow units. Based on geologic age dating, the thermal event began 34 million years ago (MYA). A one hundred thousand year heating span was investigated, decaying exponentially. The geologic section was layered to approximate age of deposition and lithology. The thermal conductivities used for pure sandstone was 6.2 watt/meter/Kelvin (w/m/k), for shales 1.5 w/m/k, for dolomites 4.8 w/m/k decline, for siltstone 2.9 w/m/k, and for coal 0.3 w/m/k as reported by Kappelmeyer[18]. The results from the thermal modeling simulation expressed as a function of time and maturity for the volume of water and gas generated by the coals are shown on Figure 6. In both areas, active thermal gas generation from coals occurred approximately 52 MYA when the formations were at their deepest burial and greatest temperature. Active gas generation ceased approximately 25 MYA. Gas generation today is at a much lower rate due to reduced depths resulting from erosion and thermal decay of the igneous event. According to Lopatin's relationship, the current reaction rate is .001 percent as compared to peak gas generation approximately 40 MYA.

A typical geothermal gradient semi-log plot of depth and vitrinite reflectance yields a straight line[14]. A vitrinite profile has been measured at the 1 Deep Seam 32-2 well (Red

GO INTERNATIONAL

COMPENSATED DENSITY LOG

FILING NO.

COMPANY AMOCO PRODUCTION COMPANY

WELL SCHNEIDER GAS COM B NO1

FIELD BLANCO PICTURED CLIFF

COUNTY SAN JUAN STATE NEW MEXICO

Location: 1110'FSL& 1185'FWL

Sec. 28 Twp. 32N Rge. 10W

Other Services: IEL

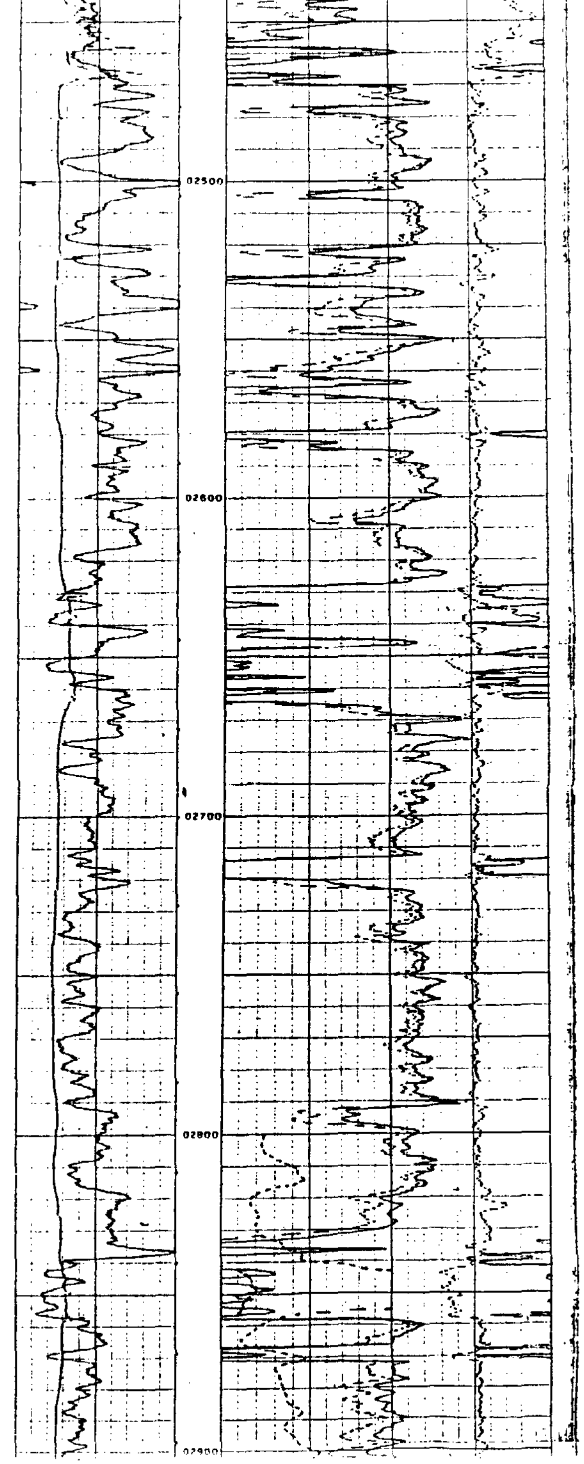
Permanent Datum: Ground Level ; Elev.: 6059
Log Measured From KB 11 Ft. Above Perm. Datum
Drilling Measured From KB

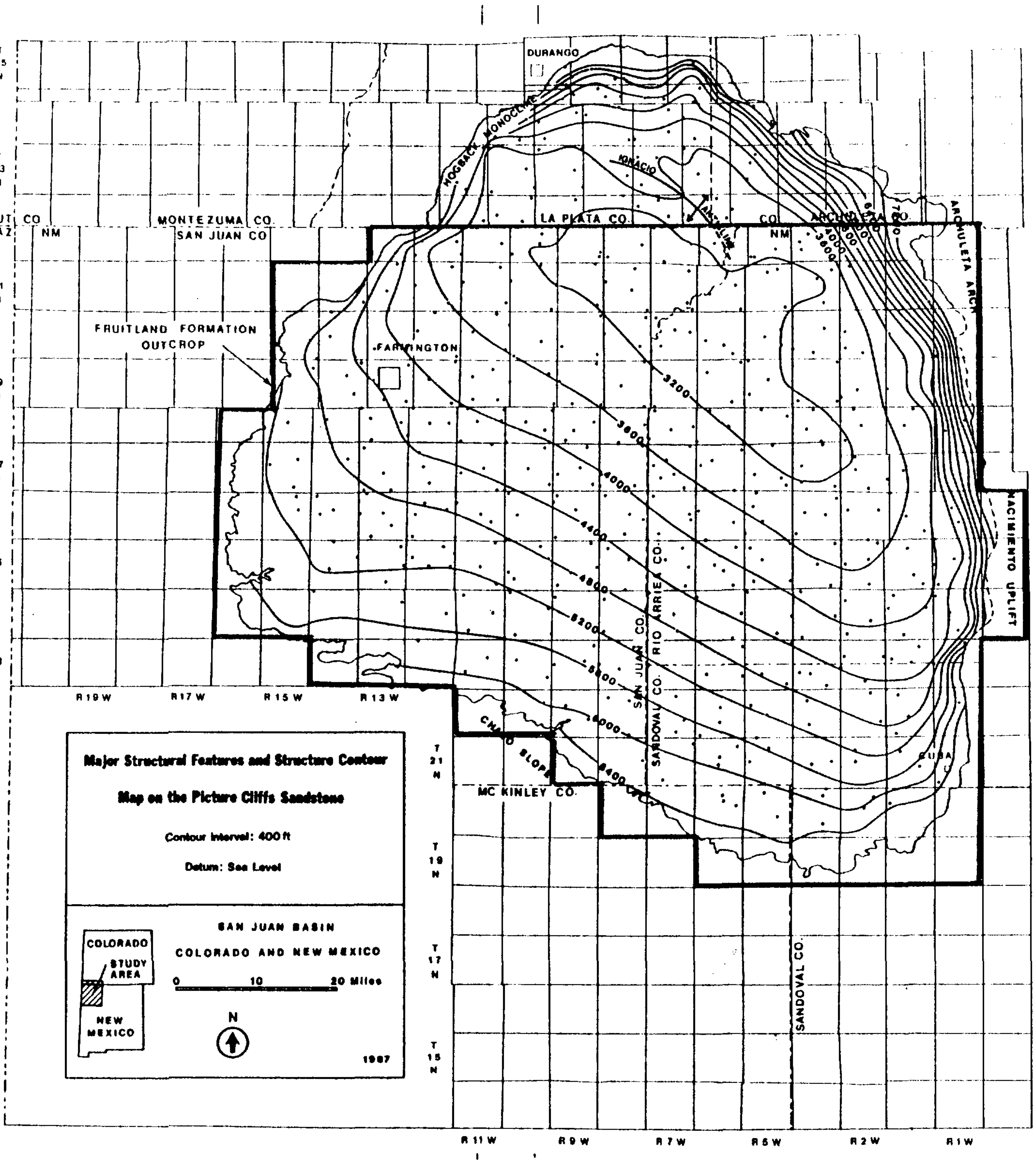
Elev.: K.B. 6070
D.F. 6069
G.L. 6059

Date	1-8-77		
Run No.	One		
Type Log	Gamma-Gamma		
Depth—Driller	[illegible]50		
Depth—Logger	3053		
Bottom logged interval	3052		
Top logged interval	2200		
Type fluid in hole	Fresh Gel		
Salinity, PPM Cl.	3600		
Density	10.6		
Level	Full		
Max rec. temp., deg F.	110		
Operating rig time	1 1/2 Hours		
Recorded by	Hamilton, Villa		
Witnessed by	Bloom		

Run	Bore-Hole Record			Casing Record			
No.	Bit	From	To	Size	Wgt.	From	To
One	7 7/8	257	3050	8 5/8		Surface	257

RECEIVED
MAR 15 1977
OIL CON. COM.
DIST. 3





Major Structural Features and Structure Contour
Map on the Picture Cliffs Sandstone
Contour Interval: 400 ft
Datum: Sea Level
SAN JUAN BASIN
COLORADO AND NEW MEXICO
0 10 20 Miles
N
1987
COLORADO
STUDY AREA
NEW MEXICO
DURANGO
HOGBACK MONOCLINE
IGNACIO
LA PLATA CO.
ARCHULETA CO.
ARCHULETA ARCH
MONTEZUMA CO.
SAN JUAN CO.
UT CO
AZ NM
CO
NM
FRUITLAND FORMATION
OUTCROP
FARMINGTON
NACIMIENTO UPLIFT
SAN JUAN CO.
RIO ARRIBA CO.
SANDOVAL CO.
CHACO SLOPE
MC KINLEY CO.
CUBA
3200
3600
4000
4400
4800
5200
5600
6000
6400
7600
R 19 W
R 17 W
R 15 W
R 13 W
R 11 W
R 9 W
R 7 W
R 5 W
R 2 W
R 1 W
T 35 N
T 33 N
T 31 N
T 29 N
T 27 N
T 25 N
T 21 N
T 19 N
T 17 N
T 15 N

IT IS THEREFORE ORDERED:

(A) That, effective ______________, a new pool in all or parts of San Juan, Rio Arriba, McKinley and Sandoval Counties, New Mexico, classified as a gas pool for production from the Fruitland Coalbed Seams, is hereby created and designated the San Juan Basin Fruitland Coalbed Methane Gas Pool, with the vertical limits comprising all coal seams within the stratigraphic interval from approximately 2450 feet to 2880 feet on the Gamma Ray/Bulk Density log of the Amoco Production Company Schneider Gas Com "B" Well No. 1, located 1110 feet from the South line and 1185 feet from the West line of Section 28, Township 32 North, Range 10 West, NMPM, San Juan County, New Mexico, which for the purpose of this order shall include all stratigraphically equivalent coal seams which by virtue of intertonguing or other geological events may be found within the upper Pictured Cliffs Formation. The horizontal limits shall consist of the following described lands:

Township 19 North, Ranges 1 West through 6 West, NMPM
Township 20 North, Ranges 1 West through 8 West, NMPM
Township 21 North, Ranges 1 West through 9 West, NMPM
Township 22 North, Ranges 1 West through 11 West, NMPM
Township 23 North, Ranges 1 West through 14 West, NMPM
Township 24 North, Ranges 1 East through 16 West, NMPM
Township 25 North, Ranges 1 East through 16 West, NMPM
Township 26 North, Ranges 1 East through 16 West, NMPM
Township 27 North, Ranges 1 West through 16 West, NMPM
Township 28 North, Ranges 1 West through 16 West, NMPM
Township 29 North, Ranges 1 West through 15 West, NMPM
Township 30 North, Ranges 1 West through 15 West, NMPM
Township 31 North, Ranges 1 West through 15 West, NMPM
Township 32 North, Ranges 1 West through 13 West, NMPM

(B) That for the purpose of this order a San Juan Basin Fruitland Coalbed Methane Gas Well is a well that is producing from the Fruitland Coalbed Seams as demonstrated by a preponderence of data which could include the following data sources:

a) Electric Log Data

b) Drilling Time

c) Drill Cutting or Log Cores

d) Mud Logs

e) Completion Data

f) Gas Analysis

g) Water Analysis

h) Reservoir Performance

i) Other evidence that indicates the production is predominately coalbed methane.

No one characteristic of lithology, performance or sampling will either qualify or disqualify a well from being classified as a Fruitland Coalbed Methane Gas Well.

SPECIAL RULES AND REGULATIONS FOR THE

SAN JUAN BASIN FRUITLAND COALBED METHANE GAS POOL

SAN JUAN, RIO ARRIBA, MCKINLEY AND SANDOVAL COUNTIES, NEW MEXICO

RULE 1. GENERAL

Each well completed or recompleted in the San Juan Fruitland Coalbed Methane Gas Pool shall be spaced, drilled, operated and produced in accordance with the Special Rules and Regulations hereinafter set forth.

RULE 2. POOL ESTABLISHMENT

That the Director may require the operator of a San Juan Basin Fruitland Coalbed Methane Gas Well, a Fruitland Sand Well or Pictured Cliffs Sand Well, which is proposed in the lands described in (A) above, furnish information and data that would demonstrate to the satisfaction of the Director that the existing wells are producing and the proposed well will produce from the appropriate common source of supply.

RULE 3 (a). WELL SPACING & LOCATION

A standard drilling unit for a San Juan Basin Fruitland Coalbed Methane Gas Well shall consist of 320 acres, plus or minus 25%, substantially in the form of a rectangle, consisting of a half section, being a legal subdivision of the U.S. Public Land Surveys, and shall be located no closer than 790 feet to any outer boundary of the tract, nor closer than 130 feet to any interior quarter section line.

In the absence of a standard 320 acre drilling unit, an application for administrative approval of a non-standard unit may be made to the Division Director provided that the acreage to be dedicated to the non-standard unit is contiguous, and the non-standard unit lies wholly within a single governmental half section, and further provided that the operator seeking the non-standard unit obtains a written waiver from all offset operators of drilled tracts or owners of undrilled tracts adjacent to any point common to the proposed non-standard unit. In lieu of the waiver requirements the applicant may furnish proof of the fact that all of the aforesaid were notified by registered or certified mail (return receipt requested) of the intent to form such non-standard unit. The Director may approve the application if no objection has been received to the formation of such non-standard unit within 20 working days after the Director has received the application.

The drilling unit orientation will be determined by the first well permitted to be drilled in any one particular standard section.

RULE 3 (b). UNORTHODOX WELL LOCATION

The Director shall have authority to grant an exception to the well location requirements of Rule 3 (a) above without notice and hearing when the necessity for such unorthodox location is based upon topographic conditions or the recompletion of a well previously drilled into a deeper horizon, provided said well was drilled at an orthodox or approved unorthodox location for such original horizon.

Applications for administrative approval of unorthodox locations shall be filed in duplicate (original to Santa Fe and one copy to the appropriate District Office) and shall be accompanied by plats showing the ownership of all leases offsetting the spacing unit for which the unorthodox location is sought, and also all wells completed thereon. If the proposed unorthodox location is based on topography, the plat shall also show and describe the existent topographic conditions.

If the proposed location is unorthodox by virtue of being located closer to the outer boundary of the spacing unit than permitted by rule, actual notice shall be given to any operator of a spacing unit or owner of an undrilled lease toward which the proposed location is being moved.

All such notices shall be given by certified mail (return receipt requested) and the application shall state that such notification has been given. The Director may approve the unorthodox location upon receipt of waivers from all such offset operators or if no offset operator has entered an objection to the unorthodox location within 20 working days after the Director has received the application.

The Director may at his discretion, set any application for administrative approval of an unorthodox location for public hearing.

RULE 4. INCREASED WELL DENSITY

The Director shall have the authority to administratively approve one (1) additional San Juan Basin Fruitland Coalbed Methane Gas Well provided the following conditions are met:

(a) The increased density well must conform to the spacing and boundary footage requirements set forth in Rule 3 (a). and the increased density well cannot be located in the same quarter section as the existing well.

(b) The operator must notify by certified mail (return receipt requested) all: offset operators located in contiguous standup or laydown drilling units; and in the case that the offsetting units are not developed, then notice shall be provided to the owners of contiguous lands.

(c) If no objection is received within 20 working days from receipt of notice, then the application will be administratively approved by the Director. If any objection is received within the time limit, then the Director will set the application for increased well density for public hearing.

RULE 5. HORIZONTALLY DRILLED WELLS

The Director shall have the authority to administratively approve an intentionally deviated well in the San Juan Basin Fruitland Coalbed Methane Gas Pool for the purpose of penetrating the coalbed seams by means of a wellbore drilled horizontally, at any angle deviated from vertical, through such coalbed seams provided the following conditions are met:

(a) The surface location of the well is within the permitted drilling unit area of the proposed well.

(b) The bore hole must not enter or exit the coalbed seams outside of a drilling window which is in accordance with the setback requirements of Rule 3 (a).

If the operator applies for a permit to drill a horizontal well in which the wellbore is intended to cross the interior quarter section line, the operator must notify by certified mail (return receipt requested) all: offset operators located in contiguous standup or laydown developed drilling units; and in the case that the offsetting units are not developed, then notice shall be provided to the owners of contiguous lands.

If no objection is received within 20 working days from receipt of notice, then the application may be administratively approved by the Director. If any objection is received within the time limit, then the Director will set the application for horizontally drilled wells for public hearing.

RULE 6 (a) TESTING.

In lieu of the gas well testing requirements of Order No. R-8170, testing for the San Juan Basin Fruitland Coalbed Methane Gas Pool shall consist of: a minimum twenty-four (24) hour shut-in period, unless otherwise specified by the Director, and a three (3) hour production test. The following information from this initial production test must be reported:

(1) the surface shut in tubing and/or casing pressure and date these pressures were recorded;

(2) the length of the shut-in period;

(3) the final flowing casing and flowing tubing pressures and the duration and date of the flow period;

(4) the individual fluid flow rate of gas, water and oil which must be determined by use of separator; and

(5) the method of production, e.g. - flowing, pumping, etc., and disposition of gas.

RULE 6 (b). VENTING OR FLARING

Venting or flaring for extended well testing will be permitted for completed San Juan Basin Fruitland Coalbed Methane Gas Wells for a test period of not more than thirty (30) days or a cumulative produced volume of 50 MMCF of vented gas, whichever occurs first, the operator will notify the Director of this testing period.

