Evaluation of the Potential for Significant Oil and Gas Discoveries in the Big Sandy Foothills and Northern Red Desert, Wyoming

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Research Summary

There has been minimal new production from the few valid oil and gas leases in the Big Sandy Foothills and Northern Red Desert (Fig. 1) in the past decade. However, in the last two years, there has been increased interest in new leases. This has raised the question: are there significant oil and gas deposits in this region? The results of this study, based on publicly available data in the Big Sandy Foothills and Northern Red Desert area, suggest minimal potential of any significant undiscovered oil and gas deposits in this area.

This report utilized a variety of assessment tools (including comparisons to data from the Jonah Field and the Pinedale Anticline) to assess the potential for undiscovered conventional oil and gas plays, anomalously pressured gas/gas condensate fields, shale gas accumulations, or areas for coalbed methane development. In all cases, the evidence points to low potential of there being significant undiscovered oil and gas deposits in the study area for any of these conventional and unconventional resource plays.

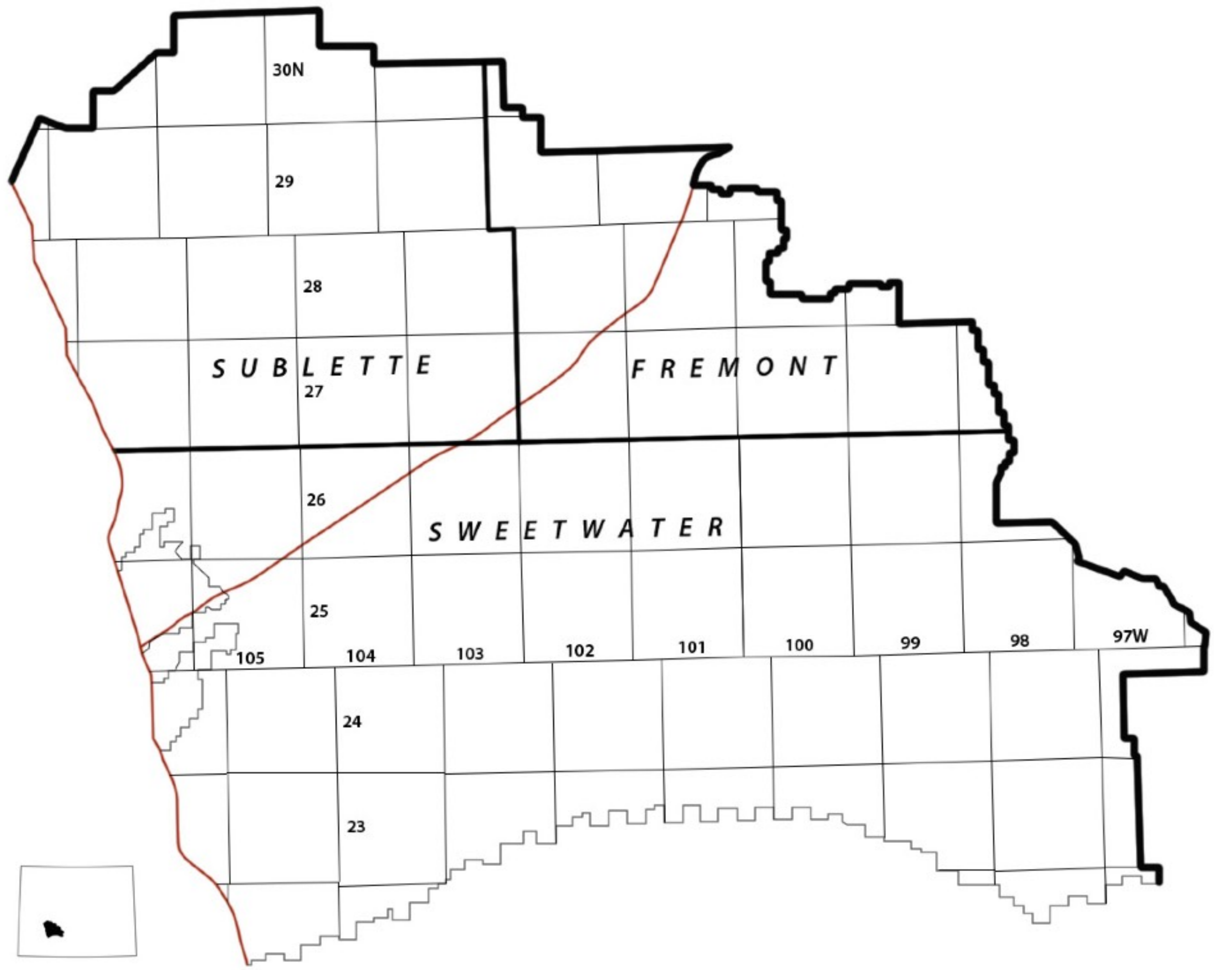


Figure 1. Map outlining the boundaries of the Big Sandy Foothills and Northern Red Desert study area.

The Research Strategy

Since 2018, there has been increased interest in purchasing oil and gas leases in the Big Sandy Foothills and Northern Red Desert, though existing leases have seen little production. This new interest, after years without much activity in this region, has raised the question: Are there significant recoverable oil and gas deposits in this region? To answer this question, a team of researchers reviewed publicly available well logs and seismic lines, utilizing the most current methodologies, to identify the potential for unconventional and conventional oil and gas deposits.

The project research group consisted of geologists and geophysicists, each with more than thirty years of experience in geological exploration research in Wyoming. Dr. Ronald Surdam, Mr. Allory Deiss, and the research team have pioneered an effective and efficient way to evaluate anomalously pressured hydrocarbon accumulations (Table 1); see Wyoming State Geological Survey, Exploration Memoir No. 1.

This new technology integrates findings from geological studies, petrophysical studies, and basin modeling with results from seismic and well log attribute analyses. It has been successfully tested at the Jonah Field and at the Pinedale Anticline, both giant anomalously pressured hydrocarbon accumulations adjacent to the area of interest, and in other basins around the world (Table 1). In the present study the new technology was applied in determining potential oil and gas resources in the Big Sandy Foothills and Northern Red Desert area.

Powder River Basin, Wyoming	**Western Anadarko Basin, Oklahoma**
Bighorn Basin, Wyoming	**Sacramento Basin, California**
Wind River Basin, Wyoming	**Mahakam Delta (East Kalimantan), Indonesia**
Badger Basin, Wyoming	**Kiru Trough (Sumatra), Indonesia**
Washakie Basin, Wyoming	**Waropen Basin, Indonesia**
Green River Basin, Wyoming	**Offshore Cameroons (W. Africa), Cameroons**
Hanna Basin, Wyoming	**Bohai Bay, China**
Great Divide Basin, Wyoming	**South China Sea, China**
Sand Wash Basin, Colorado	**Yellow River Delta, East China**
Denver Basin, Colorado	**Cooper Basin, Australia**
Piceance Basin, Colorado	**San Jorge Basin, Argentina**
South Park Basin, Colorado	**Neuquen Basin, Argentina**
Uinta Basin, Utah	**Colorado Basin, Argentina**
San Juan Basin, New Mexico	**Maturin Basin, Venezuela**
Western Canada (Alberta) Basin Canada	**Cauca Basin, Colombia**

Table 1. List of basins in which the outlined exploration strategy and associated technologies have been successfully applied.

