Geologic Characterization and Assessment of In-Place Resources, Upper Cretaceous and Lower Tertiary Low Permeability Gas-Bearing Strata, Wind River Basin, Wyoming

CONTRACT INFORMATION

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INTRODUCTION

Gas in unconventional reservoirs such as low-permeability (tight) sandstones, gas shales, and coal beds is becoming increasingly important as conventional gas reserves are depleted. The U.S. Geological Survey in its 1995 National Assessment of Oil and Gas Resources of the United States (Gautier and others, 1995), estimated 358 tcf of undiscovered technically recoverable gas in unconventional reservoirs. This represents 33.4% of all technically recoverable undiscovered gas in the United States. Of this total, about half is estimated to be in tight sandstone reservoirs in the Rocky Mountain region.

The Wind River Basin is one of several Rocky Mountain basins that contain significant resources of gas in tight sandstone reservoirs of Cretaceous and Tertiary age (Figure 1). Tight gas reservoirs have an in-situ permeability to gas of 0.1 (md) or less and cover vast areas of the structurally deeper parts of these Rocky Mountain Basins. In addition, these accumulations differ from conventional hydrocarbon accumulations in that they: (1) cut across stratigraphic units; (2) commonly occur down dip from more permeable water-charged reservoirs, (3) typically have no obvious structural or stratigraphic trapping mechanism, and (4) are either overpressured or underpressured. The abnormal pressures of these reservoirs indicate that water in hydrodynamic equilibrium with surface exposures is not the pressuring agent. Instead, hydrocarbons within the tight reservoirs are thought to pressure these rocks (Spencer, 1987).

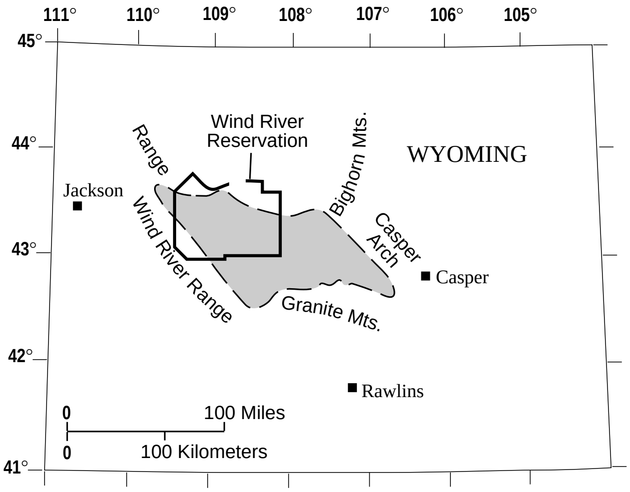

Figure 1. Index map showing location of Wind River Basin, and surrounding uplifts. Location of Wind River Reservation is also shown.

In 1977, the U.S. Geological Survey, in cooperation with the U.S. Department of Energy, initiated a program to characterize low-permeability reservoirs in Rocky Mountain basins and assess resources (Spencer and others, 1977). Masters (1979; 1984) was one of the first to publish detailed studies of these unique accumulations and proposed that gas generated in the deep, thermally mature areas of sedimentary basins is inhibited from migrating upwards and out of the basin by low permeabilities. Masters pointed out that low-permeability rocks (<0.1 md), with 40% water saturation, are only three-tenths as permeable to gas as they are to water, and at 65% water saturation, the rock is almost completely impervious to the flow of gas. The concepts for the development of basin-centered gas accumulations in Rocky Mountain basins have been further refined by a number of workers such as Jiao and Surdam (1993), Meissner (1980; 1981; 1984), McPeek (1981), Law (1984) Law and others (1979; 1989), Law and Dickenson (1985), MacGowan and others (1993), Spencer and Law (1981), Spencer (1985), and Yin and Surdam (1993). In general, these models suggest that overpressuring in basin-centered accumulations is a result of volumetric increases during hydrocarbon generation by the coals, carbonaceous shales and marine shales that are interbedded with the sandstone reservoir rocks, and that migration distances from source rock to reservoir rock are not great. Much of the water that fills the pore spaces is driven out of these basin-centered hydrocarbon accumulations as the hydrocarbons are generated. The capillary seal is activated as gas replaces water in the pore space, and hence, the basin-centered gas accumulations seal themselves as they form. Some workers believe that these seals are so efficient that they may be able to maintain abnormally high pressures for tens of millions of years (MacGowan and others, 1993). An overpressured accumulation can evolve into one that is underpressured if a basin undergoes significant cooling.

The Department of Energy, under the Western Tight Gas Sands Project, has supported basic research into the geology of tight gas sandstones in several Rocky Mountain basins including the Piceance Basin of western Colorado, the Uinta Basin of western Colorado and eastern Utah, and the Greater Green River Basin of southwestern Wyoming and northwest Colorado, and most recently the Wind River Basin of central Wyoming. This research led to assessments of in-place and recoverable tight gas resources in these basins. The development of tight gas resources has been greatly aided by the basic knowledge gained under this project.

OBJECTIVES

Prior to this study, very little work had been done on the tight gas accumulation in the Wind River Basin. In fact, so little was known that although identified, it was not assessed in the 1995 National Assessment (Gautier and others, 1995). The Wind River Basin is sparsely drilled when compared to other Rocky Mountain basins such as the Piceance, San Juan and Greater Green River basins, making it difficult to define the limits of the basin-centered accumulation. This paper summarizes the extensive work recently completed on this tight gas accumulation. For the complete results of the study please see Johnson and others (1996a; 1996b); and Nuccio and others (1996). The objectives of our investigations are to characterize the geology of the tight gas resources of the Wind River Basin, Wyoming and to assess in-place resources. These in-place numbers are used by the U.S. Geological Survey and other assessment groups to estimate recoverable resources using various economic and technological assumptions. Estimating recoverable resources is greatly aided by the detailed geologic investigations summarized here and presented in more detail in the publications mentioned above.