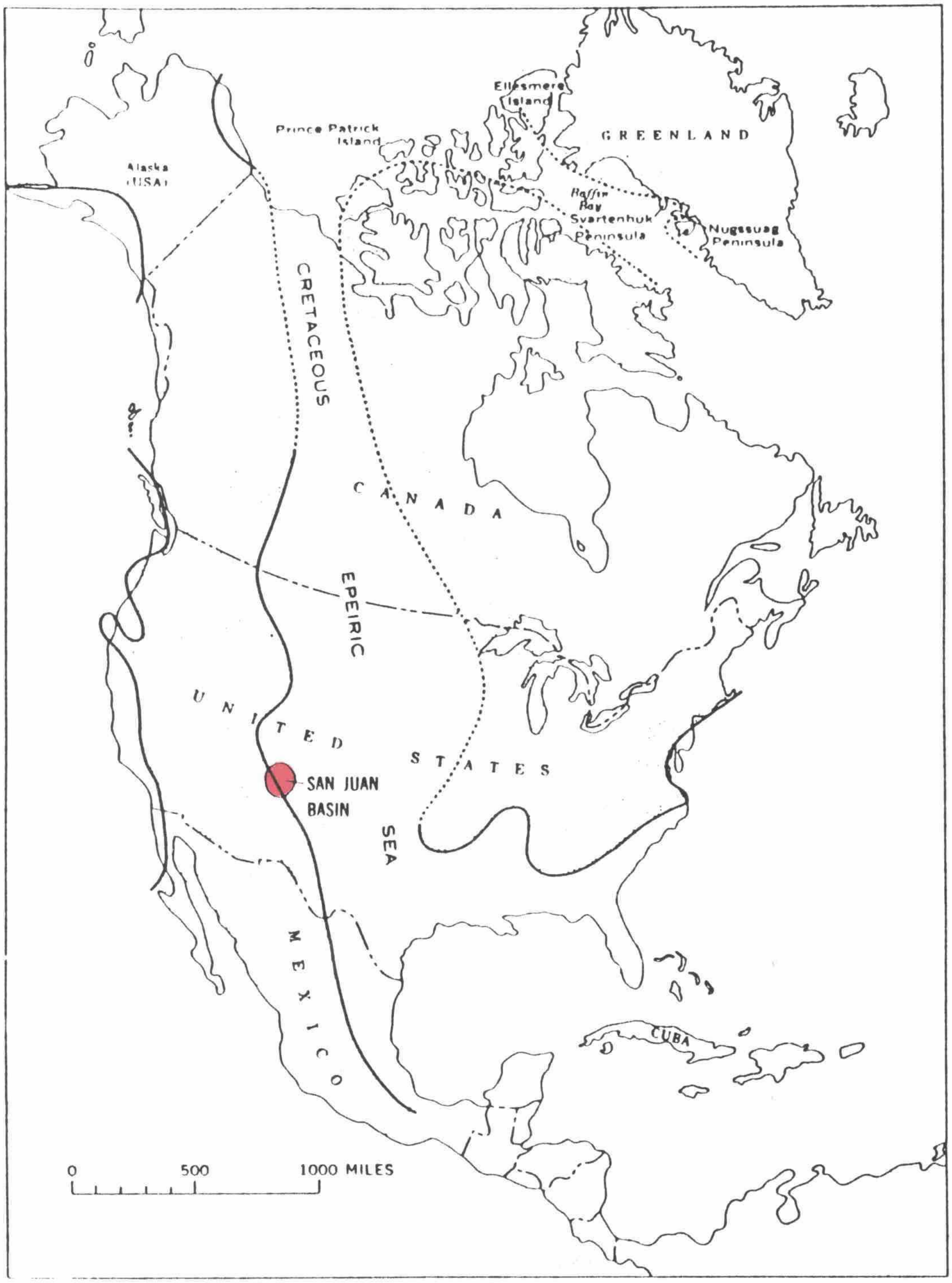
If an operator has cause to perform further testing of a well, then administrative approval may be made by the Director to permit an additional period time and volume limit, set by the Director after sufficient evidence to justify this request has been submitted. In no case shall a well be administratively authorized to vent for a period greater than twelve (12) months.

RULE 7. EXISTING WELLS

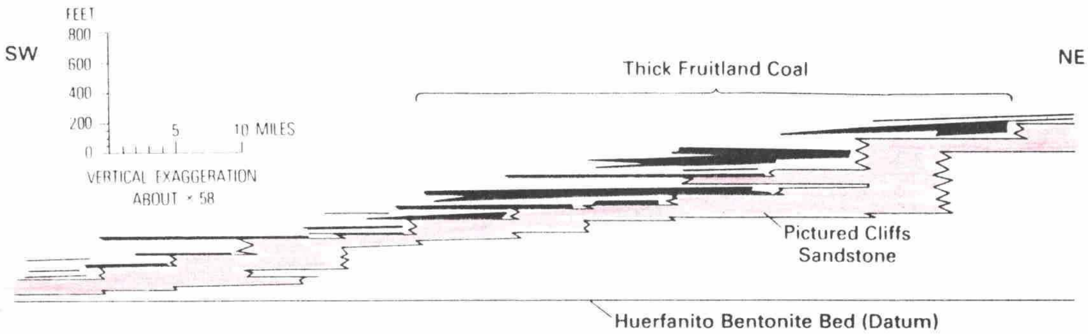
That the operator of an existing Fruitland, Pictured Cliffs or commingled Fruitland/Pictured Cliffs well, which is in conformance with Paragraphs (A) and (B) of this order and is drilling to, completed, or has an approved APD for which the actual or intended completed interval is the San Juan Basin Fruitland Coalbed Methane Gas Pool, may request such well be reclassified as a San Juan Basin Fruitland Coalbed Methane Gas Well by the submittal of a new Form C-102 and C-104 within 90 days of the effective date of this order; this well may be so designated with its original spacing unit size as a non-standard San Juan Basin Fruitland Coalbed Methane Gas Well or may be enlarged to be in conformance with Rule 3 (a).

a location staked as of the effective date of this order

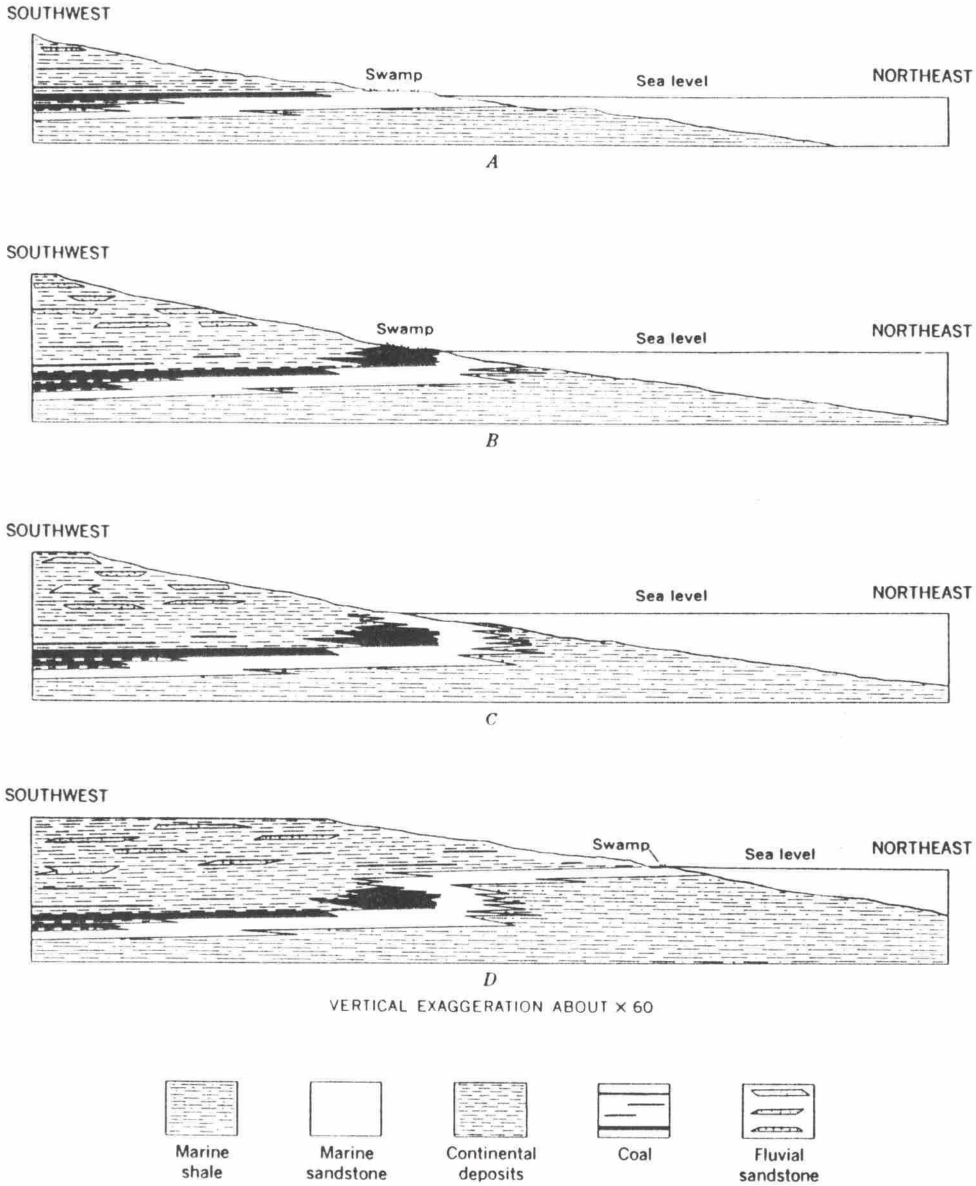
Meridian proposal.



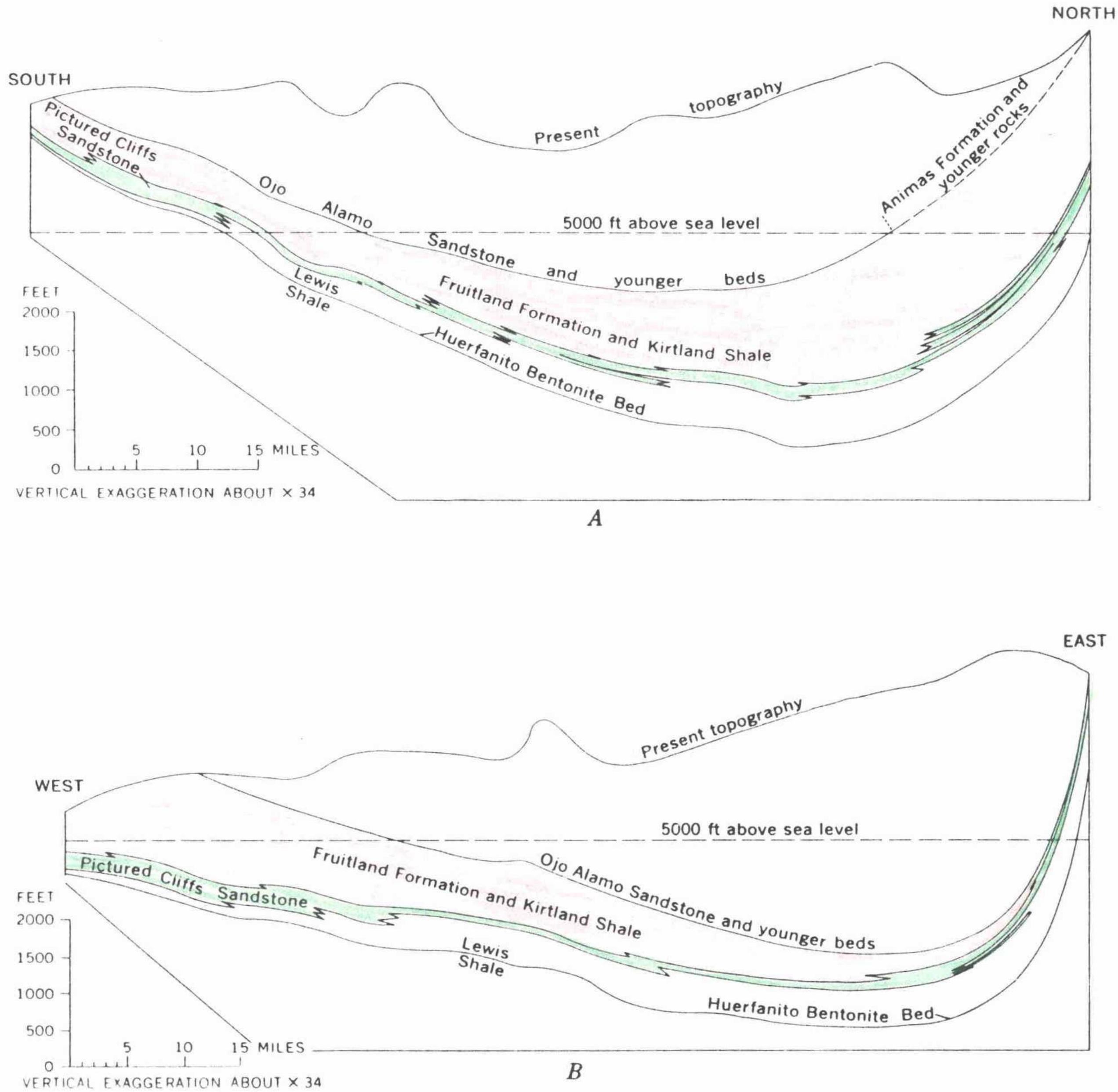
Probable configuration of the North American epeiric seaway at the time that the Upper Cretaceous rocks of the San Juan Basin were being deposited.



Northeast-trending stratigraphic cross-section showing Fruitland Formation coal beds and underlying Pictured Cliffs Sandstone. This cross section is modified from section B-B' of figure 8; coal bed thicknesses are from plate 3 of Fassett and Hinds (1971)



Diagrammatic cross sections showing the relations of the continental, beach, and marine deposits of Pictured Cliffs time after (A) shoreline regression, (B) shoreline stability, (C) shoreline transgression, and (D) shoreline regression.



North-trending (A) and east-trending (B) structural cross sections across the San Juan Basin showing the present basin structure. (From Fassett, 1985 [15].

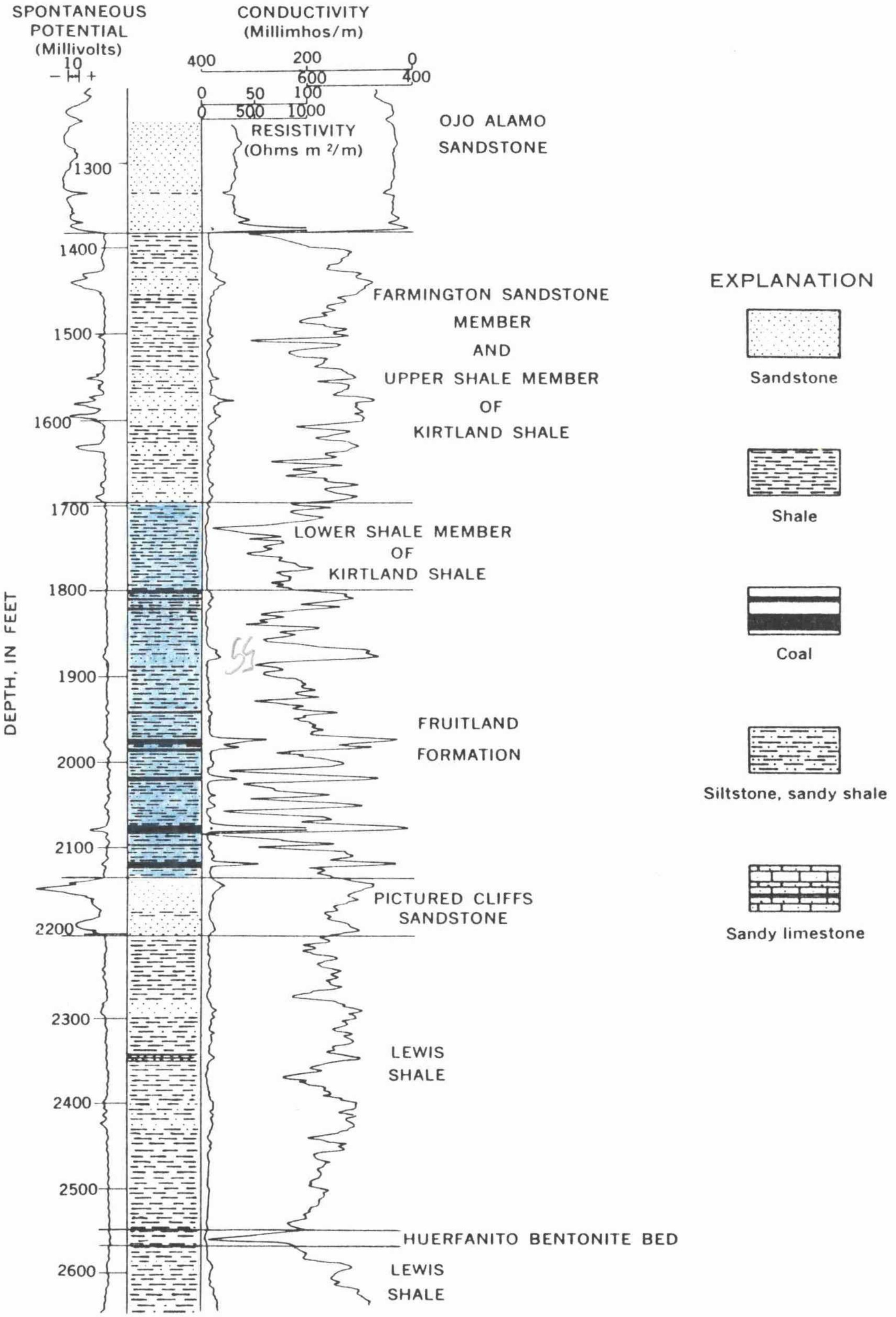


Figure 4 -- Induction-electric log and lithologic column of the type well of the Huerfanito Bentonite Bed of the Lewis Shale showing the interval from below the Huerfanito through the lower part of the Ojo Alamo Sandstone. Lithologies are based on an interpretation of the three geophysical logs shown.

THE 1987 COALBED METHANE SYMPOSIUM

8711 Influence of Coal Composition on the Generation and Retention of Coalbed Natural Gas

J.R. Levine (University of Alabama, School of Mines & Energy Development)

INTRODUCTION

In terms of composition, coal is classified according to three distinct characteristics: 1) "grade", which represents the relative proportion of organic vs. inorganic constituents, 2) "type", which represents the natural variability of the organic constituents initially deposited in the coal, and 3) "rank", which represents the physico-chemical changes imparted to the coal by elevated temperatures and pressures during burial. Grade, type, and rank influence every aspect of coal bed natural gas reservoirs either directly or indirectly. The present paper focuses on two distinct, but related topics:
1) the influence of type and rank on the the composition and quantities of volatile substances formed during coalification, and 2) the influence of grade and type on the retention of gas in the subsurface.