In the last thirty years, significant changes have occurred in the understanding of natural gas resource distribution in the Rocky Mountain Laramide Basins (RMLB). The discovery and development of the Jonah and Pinedale Anticline gas fields in Wyoming demonstrate that the largest and most significant gas resources in Wyoming are unconventional anomalously pressured gas accumulations. These unconventional gas accumulations occur in production sweet spots within pressure compartments below regional pressure seals (Fig. 2).

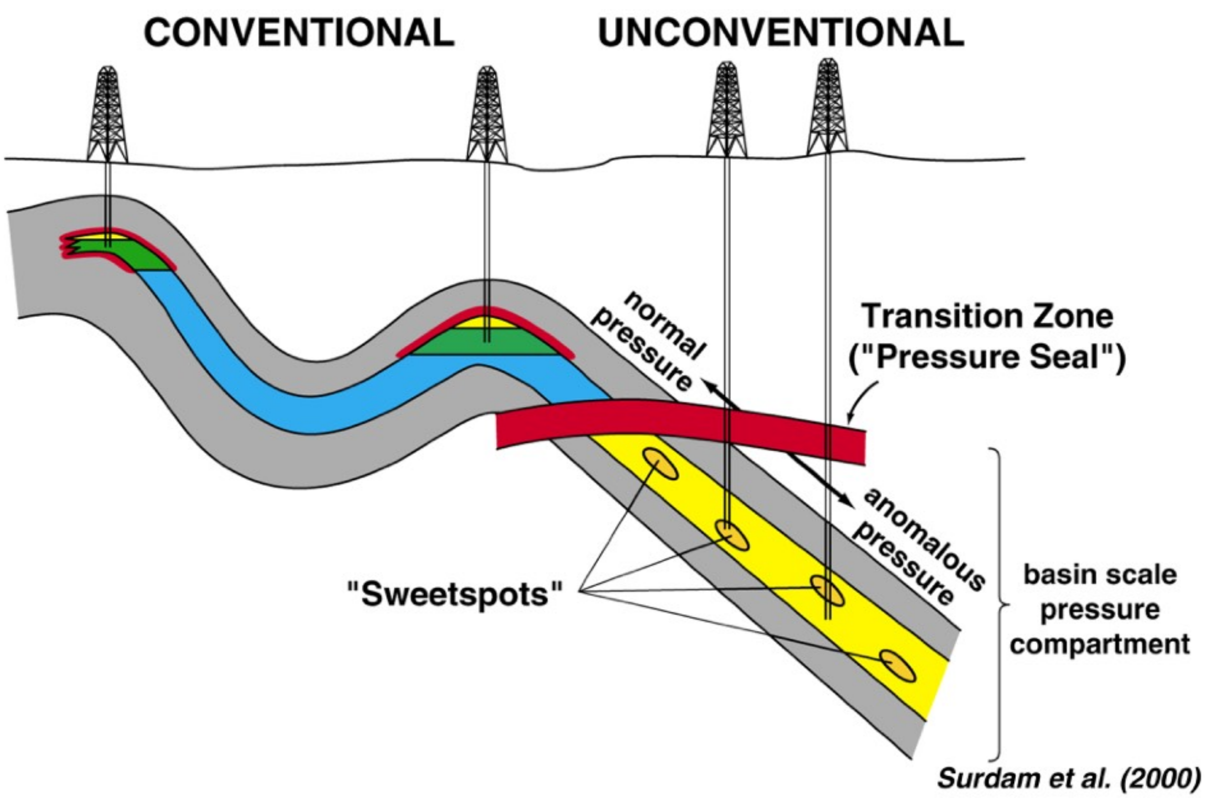


Figure 2. Schematic diagram illustrating the two elements crucial to oil and gas exploration in gas saturated anomalously pressured rocks: 1) the pressure boundary (e.g., "pressure seal"); and 2) production sweetspots. Modified from Surdam and others, 1997.

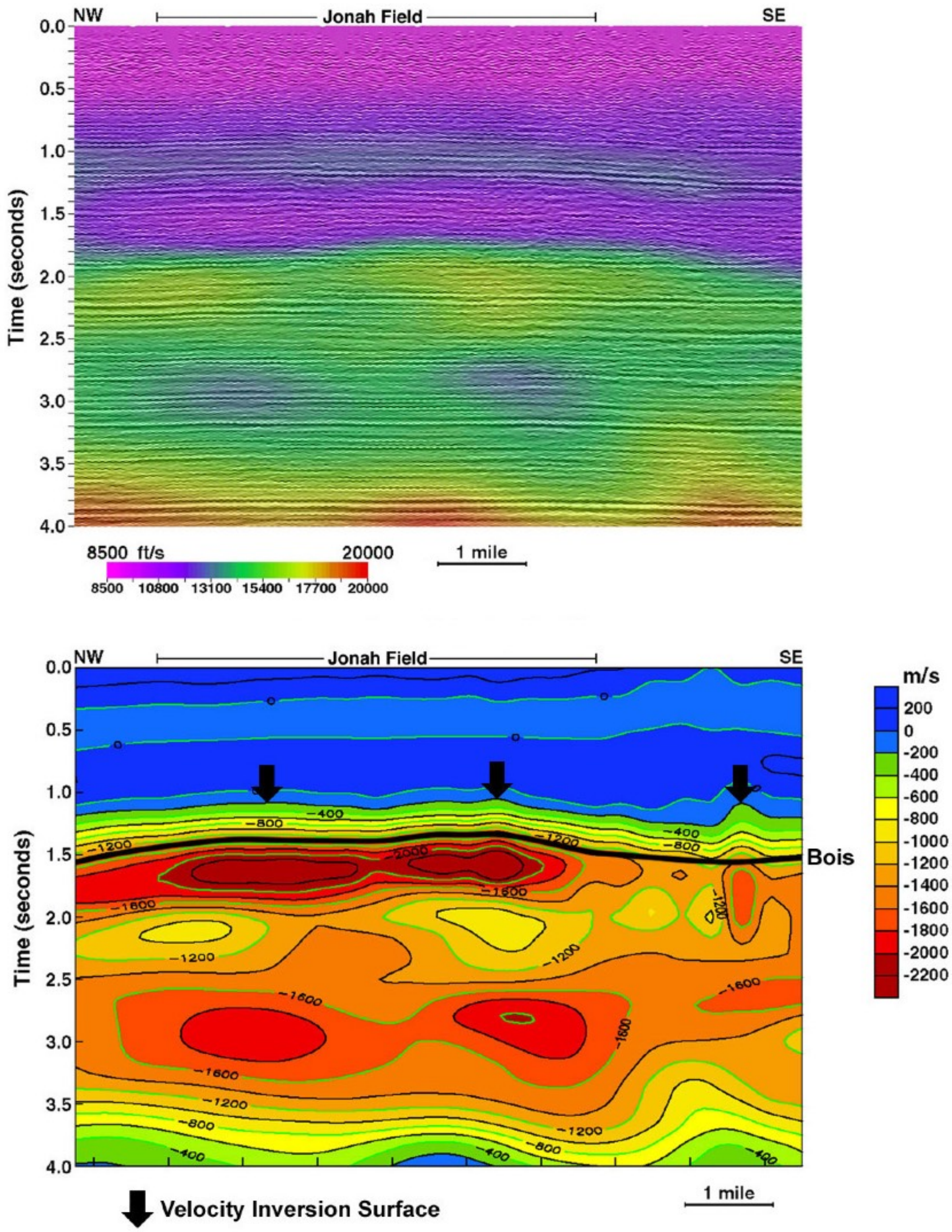


Figure 3. Top is 2-D seismic interval velocity field for the Jonah Field super-imposed on the seismic stack for purposes of illustration. Bottom panel: the anomalous velocity profile for the seismic line shown above. Note the improved resolution with respect to the position of the velocity inversion surface (black arrows) and the isolation of anomalous velocity domains beneath the velocity inversion surface. The most intense anomalously slow velocity domains beneath the velocity inversion surface are the productive Lance interval at the Jonah Field. Surdam and others, 2005.