APPROACH

Detailed geologic studies were used to characterize the basin-centered tight gas accumulation in the

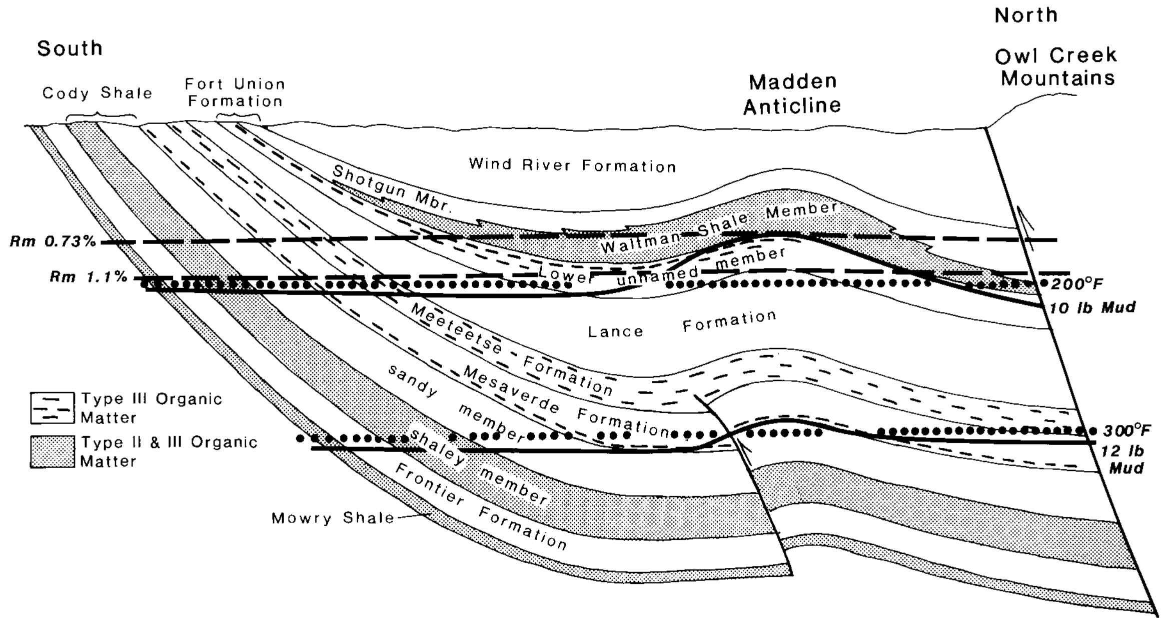

Figure 2. Schematic north-south cross section through the Wind River Basin, Wyoming showing Upper Cretaceous and lower Tertiary stratigraphic units, approximate positions (a) where 10 lb and 12 lb mud were first used during drilling, (b) of 0.73% and 1.1% vitrinite reflectance levels (Rm), and (c) of 200° F and 300° F present-day isotherms.

Wind River Basin, Wyoming, and a volumetric approach was used to estimate in-place gas resources. The approximate limits of the accumulation were defined using gas shows from mud logs, drillstem test results, variations in thermal maturity, and present-day formation temperatures. High mud weights, universally used while drilling deep tests in the Wind River Basin (Bilyeu, 1978), were an early indication that the basin contained a significant overpressured basin-centered tight gas accumulation. Mud logs in the basin also indicated nearly continuous gas shows in the overpressured interval, another characteristic of a basin-centered gas accumulation (Masters, 1979; 1984). Mud logs are typically more reliable than geophysical logs in helping to define gas productive intervals (Dunleavy and Gilbertson, 1986; Reinecke and others, 1991).

The tight gas accumulation in the Wind River Basin can generally be subdivided into three zones: 1) a highly overpressured zone where pressure gradients exceed 0.73 psi/ft; 2) a moderately overpressured zone where pressure gradients average about 0.52 psi/ft; and 3) a marginal transition zone which appears to be largely underpressured (Figure 2). The highly overpressured zone occurs where present day temperatures exceed 300° F. The moderately overpressured zone occurs where thermal maturities as measured by mean random vitrinite reflectance (Rm) are greater than 1.1%, but temperatures are less than 300° F. The transition zone occurs where thermal maturities range between an Rm of 0.73 and 1.1% and contains a mixture of gas-charged tight reservoirs, gas-charged reservoirs with conventional permeabilities, and water-filled reservoirs. These zones cut across as many as eight different stratigraphic units, and the area where a zone cuts across a stratigraphic unit is here considered a play (Figure 3). A total of 22 plays was assessed.

Relationships between variations in thermal maturity and basin-centered gas accumulations have been established in several Rocky Mountain basins. Masters (1984), in his study of the basin-centered gas accumulation in the Deep Basin of Alberta, shows that an Rm of 1.0% corresponds approximately to the limits of the accumulation. In the Piceance Basin of western Colorado, Johnson and others (1987) used an (Rm) level of 1.1% to approximately define the limits of the basin-centered accumulation while an Rm of from 0.73 to 1.1% was used to define a transition zone containing both tight reservoirs and reservoirs with near-tight