EVOLUTION OF VOLATILE SUBSTANCES DURING COALIFICATION

The most fundamental change taking place in coal during coalification is the progressive enrichment of elemental carbon, accompanied by the elimination and release of large volumes of "volatile" substances relatively rich in hydrogen and oxygen. As these volatile substances are produced, the H/C and O/C atomic ratios of the residual solid coal progressively decrease. The three principal maceral groups, vitrinite, liptinite, and inertinite, differ substantially in their initial H/C - O/C ratios, hence they also differ in the quantity and type of gases formed during coalification.

The coalification process occurs much too slowly to be observed on a human time scale. Consequently, we are constrained to examining the end product and inferring as best we can the processes that led to it. Inasmuch as only a small portion of the volatile substances formed during coalification remain in the coal today, their volume and composition is largely problematical. However, providing a number of reasonable assumptions are made, then the quantities of CH_4, CO_2, and H_2O liberated during coalification can be estimated within a fairly narrow range, based on the major element (C-H-O) composition. The model requires: 1) that the organic microconstituents of coal evolve compositionally along the four generalized maturation pathways depicted in Figure 1 (Tissot and Welte, 1978), 2) that (for the most part) CH_4, CO_2, and H_2O represent the only forms in which carbon, hydrogen, and oxygen can escape from the coal bed, and 3) that once they are formed, CH_4, CO_2, and H_2O cannot recombine with the solid matrix of the coal.

The elemental compositions of coalification "products" and "reactants" can be plotted on a Van Krevelen diagram (Figure 1) which depicts both the rank and type of the organic constituents. Coalification paths for the four principal kerogen types are labeled I, II, III and IV. Kerogen type II is roughly equivalent to the liptinite (a.k.a. exinite) maceral group in coal. Kerogen type III is equivalent to vitrinite, by far the most common microscopic constituent of coal, and kerogen type IV is equivalent to the inertinite maceral group in coal. At low rank the maceral groups differ substantially in composition, but progressively converge upon one another they approach the origin. For example points A and B represent, respectively, the elemental compositions of liptinite and vitrinite macerals coexisting in a coal of vitrinite reflectance 0.5%, but by the time they have been coalified to 2.0% reflectance, they have virtually identical compositions.

A vector connecting any pair of starting and end points can be used to represent the compositional evolution of a particular coal or coal constituent. This vector can be resolved into 1,2, or 3 components, parallel to the dehydration, decarboxylation, and/or demethanation pathways plotted on the diagram. These devolatilization paths represent the change in composition brought about by the progressive removal of H_2O, CO_2, or CH_4 from the coal structure. Applying the constraints of the model, it is possible to reach an end point by a variety of pathways--but only within a limited range--or else condition (3) may be violated. For example, a liptinite maceral of initial composition A on the liptinite curve is coalified to composition C. There are two limiting end member paths to get from point A to point C. In the first, all oxygen is eliminated as CO_2 and none as H_2O while in the second the reverse is true. In the first case, the decarboxylation vector intersects the demethanation path at A', from which point all subsequent compositional changes can be accounted for by progressively removing CH_4. , plus CH_4 (Path A-A"-C). Any other evolutionary pathways will include both decarboxylation and dehydration components and, con-sequently, and must fall between A-A' and A-A". (Note that the "head-to-tail" construction of the vectors in these examples does not necessarily imply a time sequence in volatile evolution. Volatile evolution occurs concurrently, with either one or the other substance predominating. However, the vectors do imply an explicit quantity of gases evolved.

To quantify this model and determine the precise composition and quantity of gases for each path, a set of equations is formulated whereby the total number of atoms of C, H, and O are equated between reactants (subscript r) and products (subscript p), and the H/C and O/C ratios of the reactants and products are adhered to:

$$Cp = Cr - CH_4 - CO_2 \quad (1)$$
$$Hp = Hr - 4*CH_4 - 2*H_2O \quad (2)$$
$$Op = Or - 2*CO_2 - H_2O \quad (3)$$
$$Hp = Cp * 0.50 \quad (4)$$
$$Op = Cp * 0.06 \quad (5)$$

where Cp, Hp, and Op are the number of atoms or moles of carbon, hydrogen, and oxygen per unit of the product. Cr, Hr, and Or are the number of atoms or moles of carbon, hydrogen, and oxygen in the starting (reactant) mixture; and CH_4, CO_2, and H_2O are the number of molecules or moles of methane, carbon dioxide, and water formed from the reactants during coalification.

The composition of the starting material can be determined by solving the following set of 3 equations with 3 unknowns:

$$Hr/Cr = 1.25 \quad (6)$$
$$Or/Cr = 0.07 \quad (7)$$
$$Cr + Hr + Or = 1000, \quad (8)$$

the solution to which is:

$$Cr = 431 \quad (9)$$
$$Hr = 539 \quad (10)$$
$$Or = 30 \quad (11)$$

The value of 1000 in equation (8) is arbitrary. It can be thought of as representing an imaginary coal "molecule" comprised of 1000 atoms. In subsequent calculations these 1000 atoms shall be partitioned among the various volatile products and coal.

Substituting equations (9-11) into equations (1-5) we are left with 5 equations and 6 unknowns. Hence, in order to derive a unique solution, one additional relationship must be defined. For end member case A-A'-C, $H_2O = 0$; and for case A-A"-C, $CO_2 = 0$. For intermediate paths, some ratio of CO_2 to H_2O must be selected. This needn't be an arbitrary choice, but may be based on knowledge of the functional group composition. For example Van Krevelen (1963) indicates that throughout most of the coal ranks under consideration, approximately half of the oxygen in coal is bound to hydrogen, and about half to carbon. We can propose then that CO_2 an H_2O leave the coal in roughly equal amounts; hence $CO_2 = H_2O$.

Depending on the path chosen, the relative proportions and total weight percentages of the volatile products vary considerably. Table 1 lists the yields of CH_4, CO_2, and H_2O and volatile matter produced along the various maturation pathways depicted in Figure 1. For example, as coal increases from R_o(vit) = 0.5 to R_o = 2.0, vitrinite can evolve anywhere from 24 to 173 cm^3 CH_4(stp)/g coal, depending upon whether B-B'-C or B-B"-C is followed. Assuming a ratio of 1:1 $H_2O:CO_2$ production, vitrinite will cumulatively generate around 116 cm^3 CH_4(stp)/g. Over this same rank range, and within the constraints of the model, liptinite macerals generate between 421 and 466 cm^3 CH_4(stp)/g; however, in reality, liptinites probably lose a significant proportion of their hydrogen as longer chain hydrocarbons rather than as methane. The devolatilization model can be modified or expanded to accommodate other hydrocarbon gases, however, a new functional relationship must be added for each new unknown.

This method of quantitatively estimating the volatile yield using simultaneous equation.is similar to a widely cited coal devolatilization model proposed by Juntgen and Karweil (1966) but differs in that it does not require that the coal liberate specific quantities of volatile substances. Juntgen and Karweil speculated that the proximate analysis volatile matter content (measured by pyrolysis at 950°C) could be used as an estimate of the total weight of material evolved as volatile products during coalification. However, this assumption is unwarranted and thermodynamically unsound. Moreover, by requiring that their coals produce such a large volume of volatile substances, Juntgen and Karweil's equations yielded negative values for water production--in other words, it was required that water be added to the coal structure to maintain the proper elemental ratios. Thus, the estimates of gas volumes based on this model are exaggerated. A subsequent article by Juntgen and Klein (1975), however, published a lower revised estimate, discussed subsequently, that is in close agreement with the one calculated herein.

Table 2 shows the progressive devolatilization path to Ro(vit) = 2.0% of an hypothetical coal, comprised of 80% vitrinite, 10% liptinite, and 10% inertinite. The total CH_4 production is 107 cm^3/g (Table 1, Path D-D'-C), almost identical to the quantity calculated by Juntgen and Klein (1975) based on experimental pyrolysis. The older estimate by Juntgen and Karweil (1966) for a whole coal was more than 200 cm^3. Unfortunately, the older figure seems to be used more commonly than the more recent one, (e.g. Meissner, 1984)

INFLUENCE OF COAL COMPOSITION ON IN SITU METHANE CONTENTS

With increasing rank coal loses its capacity to retain H_2O; hence, assuming that the beds remain fully water saturated, any water formed during coalification must be produced. Coal has a relatively strong affinity for CO_2 (as opposed to

CH_4 for example), but CO_2 is readily soluble in water; hence, its abundance will tend to diminish over time. Consequently, in comparison with other volatile substances formed during coalification CH_4 tends to become progressively enriched in the coal bed reservoir .

Coal has an attractive affinity for methane that enables it to absorb or adsorb more CH_4 under pressure than would be the case if the methane were a free gas. During the course of coalification coals generate much more methane than they have the capacity to retain (Juntgen and Karweil, 1966), so in a natural setting, most coals should be at or near their maximum methane capacity (at P,T), provided that the coals were not exposed to abnormally low fluid pressures in the past. Bearing this model in mind, the gas content of coal in situ should be proportional to the pressure, temperature, and whatever compositional parameters limit the coal's capacity to sorb gas.

A suite of 57 samples was recently collected from a 3000 ft-deep coal bed methane exploration core hole in the Cahaba basin, central Alabama. The gas contents of the samples were measured using the Bureau of Mines canister desorption test. Then the coals were subjected to a comprehensive suite of analyses, including proximate, ultimate, BTU, and petrography. These data were then normalized and used to develop a multiple linear regression model to predict the gas contents of the samples. The resulting linear model was very successful, explaining 88.5% of the variability in gas content. A large component of the remaining 11.5% variability is probably due to measurement error.

Multiple Linear Regression Model
Gas Contents of Cahaba Core Samples

$$\text{Gas Content } (cm^3/g) = 6.822 + 0.0025 * \text{Depth (ft)} - 0.0957 * \text{ParrMM} + 0.1112 * (\%\text{Fusinite} + \%\text{Semifusinite} + \%\text{Macrinite}) - 5.449 * \text{H/C (daf)}$$

$$r^2 = .885$$

This regression model indicates that for the suite of coals examined, gas content increases linearly with depth. In laboratory sorption isotherm studies, the gas capacity of coal increases at a less than linear rate, so the anomalously high gas contents at depth may be due to increasing rank (W. Telle, personal communication). There was not, however, enough of a systematic rank variation in the samples to produce a measurable effect in the regression model. The third term, ParrMM, is an estimate of the mineral matter content of the coal using Parr's equation based on ash and sulfur content. Once again the correlation is linear, but with a negative coefficient. The predicted gas content using the model is very close to 0.0 at 100% ParrMM, showing that for these samples, the mineral matter does not participate measurably in the gas sorption process. The fourth term is a indication of the influence of coal petrography on gas sorption capacity. This composite variable, comprised of members of the inertinite maceral group, indicates that while inertinite does not contribute significantly to gas generation, it has a positive influence on the gas content. The fifth term, the hydrogen to carbon ratio (dry, ash-free basis) does not contribute strongly toward the model, but indicates that an increasing H/C ratio has a negative influence on the gas capacity. It is uncertain whether this is related to decreasing rank, or increasing liptinite content. Neither standard rank parameters nor the liptinite percentages showed a significant effect.

It remains to be seen whether this model can be applied to coals in other basins as well. As additional data become available the model will be tested and refined.

REFERENCES CITED

Jüntgen, H. and Karweil, J., 1966, Gasbildung und Gasspeicherung in Steinkohlenflözen, Part I and II: Erdöl u. Kohle, Erdgas, Petrochem, v. 19, p. 251-258 and 339-344.

Jüntgen, H. and Klein, J., 1975, Entstehung von Erdgas aus kohlingen Sedimenten.: Erdöl u. Kohle, Erdgas, Petrochem., Ergänzungsband, I, 74/75, p. 52-69. Industrieverlag v. Hernhausen Leinfelden bei Stuttgart.

Krevelen, D.W. van, 1963, Geochemistry of coal, in Breger, I.A., ed., Organic Geochemistry: Oxford, Pergamon Press, p. 183-247.

Meissner, F.F., 1984, Cretaceous and Lower Tertiary coals as sources for gas accumulations in the Rocky Mountain Area: Hydrocarbon Source Rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists, Denver, CO, p. 401-432.

Tissot, B.P. and Welte, D.H., 1978, Petroleum Formation and Occurrence: Springer-Verlag, Berlin, 538 p.

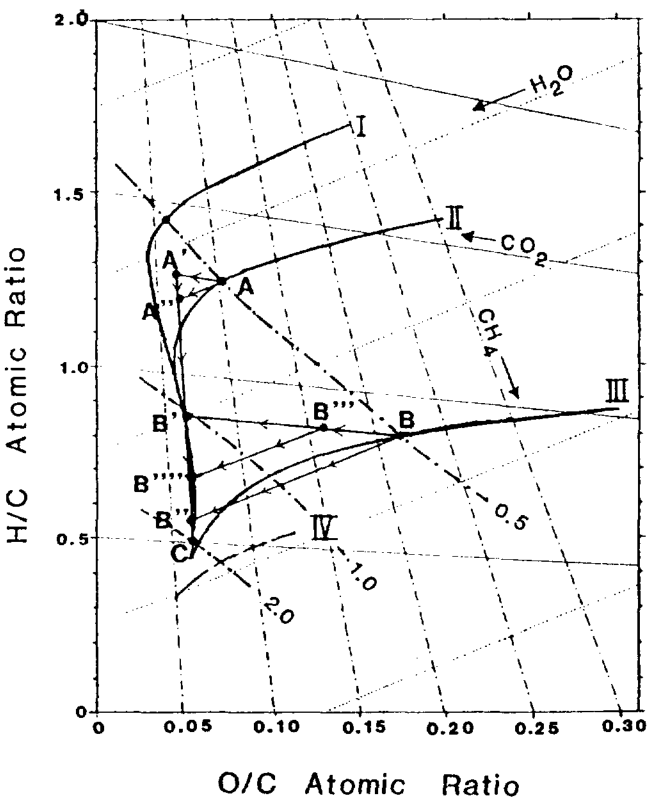


Figure 1 - Van Krevelen diagram depicting evolutionary devolatization paths. Liptinite (A) and vitrinte (B) are situated at the intersections of the Type II and Type III kerogen maturation paths and the 0.5% R_o isoreflectance line. A number of alternate devolatilization paths may be followed for each starting material, each path yielding different quantities of volatile products (see Table 1 for details).

Coalification from R_o(vit) = 0.5 to R_o(vit) = 2.0		Cumulative Grams of Volatiles per Gram of Coal			% of Original Weight Lost as Volatiles	Volume of CH_4 (stp) per Gram of Solid Coal
Path	Description	CH_4	CO_2	H_2O		
A-A'-C	Max. CH_4, Max. CO_2, Min. H_2O	0.333	0.049	0	27.6	466.
A-A"-C	Min. CH_4, Min. CO_2, Max. H_2O	0.301	0	0.036	25.2	421.
B-B'-C	Max. CH_4, Max. CO_2, Min. H_2O	0.124	0.236	0	26.5	173.
B-B"-C	Min. CH_4, Min. CO_2, Max. H_2O	0.017	0	0.156	14.7	24.
B-B"'-B""-C	Intermediate Path: $H_2O \equiv CO_2$	0.083	0.146	0.059	22.4	116.
D-D'-C	Intermediate Path: $H_2O \equiv CO_2$	0.076	0.110	0.045	18.7	107.

TABLE 1. Volatile Products of Coalification

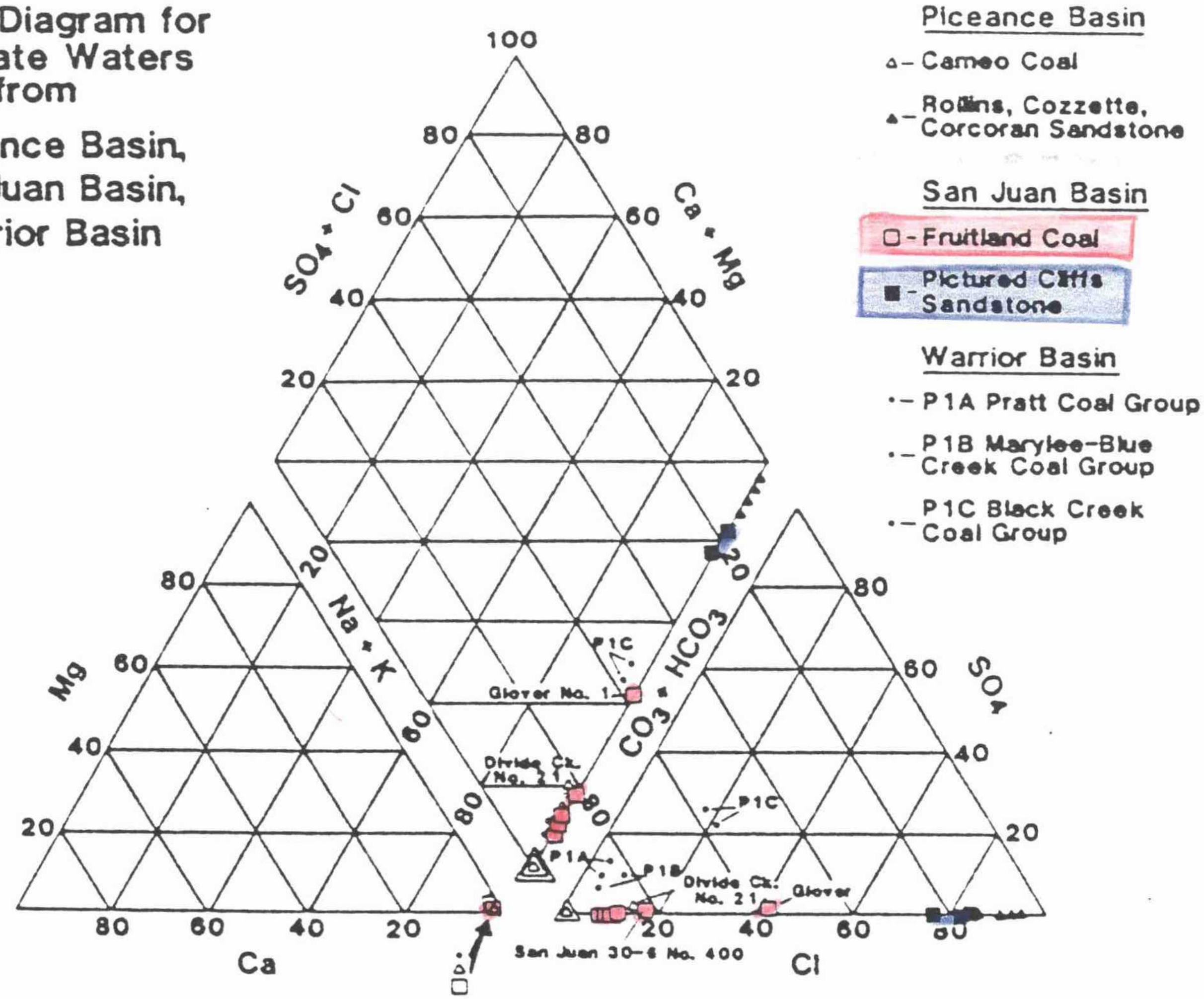
Step:	C	H	O	H/C	O/C
Starting Material:					
80 % Vitrinite:	4096	3192	712	0.78	0.17
+ 10 % Liptinite:	431	539	30	1.25	0.07
+ 10 % Inertinite:	746	224	30	0.30	0.04
Total:	5273	3955	772	0.75	0.15
Decarboxylation: (79 * CO_2)	-79	0	-158		
	5194	3955	614	0.76	0.12
Dehydration: (315 * H_2O)	0	-630	-315		
	5194	3325	299	0.76	0.06
Demethanation: (208 * CH_4)	-208	-832	0		
	4986	2493	299	0.50	0.06

TABLE 2. Devolatilization Path for Whole Coal (D-D'-C, Table 1.)