In contrast, conventional oil and gas deposits are typically found in structural and/or stratigraphic traps; these gas resources are normally pressured, and with strong water drives (Fig. 2). The newly recognized unconventional gas resources are found beneath regional velocity inversion surfaces that can be detected both from sonic velocity logs and/or seismic velocity profiles (Figs. 3 and 4).

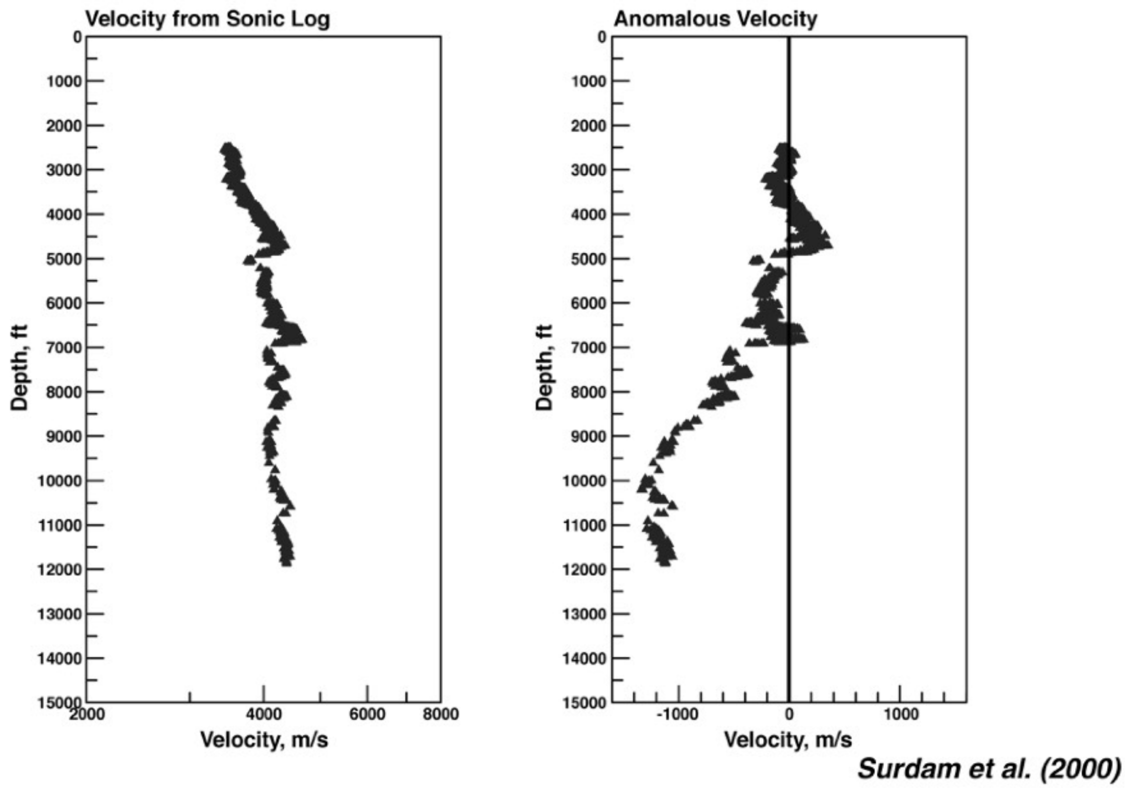


Figure 4. Typical sonic log from Jonah Field as shown on the left. In the sonic profile shown on right, the regional sonic velocity/depth gradient has been removed. The velocity inversion occurs at approximately 7000 ft. depth. From 7,000 to 12,000 ft. depth, the rocks are characterized by anomalously slow velocities and are anomalously pressured. From Surdam and others, 2000.

Of particular importance in the search for unconventional gas resources are <u>anomalous velocity profiles</u>, for they can be utilized to determine the spatial aspects of over-, or under- pressured gas accumulations. The anomalous velocity profiles are constructed by removing the observed typical regional velocity/depth trend (Fig. 5).

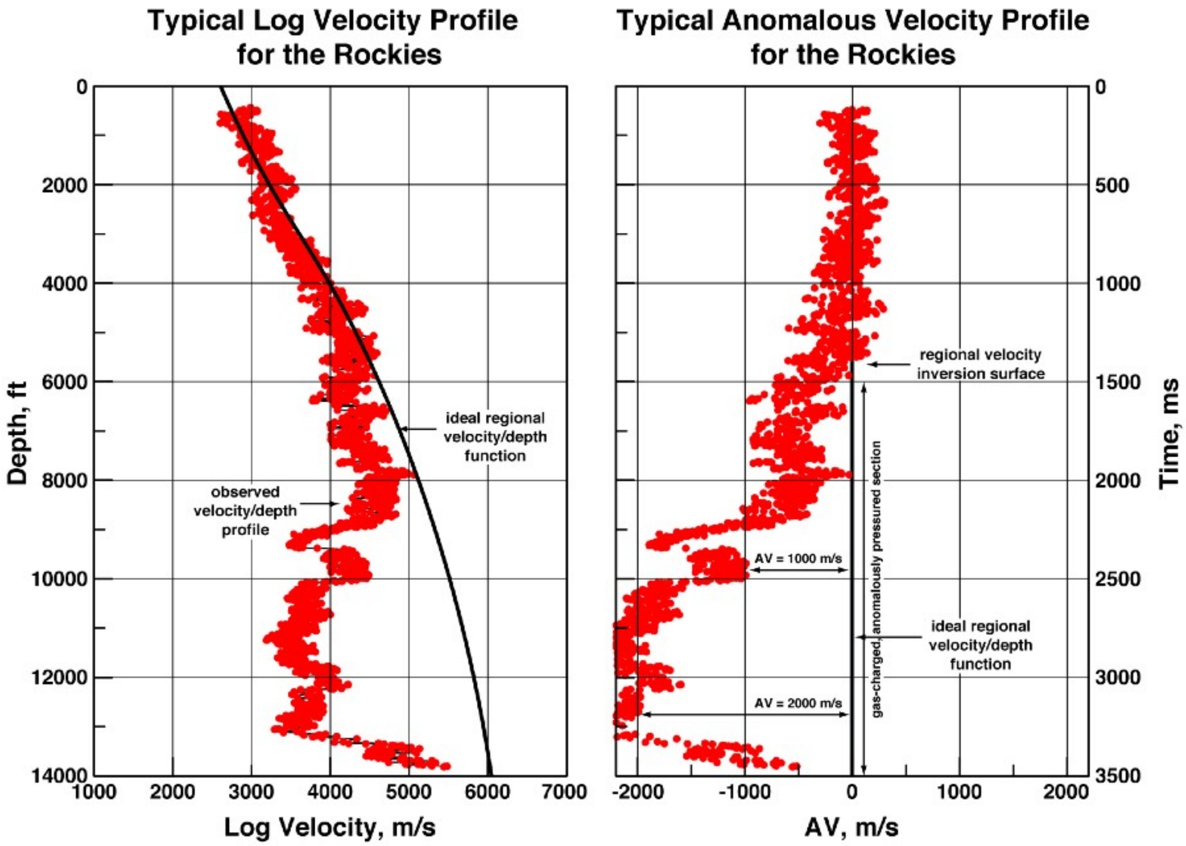


Figure 5. An observed sonic velocity profile (red) and an ideal regional velocity/depth trend (black line) are shown on the left panel. On the right panel, the velocities computed from the ideal regional velocity/depth trend have been removed from the sonic velocity profile shown on the left panel. The vertical black line is the ideal regional velocity/depth trend. Surdam and others, 2005.