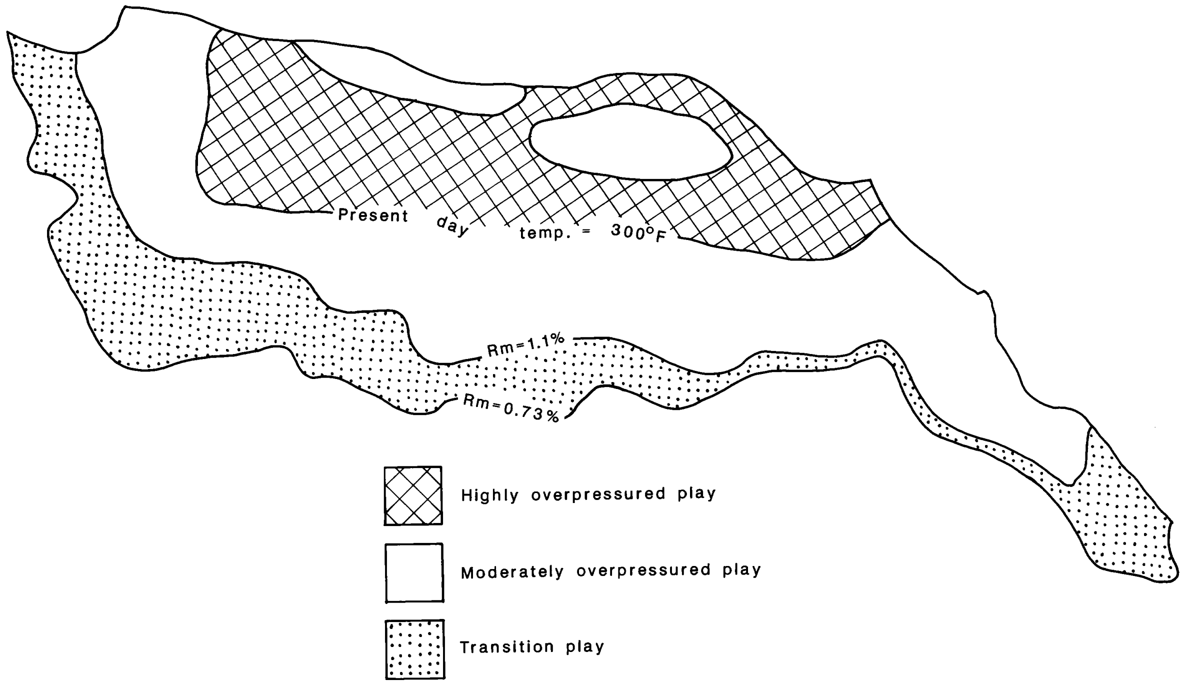

Figure 3. Map showing gas plays for the Upper Cretaceous Meeteetse Formation. From Johnson and others (1996a). See Figure 4 for more precise location.

and conventional permeabilities. In the Greater Green River Basin of Wyoming and Colorado, Law and others (1989) found that an Rm of 0.80% generally corresponds to the top of the overpressured zone.

PROBABILISTIC METHODOLOGY FOR GAS RESOURCE ASSESSMENT

A probabilistic methodology was developed for the assessment of the total in-place gas resources in the study area (Crovelli and Balay, 1996; Crovelli and others, 1996). The methodology utilizes a reservoir engineering equation in which the hydrocarbon volume attributes (1) area, (2) thickness of reservoir rock, (3) effective porosity, (4) trap fill, (5) hydrocarbon saturation, and (6) depth to reservoir must be estimated. Trap fill is the % of total sandstone volume that is saturated with gas while hydrocarbon saturation is the % of the effective porosity in the gas saturated sandstones that contains gas. Because of the small pore spaces, irreducible water in gas-charged tight sandstones is typically quite high, averaging about 50%.

In order to increase precision, each of the 22 plays were subdivided into as many as 126 subplay areas. The subplay areas were defined using a combination of overburden maps and sandstone isopach maps (Figure 4). Each subplay was assessed individually, and then all of the subplays of a play were aggregated to make an assessment of the overall play. Finally, all of the plays were aggregated for an assessment of the total in-place gas resources in the study area. The following reservoir engineering equation is used to calculate the in-place volume of gas in cubic feet:

$$\text{Gas in-place} = 1.5378*640*A*H*P*F*S_h*P_e/(T*Z),$$

where
A = area of closure (square miles)
H = reservoir thickness (feet)
P = effective porosity (percent)
F = trap fill (percent)
S_h = hydrocarbon saturation (percent)
P_e = original reservoir pressure (psi)
T = reservoir temperature (degrees Rankine)
Z = gas compressibility factor (no units)

The equation consists of a product of factors that are functions of the hydrocarbon-volume attributes. The geologic variables P_e, T, and Z are each taken to be linear functions of reservoir depth D (feet) in the form $a * D + b$., e.g., T = a * D + b where a is the geothermal gradient and b is the mean annual temperature at the ground surface.

To obtain a point estimate of the in-place gas of a subplay, point estimates are made of the six attributes