COMPARISON OF GAS ANALYSES

FORMATION	WELL LOCATION	C1	CO2	BTU
Fruitland coal	A-18-32-7	94.84	4.25	976
"	O-08-32-9(CO)	95.92	2.61	997
"	D-11-33-10(CO)	95.53	2.20	1011
"	N-07-31-09	89.67	8.54	949
Fruitland sand	G-08-29-10	83.22	0.65	1235
"	E-22-28-12	85.55	1.45	1138
"	D-34-30-11	82.50	0.33	1223
"	O-28-32-11	83.41	0.42	1224
Pictured Cliffs	J-06-33-10(CO)	79.55	1.66	1234
"	O-26-32-07	85.23	0.58	1188
"	F-13-28-09	91.77	0.48	1102
"	O-18-30-08	88.20	0.94	1157

Piper Diagram for Connate Waters from Piceance Basin, San Juan Basin, Warrior Basin



Proceedings of the 1987 Coalbed Methane Symposium, Tuscaloosa, Alabama, Nov. 16-19, 1987

THE 1987 COALBED
METHANE SYMPOSIUM

8714 Origin and Production Implications of Abnormal Coal Reservoir Pressure

A.D. Decker (Resource Enterprises, Inc.); D.M. Horner (Gas Research Institute)

ABSTRACT

The ability to produce low cost, pipeline quality gas from deep coal reservoirs depends largely on thorough integration of exploration methods with appropriate drilling, completion and production strategies. In the extreme case, areas that are not economic with current completion technologies should be avoided with adherence to prudent exploration practices. Therefore, reliable predictive geologic methods to specify coal reservoir conditions need to precede drilling and completion decisions.

Dominant coal reservoir mechanisms include: permeability, saturation, reservoir pressure and gas-in-place. Production characteristics from low permeability coal reservoirs are most sensitive to the interaction between type of saturation and reservoir pressure. The geologic processes responsible for these reservoir conditions have been examined in the Piceance Basin. This basin, known for low permeability reservoirs, was selected for geologic evaluation due to the large coalbed methane resource and large data base. Also located in the basin is the Deep Coal Seam Project, a multi-year, multi-well, field laboratory joint venture by the Gas Research Institute and Resource Enterprises, Inc., providing fully integrated reservoir and geologic engineering data on deep coal reservoirs.

Reservoir diagnostics and modeling suggests that reservoir pressure and type of saturation demonstrate an interaction between catagenesis and permeability. Thick, thermally mature coal deposits actively generate more gas and water than can be adsorbed by the coal or be diffused through a low permeability system. In these regions over-pressuring occurs. Ultimately, pore pressure will exceed in-situ stresses resulting in tensional fractures through the coal bearing sequences. While the coal seams remain in the active gas generation phase, the fractures and pore spaces become gas saturated. Eventual temperature reduction through erosion will halt the gas generating phase, resulting in an under-pressured reservoir. Imbibition of water into these reservoirs is unlikely in areas of low permeability. In contrast, coal seams that have not reached an active gas generation phase may be overpressured and water saturated due to compaction and coal dewatering in a shale bounded situation. Overpressured water saturated coal reservoirs of the Cedar Hills and San Juan 30-6 Unit in the San Juan Basin have, to date, shown the highest production capacity for coalbed methane production.

In summary, geochemical evaluation techniques have been applied to characterize and predict coal reservoir mechanisms in the Piceance and San Juan Basin.

INTRODUCTION

A portion of the extensive gas accumulations found in the San Juan Basin[1], the Green River Basin[2], and the Alberta Basin[3] have been sourced largely by coal. Despite the amount of data collected on coal reservoir characteristics and coal as a source rock, little work has been done integrating the two sciences. A coupled understanding of coal reservoir mechanisms and coal maturation will assist the explorationist in his pursuit of coalbed gas resources. This work was sponsored by the Gas Research Institute under Contract No 5083-214-0844 with Resource Enterprises, Inc.

A geologic model is presented which incorporates coal's resistance to transfer heat with its ability to generate large volumes of gas over a specific temperature and time sequence. In basins where low permeability prohibits cross formational fluid flow, gas generation can exceed the quantity of gas that can migrate through the geologic system. This results in high pore pressure within the coal reservoirs. Conversely, where migration exceeds rate of gas generation, low pore pressure will be observed. These stages of reservoir disequilibrium have been observed in other deep coal basins of the western United States.

The focus of this paper is to describe and quantify these states of pore pressure disequilibrium within some coal reservoirs of the Piceance Basin and San Juan Basin. A sequential approach is undertaken to examine the coal system in each phase of basin evolution, as follows:

1. Determination of the volumes of water and gas produced from coal at specific maturity levels during the coalification process.

2. Relate the maturity levels to specific time periods using thermal maturation models.

3. Determination of the amount of gas that cannot be retained by the coal and, therefore, which must diffuse through the geologic section for specified time interval.

This paper is directed at providing the volumetric calculations of Step 1 and the methodology (using a case study) for Steps 2 and 3.

Included in this paper are geologic observations and interpretations of areas within the Piceance Basin where underpressured and overpressured (less than and greater than hydrostatic pressure, respectively) coal seams have been identified. Also included is a section suggesting a relationship between well deliverability, permeability and reservoir pressure in coal degasification wells in the San Juan Basin. A relationship between material balance, gas/water flow and abnormal coal pore pressure is presented.

THE EVOLUTION OF COAL

In response to burial depth, time and temperature, deposits of terrestrially derived plant tissue evolves physically and chemically into thermally mature coal. Compaction and temperature increases transform the organic material into three primary coal components or macerals. (Macerals are the microscopically recognizable constituents of coal.) The vitrinite maceral represents jellified cell walls or woody material, the exinite maceral is representative of plant resin (cuticles and spores) and the inertinite maceral represents carbonized woody material.

The degree of maturation or coal rank during the coalification process is most accurately measured from the vitrinite maceral. The percentage of vitrinite optical reflectivity (Ro) increases correspondingly with increases in coal rank. The temperature necessary to increase rank as indicated by Ro and derived by Gijzel[4] is shown on Table 1. Systematic chemical and biological degradation of organic material during the coalification process yield varying amounts of water and gas. Examination of such chemical products is important in understanding the water and gas accumulations within present-day coal reservoirs.

The two most significant stages of coal maturation, diagenesis and catagenesis, are defined largely by the products of biological and thermal evolution. Water, biogenic methane and carbon dioxide are the primary coal diagenetic products. Water originates from the depositional system and organic decomposition[5]. All biogenic gas and 98 percent of the coal's water generative capacity occurs during diagenesis at maturity levels of 0.23 to 0.76 Ro[6].

Continued exposure of coal to pressure and temperature allow coal to enter the stage of catagenesis. Juntgen and Klein[7] determined that thermal methane generation commences during catagenesis for coal with a vitrinite reflectance of 0.73 Ro. As shown in Figure 1, active gas generation accelerates at 0.90 Ro and continues through 1.30 Ro, accounting for 76 percent of thermal methane generation. Water produced during catagenesis is from the hydration of inorganic minerals and clays[8]. Water and thermal methane volumetrics as a function of increasing coal maturity is summarized in Figure 2.

Coal's ability to absorb gas decreases with higher temperature[9] and pressure[10], but increases with higher coal rank[11]. Eight to ten times more gas is generated than can be retained, thereby initiating gas migration from the coal into other strata. Therefore, the development of a time framework for the coal generative episodes becomes necessary to understand the possible influence that thermal generation rates have on coal reservoir properties. Deterministic relations between time, temperature and ensuing gas generation episodes are derived from thermal maturity modeling.

Thermal Maturity Modeling

The timing of coal digenetic and catagenetic history may be identified through use of a time-dependent, three-dimensional mathematical model to simulate gas generation dependence on variables such as sedimentary burial rate, paleotemperature, paleopressure, thermal conductivity and heat flow. The simulation initially requires the computation of three-dimensional pore pressure in sediments as a function of time. The system assumes that the inflow-outflow is equal to the net accumulation due to grain and fluid compressibility plus the net accumulation to change in sediment density, rate of sedimentation and change in water depth[12]. The next step of the simulation is evaluation of the simultaneous transfer of heat by conduction and convection[13]. In this step, thermal parameters of the evolving system are particulary sensitive to pressure and temperature. The third step in thermal modeling is relating temperature to specific geologic periods. Lopatin[14] determined for coalification reactions, the reaction rate doubles with each increase of 10°C. He further related time and temperature by specifying a geologic time period with 10°C intervals as follows:

$$TTI = T_1 G_1 + T_2 G_2 + T_n G_n$$

where: TTI = Time Temperature Index
T_1 = Temperature Correction Factor
G_1 = Geologic Heating Time

Next, a correlation between vitrinite reflectance is incorporated as a maturity indicator and the TTI is established. The relationship between vitrinite reflectance (Ro) and the time-temperature index is:

$$R_0\% = 1.301 \lg TTI - 0.5282...$$

The final output of the thermal model reveals the type of depositional basin, tectonic and structural histories, sediment accumulation (or erosion) through time, thermal history of the basin and its effect on coal maturation and compactional history. A comparison of measured vitrinite reflectance and bottomhole temperatures with that predicted by the model indicates the accuracy of modeled events.

ABNORMALLY PRESSURED COAL RESERVOIRS, PICEANCE BASIN

The preceding coal volumetrics and thermal modeling may be used to study the implications of abnormally pressured coal reservoirs within the Piceance Basin of northwestern Colorado. The Basin was selected due to the availability of reservoir and geologic data collected for the Cretaceous coal reservoirs as are dominate in the western U.S. and which contain significant coalbed accumulations.

To date, the thick coal seams of the laterally continuous Cameo Coal Group, (Williams Fork Formation, Mesaverde Group) have been the objective for coalbed gas exploration within the Piceance Basin. A significant coalbed methane resource also exists within the Coal Ridge Coal Group[15], stratigraphically 200 to 400 feet above the top of the Cameo Coal Group, laterally confined to the eastern margin of the basin.

The primary questions to address are: i) what is the origin and implications of abnormally pressured coal reservoirs?, and ii) why stratigraphically equivalent coal seams with similar coal ranks and burial depths have such diverse coal reservoir conditions.

The integration of drill stem test data, bottomhole pressure, buildup tests and drilling mud weights have resulted in identification of a regional northeastern overpressured trend approximately 25 miles in length and eight miles in width (Figure 3). The East Divide Creek Area (which has a reservoir pressure gradient in the Cameo coal seam of 0.59 psi/ft) is located on the southern-most extension of the regional trend. In contrast, the reservoir pressure gradient at the Red Mountain Area is .33 psi/ft. The over-pressured region coincides with: i) maximum total coal development in the Basin (Figure 4), ii) thermally mature coals (Figure 5), and iii) northern plunging nose of the Divide Creek Anticline (Figure 3). These coal characteristics are interrelated and result in dynamic reservoir conditions.

The Divide Creek anticline has brought deeply buried, mature coal seams 4,000 - 5,000 feet closer to the surface than laterally equivalent coal seams. The abrupt post-laramide uplift appears to have contributed to the coal disequilibrium state along the axis of the anticline. The timing of coalbed gas and water generative events and material balance calculations may be determined using thermal maturation modeling.

Material Balance

An examination of regional maps (Figure 4 and 5) indicate that up to 100 feet of low-volatile bituminous coal exists in the over-pressured region. Following lithification and compaction, 9.18 x 10^8 barrels of water and 4.27 x 10^{11} cubic feet of gas are calculated to have been displaced by the coal seams per square mile. To determine the coal's fluid retention capability, earth strain analysis was conducted at the East Divide Creek Site. The upper bound interpretation for coal porosity was calculated to be 6.0 percent[16]. Therefore, if all pore space in the coal was saturated with water, the coal could only contain .41 x 10^{-3} percent of generated water. If completely gas filled, at equivalent pressure and temperature, the coal could retain roughly 12 percent of the generated gas. Clearly the volumetric difference between the gas and water generated and that which may be stored in the coal system is large and suggests a reason for overpressuring in this region.

Determination of Sequential Thermal Events

The timing of coal generative events at the East Divide Creek Area and Red Mountain Unit was determined by Waples using computer-aided thermal modeling[18]. In order to best match present-day calculated subsurface temperatures of 164°F at Red Mountain and 176°F at East Divide Creek, and to obtain good agreement between measured maturity data and calculated maturity levels, paleo heat flow was varied. This facilitates simultaneous corrections for a nearby late Eocene intrusive event and post-Eocene uplift and erosion. Pre-Eocene heat flows were held constant at 1.5 heat flow units. Based on geologic age dating, the thermal event began 34 million years ago (MYA). A one hundred thousand year heating span was investigated, decaying exponentially. The geologic section was layered to approximate age of deposition and lithology. The thermal conductivities used for pure sandstone was 6.2 watt/meter/Kelvin (w/m/k), for shales 1.5 w/m/k, for dolomites 4.8 w/m/k decline, for siltstone 2.9 w/m/k, and for coal 0.3 w/m/k as reported by Kappelmeyer[18]. The results from the thermal modeling simulation expressed as a function of time and maturity for the volume of water and gas generated by the coals are shown on Figure 6. In both areas, active thermal gas generation from coals occurred approximately 52 MYA when the formations were at their deepest burial and greatest temperature. Active gas generation ceased approximately 25 MYA. Gas generation today is at a much lower rate due to reduced depths resulting from erosion and thermal decay of the igneous event. According to Lopatin's relationship, the current reaction rate is .001 percent as compared to peak gas generation approximately 40 MYA.

A typical geothermal gradient semi-log plot of depth and vitrinite reflectance yields a straight line[14]. A vitrinite profile has been measured at the 1 Deep Seam 32-2 well (Red

Mountain Unit), at the 1 Cameo 20-4 (East Divide Creek Area), and other areas of the Piceance Basin as reported by Law[19]. All wells examined displayed an increased maturation profile occurring at approximately 0.90 Ro. The unusual vitrinite reflectance profiles measured at the 1 Deep Seam 32-2 and 1 Cameo 20-4 were closely matched by Waples[18] maturation modeling (Figure 7) indicating that maturity modeling in coal-bearing basins must take heat transfer through coalbeds into consideration. Poor thermal conductors, such as coal, result in a heat buildup under the low conductive section. This phenomenon is well documented by a static, cased hole temperature log from the East Divide Creek Area, Mamm Creek and Rullison Field (Figure 8). Note the repeated thermal anomalies at the base of the Cameo and Coal Ridge groups.

Yukler[20] first described the temperature and pressure interrelationship with abnormally pressured reservoirs. He observed a sharp increase in the temperature gradient on top of a high-pressure medium and a sharp decrease in the temperature gradient on top of a low-pressure medium (Figure 9). These findings are consistent with temperature profiles for overpressured coal sections as shown in Figure 8. The abnormally high-pressured sedimentary unit resulted from an insulation effect caused by a zone of low thermal conductivity. A barrier to heat flow is created in the areas of thick, laterally continuous coal seams found in the overpressured region of the Piceance Basin due to the low thermal conductivity of coal. This results in high temperatures and pressures which accelerate coal maturation as noted in vitrinite profiles from wells at the Red Mountain Area and East Divide Creek (Figure 7). The sequential results of thermal maturation events in the Piceance Basin may be summarized as follows:

1. The coal's insulating property which exists from deposition results in heat buildup and accelerates both the initiation and degree of coal maturation. Therefore, increasing temperature initiates increasing gas generation.

2. The rapid decay of the gas generative system is caused by reduced temperatures resulting from erosion of the stratigraphic section.

3. Once in the passive gas generation stage, the migration of gas from the coal seam to achieve equilibrium will result in decreasing pore pressure.

From the perspective of the Piceance Basin evolution, the coal seams underlying the Red Mountain and East Divide Creek Unit have similar thermal histories and generally evolved as a single system. However, thermal maturation and gas generation events alone fail to explain the different reservoir pressure gradients measured within the coal seams at the two areas. (e.g. Red Mountain Area = 0.33 psi/ft, East Divide Creek Area = 0.59 psi/ft). Distinguishing factors between the two areas include the post-laramide uplift paralleling the overpressured, East Divide Creek region, and absent at the Red Mountain Area and nearly twice the gas generation in the overpressured area due to increased coal thickness (Table 2).

The following thermal maturation events are presented as mechanisms for high coal pore pressure. During active gas generation, coal seams in the overpressured region were located in the deepest portion of the basin. Therefore, coalbed gas adsorption reached peak levels due to high formation pressures and temperatures from burial. The gas retention capacity was reduced during rapid post-laramide uplift and erosion. As a result of the uplift, the coal seams are currently at elevated maturation and temperature levels relative to laterally equivalent coal sections (Table 2). High pore pressure may then be related to coalbed gas retention in excess of equilibrium temperatures and pressures. Disequilibrium may have been accentuated by the large concentration of coal volume in the overpressured area (Figure 4).

OVERPRESSURED COAL RESERVOIRS

Gas is produced from overpressured, water saturated Fruitland coal reservoirs at the Cedar Hill Field and San Juan 30-6 Unit in the San Juan Basin. The two fields have been examined in detail[21] in an effort to: (i) determine geologic processes responsible for reservoir characteristics, and (ii) establish reservoir parameters controlling production.

The fields were selected because of their high productivity. The Cedar Hill Field has produced a cumulative of 7.1 Bcf from 7 wells since 1979 and is still producing at a rate of 1.3 Bcf/year. The Fruitland coal discovery was made in the San Juan Unit 30-6 during 1985. Three wells in that field have produced 2.3 Bcf during the first 15 months of production and continue to flow at a rate of 2.2 Bcf/year.

A detailed geologic study of both fields failed to detect significant geologic anomalies that might explain favorable production characteristics. Similarly investigation of drilling and completion techniques failed to yield technological reasons for high productivity. The only obvious factor that both fields share which is lacking in approximately 200 less successful coalbed completions in the San Juan Basin is overpressured coal reservoir conditions over a large lateral area. From the stand point of decreasing formation pressure below gas desorption pressure, over pressure, water saturated coals should have negative production implications. However, the overpressuring condition maybe indicative of a permeability enhancement process resulting in highly permeable coal reservoirs.