The detection technology and improved understanding of the factors responsible for the development of gas production sweet spots below regional pressure surface boundaries are available and will be utilized in this hydrocarbon resource evaluation for the Big Sandy Foothills and Northern Red Desert (BSF/NRD) area.

Previously used predictions of oil and gas resources for the RMLB based primarily on structural and stratigraphic attributes are inadequate and characterized by significant uncertainty. By utilizing the new evaluation technology and improved understanding of anomalously pressured gas accumulations outlined above (Fig. 6), it is possible to develop improved evaluations of the distribution of natural gas resources. These techniques will be utilized in evaluating hydrocarbon resources in the Big Sandy Foothills and Northern Red Desert area. The only constraint on this evaluation program is data availability.

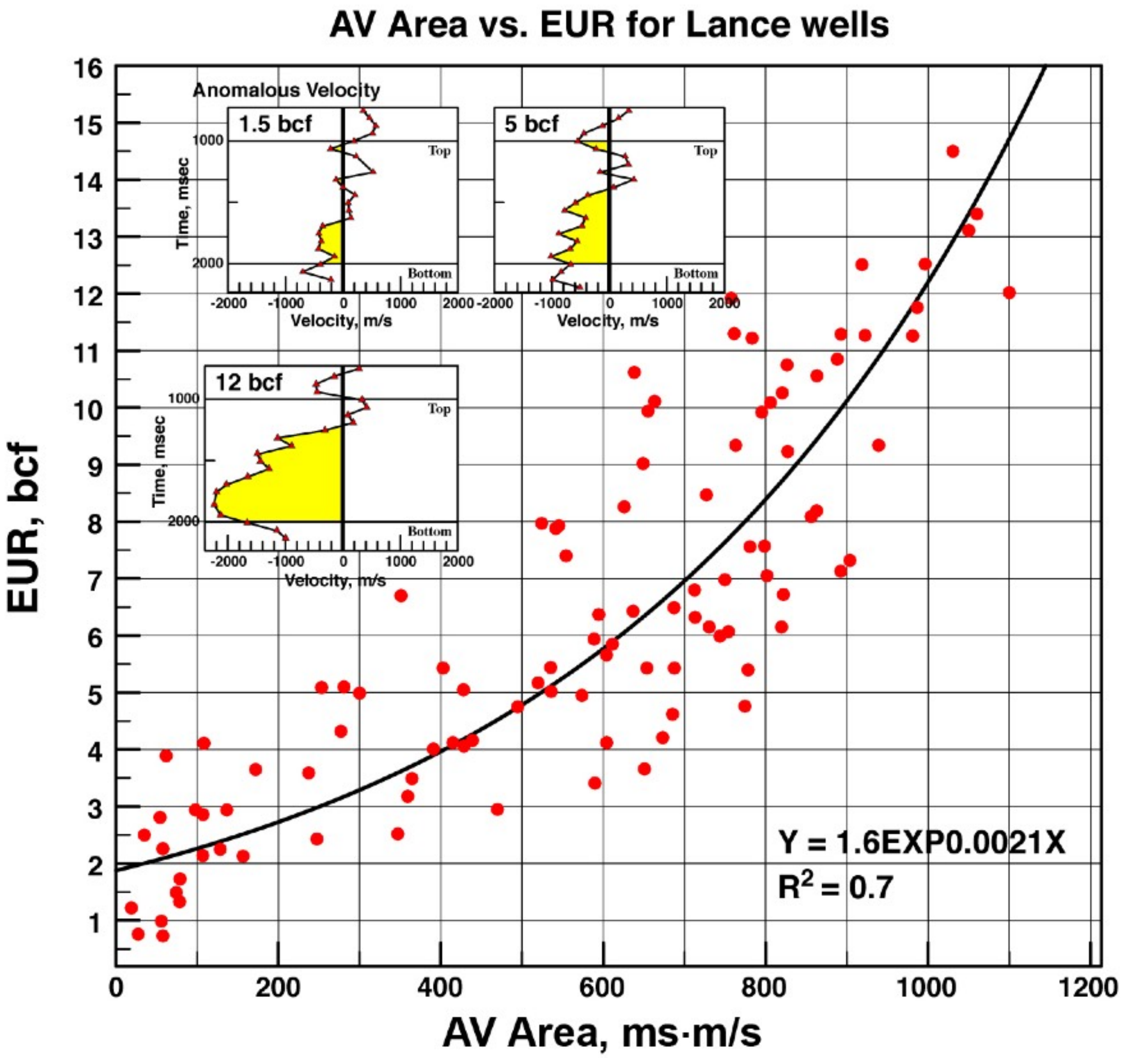


Figure 6. Plot of AV (anomalous velocity) areas versus EURs (estimated ultimate recovery) illustrates the correlation between anomalous velocity (AV) and estimated ultimate recovery (EUR). Figure 5 was constructed from the Lance Formation wells in the Greater Green River Basin, Wyoming. The three examples (shown in yellow) are for Lance wells with EURs of 1.5, 5, and 12 bcf. Surdam and others, 2005.

In addition to the above described oil and gas resource types, the evaluation also concentrates on the potential for shale gas and coalbed methane resources in the Big Sandy Foothills and Northern Red Desert area. Shale gas and coalbed methane resources have not been exploited in the BSF/NRD area but have been exploited in other Laramide Basins in Wyoming.

The Study Area

The Big Sandy Foothills and Northern Red Desert study area is defined as the area of Wyoming with the eastern border being the Bureau of Land Management's Rock Springs Field Office boundary; the northeastern boundary being the BLM Lander Field Office boundary; the northern boundary is the BLM Pinedale Field Office boundary; the western boundary is US Highway 191; and the southern boundary is the interface of private and public land generally referred to as the "checkerboard" (Fig. 1). This study area is almost entirely public land managed by the Bureau of Land Management, though there are some private and state sections. The public land is managed entirely by the BLM Rock Springs Field Office.

Available Database

The geological observations and analytical results discussed in this report are based on the available public database. This database was provided by 1) WyRIT (The Wyoming Reservoir Information Tool) from the Enhanced Oil Recovery Institute, Wyoming, 2) The Wyoming Geological Map compiled by the Wyoming State Geological Survey, 3) The Interactive Oil and Gas Map of Wyoming from the Wyoming State Geological Survey, 4) The Wyoming Oil and Gas Conservation Commission, and 5) The United States Geological Survey and 6) the National Archive of Marine Seismic Surveys. For a more detailed description of the database, see Table 2.