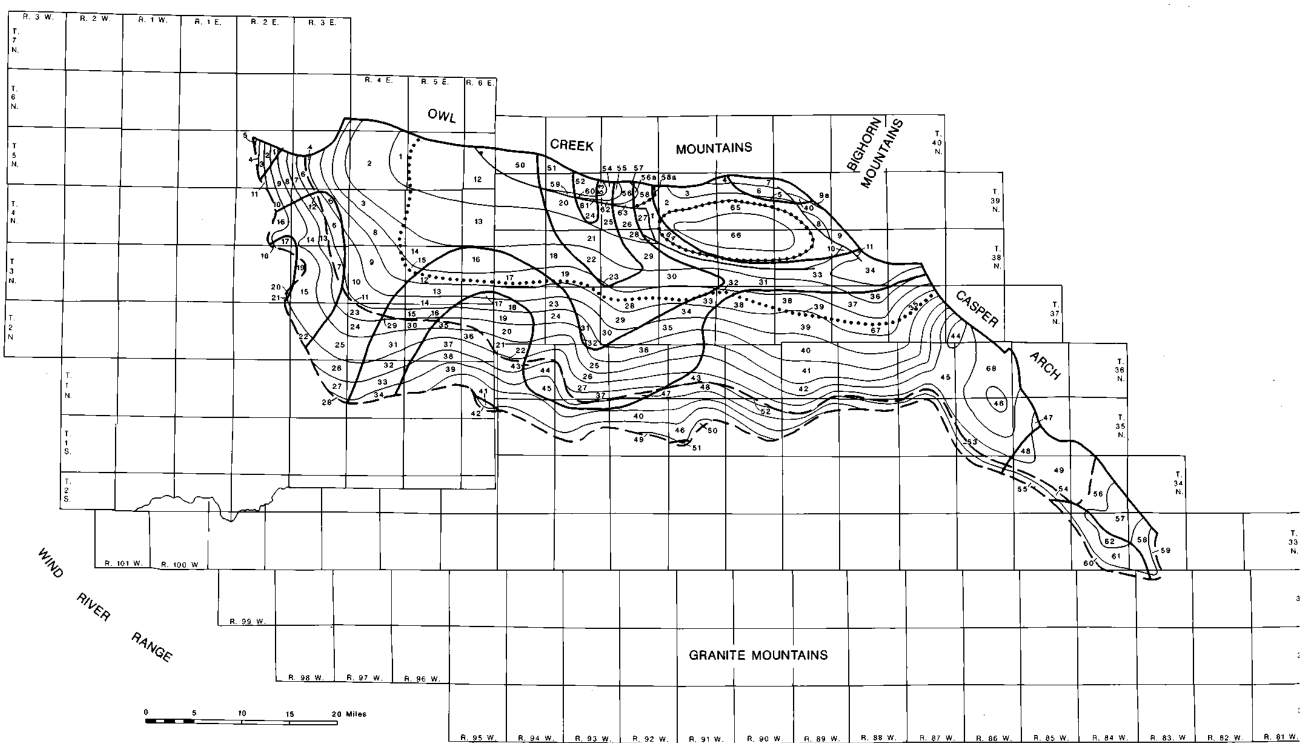

Figure 4. Map showing gas subplays in the Upper Cretaceous Meeteetse Formation. From Johnson and others (1996a).

A, *H*, *P*, *F*, S_h, and *D* which may vary from subplay to subplay within a play. The parameters *a* and *b* for each of the variables P_e, *T*, and *Z* (i.e., three pairs of *a* and *b*) are estimated for a play, and the one set of parameter values is used in all subplays of the play. The point estimate of the in-place gas of a subplay is taken to be a mean estimate (Table 1).

To obtain an interval estimate of the in-place gas of a subplay, estimates are made of the ranges (range = F5–F95) of the six attributes *A*, *H*, *P*, *F*, S_h, and *D* (Table 2). The attributes are treated as independent continuous random variables. The probabilistic methodology used to process the geologic data is an analytic method derived from probability theory. The analytic methodology is developed by the application of the laws of expectation and variance. The methodology systematically tracks through the geologic model and computes all of the means and variances of the appropriate random variables. An estimate of the standard deviation of the in-place gas of a subplay is computed and varies from subplay to subplay (Table 3). The lognormal distribution is used as a probability model in order to generate probability fractiles for gas in-place.

All of the means, standard deviations, and fractiles of the subplays of a play are aggregated, assuming complete dependency or perfect positive correlation (P.P.C.), to make an assessment of the play (Table 3). Finally, all of the plays are aggregated, assuming complete dependency, by applying a separate methodology for an assessment of the total in-place gas resources in the study area (Table 4). This probabilistic methodology for gas resource assessment lends itself as an ideal application for spreadsheet software.

Heterogeneities within the basin-centered gas accumulation

Heterogeneities exist within all basin-centered gas accumulations, and understanding how various parts of the accumulation vary from the norm can have a significant impact on economics. Drilling is sparse in the Wind River Basin, and only a few broad observations concerning heterogeneities can be discerned. These variations were handled in the resource calculations by either changing the boundaries of the accumulation or varying the percent trap fill.

The lower unnamed member of the Paleocene Fort Union Formation, the stratigraphically youngest unit included in the basin-centered gas accumulation, is

Table 1. List of subplays for the highly overpressured (present-day temperatures >300°F) Upper Cretaceous Meeteetse Formation play. Mean estimates of volume attributes and mean estimate of in-place gas for each subplay are listed. From Johnson and others (1996b).

Play Name :		Meeteetse > 300								(Panel 1)
						a =	0.727	0.016	0.00008	
						b =	14.7	505	0	
Subplay No.	Closure (sq.mi.)	Thickness (feet)	Porosity (%)	Trap fill (%)	HC Sat. (%)	Depth (feet)	Pressure (PSI)	Temp. (Deg.Rank.)	Gas Comp. (no units)	Gas in place (CF)
1	15.2	220	6	100	50	17,000	12373.7	777	1.36	1.16E+12
2	30.3	180	6	100	50	17,000	12373.7	777	1.36	1.89E+12
3	7.3	180	6	100	50	18,000	13100.7	793	1.44	4.45E+11
4	1.4	200	6	100	50	19,000	13827.7	809	1.52	9.30E+10
5	0.76	200	6	100	50	17,500	12737.2	785	1.4	5.20E+10
6	5.4	210	6	100	50	18,000	13100.7	793	1.44	3.84E+11
7	6.9	210	6	100	50	19,000	13827.7	809	1.52	4.81E+11
8	2.1	180	6	100	50	17,000	12373.7	777	1.36	1.31E+11
9	8.7	180	6	100	50	18,000	13100.7	793	1.44	5.30E+11
9a	0.1	200	6	100	50	18,500	13464.2	801	1.48	6.71E+09
10	0.86	200	6	100	50	17,500	12737.2	785	1.4	5.89E+10
11	0.36	200	6	100	50	18,500	13464.2	801	1.48	2.41E+10
12	62.6	375	6	100	50	19,000	13827.7	809	1.52	7.79E+12
13	66.8	350	6	100	50	18,000	13100.7	793	1.44	7.92E+12
14	13.5	320	6	100	50	17,000	12373.7	777	1.36	1.49E+12
15	1	310	6	100	50	16,500	12010.2	769	1.32	1.08E+11
16	20.7	275	6	100	50	17,000	12373.7	777	1.36	1.97E+12
17	11.3	260	6	100	50	16,000	11646.7	761	1.28	1.04E+12
18	16.9	350	6	100	50	17,000	12373.7	777	1.36	2.05E+12
19	20.3	350	6	100	50	16,000	11646.7	761	1.28	2.51E+12
20	7.6	450	6	100	50	19,000	13827.7	809	1.52	1.14E+12
21	23.2	450	6	100	50	18,000	13100.7	793	1.44	3.54E+12
22	12.5	420	6	100	50	17,000	12373.7	777	1.36	1.82E+12
23	0.15	400	6	100	50	16,500	12010.2	769	1.32	2.10E+10
24	4	520	6	100	50	19,000	13827.7	809	1.52	6.91E+11
25	5.6	450	6	100	50	19,000	13827.7	809	1.52	8.37E+11
26	8.2	350	6	100	50	19,000	13827.7	809	1.52	9.53E+11
27	4	275	6	100	50	19,000	13827.7	809	1.52	3.65E+11
28	0.5	290	6	100	50	18,500	13464.2	801	1.48	4.86E+10
29	11.3	350	6	100	50	18,000	13100.7	793	1.44	1.34E+12
30	17	350	6	100	50	17,000	12373.7	777	1.36	2.06E+12
31	16.6	240	6	100	50	17,000	12373.7	777	1.36	1.38E+12
32	0.97	250	6	100	50	16,500	12010.2	769	1.32	8.47E+10
33	27.4	250	6	100	50	18,000	13100.7	793	1.44	2.32E+12
34	15.8	220	6	100	50	19,000	13827.7	809	1.52	1.15E+12
35	3.2	180	6	100	50	15,000	10919.7	745	1.2	2.08E+11
36	4.2	190	6	100	50	18,000	13100.7	793	1.44	2.70E+11
37	16.3	190	6	100	50	17,000	12373.7	777	1.36	1.07E+12
38	25.9	190	6	100	50	16,000	11646.7	761	1.28	1.74E+12
39	0.86	190	6	100	50	15,500	11283.2	753	1.24	5.83E+10
40	0.73	200	6	100	50	18,500	13464.2	801	1.48	4.90E+10
									Total =	5.13E+13