Based on regional isoreflectance maps, coal reservoirs in both fields fall in the maturation range of .80 - .90 Ro. According to Figure 2 this maturity level falls below peak gas generation phase. Therefore, sufficient volumes of gas have not been generated to cause high pore pressure. However, coal rank and age are appropriate for relict overpressuring conditions during the coal dewatering phase. Overpressuring during shale compaction and dewatering has been well documented[22] in detrital sequences. Coal seams bounded by impermeable shales would similarly develop high pore pressure due to the inhibited ability to expel water during compaction. Produced waters from both field contain 12,000 to 14,000 ppm sodium bicarbonate type coal water which is suggestive of sluggish or isolated reservoirs conditions. Coal derived should be a sodium bicarbonate water[23], however, the high levels measured at the Cedar Hill and San Juan 30-6 Unit indicates little dilution of connate water over time, supporting bounded reservoir conditions. In theory, incompressible water under high pressure could be acting as a hydraulic proping mechanisms in coal cleats limiting porosity and permeability reduction effects from lithostatic loading.

Overpressured coal reservoirs are a product of shale bounded coal seams during diagenetic compaction during water expulsion. The process is similar to the origin of overpressured shales and sandstone in the Gulf Coast region. To date, coalbed methane wells producing from deeply buried coal seams with high permeability and deliverability occurring in overpressured, water saturated areas of the San Juan and Piceance Basins. The simultaneous occurrence of overpressuring, water saturation and high permeability in coal seams is not thought to be coincidental but rather suggestive of a common relationship. That relationship could be quantified through integration of geologic and reservoir modelling using data collected from laboratory core measurements in conjunction with field level reservoir tests.

SUMMARY

Recognition of the geologic and resulting reservoir processes controlling gas production from deeply buried coals is the first steps in the formulation of an exploration strategy for coalbed gas. The dominant coal reservoir mechanisms affecting production include: permeability, reservoir pressure, saturation and gas-in-place[24]. The relationship between decreasing coal permeability with increasing depth has been described by McKee[25]. In order to overcome the inherent low coal permeability at depth, permeability enhancement through structural deformation should be sought. Utilizing fundamental relationships including Darcy's Law and equation of state, at a given permeability, overpressured coal reservoirs will have better deliverabilities and, therefore, are a preferred exploration target over underpressured and normally pressured coal seams.

Based on observations resulting from drill stem tests, blowouts from intercepted coal seams, gas flares while drilling through coal seams and coalbed gas production, inferences may be made regarding areas in the Piceance Basin that are either water productive or predominantly flow gas with little or no mobile water (reference Figure 10). The pattern shown in Figure 10 coincides with : (i) an area within an vitrinite isoreflectance contour of 1.1 Ro (Figure 5), and (ii) proximity to the basin outcrop. A relationship is suggested where active gas generation has occurred in coals at depths greater than 4500 feet from the surface and isolated from the outcrop will result in little or no mobile water from coal reservoirs. Large volumes of gas generated from the coals and redistributed laterally and vertically throughout the geologic section is a possible mechanism for relocation of water from the coal reservoirs. Imbibition of water back into the system may be precluded by the absence of cross-formational fluid flow in low permeability basins.

Thermal modeling of geologic evolution has been used to describe and quantify existing reservoir conditions for deep coal seams within the Piceance Basin. Various conclusions and observations regarding coal reservoir conditions as a function of time, temperature and cross-formational fluid migration include:

1. Gas occluded in coal seams with maturities less than .73 Ro vitrinite reflectance may have largely originated from a deeper source or are a biogenic origin.

2. The unusual vitrinite reflectance profile observed in the Piceance Basin (and other deep coal basins) is caused by the low thermal conductivity of the coal.

3. Simplistic and commonly used geothermal gradient maturation models that do not account for heat transfer will fail to predict the accelerated phase of coal maturation and resulting hydrocarbon generation.

4. Active gas generation from coal seams in the Piceance Basin discontinued approximately twenty-five million years ago.

5. In the Piceance Basin, underpressured and overpressured coal reservoirs are part of a single hydrocarbon generation cycle, differing by the volume of hydrocarbons generated and a post-laramide uplift.

6. To date, overpressured coal reservoirs in the San Juan Basin are water saturated and highly permeable. These reservoir conditions may be related to coal water generative cycle under shale bounded conditions.

7. Water and gas generated during the coalification process may have fractured overlying sediments during expulsive cycles.

8. High permeability overpressured coals with high gas-in-place represent attractive coal reservoir conditions. For low permeability basins (such as the Piceance Basin), these reservoir parameters are most likely to occur along positive structural features that overlap thick, thermally mature coal seams.

REFERENCES

1. Meissner, F.E., 1984, Cretaceous and Lower Tertiary Coals as Sources for Gas Accumulations in the Rocky Mountain Area: Hydrocarbon Source Rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists, Denver, Colorado, p. 401-432.

2. McPeek, L.A., 1981, Eastern Green River Basin: A Developing Giant Gas Supply from Deep, Overpressured Upper Cretaceous Sandstones: AAPG Bull., Vol. 65, p. 1078-1098.

3. Wyman, R.E., Gas Resources in Elmworth Coal Seams: Elmworth - Case Study of a Deep Basin Gas Field, AAPG Memoir 38, p. 173-189.

4. van Gijzel, P., 1982, Characterization and Identification of Kerogen and Bitumen and Determination of Thermal Maturation by Means of Qualitative Microscopical Techniques, in How to Assess Maturation and Paleotemperatures: SEPM Short Courses No. 7, p. 159-216.

5. Law, B.E. et al., 1983, Geologic Implications of Coal Dewatering: AAPG Bull., Vol. 67, p. 2255-2260.

6. Allardice, D.J., and D.G. Evans, 1971, The Brown Coal/Water System: Part 2; Water Sorption Isotherms on Bed Moist Yallourn Brown Coal: Fuel, V. 50, p. 236-253.

7. Juntgen, H. and J. Klein, 1975, Enstehung Von Erdgas Aus Kohligen Sedimenten: Erdol und Kohle, Erdgas, Petrochemie, Erganzungsband, V. 1, p. 52-69.

8. Allardice, D.J. and D.G. Evans, 1978, Moisture in Coal, in C. Karr, Jr., ed., Analytical Methods for Coal and Coal Products, V. 1: New York. Academic Press.

9. Kim, A.G., 1977, Estimating Methane Content of Bituminous Coalbeds From Adsorption Data: U.S. Bureau of Mines Report of Investigations 8245, p. 22.

10. Kissev, F.N., C.M. McCulloch, and C.H. Elder, 1973, The Direct Method of Determining Methane Content of Coalbeds for Ventilation Design: U.S. Bureau of Mines Report.

11. Eddy, G.E., Rightmire, C.T., and C. Byrer, 1982, Relationship of Methane Content of Coal, Rank and Depth: Proceedings of the SPE/DOE Unconventional Gas Recovery Symposium, Pittsburgh, Penn., SPE/DOE 10800, p. 117-122.

12. Welte, D.H., et al., 1981, Application of Organic Geochemistry and Quantitative Analysis to Petroleum Origin and Accumulation - An approach for a Quantitative Basin Study, in G. Atkinson and J.J. Zuckerman, eds., Origin and Chemistry of Petroleum: Elmsford, NY, Pergamon Press, p. 67-88.

13. Stallman, R.W., 1963, Computation of Ground-Water Velocity from Temperature Data, in Methods of Collecting and Interpreting Ground-Water Data: U.S. Geological Survey Water - Supply Paper 1544-H. p.36-46.

14. Lopatin, N.V., 1971, Temperature and Geologic Time as Factors in Coalification: Akademiya Nauk, Uzb. SSSR, Ser. geologicheskaya, Izvestiya, No. 3, p. 95-106. (Translation by N.H. Bostick, Illinois State Geological Survey, February 1972).

15. Decker, D., 1985, Appropriate Stratigraphic Nomenclature for Coal Reservoirs in the Piceance Basin, Abstract Presented at the Rocky Mountain AAPG Convention, Denver, Colorado (June 1985).

16. Hanson, J.M., 1987, Evaluation and analysis of the response of "Cameo" and "Hoffmeister-Rogers" wells to solid earth tides and barometric pressure. Unpublished paper submitted to Resource Enterprises, Inc. under contract to GRI #5083-214-0844.

17. Waples, D.W., 1987, Maturity Modeling of the 1 Cameo 20-4 Well, Unpublished report submitted to Resource Enterprises, Inc.

18. Kappelmeyer, O., Haenel, R.: Geothermics--with Special Reference to Application. Berline-Stuttgart: Borntraeger, 1974.

19. Law, B.E., and V.F. Nuccio, "Segmented Vitrinite Reflectance Profile from the Deep Seam Project, Piceance Basin, Colorado--Evidence of Previous High Pore Pressure". Abstract presented at the Rocky Mountain AAPG Convention, Casper, Wyoming (Sept. 1986).

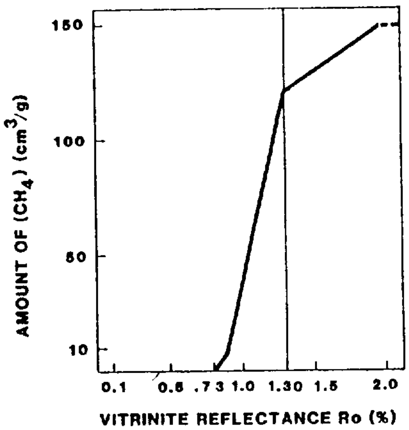
20. Yukler, M.A., 1976, Analysis of Groundwater Flow Systems and an Application to a Real Case, in D. Gill and D.F. Merriam, eds., Geomathematical and Petrophysical Studies in Sedimentology, Computery and Geology, V. 3: Elmsford, NY, Pergamon Press, p. 33-49.

21. Kelso, B.S. and A.D. Decker, et al., 1987, GRI Geologic Appraisal of Coalbed Methane in the San Juan Basin. The 1987 Coalbed Methane Symposium Proceedings, held at the University of Alabama, Tuscaloosa, Alabama, November 16-19, 1987.

22. Hays, J.B., 1979, Sandstone diagenesis- The hole truth. In: Aspects of Diagenesis. P.A. Scholle adn P.R. Schluger, eds., Soc. Econ. Paleontologists and Mineralogists, Spec. Publ. No. 26, pp. 127-139.

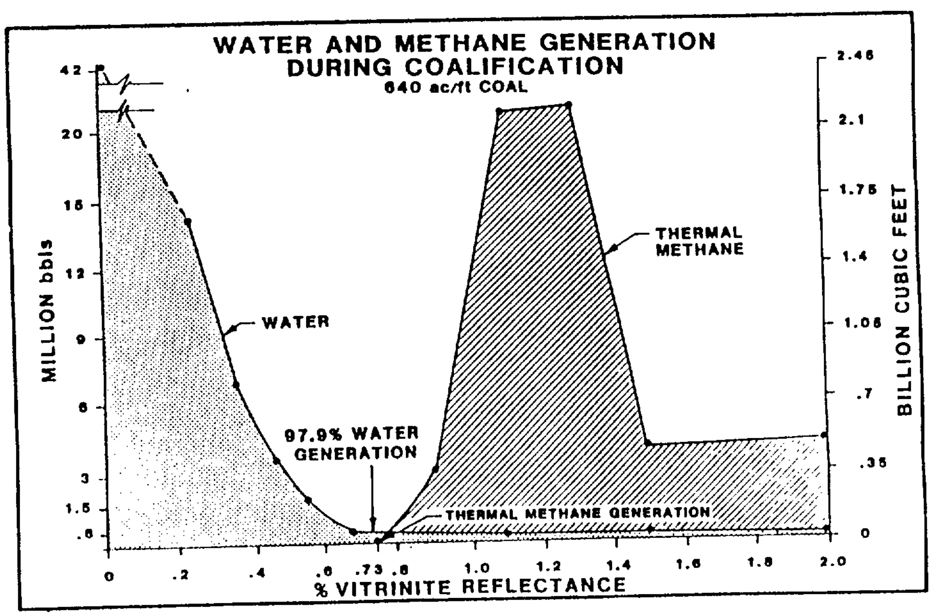
FIGURE 1

METHANE GENERATION



(AFTER WELTE, 1984)

FIGURE 2



COAL VOLUMETRICS

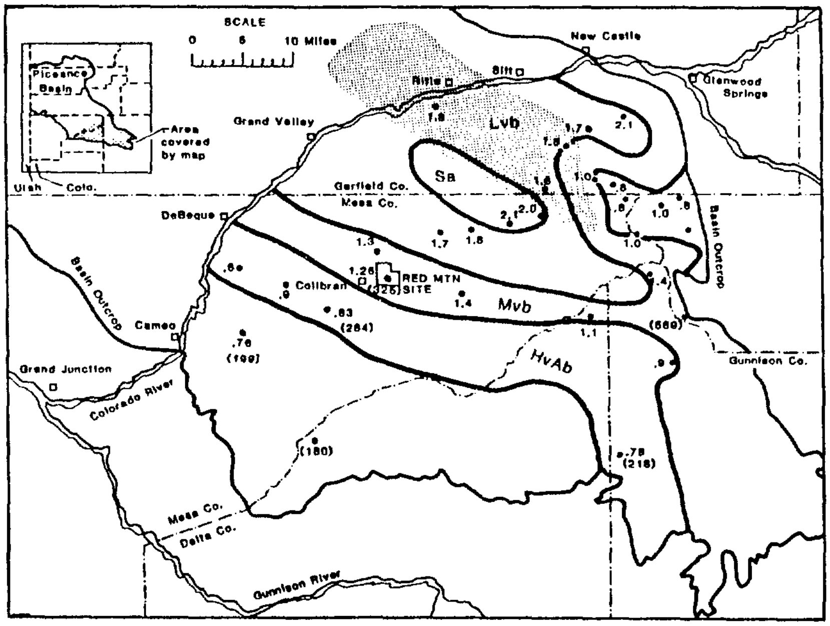
[illegible]	COAL SEAM	METHANE (M³)	[illegible]	THICKNESS FEET	
	[illegible]			[illegible]	
	[illegible]			[illegible]	
	[illegible]			[illegible]	
	S[illegible]			[illegible]	DIAGENESIS
	S[illegible]			[illegible]	
	S[illegible]			[illegible]	
	[illegible]			[illegible]	
	[illegible]			[illegible]	CATAGENESIS
	[illegible]				
	M[illegible]			[illegible]	
	M[illegible]				
	[illegible]			[illegible]	
	[illegible]			[illegible]	META-GENESIS
	T[illegible]				

TABLE [illegible]

COAL RESERVOIR AND GEOLOGIC PROPERTIES

[illegible]

FIGURE 5



PICEANCE BASIN

• ISOREFLECTANCE CONTOURS

OVERPRESSURED AREA

FIGURE 6

WATER AND THERMAL METHANE GENERATION AS A FUNCTION OF TIME AND COAL MATURATION

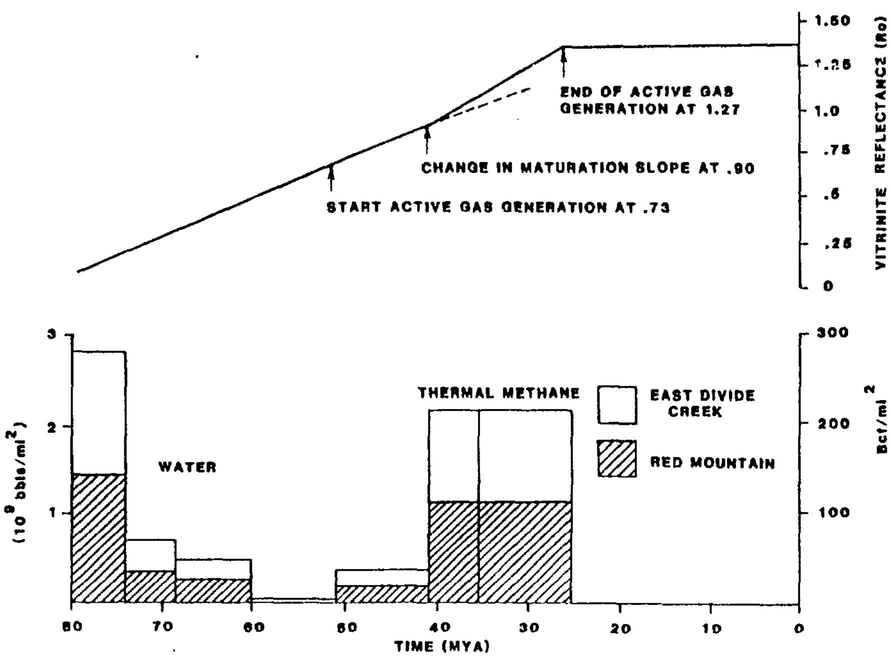
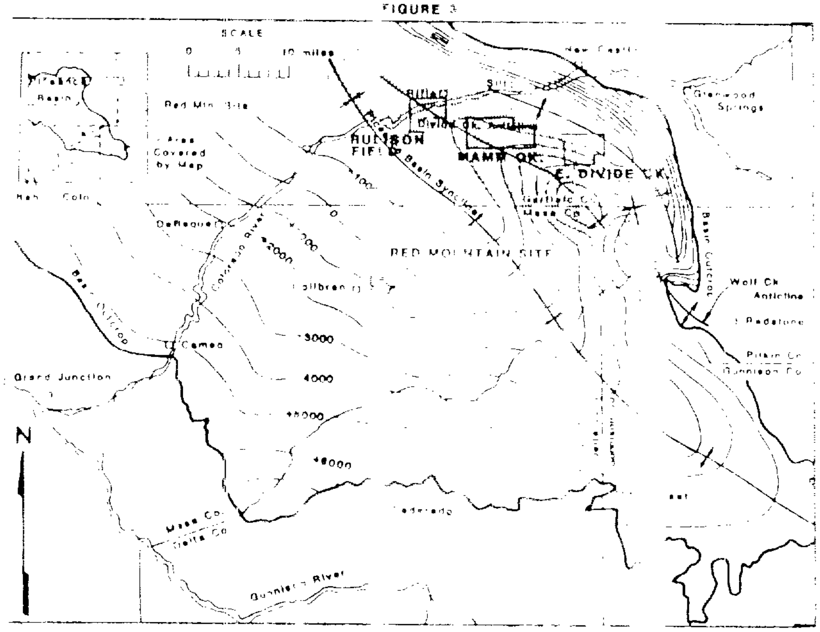