Table 2. List of wells and seismic data used in this study of the Big Sandy Foothills and Northern Red Desert area.

API	Well Name	Township	Range	Section	TD
1305060	Unit 1	27	101	24	1858
1320063	Govenment 18-1 A	27	102	18	12492
1321119	Harriss Slough Unit	27	99	26	13620
1321124	South Pass Unit 1	27	100	17	22970
3506360	Government Rweason 1	27	103	28	13313
3506376	government 1	28	106	34	8502
3520245	State 14-16	29	106	16	10050
3521289	Elk Horn 4-31	28	105	31	12763
3525558	big Sandy Federal 1-1	27	106	1	16155
3705891	Government Bosworth 1	22	105	1	4999
3720900	Polumbus Federal	26	100	25	11564
3721109	Amoco Federal 13-3	23	103	3	10091
3721219	Five fingers Unit 1	25	98	14	13005
3721300	Lost Valley 2A	25	99	22	11214
3721425	Packsaddle Unit 1	25	103	24	14850
3721449	Boars Tusk 1-15	23	104	15	10400
3721513	Steamboat Mtn Unit 3	24	102	34	13004
3721653	Rim Rock Unit 1	24	103	10	12657

3721839	Buccaneer Unit 1	26	102	23	17825
3721955	Saddle Bag Unit 1	24	100	22	16566
3721966	Musketeer Unit 1	26	101	8	19569
3722032	Unit 4	24	101	28	14930
3722057	Citation 1	25	100	10	11000
3722528	North Nitchie Gulch 40-25	24	104	25	10049
3723812	Encore Federal 1	24	99	32	8200
3724360	Gold Coast	25	102	16	15900
3736324	Jade 1011	24	98	11	12150
1320246	Grady Federal 1-Z	24	105	22	7997

Well_Name	API	Sect-Township-Range	County
Entelope 5-4	3522429	4-29N-107W	Sublette
Habanero Federal 14-21	3522766	21-29N-106W	Sublette
Pacific Creek 1-33	3521227	33-27N-103W	Sublette
Dickie Springs Unit 1	1320246	24-27N-101W	Fremont
Musketeer Unit 1	3721966	8-26N-101W	Sweetwater
Buccaneer Unit 1	3721839	23-26N-102W	Sweetwater
Gold Coast 2-16	3724360	16-25N-102W	Sweetwater
Essex Mountain 1-8	3722895	8-24N-103W	Sweetwater
Boars Tusk W-19510 1-15	3721449	15-23N-104W	Sweetwater
Jade 10-11	3726324	11-24N-98W	Sweetwater
Hay Reservoir Unit 85	3725449	36-24N-97W	Sweetwater

List of Used Seismic Data

Seismic Data were downloaded from: http://walrus.wr.usgs.gov/NAMSS/
(NAMSS: The National Archive of Marine Seismic Surveys)
Survey ID: W-2-91-WY, Green River Basin Phase 2 survey by WesternGeco
Contributor: WesternGeco
Year: 1991
Line Names: GRB 91-7 and GRB 91-7x

Geology of the Big Sandy Foothills and Northern Red Desert Area

A brief discussion of the geology of the BSF/NRD area is critical in evaluating the oil and gas resources in the area. Figure 7 was extracted from the State Geological Map of Wyoming (the Wyoming State Geological Survey). The geological map shows the sedimentary package of rocks plunging from the north edge of the Rock Springs Uplift north into the northern Green River Basin. The northern portion of the BSF/NRD area is bounded by the Wind River Mountains in the form of the Wind River Thrust Fault. The distribution of the sedimentary rocks in the BSF/NRD area is best illustrated by a series of structural top-maps for each of the stratigraphic units (i.e., Muddy Sandstone, Mowry Shale, Frontier Formation, Mesaverde Group, Blair Formation, Lance Formation and the Fort Union Formation). Each of the stratigraphic units is characterized by a similar pattern (Figs. 8a-8g). That pattern is shallow and thin in the south , adjacent to the Rock Springs Uplift, and plunging and getting thicker to the north. This regional pattern is nicely illustrated by a north-south cross section constructed from the structural-top maps of each unit (Fig. 9). The same trend is also illustrated by the SW to NE cross section across at the Big Sandy Foothills and Northern Red Desert area (Fig. 10). This later section was constructed utilizing log data from drilled wells; and was constructed with no vertical exaggeration.