Table 2. Estimates of ranges in percent for the six play attributes for all of the subplays in the Meeteetse highly overpressured play. Outline of play shown on Figure 3. Subplays are shown on Figure 4. From Johnson and others (1996b). Probabilsitic methodology described in Crovelli and Balay (1996), and Crovelli and others (1996).

Play Name :		Meeteetse > 300									(Panel 2)
		Depth		Closure	Thickness	Porosity	Trap Fill	HC Sat.	*Pe /TZ*		
	Range (%) =	30		30	50	30	20	40			
Subplay	Expect	F95 D.	F5 D.	Expect	Expect	Expect	Expect	Expect	Expect		Expect
No.	*Pe /TZ*	*Pe /TZ*	*Pe /TZ*	(Clo.)^2	(Thick.)^2	(Por.)^2	(Trap)^2	(HC S)^2	(*Pe /TZ*)^ 2		(Gas)^2
1	11.71	12.36	11.12	232.96	49517.9	36.30	10037.0	2536.95	137.25		1.42E+24
2	11.71	12.36	11.12	925.72	33148.3	36.30	10037.0	2536.95	137.25		3.77E+24
3	11.47	12.14	10.88	53.73	33148.3	36.30	10037.0	2536.95	131.76		2.10E+23
4	11.24	11.92	10.64	1.98	40923.9	36.30	10037.0	2536.95	126.60		9.17E+21
5	11.59	12.25	11.00	0.58	40923.9	36.30	10037.0	2536.95	134.47		2.87E+21
6	11.47	12.14	10.88	29.40	45118.6	36.30	10037.0	2536.95	131.76		1.56E+23
7	11.24	11.92	10.64	48.01	45118.6	36.30	10037.0	2536.95	126.60		2.46E+23
8	11.71	12.36	11.12	4.45	33148.3	36.30	10037.0	2536.95	137.25		1.81E+22
9	11.47	12.14	10.88	76.32	33148.3	36.30	10037.0	2536.95	131.76		2.98E+23
9a	11.36	12.03	10.76	0.01	40923.9	36.30	10037.0	2536.95	129.14		4.77E+19
10	11.59	12.25	11.00	0.75	40923.9	36.30	10037.0	2536.95	134.47		3.67E+21
11	11.36	12.03	10.76	0.13	40923.9	36.30	10037.0	2536.95	129.14		6.18E+20
12	11.24	11.92	10.64	3951.34	143873.0	36.30	10037.0	2536.95	126.60		6.44E+25
13	11.47	12.14	10.88	4499.34	125329.3	36.30	10037.0	2536.95	131.76		6.65E+25
14	11.71	12.36	11.12	183.77	104765.1	36.30	10037.0	2536.95	137.25		2.37E+24
15	11.83	12.48	11.25	1.01	98319.6	36.30	10037.0	2536.95	140.13		1.24E+22
16	11.71	12.36	11.12	432.05	77371.7	36.30	10037.0	2536.95	137.25		4.11E+24
17	11.96	12.59	11.38	128.75	69161.3	36.30	10037.0	2536.95	143.10		1.14E+24
18	11.71	12.36	11.12	287.98	125329.3	36.30	10037.0	2536.95	137.25		4.44E+24
19	11.96	12.59	11.38	415.52	125329.3	36.30	10037.0	2536.95	143.10		6.67E+24
20	11.24	11.92	10.64	58.24	207177.1	36.30	10037.0	2536.95	126.60		1.37E+24
21	11.47	12.14	10.88	542.72	207177.1	36.30	10037.0	2536.95	131.76		1.33E+25
22	11.71	12.36	11.12	157.55	180474.2	36.30	10037.0	2536.95	137.25		3.49E+24
23	11.83	12.48	11.25	0.02	163695.5	36.30	10037.0	2536.95	140.13		4.66E+20
24	11.24	11.92	10.64	16.13	276645.3	36.30	10037.0	2536.95	126.60		5.06E+23
25	11.24	11.92	10.64	31.62	207177.1	36.30	10037.0	2536.95	126.60		7.43E+23
26	11.24	11.92	10.64	67.80	125329.3	36.30	10037.0	2536.95	126.60		9.63E+23
27	11.24	11.92	10.64	16.13	77371.7	36.30	10037.0	2536.95	126.60		1.41E+23
28	11.36	12.03	10.76	0.25	86042.4	36.30	10037.0	2536.95	129.14		2.51E+21
29	11.47	12.14	10.88	128.75	125329.3	36.30	10037.0	2536.95	131.76		1.90E+24
30	11.71	12.36	11.12	291.40	125329.3	36.30	10037.0	2536.95	137.25		4.49E+24
31	11.71	12.36	11.12	277.85	58930.4	36.30	10037.0	2536.95	137.25		2.01E+24
32	11.83	12.48	11.25	0.95	63943.5	36.30	10037.0	2536.95	140.13		7.61E+21
33	11.47	12.14	10.88	757.00	63943.5	36.30	10037.0	2536.95	131.76		5.71E+24
34	11.24	11.92	10.64	251.72	49517.9	36.30	10037.0	2536.95	126.60		1.41E+24
35	12.21	12.84	11.65	10.33	33148.3	36.30	10037.0	2536.95	149.32		4.58E+22
36	11.47	12.14	10.88	17.79	36933.8	36.30	10037.0	2536.95	131.76		7.75E+22
37	11.71	12.36	11.12	267.90	36933.8	36.30	10037.0	2536.95	137.25		1.22E+24
38	11.96	12.59	11.38	676.39	36933.8	36.30	10037.0	2536.95	143.10		3.20E+24
39	12.08	12.72	11.51	0.75	36933.8	36.30	10037.0	2536.95	146.16		3.60E+21
40	11.36	12.03	10.76	0.54	40923.9	36.30	10037.0	2536.95	129.14		2.54E+21