FIGURE 3

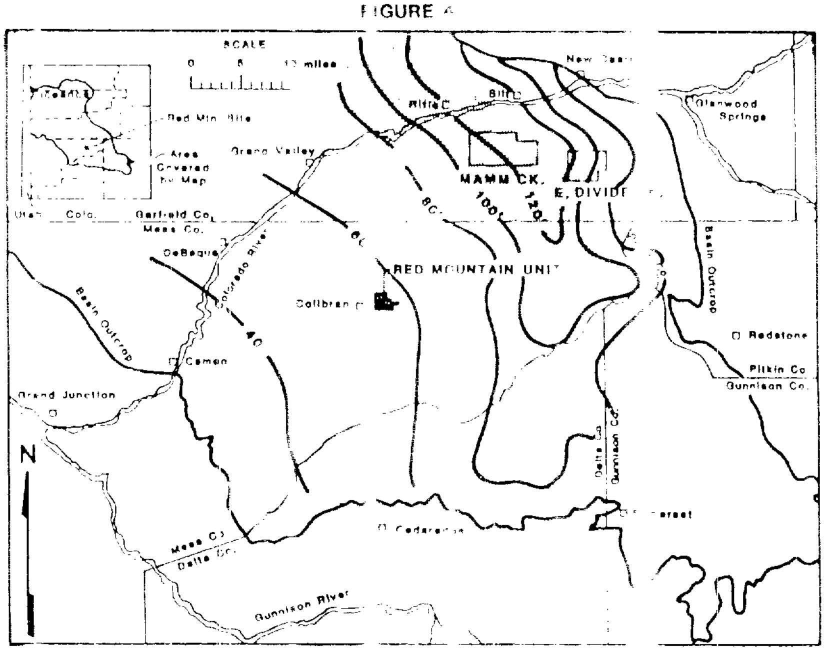


C.I. = 1000'
SUBSEA ELEVATIONS

STRUCTURE CONTOUR MAP
TOP OF ROLLINS SANDSTONE
PICEANCE BASIN, COLORADO

OVERPRESSURED AREA

FIGURE 4



TOTAL COAL ISOPACH TREND MAP

OVERPRESSURED AREA

FIGURE 7

MATURITY vs. DEPTH

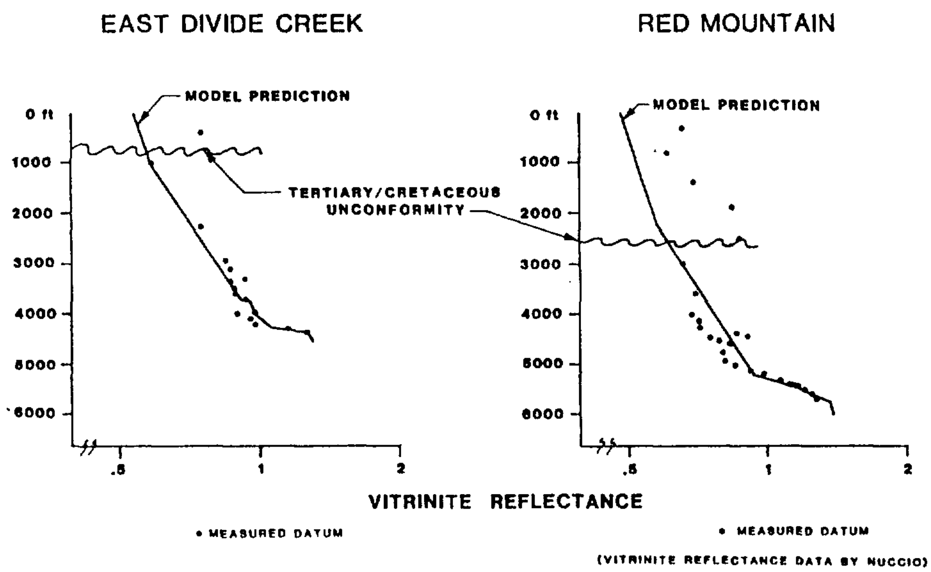


FIGURE 8

STATIC TEMPERATURE LOGS

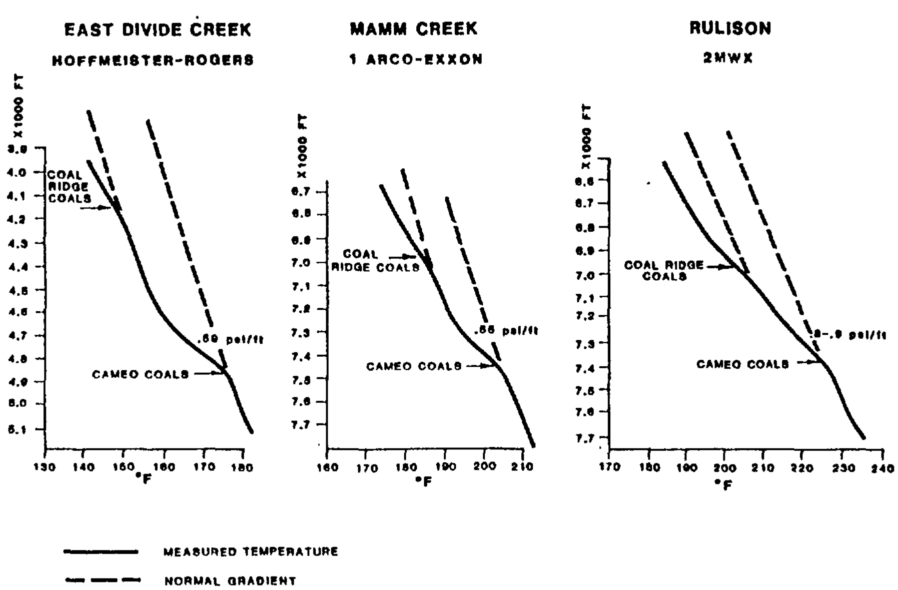
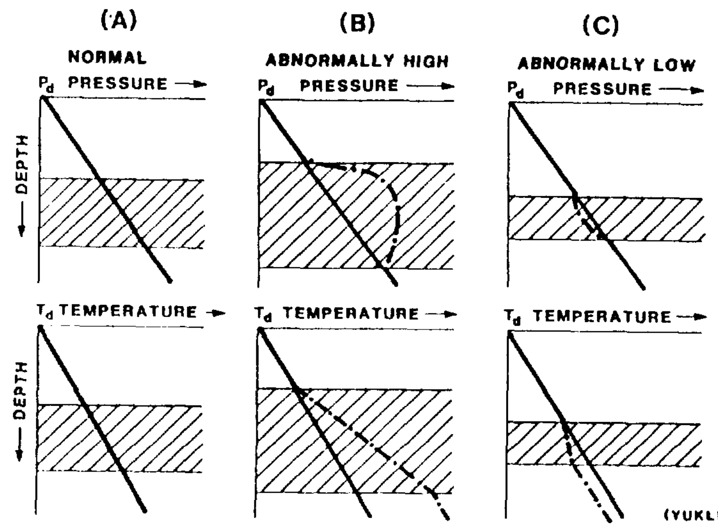


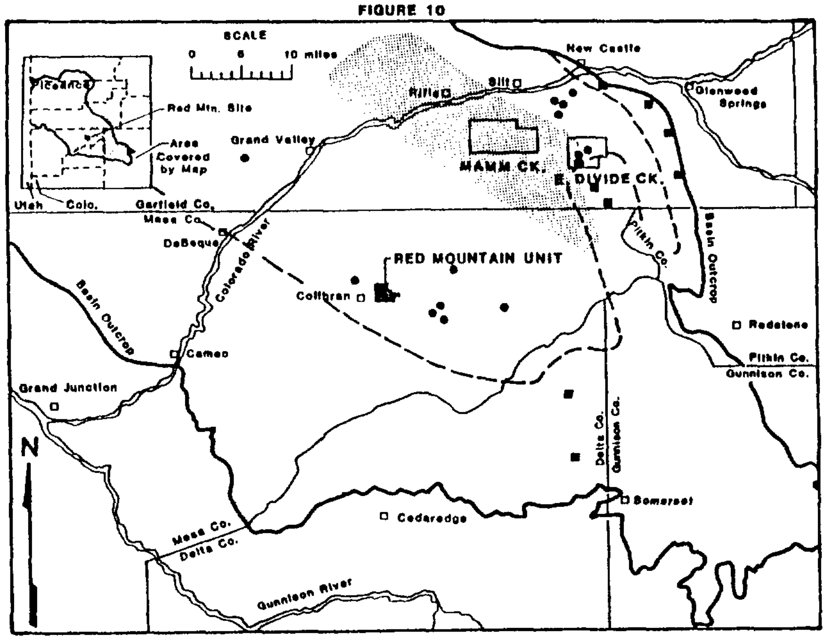
FIGURE 9

PRESSURE - TEMPERATURE RELATIONSHIP



(YUKLER, 1978)

FIGURE 10



■ WATER SATURATED
● GAS SATURATED

GAS & WATER SATURATED
COALBED METHANE WELLS

OVERPRESSURED AREA

Proceedings of the 1987 Coalbed Methane Symposium, Tuscaloosa, Alabama, Nov. 16-19, 1987

THE 1987 COALBED
METHANE SYMPOSIUM

8731 GRI Geologic and Economic Appraisal of Coalbed Methane in the San Juan Basin

B.S. Kelso (Colorado Geological Survey); A.D. Decker (Resource Enterprises, Inc.); D.E. Wicks (Lewin & Associates, Inc.); D.M. Horner (Gas Research Institute)

ABSTRACT

A regional geologic assessment of the Fruitland Formation coals in the San Juan Basin indicates that this formation has a high potential for natural gas production from coal seams. This study, sponsored by the Gas Research Institute, includes subsurface structure, depth, thickness, and geometry interpretations. Coal ranks were assessed using vitrinite reflectance data and gas contents were compiled from public databases.

In addition to the regional geologic investigation, four sites were chosen for detailed field-level geologic and reservoir analyses. The geologic assessment employed cross-sections, net coal isopachs, and structure maps. Reservoir analyses included pressure, temperature, and permeability, in conjunction with coalbed methane well completion and production histories.

The regional geologic analysis concluded that the Fruitland Formation coals have an estimated in-place methane resource of 56 trillion cubic feet (TCF) - nearly double the previous estimate of 31 (TCF). Field-level investigations concluded that no single completion practice provided better production results than any other and overpressured reservoirs are significant contributing factors in the better producing wells.

An economic evaluation of the coalbed methane resource is due to be completed in early 1988.

INTRODUCTION

Activity of coalbed methane development is greater in the San Juan Basin than in other western coal basins. Production of the vast coalbed methane resource of the Fruitland Formation dates back to 1953, with the Phillips Petroleum Co., No. 6-17, San Juan 32-7 Unit well. More recent activity, specifically directed at resource development, started in the mid-1970's. To date, more than 200 wells have been documented as Fruitland Formation coalbed methane tests. Several pools or fields have been designated in the basin reporting Fruitland coal seams, or the "basal" Fruitland as the producing horizons.

The geologic analysis of the Fruitland Formation coalbed methane resource is part of a larger economic evaluation to determine recoverable coalbed methane in the San Juan and other U.S. coal basins. The San Juan Basin evaluation is divided into three phases: 1) a geologic appraisal of the Fruitland Formation coals, concluding with a gas-in-place resource estimate; 2) case history studies and history matching of Fruitland coalbed methane wells; and 3) an economic appraisal of the resource, using various technology cases. At this time, the regional geologic appraisal and four detailed field investigations have been completed. History matching of wells is underway and the economic evaluation has not been initiated. All three phases of the project will be completed by early 1988.

GEOLOGIC SETTING OF THE SAN JUAN BASIN

Regional Setting

The San Juan Basin is located in northwestern New Mexico and southwestern Colorado, with the study area of this project defined by the Pictured Cliffs Sandstone outcrop (Figure 1). It is approximately 90 miles wide, west to east, and 100 miles long, north to south and covers 7500 square miles.

Stratigraphy and Depositional Environments

The coals of the San Juan Basin are Cretaceous age and located in the Dakota, Mesaverde, and Fruitland formations (Figure 2). The Fruitland, the youngest of these, contains the largest coal resource. Deposition of the Fruitland coals occurred predominantly in lagoons, landward of the Pictured Cliffs barrier strandline. The thickest and most continuous seams are located in the lowermost 70 feet of the formation and are often associated with stratigraphic rises in the Pictured Cliffs. A detailed discussion of the Fruitland-Pictured Cliffs depositional environment is presented in Fassett, 1987 [1] and in the Fassett paper in this proceeding.

The Fruitland Formation is a coastal plain deposit of paludal carbonaceous shales, siltstones, sandstones and coals deposited behind the regressing Pictured Cliffs strandline. Formation thickness ranges from less than 100 to greater than 600 feet and contains evidence of fresh and brackish water environments. The sandstones are soft to hard and grey-white to brown in color. The shales are firm and grey to black in color. The coals were deposited in lagoons, marshes, swamps and abandoned channels and are overlain by fluvial shales and sandstones. The coals are the most correlative units of the fluvial Fruitland sediments.

The underlying Pictured Cliffs is a regressive, coastal-barrier sandstone. Formation thickness varies from 125 to 400 feet due to minor transgressive episodes, which locally intertongue the Fruitland and Pictured Cliffs. The lower portion of the Pictured Cliffs is primarily interbedded sandstone and shales, with the upper unit a quartzitic, fine-to-medium grained sandstone.

Structure

The San Juan Basin's arcuate structural axis lies just south of the Colorado-New Mexico state line. The U-shaped Hogback Monocline forms the western and northern rims of the basin. To the east, the Nacimiento Uplift and Archuleta Arch bound the basin. The south and southwestern boundaries of the basin are not structurally defined and sediments gently dip northward from the Chaco Slope (Figure 3).

There are few major structural elements within the San Juan Basin and most are of Laramide age. The Ignacio Anticline, located in the north central portion of the basin, is the largest and best documented structure. Minor northwest trending en echelon folds and northeast-trending, high angle, low displacement faults are found on the eastern and southeastern edges of the basin. Radial folds, which plunge toward the basin's center, can be found around the perimeter. Minor structures resulting from Tertiary intrusive activity are located in the basin. Kelly, 1951 [2] and Woodward and Callender, 1977, [3] provide complete structural and tectonic descriptions of the San Juan Basin.

Detailed Field Investigation Settings

The four field investigation sites are located in the northern end of the basin where operator activity levels have been concentrated (Figure 4). The sites selected provide wells with production histories over extensive time periods and all four sites lack major structural features. Two sites are located in the Colorado Ignacio Blanco Field and one each in the New Mexico Cedar Hill and Undesignated Fruitland Fields. Site 1 of the Ignacio Blanco Field and the Undesignated Fruitland Field are in areas of a Pictured Cliffs stratigraphic rise, that is, an area of intertonguing with the Fruitland. The other two sites are stratigraphically less complex.

METHODOLOGY

The geologic evaluation of coal bearing formations is a key element in an economic appraisal of any coalbed methane resource. The San Juan Basin provided an opportunity for detailed geologic field investigations as well as a regional scale study, because of the large number of exploration control points and Fruitland coalbed methane tests. The purpose of the regional geologic investigation was to determine a gas-in-place resource estimate for the Fruitland Formation coals. The detailed geologic field studies were performed to analyze the geology and reservoir properties associated with producing coalbed methane wells, and for use in the regional economic evaluation of the basin.

The regional geologic evaluation consisted of the construction of two geologic cross-sections and the interpretation of several thousand geophysical logs for subsurface geologic data. The cross-sections provided insight into the lateral and vertical distribution of the Fruitland coals. The subsurface geophysical log data were used to construct structure, overburden, and net coal thickness maps associated with the Fruitland Formation and underlying Pictured Cliffs Sandstone.

The geology and coal resources of the Fruitland Formation have previously been documented [4] and other coalbed methane resource estimates have been based upon this work [5,6]. In order to independently evaluate the Fruitland coalbed methane resource, an original investigation of Fruitland coal resources was conducted.

After the resource and distribution of Fruitland coals was determined, an emperical formula was derived using measured gas contents, depth, and coal rank. The formula allowed projection of gas contents into areas lacking measured data. Gas-in- place estimates were then calculated on a township and range basis using the following equation.

$$GIP = GC * h * A * p \quad (1)$$

Where: GIP = Gas in-place (trillion cubic feet)
GC = Gas content (cubic feet/ton)
h = Net coal thickness (feet)
A = Drillable area (acres)
p = Coal density (tons/acre-foot)

The gas-in-place values for 210 townships with sufficient coal thickness and depth of cover were summed to derive the Fruitland Formation gas-in-place resource estimate.

Four detailed field investigation sites in three producing fields were chosen in areas with sufficient coalbed methane well populations for analysis. Detailed geologic cross-sections and subsurface structure and net coal thickness maps were prepared for each area. In addition to the geologic data, reservoir data including pressure, temperature, permeability (very little data), and cleat spacing were collected. Drilling, completion and production history data for each coalbed methane well in the four areas were also compiled. An analysis of the geologic, reservoir and completion data is being performed in an attempt to establish trends between the reservoir data and production histories.

REGIONAL GEOLOGIC ANALYSIS

The primary products of the regional geological analysis are two cross-sections, a net coal isopach map, an overburden map of the Fruitland-Pictured Cliffs contact, and a thermal maturity rank map. All of the products were used to evaluate the geology and properties of the coals necessary to determine a gas-in-place estimate.

:ial wells. No permeability data was available any of the coal seams in the field. A -in-place estimate of 5 to 35 billion cubic /section (BCF/sec.) was calculated for the ar Hill Field.

Analysis of the completion histories of eight :o Production Company wells in the field showed : five were completed open-hole and three were pleted through pipe with stimulation. Both pletion techniques have proven successful and a clusion can not be drawn on the best method of pletion. Five of the eight wells are completed a single seam and the remaining three are tiple seam completions. One conclusion drawn n this geologic and reservoir study is that the ar Hill Field area is overpressured.

Undesignated Fruitland Field

The Undesignated Fruitland Field is located Township 30 North, Range 7 West. The field tains four coalbed methane wells with duction histories dating from early 1986. This ld, much like the Cedar Hill Field, shows very tle structural relief on the Pictured Cliffs dstone. Structural relief does not exceed 80 : across the area and a northwest-southeast uctural trend is present. Structural closures small magnitude exist along the trend. Net thickness ranges from 36 to 75 feet and roximately 95 percent of the coal occurs within feet of the Pictured Cliffs. The thickest gle seam in the area is 30 feet and the coal is ked high volatile A bituminous. There are no sured gas contents in the study area. efore, data from the Cedar Hill Field, based similar coal rank and depths, were used for ; parameter.

Reservoir pressure data in the area range n 1332 to 1521 psi which converts to gradients).45 to 0.50 psi/foot. Based on this data, the is overpressured. Reservoir temperatures ge from 93 to 112 degrees Fahrenheit in the er Fruitland interval. This field appears to tain both gas and water saturated coal seams. well in the area exhibits a predominantly -saturated coal seam, as shown by recent reases in gas production and unchanged water duction rates. There is no permeability data ilable for the coal reservoirs in the study . The gas-in-place resource estimate for the esignated Fruitland Field, assuming similar gas tent data for the Cedar Hill Field, ranges from :o 38 BCF/sec.