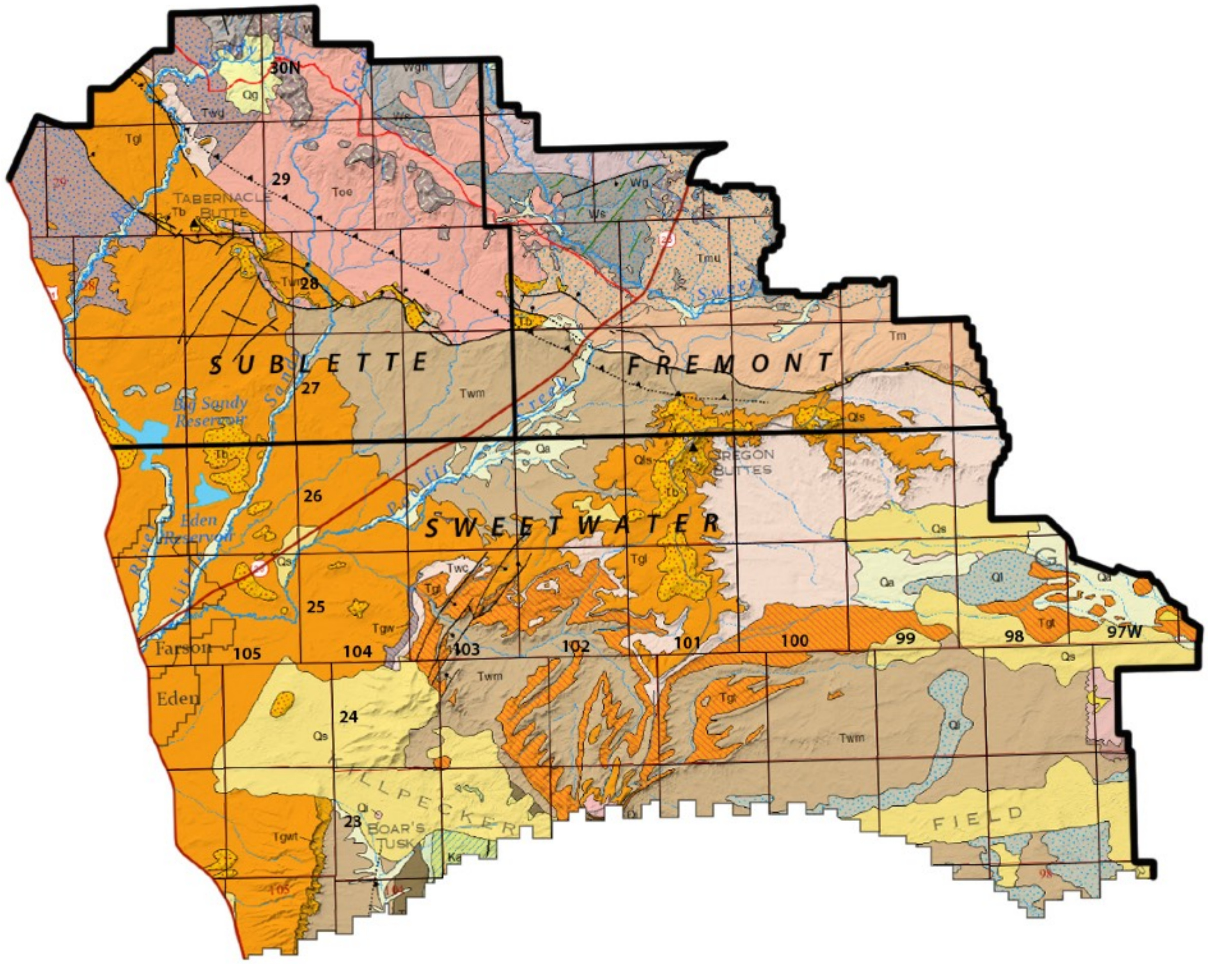
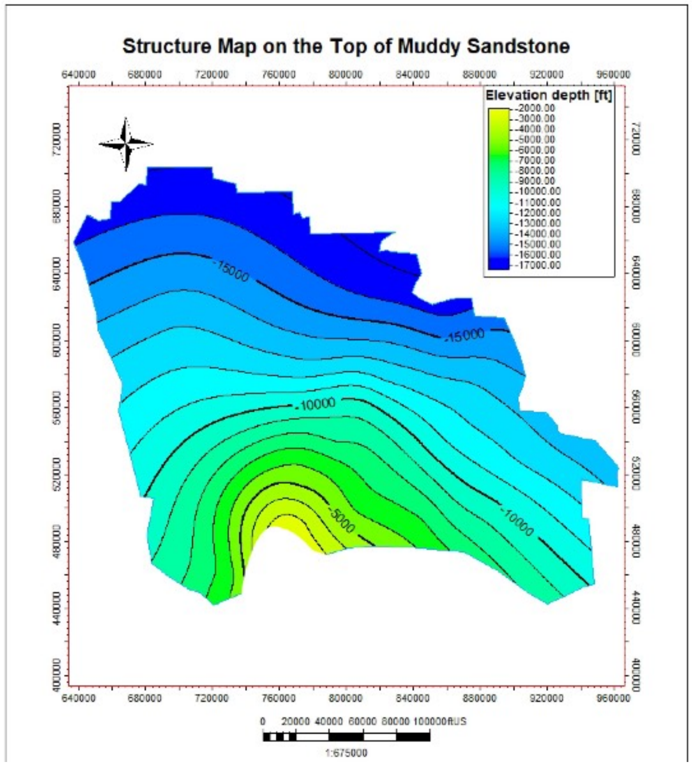
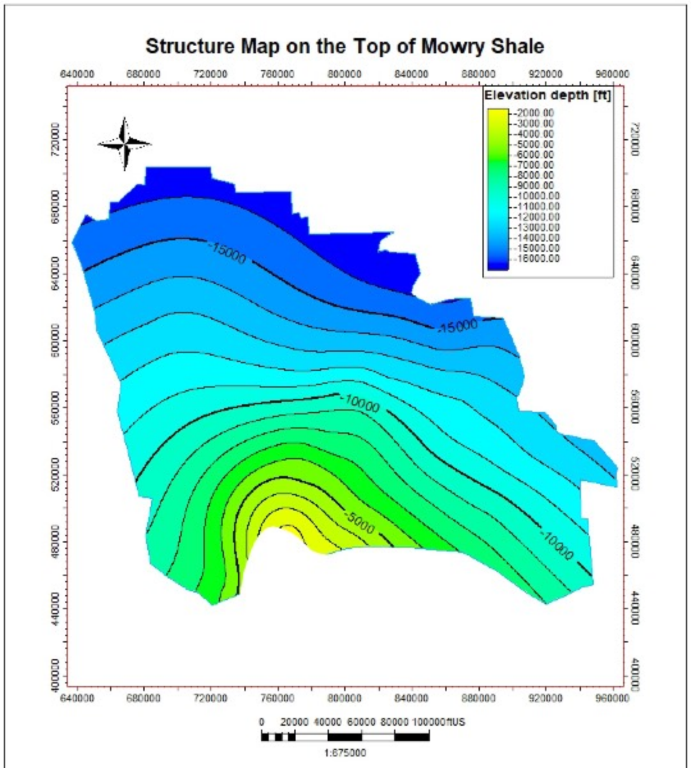
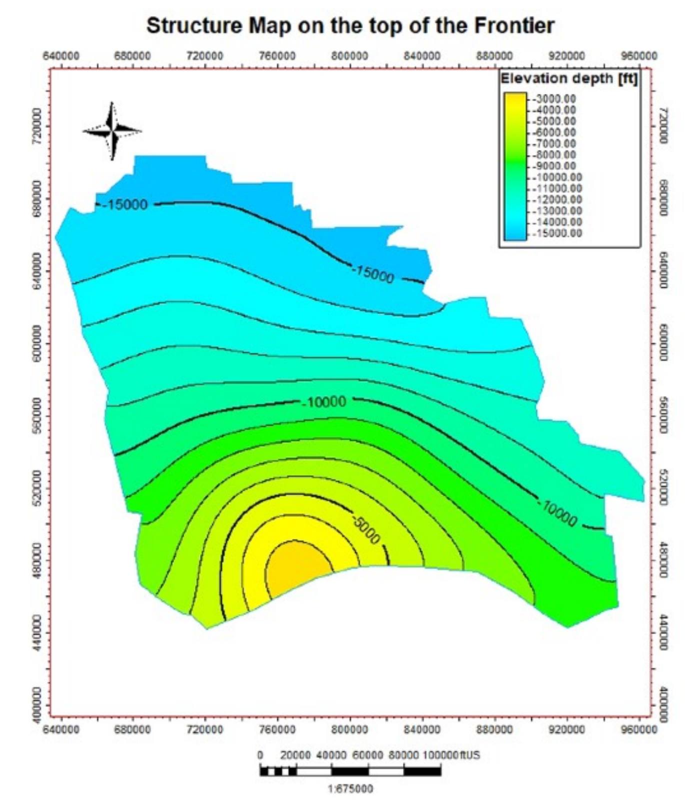


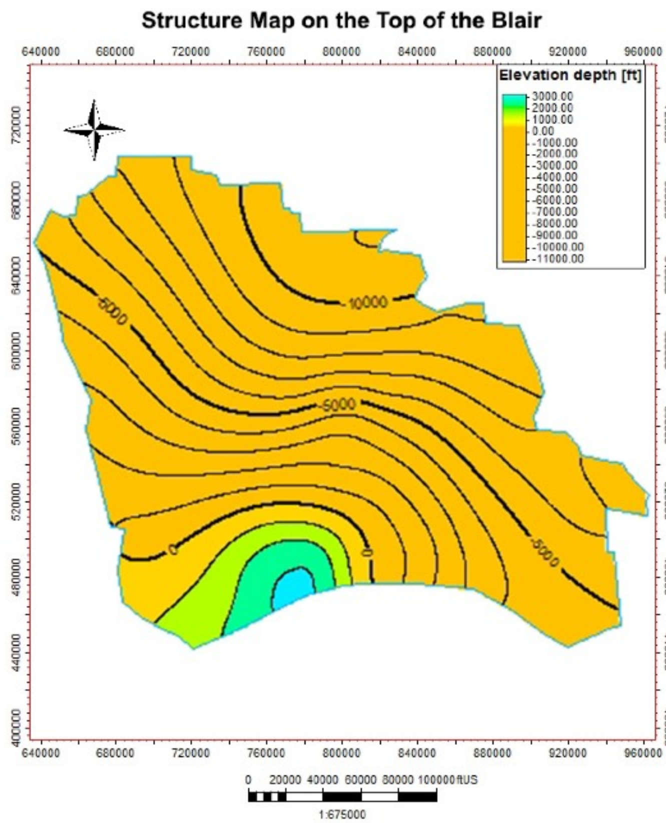
Figure 7. Geology map of the Big Sandy Foothills and Northern Red Desert extracted from the Wyoming Geological Map compiled by the Wyoming State Geological Survey.