Table 3. Calculated fractiles for in-place gas in subplays for the Meeteetse highly overpressured play. Outline of play shown on Figure 3. Subplays shown on Figure 4. From Johnson and others (1996b). Probabilsitic methodology described in Crovelli and Balay (1996), and Crovelli and others (1996).

Play Name :		Meeteetse > 300								(Panel 3)
	In-place	In-place	In-place			In-place Fractiles				
Subplay	Mean gas	Var. gas	S.D. gas			F95	F75	F50	F25	F5
No.	(CF)	(CF)^2	(CF)	Mu	Sigma	(CF)	(CF)	(CF)	(CF)	(CF)
1	1.16E+12	8.09E+22	2.84E+11	27.7467	0.2424629	7.53E+11	9.53E+11	1.12E+12	1.32E+12	1.67E+12
2	1.89E+12	2.15E+23	4.64E+11	28.2359	0.2424629	1.23E+12	1.55E+12	1.83E+12	2.16E+12	2.73E+12
3	4.45E+11	1.20E+22	1.10E+11	26.7921	0.2426246	2.90E+11	3.67E+11	4.32E+11	5.09E+11	6.44E+11
4	9.30E+10	5.25E+20	2.29E+10	25.226	0.2427855	6.05E+10	7.66E+10	9.03E+10	1.06E+11	1.35E+11
5	5.20E+10	1.64E+20	1.28E+10	24.6454	0.2425438	3.39E+10	4.29E+10	5.05E+10	5.95E+10	7.53E+10
6	3.84E+11	8.95E+21	9.46E+10	26.6448	0.2426246	2.50E+11	3.17E+11	3.73E+11	4.39E+11	5.56E+11
7	4.81E+11	1.41E+22	1.19E+11	26.8699	0.2427855	3.13E+11	3.97E+11	4.67E+11	5.50E+11	6.96E+11
8	1.31E+11	1.03E+21	3.22E+10	25.5667	0.2424629	8.52E+10	1.08E+11	1.27E+11	1.49E+11	1.89E+11
9	5.30E+11	1.71E+22	1.31E+11	26.9676	0.2426246	3.46E+11	4.37E+11	5.15E+11	6.07E+11	7.68E+11
9a	6.71E+09	2.73E+18	1.65E+09	22.5969	0.2427051	4.37E+09	5.53E+09	6.51E+09	7.67E+09	9.71E+09
10	5.89E+10	2.10E+20	1.45E+10	24.769	0.2425438	3.83E+10	4.85E+10	5.72E+10	6.73E+10	8.52E+10
11	2.41E+10	3.54E+19	5.95E+09	23.8779	0.2427051	1.57E+10	1.99E+10	2.34E+10	2.76E+10	3.49E+10
12	7.79E+12	3.69E+24	1.92E+12	29.6549	0.2427855	5.08E+12	6.43E+12	7.57E+12	8.91E+12	1.13E+13
13	7.92E+12	3.80E+24	1.95E+12	29.6709	0.2426246	5.16E+12	6.53E+12	7.69E+12	9.06E+12	1.15E+13
14	1.49E+12	1.35E+23	3.68E+11	28.0028	0.2424629	9.73E+11	1.23E+12	1.45E+12	1.71E+12	2.16E+12
15	1.08E+11	7.10E+20	2.66E+10	25.3788	0.2423818	7.06E+10	8.93E+10	1.05E+11	1.24E+11	1.57E+11
16	1.97E+12	2.35E+23	4.84E+11	28.2787	0.2424629	1.28E+12	1.62E+12	1.91E+12	2.25E+12	2.85E+12
17	1.04E+12	6.50E+22	2.55E+11	27.6382	0.2423007	6.76E+11	8.55E+11	1.01E+12	1.19E+12	1.50E+12
18	2.05E+12	2.53E+23	5.03E+11	28.317	0.2424629	1.33E+12	1.69E+12	1.99E+12	2.34E+12	2.96E+12
19	2.51E+12	3.80E+23	6.17E+11	28.5213	0.2423007	1.64E+12	2.07E+12	2.44E+12	2.87E+12	3.63E+12
20	1.14E+12	7.83E+22	2.80E+11	27.7286	0.2427855	7.39E+11	9.36E+11	1.10E+12	1.30E+12	1.64E+12
21	3.54E+12	7.58E+23	8.71E+11	28.8647	0.2426246	2.30E+12	2.92E+12	3.43E+12	4.04E+12	5.12E+12
22	1.82E+12	1.99E+23	4.47E+11	28.1978	0.2424629	1.18E+12	1.50E+12	1.76E+12	2.08E+12	2.63E+12
23	2.10E+10	2.66E+19	5.16E+09	23.7365	0.2423818	1.37E+10	1.73E+10	2.04E+10	2.40E+10	3.03E+10
24	6.91E+11	2.90E+22	1.70E+11	27.2313	0.2427855	4.50E+11	5.69E+11	6.71E+11	7.90E+11	1.00E+12
25	8.37E+11	4.25E+22	2.06E+11	27.4232	0.2427855	5.45E+11	6.90E+11	8.12E+11	9.57E+11	1.21E+12
26	9.53E+11	5.51E+22	2.35E+11	27.5533	0.2427855	6.21E+11	7.86E+11	9.25E+11	1.09E+12	1.38E+12
27	3.65E+11	8.10E+21	9.00E+10	26.5943	0.2427855	2.38E+11	3.01E+11	3.55E+11	4.18E+11	5.29E+11
28	4.86E+10	1.43E+20	1.20E+10	24.5779	0.2427051	3.17E+10	4.01E+10	4.72E+10	5.56E+10	7.04E+10
29	1.34E+12	1.09E+23	3.30E+11	27.894	0.2426246	8.73E+11	1.10E+12	1.30E+12	1.53E+12	1.94E+12
30	2.06E+12	2.56E+23	5.06E+11	28.3229	0.2424629	1.34E+12	1.70E+12	2.00E+12	2.35E+12	2.98E+12
31	1.38E+12	1.15E+23	3.39E+11	27.9218	0.2424629	8.98E+11	1.14E+12	1.34E+12	1.57E+12	1.99E+12
32	8.47E+10	4.34E+20	2.08E+10	25.1332	0.2423818	5.52E+10	6.99E+10	8.23E+10	9.69E+10	1.23E+11
33	2.32E+12	3.26E+23	5.71E+11	28.4433	0.2426246	1.51E+12	1.91E+12	2.25E+12	2.65E+12	3.36E+12
34	1.15E+12	8.09E+22	2.84E+11	27.7449	0.2427855	7.52E+11	9.51E+11	1.12E+12	1.32E+12	1.67E+12
35	2.08E+11	2.61E+21	5.10E+10	26.0302	0.2421385	1.35E+11	1.71E+11	2.02E+11	2.37E+11	3.00E+11
36	2.70E+11	4.43E+21	6.66E+10	26.2934	0.2426246	1.76E+11	2.23E+11	2.62E+11	3.09E+11	3.91E+11
37	1.07E+12	6.94E+22	2.63E+11	27.67	0.2424629	6.98E+11	8.83E+11	1.04E+12	1.22E+12	1.55E+12
38	1.74E+12	1.82E+23	4.27E+11	28.154	0.2423007	1.13E+12	1.43E+12	1.69E+12	1.99E+12	2.51E+12
39	5.83E+10	2.05E+20	1.43E+10	24.7595	0.2422196	3.80E+10	4.81E+10	5.66E+10	6.67E+10	8.43E+10
40	4.90E+10	1.45E+20	1.21E+10	24.5848	0.2427051	3.19E+10	4.04E+10	4.75E+10	5.60E+10	7.09E+10
P.P.C.	5.13E+13	1.59E+26	1.26E+13			3.34E+13	4.23E+13	4.98E+13	5.86E+13	7.42E+13