The four coalbed methane wells in the field e drilled by Meridian Oil Company. Two are pleted open-hole with production liners and two completed through casing. Three of the four s have been stimulated. All of the wells have tiple coal seam completions and net coal kness ranges from 43 to 63 feet per well. One the open-hole completion wells has had nendous gas production rates, at times eeding 4 million cubic feet per day (MMCF/d). worst well in the field only averages 150 sand cubic feet per day (MCF/d). The ining two wells have production rates ranging een 1 and 2 MMCF/day.

Ignacio Blanco Field

The Ignacio Blanco Field encompasses most of the Colorado portion of the basin. Two areas within the field were selected for detailed site investigations. It should be noted that the majority of the coalbed methane wells in the two areas were initially drilled and completed by William Perlman between 1982 and 1984. Amoco Production Company recently took over the Perlman acreage and recompleted a number of the wells in 1986 and 1987. Preliminary production statistics from recompleted wells indicate improvement over past production.

Area 1 - Township 34 North, Range 8 West. Area 1 contains 18 Fruitland coalbed methane wells with erratic production histories dating back to 1982. There is 1100 feet of structural relief across the area with structural lows and possible closures located in the southern half. A stratigraphic rise of the Pictured Cliffs Sandstone and intertonguing with the Fruitland Formation is located in the north and west portions of the study area. Net coal thickness throughout the area ranges from 26 to 76 feet with the thickest individual seam being 35 feet. The coal is ranked medium and low volatile bituminous and gas contents from five samples average 315 cubic feet/ton.

This area contains the two Southern Ute Indian, Oxford wells in section 25, which were part of a Department of Energy (DOE) coalbed methane research project. The coring of these wells revealed 1/4 to 1/2 inch cleat spacing. The Oxford #2 well was used in 1985 by In-situ, Inc., a GRI contractor, for reservoir data analysis. In-situ, Inc. determined a static reservoir pressure of 1490 psi or a gradient of 0.52 psi/ft and a calculated permeability of 5 md [11]. Reservoir temperature data across the area, for the lower Fruitland Formation ranges from 100 to 128 degrees Fahrenheit. The pressure data from In-situ's research and from additional Fruitland Formation drill-stem test data indicate that the southern region of the study area is overpressured. All of the coalbed methane wells produced significant volumes of water in the field. A gas-in-place estimate of 18 to 52 BCF/section is estimated for this area.

Completion methods of the 18 wells in the area included cased and open-hole, with stimulated and unstimulated examples of each. No one method has proven more successful than another and erratic production histories from the wells make it difficult to draw a completion/production history conclusion. As noted before, Amoco has recompleted 6 of the 18 wells in the area with small to moderate size sand/water stimulations. Production data from the recompleted wells is not yet available, but will be valuable for additional analysis.

Area 2 - Township 32 and 33 North, Range 6 West. Area 2 of the Ignacio Blanco Field contains 28 coalbed methane wells. A maximum of 350 feet of structural relief is found in the area and a structural nose is located in the northwest portion of the area. A north-south trend of structural depressions is located along the western edge of the area. Net coal thickness ranges from 20 to 68 feet, with the thickest individual coal seam being 42 feet. Coal rank is medium volatile bituminous and the area has an average measured gas content of 380 cubic feet/ton.

A research project was conducted at the Tiffany Gas, Glover #1 well in section 2, T32N, R6W, by [illegible] under GRI contract. The purpose of the project was to identify the resource potential and characteristics at a site, and provide the operator with a completion technique that would lead to economical production of Fruitland coalbed methane. Extensive work on reservoir characteristics was conducted and reported by Jones, 1985 [12]. A static reservoir pressure of 1483 psi or gradient of 0.48 psi/foot was measured at the site by In-Situ, Inc. This indicates an overpressured reservoir, at least in the southeastern corner of the study area. A measured permeability value of 3.5 md was obtained from coal samples and 1/4 inch cleat spacing was measured on recovered coal cores. As in Area 1 of the Ignacio Blanco Field, most of the wells in Area 2 produce significant volumes of water. Gas-in-place estimates for this area range from 14 to 45 BCF/section.

Completions of the 28 wells in this area are similar to those discussed in Area 1 of the Ignacio Blanco Field. Amoco has attempted recompletion on a number of the Perlman wells, but production data is not yet available. A variety of completion and stimulation methods have been applied to wells in this area and no single method provides better results than another.

CONCLUSION

The following conclusions have been drawn from the regional geologic analysis and detailed field site investigations of this coalbed methane resource study:

- This extensive subsurface geologic analysis provides a foundation for additional research and development of the Fruitland Formation coalbed methane resource.
- Additional measured gas content data is needed for assessment of the resource.
- It is estimated that the Fruitland Formation coals contain 56 trillion cubic feet of natural gas.
- Lower Fruitland coals at the four field investigation sites are overpressured.
- Permeability measurements at two locations in the Ignacio Blanco Field are low and measurements are not available for the Cedar Hill and the Undesignated Fruitland Fields. Structural enhancement of permeability may exist within all four fields. Fracture and lineament studies are needed for possible identification of enhanced areas.
- Numerous well completion and stimulation methods have been utilized with varying degrees of success.

ACKNOWLEDGEMENTS

The Gas Research Institute (GRI) has sponsored a geologic and economic analysis of the Fruitland Formation coalbed methane resource under its Natural Gas Supply Program. This effort is part of a much larger economic evaluation of recoverable coalbed methane in the San Juan Basin and other U.S. coal basins. The scope of the program is in support of GRI's goal of adding low cost gas to the United States gas supply reserves through research and development. The authors of this paper wish to thank the Gas Research Institute for their support of this project and for their permission to publish the findings.

References

1. Fassett, J., "The non-transferability of a Cretaceous coal model in the San Juan Basin of New Mexico and Colorado", in Paleoenvironmental and Tectonic Control of Coal-Forming Basins of the United States, Geological Society of America Special Paper 210, (1986), p. 155-171.

2. Kelly, V.C., "Tectonics of the San Juan Basin", in Guidebook of the south and west sides of the San Juan Basin, New Mexico and Arizona, New Mexico Geological Society, 2nd Field Conference, (1951), p. 124-131.

3. Woodward, L. and Callender J., "Tectonic framework of the San Juan Basin", in Guidebook to the San Juan Basin III, New Mexico Geological Society, 28th Field Conference, (1977), p. 209-212.

4. Fassett, J.E. and Hinds, J.S., "Geology and fuel resources of the Fruitland Formation and Kirtland Shale, of the San Juan Basin, New Mexico and Colorado", U.S. Geological Survey Professional Paper 676, (1971), 76 p.

5. Choate, R., Lent, J., and Rightmire, C.T., "Upper Cretaceous geology, coal, and the potential for methane recovery from coalbeds in the San Juan Basin-Colorado and New Mexico", in Coalbed Methane Resources of the United States, Am. Assoc. of Petroleum Geologist Studies in Geology Series #17, (1984), p. 185-222.

6. Kelso, B., Goolsby, S., and Tremain, C., "Deep coalbed methane potential of the San Juan River Region, southwestern Colorado", Colorado Geological Survey Open-File Report 80-2, (1980), 56 p.

7. Rice, D., "Relation of natural gas composition to thermal maturity and source rock type in San Juan Basin, northwestern New Mexico and southwestern Colorado", Am. Assoc. Petroleum Geologists Bull., v. 67 no. 8, (August 1983), p. 1199-1218.

8. Diamond, W.P. and Levine, J.R., "Direct method determination of the gas content of coal: Procedures and results", U.S. Bureau of Mines, Report of Investigation No. 8515, (1981), 36 p.

Stratigraphic Cross-Sections

Two regional, basin-wide, geologic cross-sections were constructed with density-porosity or gamma-density geophysical logs. (Figure 4). Both were segmented due to the length of the sections and the number of logs used. Section A-A", trending northwest to southeast, is parallel to the depositional strike of the Pictured Cliffs strandline. Section B-B" is constructed perpendicular to depositional strike, or southwest to northeast. Orientation of the cross-sections was designed to support the concept that coals parallel to depositional strike can be followed for greater distances than those perpendicular to strike. Interpretations of the cross-sections were used to understand the lateral continuity of the Fruitland coals and to determine if the Fruitland Formation could be divided into zones, based on vertical coal distribution.

In cross-section A-A", the Fruitland Formation thins from the northwest to the southeast. Maximum thickness is greater than 450 feet. Thinning of the Fruitland in the southeast to less than 100 feet is the result of erosion and a stratigraphic rise of the Pictured Cliffs [4], as seen on the cross-section. Coals are found at depths ranging from 2400 to 4200 feet, with the deeper coals along the southeast extension of A-A". Maximum net coal thickness and thicker individual seams are located on the northwest extension of this cross-section with net coal thickness ranging from 4 to 95 feet, and frequent 20 foot individual seams. The spacing between control points averages 5 miles and correlation of individual beds was not possible at this scale. No grouping or zone determination was established due to the lack of traceable markers.

The cross-section B-B" trends southwest to northeast and shows minor thickness variations in the Fruitland ranging from 200 to 350 feet. A stratigraphic rise is present to the northeast, approximately 10 miles south of the Colorado-New Mexico state line. Coals on the southeast end of the cross-section are located at 1100 foot depths and gradually deepen towards the basin's center, with the deepest coals found at 4000 feet. Net coal thickness ranges from 19 to 67 feet with a single seam of 40 feet found near the northeast limit of the cross-section. Most wells used in this cross-section have a well developed coal in close proximity to the Pictured Cliffs. These basal coals range from 8 to 40 feet in thickness and are sometimes correlative over many miles. The average spacing between wells on section B-B" is 5 miles and no correlation of individual beds was attempted. As with A-A", no division of the Fruitland Formation into coal groups or zones was made.

Net Coal Thickness and Overburden

A Fruitland Formation net coal isopach map was constructed using data from gamma-density, density-porosity, and a limited number of gamma ray-neutron geophysical logs (Figure 5). Net coal values do not include coals thinner than 2 feet with efforts made to exclude partings and shaley units within individual coals. Net coal thickness values ranged from 0 to greater than 100 feet. An eastern area of the basin exhibits 0 net coal values which are the results of non-desposition and erosion of the Fruitland. The maximum net coal values are found in the northwest part of the basin with net thickness exceeding 100 feet. An approximate 10 mile wide, northwest trend is observed in the north central portion of the basin. This trend is parallel to the structural axis of the basin with average net coal thicknesses of 70 to 80 feet. It can be generally stated that the southern end of the basin has less than 30 feet of net coal, with the exception of a small area in the southwest. Net coal values and the geologic cross-sections were used to determine the lateral and vertical distribution of coals in the Fruitland.

The overburden map or depth parameter of the Fruitland coals in the regional geologic analysis was utilized as part of the gas content and containment evaluation. Depths of coals range from 0 feet at the basin's outcrop to more than 4200 feet along the basin's structural axis. Depths change rapidly along the north, northeastern, and northwestern margins of the basin due to the structural monoclines. In the southern part of the basin, coal depths gradually increase as the structural slope increases to the northeast. The deepest coals are found in the northeastern quarter of the basin.

Coal Rank

Fassett and Hinds, 1971 [4] reported the coals of the Fruitland Formation as subbituminous. Support for their conclusion comes from an observation of the weathering nature of the coals when mined and stockpiled. Viewing the coals as a reservoir for natural gas requires a different approach to rank assessment. The approach used in this study was based on the thermal maturity of the coals, which is measured by the vitrinite reflectance. This approach is applicable to all coal basins. Rank generally increases from south to north, with the highest ranks found in the north central portion of the basin. A vitrinite reflectance rank map of the San Juan Basin (Rice, 1983) [7] was modified with additional data and used to establish the various Fruitland coal ranks, ranging from high volatile C bituminous to low volatile bituminous with 0.46 to 1.51 reflectance values.

GAS CONTENTS OF FRUITLAND COALS

A moderately small public domain database of measured gas contents exists for the Fruitland Formation coals. The primary source of the data was the U.S. Bureau of Mines (USBM) gas content measurement database for samples from around the United States. A description of the desorption process and a partial list of samples is found in Diamond and Levine, 1981 [8]. Additional desorption data were acquired from the Colorado Geological Survey.

Twenty-eight data points were standardized for ash content, temperature, and pressure. The data was sorted by coal rank and sample depth to develop correlations relating gas content to depth and rank. Curves were established for high volatile A bituminous and high volatile B and C bituminous coals combined. Insufficient data was available for medium and low volatile coals and analog curves were founded on the results of similar analyses in a Piceance Basin study [9]. The mathematical relationship that resulted from the analysis is:

$$GC = m * (\ln d) + b \qquad 2$$

Where: GC = Gas content (cubic feet/ton)
m = Scaling coefficient
ln d = Natural log of depth (feet)
b = y intercept

GAS IN-PLACE OF THE FRUITLAND COALS

The regional geologic evaluation of the Fruitland Formation coals, San Juan Basin, concluded with a gas-in-place resource estimate. The unit of analysis is a township and range and a gas-in-place value was calculated for each of the 210 units in the study area. Elements of the gas-in-place calculation are gas content, net coal thickness, drillable area, and coal density.

Each of the 210 units was assigned an estimated gas content value using the mathematical relationship discussed previously. Depths used in the calculation were average maximum overburden on the Pictured Cliffs Sandstone. Analysis of the vertical distribution of Fruitland coals showed more than 85 percent of the net coal thickness is within 200 feet of the Pictured Cliffs. Insignificant differences result in gas content values when depth values are varied within this 200 foot range.

Net coal thickness and coal density are factors in the coal resource portion of the gas-in-place calculation. An average net coal thickness was determined for each unit from the coal isopach map constructed in the geologic evaluation. The coal rank map was used to assign coal density to the unit. Densities increase with rank as documented by Averitt, 1975 [10]. The following table shows the variation of coal density with rank used in this study.

Rank	Density (Tons/acre-foot)
High Volatile Bituminous (A, B, and C)	1800
Medium Volatile Bituminous	1850
Low Volatile Bituminous	1900

The drillable area of a unit is determined by totaling the number of acres in the unit and subtracting undevelopable acreage. Undevelopable acreage includes areas with urban development; abandoned, active or permitted coal mining operations; acreage already containing coalbed methane wells; and areas of insufficient coal overburden (gas containment) or coal thickness.

Gas-In-Place Estimate

The total gas-in-place resource estimate for the Fruitland Formation coals is 56 trillion cubic feet (TCF). This is only a resource estimate, not a reserve estimate and no recovery factor has been applied. It must be pointed out that up to this point, we have only been discussing gas in the micro-pore system of the coals and not dealt with "free" gas or gas in the cleat system of the coals. Calculation of the gas in the cleat system will be based on the results from history matching work and is expected to increase the current gas-in-place estimate by 2 to 3 percent. Figure 6 is a gas-in-place contour map for the Fruitland Formation coals.

The 56 TCF gas-in-place estimate is nearly twice the estimate previously reported by Choate and others, 1984 [5]. A comparison of the two estimates revealed that coal resource values used for each were within 10 percent. The conclusion was drawn that gas content data in the two studies were drastically different. Analysis of the data set used by Choate showed the use of fewer core desorption data and a large percentage of chip desorption samples. This explains the increase in the gas-in-place estimate resulting from this study.

DETAILED FIELD INVESTIGATIONS

Four sites located in three coalbed methane production fields were selected for detailed geologic and reservoir analysis. The number of completed wells in each area and their production histories aided in site selection. Figure 4 shows the location of the four sites studied. They are the Cedar Hill Field, New Mexico; an Undesignated Fruitland Field, New Mexico; and two sub-areas of the Ignacio Blanco Field, Colorado. The primary purpose of the field site investigations was to validate the regional geologic study at a field level. In addition, the field investigations incorporated production data into the geologic analysis and established the stratigraphic intervals contributing to the Fruitland coalbed methane production.

Cedar Hill Field

The Cedar Hill Field is located in portions of Townships 31 and 32 North, Range 10 West. Development of the coalbed methane resource in this area was initiated more than ten years ago and presently, the field contains 12 coalbed methane wells. A structure map on the Pictured Cliffs Sandstone for the area shows a maximum of 100 feet structural relief with a series of subtle northeast-southwest trends. Most of the structures in these trends exhibit relief of 20 feet or less. Net coal thickness across the area ranges from 9 to 55 feet. A coal in the basal section of the Fruitland Formation has been the primary production target and thickness ranges from 5 to 27 feet. This seam thins and splits to the southeast. The coal rank in the area is high volatile A bituminous and gas contents average 358 to 521 cubic feet/ton from four samples.

The reservoir parameters assessed in this evaluation are pressure, temperature, saturation, permeability and a gas-in-place estimate. Three bottom hole pressures were available from public records. They range from 1362 psi to 1590 psi or 0.49 to 0.56 psi/foot and indicate an overpressured coal reservoir. Reservoir temperatures of the basal coal ranged from 95 to 114 degrees Fahrenheit. Reservoir saturation status for this area is unknown and based on production histories of the earliest wells, 100 percent water saturation was assumed. Wells drilled at later dates were probably less than 100 percent water saturated and were partially dewatered by the

9. McFall, K., Wicks, D., Kelso, B., Sedwick, K., and Brandenburg, C., "An analysis of the coal and coalbed methane resources of the Piceance Basin, Colorado", SPE/DOE Paper 16418, in Proceedings of the 1987 SPE/DOE Low Permeability Symposium, Denver, May 18-19, p. 283-295.

10. Averitt, P., "Coal resources of the United States, January 1, 1974", U.S. Geological Survey, Bulletin 1412, (1975), 131 p.

11. Koenig, Robert, In-situ, Inc., (1987) personal communication.

12. Jones, A.H., "Methane production characteristics of deeply buried coalbed reservoirs", Gas Research Institute Topical Report No. 85/0033, (March 1985), 176 p.