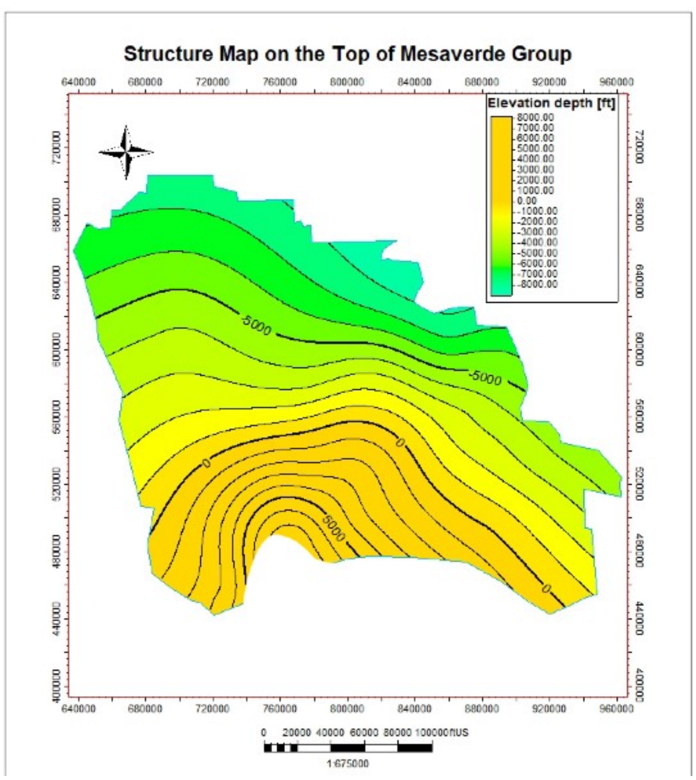


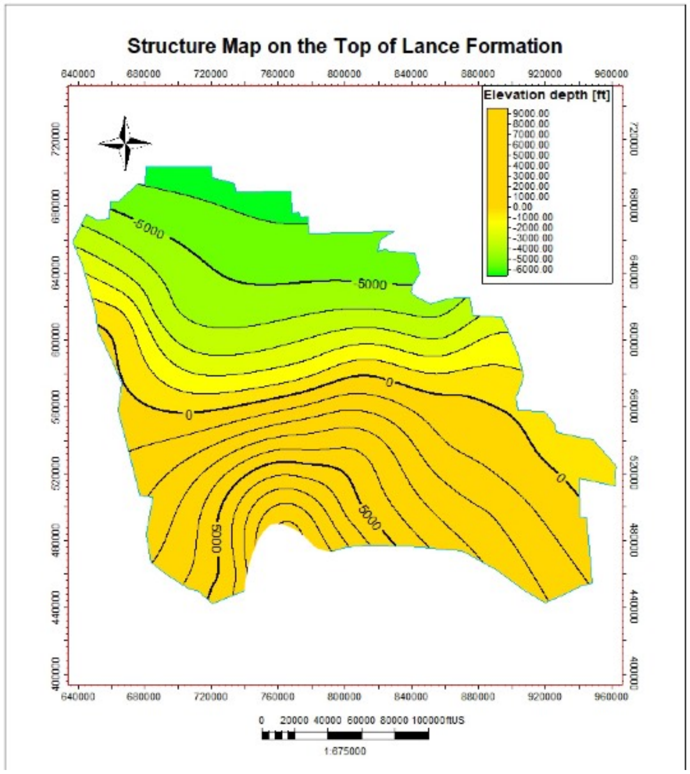
Figures 8a-g. Structural maps for the tops of Muddy Sandstone, Mowry Shale, Frontier Formation, Blair Formation, Mesasverde Group, Lance Formation, and Fort Union Formation.

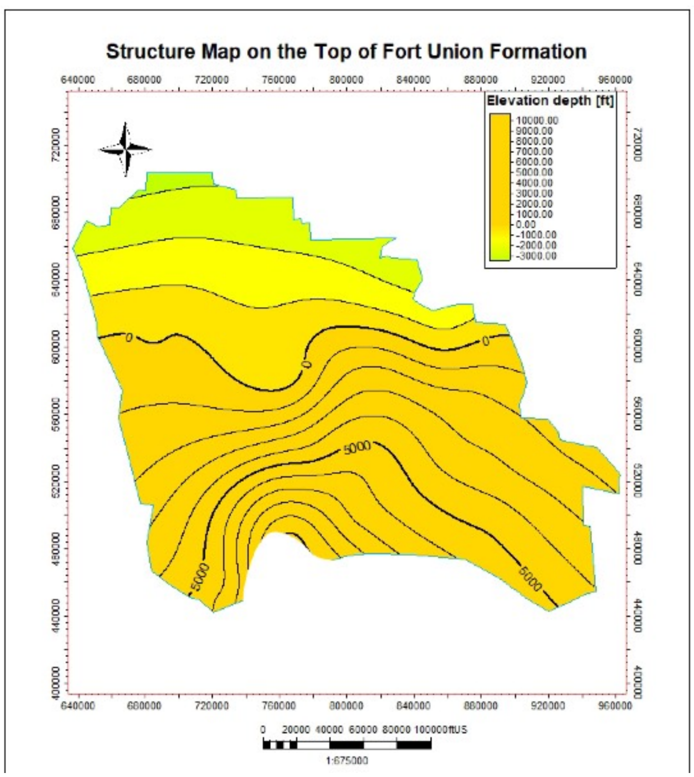

Structure Map on the Top of Mowry Shale
Elevation depth [ft]
-15000
-10000
-5000
1:675000


Structure Map on the top of the Frontier
Elevation depth [ft]
-15000
-10000
-5000
1:675000


Structure Map on the Top of the Blair
Elevation depth [ft]
3000.00
2000.00
1000.00
0.00
-1000.00
-2000.00
-3000.00
-4000.00
-5000.00
-6000.00
-7000.00
-8000.00
-9000.00
-10000.00
-11000.00
-10000
-5000
0
0 20000 40000 60000 80000 100000ftUS
1:675000


Structure Map on the Top of Mesaverde Group
Elevation depth [ft]
8000.00
7000.00
6000.00
5000.00
4000.00
3000.00
2000.00
1000.00
0.00
-1000.00
-2000.00
-3000.00
-4000.00
-5000.00
-6000.00
-7000.00
-8000.00
-5000
0
5000
0 20000 40000 60000 80000 100000ftUS
1:675000


Structure Map on the Top of Lance Formation
Elevation depth [ft]
9000.00
8000.00
7000.00
6000.00
5000.00
4000.00
3000.00
2000.00
1000.00
0.00
-1000.00
-2000.00
-3000.00
-4000.00
-5000.00
-6000.00
-5000
-5000
0
0
0
5000
5000
0 20000 40000 60000 80000 100000ftUS
1:675000