Table 4. Aggregation of in-place gas for the 22 plays in the Wind River Basin, Wyoming. From Johnson and others (1996a).

Aggregation Name :			Wind River Basin					
	In-place	In-place	In-place	In-place Fractiles				
Play Name	Mean gas (CF)	Var. gas (CF)^2	S.D. gas (CF)	F95 (CF)	F75 (CF)	F50 (CF)	F25 (CF)	F5 (CF)
TFU1	8.3E+13	1.39E+27	3.73E+13	3.74E+13	5.67E+13	7.57E+13	1.01E+14	1.53E+14
TFU2	1.82E+13	7.95E+25	8.92E+12	7.64E+12	1.20E+13	1.64E+13	2.24E+13	3.51E+13
LANCE1	3.16E+14	6.37E+27	7.98E+13	2.03E+14	2.59E+14	3.06E+14	3.62E+14	4.61E+14
LANCE2	4.89E+13	5.72E+26	2.39E+13	2.05E+13	3.22E+13	4.40E+13	6.01E+13	9.41E+13
MEET1	5.13E+13	1.59E+26	1.26E+13	3.34E+13	4.23E+13	4.98E+13	5.86E+13	7.42E+13
MEET2	5.97E+13	2.27E+26	1.51E+13	3.84E+13	4.89E+13	5.79E+13	6.84E+13	8.71E+13
MEET3	1.25E+13	3.72E+25	6.1E+12	5.23E+12	8.20E+12	1.12E+13	1.53E+13	2.40E+13
KMV1	3.47E+13	7.3E+25	8.55E+12	2.26E+13	2.86E+13	3.37E+13	3.97E+13	5.02E+13
KMV2	1.72E+13	1.89E+25	4.35E+12	1.11E+13	1.41E+13	1.67E+13	1.98E+13	2.52E+13
KMV3	3.84E+12	3.52E+24	1.88E+12	1.61E+12	2.52E+12	3.45E+12	4.71E+12	7.38E+12
KMV4	4.89E+13	1.45E+26	1.21E+13	3.19E+13	4.03E+13	4.75E+13	5.60E+13	7.08E+13
KMV5	7.18E+13	3.28E+26	1.81E+13	4.63E+13	5.89E+13	6.96E+13	8.23E+13	1.05E+14
KMV6	1.74E+13	7.24E+25	8.51E+12	7.30E+12	1.14E+13	1.56E+13	2.14E+13	3.35E+13
CODY1	3.06E+13	5.67E+25	7.53E+12	1.99E+13	2.52E+13	2.97E+13	3.50E+13	4.42E+13
CODY2	1.92E+13	2.34E+25	4.84E+12	1.24E+13	1.57E+13	1.86E+13	2.20E+13	2.80E+13
CODY3	1.97E+12	9.31E+23	9.65E+11	8.25E+11	1.29E+12	1.77E+12	2.42E+12	3.79E+12
FRONT1	1.18E+14	8.39E+26	2.9E+13	7.65E+13	9.69E+13	1.14E+14	1.34E+14	1.70E+14
FRONT2	2.92E+13	5.46E+25	7.39E+12	1.88E+13	2.39E+13	2.83E+13	3.35E+13	4.26E+13
FRONT3	3.95E+12	3.74E+24	1.93E+12	1.65E+12	2.60E+12	3.55E+12	4.85E+12	7.60E+12
FALES1	1.18E+12	8.5E+22	2.92E+11	7.71E+11	9.76E+11	1.15E+12	1.35E+12	1.71E+12
FALES2	7.31E+12	3.42E+24	1.85E+12	4.70E+12	5.99E+12	7.08E+12	8.38E+12	1.07E+13
FALES3	5.36E+11	6.89E+22	2.62E+11	2.25E+11	3.53E+11	4.82E+11	6.58E+11	1.03E+12
Aggregation:								
P.P.C.	9.95E+14	8.48E+28	2.91E+14	6.03E+14	7.88E+14	9.52E+14	1.15E+15	1.53E+15