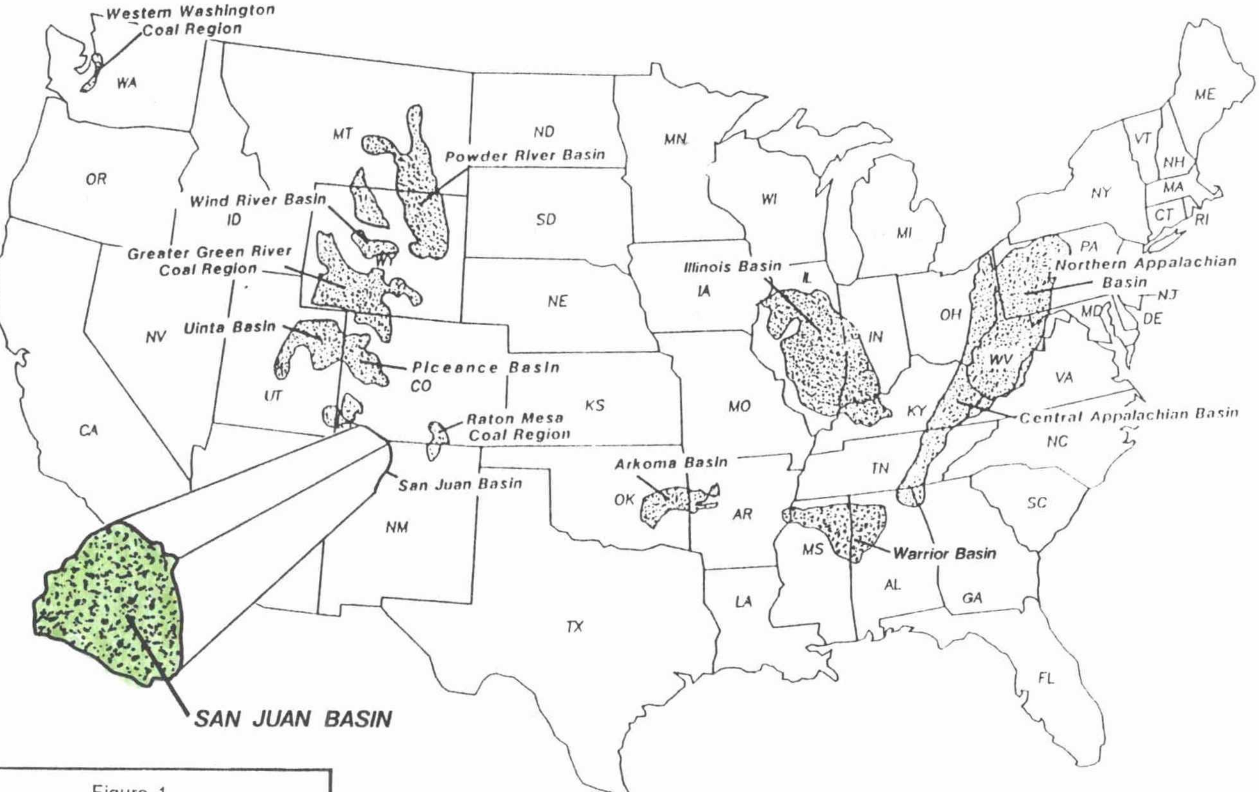


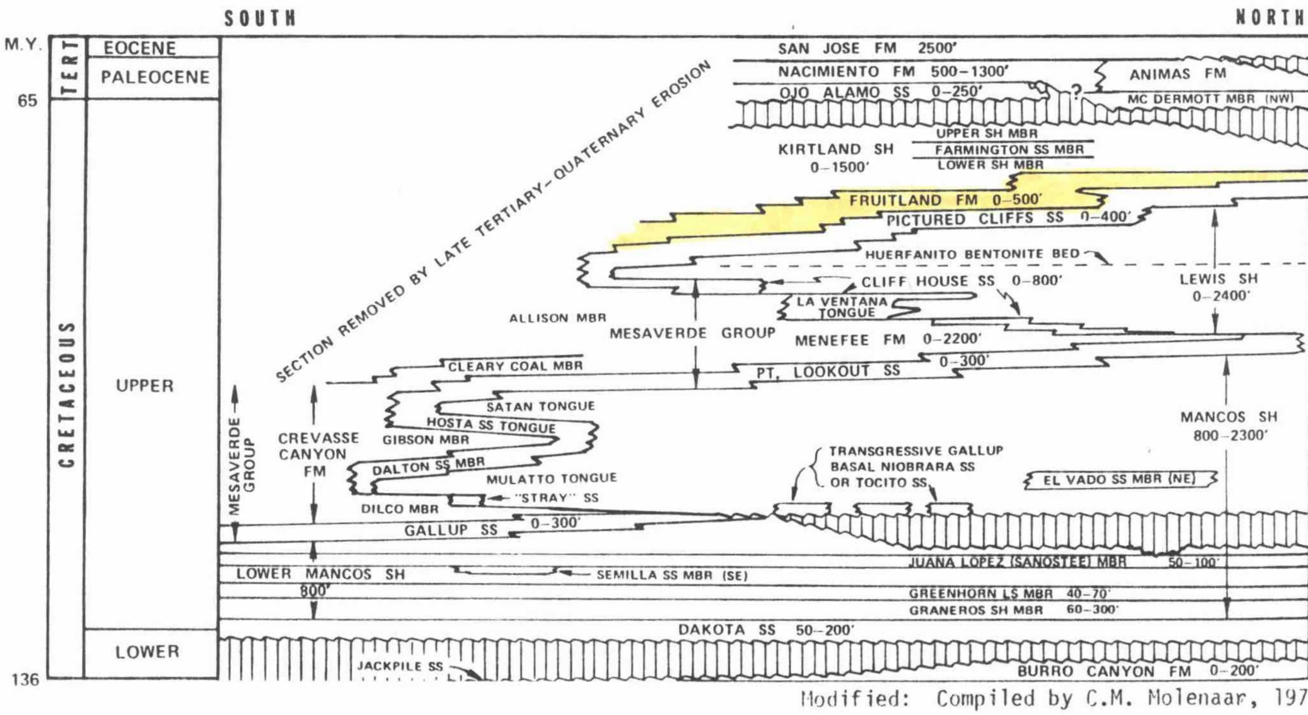
Figure 1

MAJOR COAL BASINS OF THE UNITED STATES

0 100 300 Miles

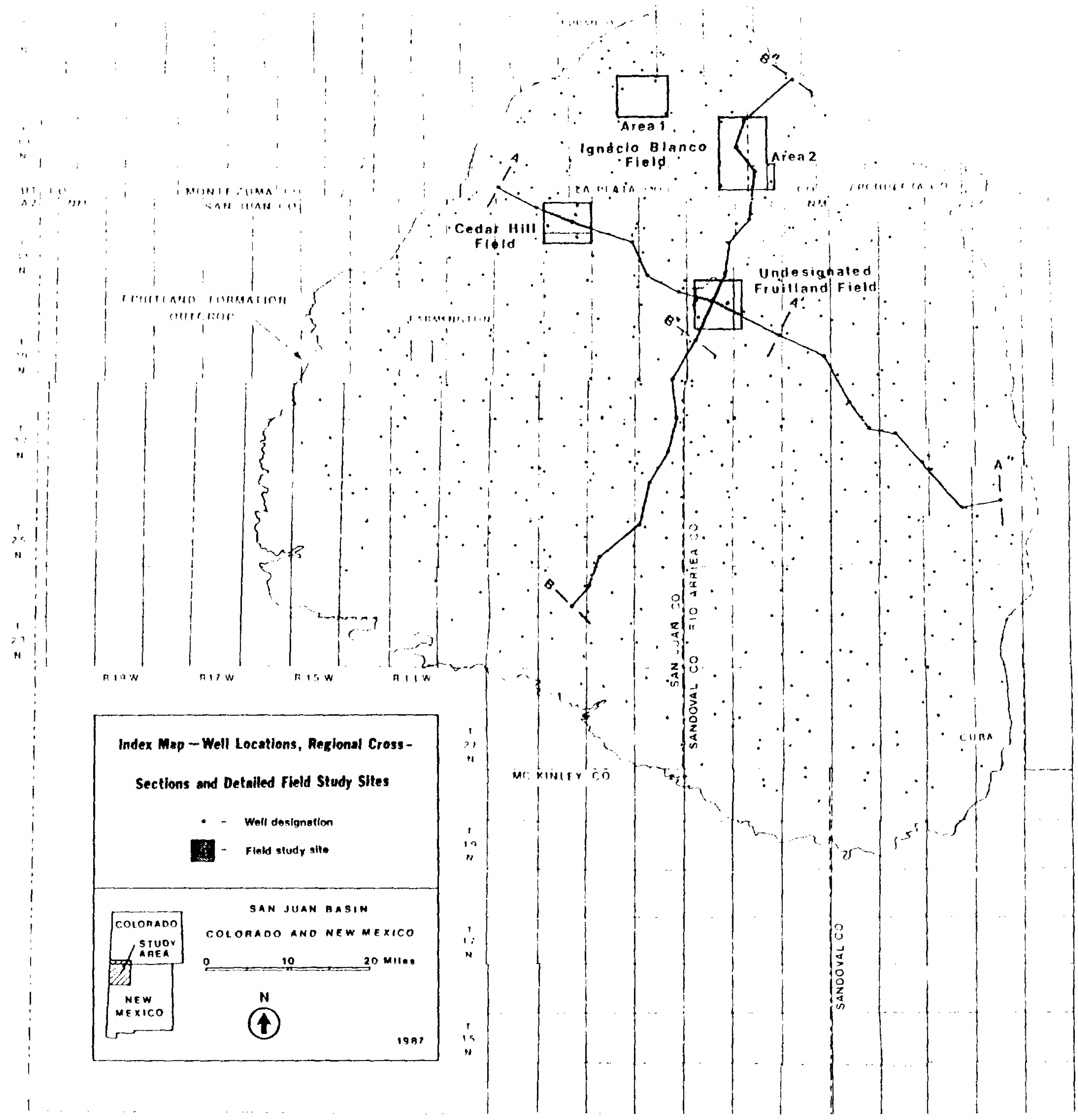
N

After: Rightmire, 1984.



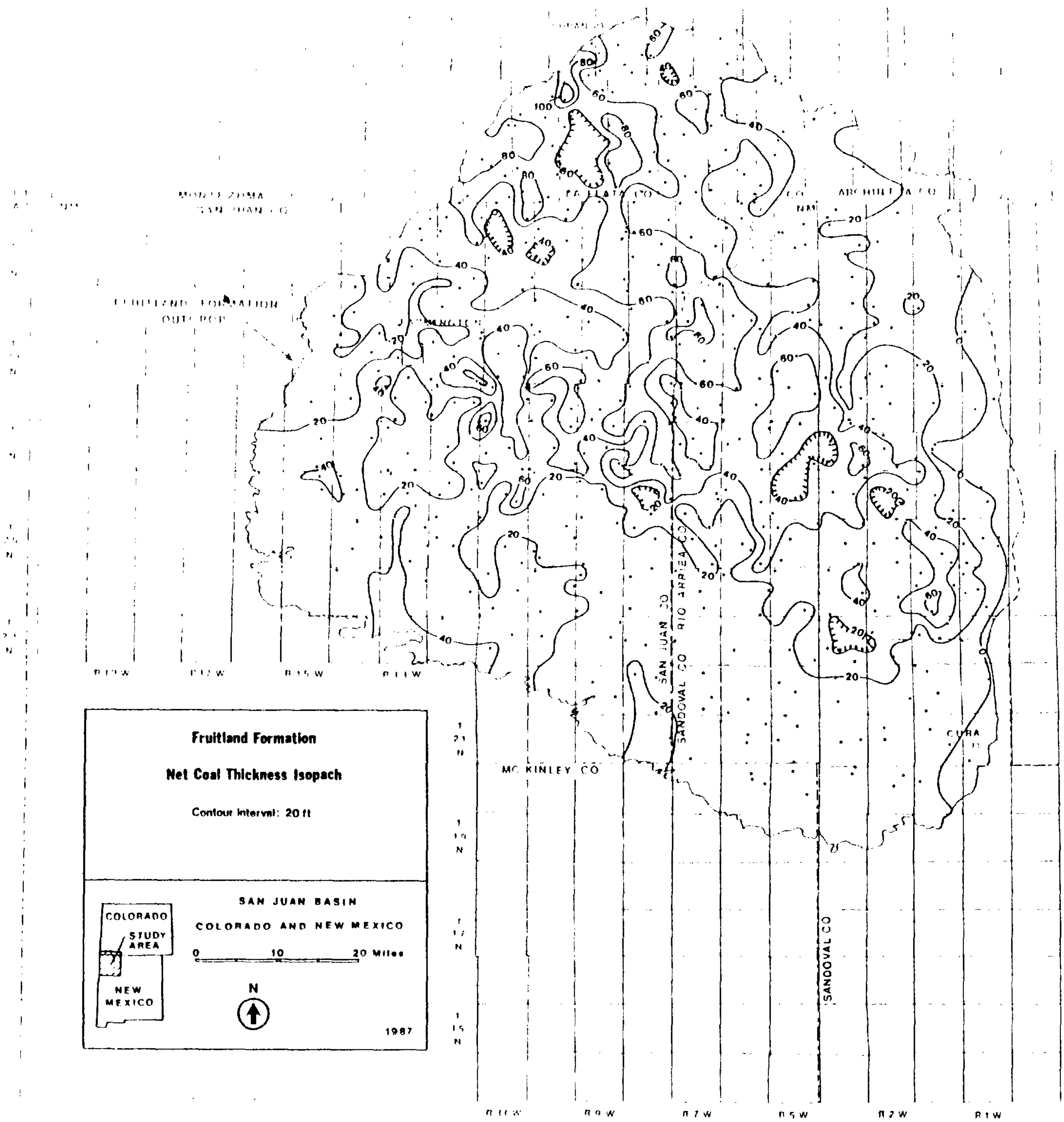
Modified: Compiled by C.M. Molenaar, 1977.

Figure 2. San Juan Basin time - stratigraphic nomenclature chart.



Area 1
Ignacio Blanco
Field
Area 2
Cedar Hill
Field
Undesignated
Fruitland Field
B"
A'
B'
A"
B
CUBA
MC KINLEY CO
SAN JUAN CO
SANDOVAL CO
RIO ARRIBA CO
SANDOVAL CO
R 11 W
R 9 W
R 7 W
R 5 W
R 2 W
R 1 W
Index Map — Well Locations, Regional Cross-Sections and Detailed Field Study Sites
Well designation
Field study site
SAN JUAN BASIN
COLORADO AND NEW MEXICO
0
10
20 Miles
COLORADO
STUDY AREA
NEW MEXICO
N
1987

Figure 4.



Fruitland Formation
Net Coal Thickness Isopach
Contour Interval: 20 ft
SAN JUAN BASIN
COLORADO AND NEW MEXICO
0
10
20 Miles
COLORADO
STUDY AREA
NEW MEXICO
N
1987
MC KINLEY CO
SAN JUAN CO
SANDOVAL CO
RIO ARRIBA CO
SANDOVAL CO
CUBA
R 11 W
R 9 W
R 7 W
R 5 W
R 3 W
R 1 W

Figure 5.

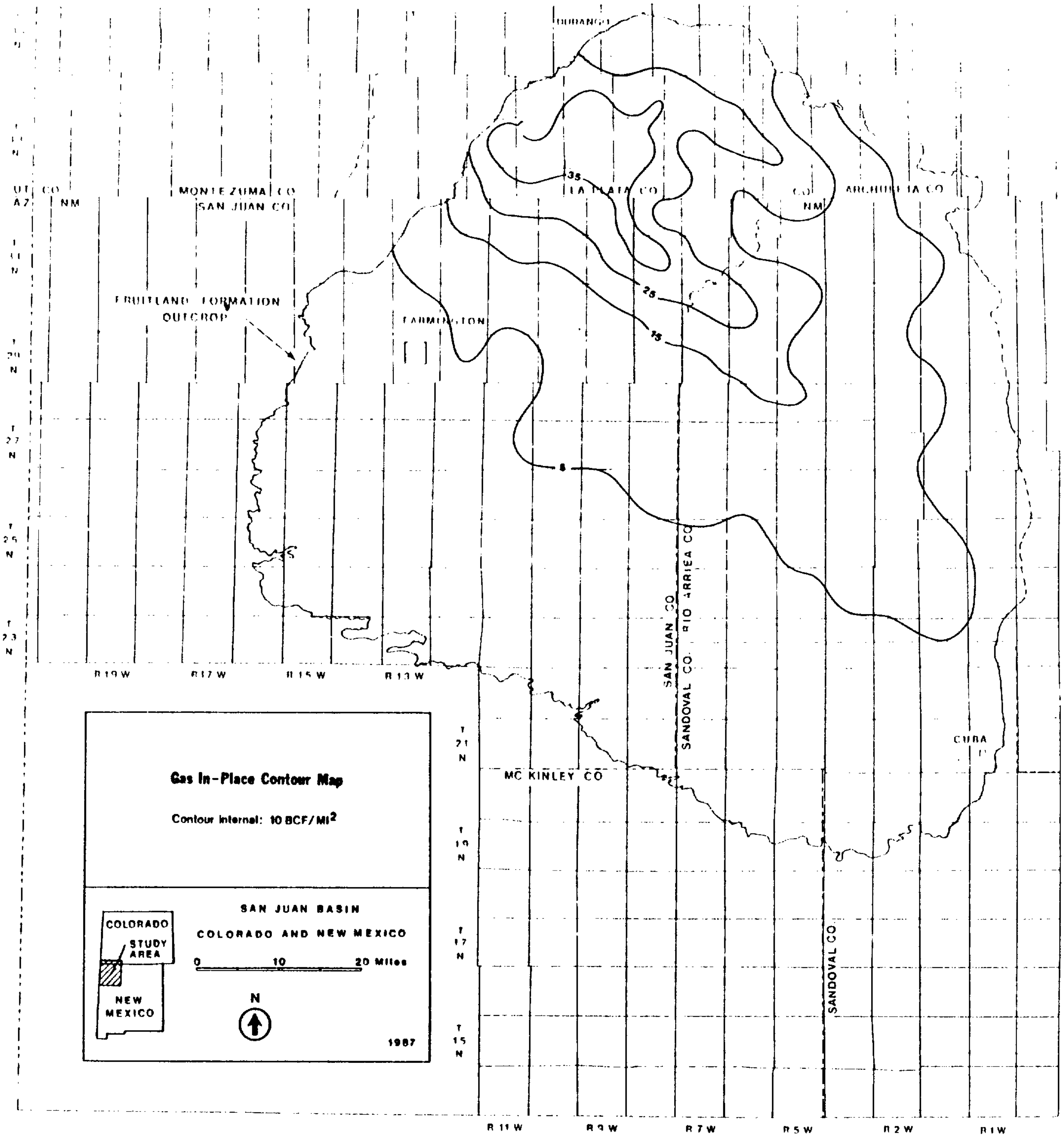

DURANGO
UT CO
AZ NM
MONTEZUMA CO
SAN JUAN CO
LA PLATA CO
CO
NM
ARCHULETA CO
FRUITLAND FORMATION OUTCROP
FARMINGTON
35
25
15
5
SAN JUAN CO
SANDOVAL CO.
RIO ARRIBA CO
MC KINLEY CO
CUBA
SANDOVAL CO
R 19 W
R 17 W
R 15 W
R 13 W
R 11 W
R 9 W
R 7 W
R 5 W
R 2 W
R 1 W
T 29 N
T 27 N
T 25 N
T 23 N
T 21 N
T 19 N
T 17 N
T 15 N
Gas In-Place Contour Map
Contour Internal: 10 BCF/MI²
SAN JUAN BASIN
COLORADO AND NEW MEXICO
0
10
20 Miles
N
COLORADO
STUDY AREA
NEW MEXICO
1987

Figure 6.