unusual in that gas shows occur on mudlogs throughout the member, even where thermal maturities are as low 0.5 to 0.6% Rm. The overlying lacustrine Waltman Shale Member of the Fort Union Formation appears to be acting as a seal inhibiting the vertical migration of gas out of the member (Figure 2). The presence of this seal has blurred the boundary between the basin-centered accumulation and reservoirs with conventional permeabilities above. For convenience, the gas resources for the entire lower member of the Fort Union Formation are assessed, although most of the gas charged sandstones where thermal maturities are less than 0.73% Rm probably have conventional permeabilities. The lower member was divided into two plays, the first where the overlying Waltman Shale is present, and the second where the lacustrine shale has been replaced marginward by deltaic and fluvial deposits. The seal is assumed to be absent in the second play.

Shale seals of regional extent are seldom considered in conjunction with low-permeability gas accumulations. Masters (1984, p. 10), however, stressed the importance of the widespread Lower Cretaceous Joli Fou Shale as a regional seal inhibiting the vertical migration of hydrocarbons out of the low-permeability hydrocarbon accumulation in the Alberta Deep Basin. Shale seals, however, are commonly invoked as a mechanism for maintaining abnormally high pressures for extended periods of time in isolated sandstone lenses within basin-centered gas accumulations (Bradley, 1975; Heasler and Surdam, 1992). In this model each sandstone lens within the accumulation is an individual isolated compartment.

Variations in sandstone geometries have a noticeable effect on this basin-centered gas accumulation in the Wind River Basin, particularly in the comparatively shallow transition plays. Sandstones in the marginal marine interval of the Mesaverde Formation persist for considerable distances in a north-south direction parallel to the paleo-shoreline. As a result, many of the sandstones in the transition play persist to outcrop along the south margin of the basin and are subject to surface water recharge and degassing. To compensate for this, an unusually low trap fill of 20% was estimated for these sandstones. Fluvial sandstones in the overlying nonmarine interval of the Mesaverde, in contrast, trend largely east-west or perpendicular to paleo-shoreline. These sandstones are unlikely to persist to outcrop along the south margin of the basin and are not subject to surface water recharge and degassing. Trap fill for these fluvial sandstones in the transition zone is estimated at 50%.

RESULTS

A total mean of 995 tcf of gas in place is estimated for the 22 plays in the Wind River Basin (Table 4). Using probability theory, a 95% chance exists that there is at least 603 tcf of gas in place in the basin-centered gas accumulation in the Wind River Basin, and a 5% chance that there is at least 1,530 tcf of gas in place. This is more than twice the estimated 420 tcf of in-place gas for the Piceance Basin of western Colorado (Johnson and others, 1987), which is roughly comparable in size, but less than one-fifth of the estimated in-place gas for the much larger Greater Green River Basin (Law and others, 1989). Of the total in-place gas in the Greater Green River Basin, a mean of only 73 tcf is considered recoverable using current technology and 433 tcf using future technology (Law and others, 1989). Although recoverable gas was not estimated for the Wind River Basin, it is assumed that, as in the Green River Basin, only a small percentage of the in-place gas will ever be recoverable. The tight gas interval is considerably thicker in the Wind River Basin than in the Piceance Basin, and this probably accounts for much of the difference in the in-place gas estimates for the two basins. Maximum thickness of the basin-centered gas interval in the Piceance Basin is about 6,000 ft (Johnson and others, 1987, Figures 3 and 4) whereas the interval is as much as 12,000 ft in the Wind River Basin (Johnson and others, 1996, Figures 7, 23, and 28). These thicknesses do not include the Frontier Formation which was not assessed in the Piceance Basin.

APPLICATION

The in-place gas estimate for the Wind River Basin can be used in far more specific ways than the 1989 estimate for the Green River Basin (Law and others, 1989) and the 1987 estimate for the Piceance Basin (Johnson and others, 1987). An estimate of in-place gas for any area of the Wind River Basin can be made because of the large number of subplays used in the assessment. The total gas estimated for a subplay can be divided by the number of acres in the subarea to generate an estimate of in-place gas per acre within the subplay. This information could be used to help determine optimum well spacing needed to develop the gas resource anywhere in the basin. Assessing each stratigraphic unit separately is important for gas exploration because gas leases commonly cover only certain stratigraphic intervals within the lease boundaries. Economic analysis is also aided by the average depth of each subplay which is included in the tables. If, for instance, it is determined that the nonmarine part of the Mesaverde is only economic at depths of less than 12,000 ft, then all of the subplays with average depths greater than 12,000 ft can be easily eliminated. The spreadsheet format used to calculate in-place resources is also very flexible and amenable to changes when future drilling data becomes available to more precisely define the volume attributes used in the estimate.

FUTURE ACTIVITIES

A study to characterize and assess the low-permeability, basin-centered gas resources in the Bighorn Basin of Wyoming was initiated in May of 1996 and is scheduled to be completed by September 15, 1998.

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