Structure Map on the Top of Fort Union Formation
Elevation depth [ft]
10000.00
9000.00
8000.00
7000.00
6000.00
5000.00
4000.00
3000.00
2000.00
1000.00
0.00
-1000.00
-2000.00
-3000.00
0
0
0
5000
5000
5000
0 20000 40000 60000 80000 100000ftUS
1:675000

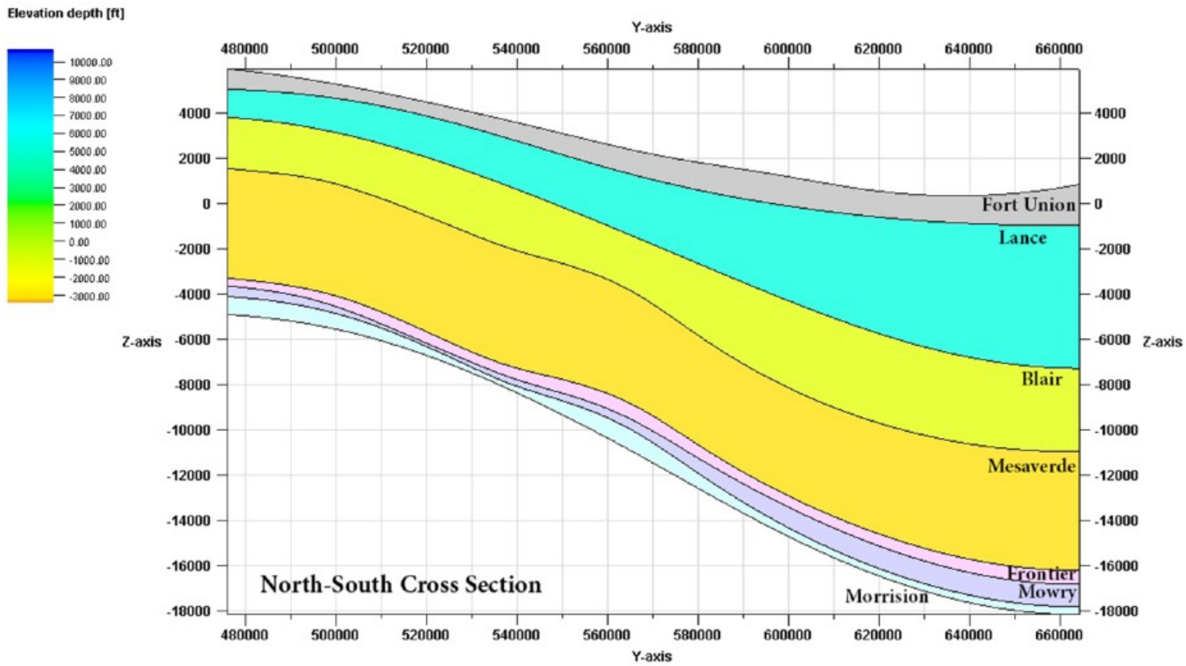


Figure 9. North-South cross section constructed using the information from Figures 8a-8g.

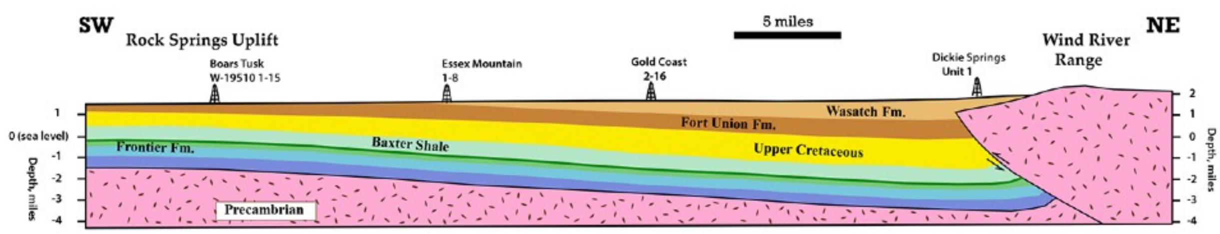


Figure 10. Stylized cross section across the Big Sandy Foothills/Northern Red Desert area showing the position of drilled wells with log data used for analysis. Note formations dipping steadily about 4° towards the northeast (no vertical exaggeration).

Figure 11 illustrates two generalized stratigraphic sections for two different portions of the BSF/NRD area within the northern Green River Basin. The most important aspect shown by these two stratigraphic sections is that both show a variety of rock units that are known to contain both reservoir and source rock intervals in other parts of the Green River Basin.

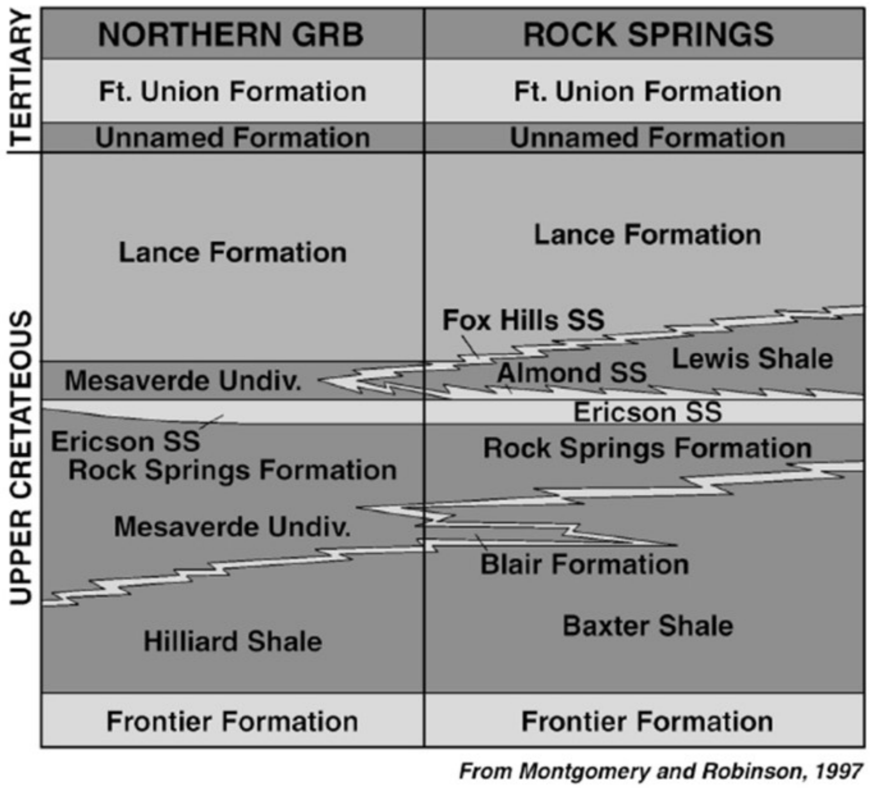


Figure 11. Generalized stratigraphic chart for the Upper Cretaceous and Lower Tertiary units in the northern Greater Green River Basin.

The Lance Formation is the main reservoir unit in the Jonah area.

For example, at the Jonah Field (giant gas field), northwest of the BSF/NRD area, the gas production is derived from the anomalously pressured fluvial channel sandstones in the Lance Formation. The productive sandstone reservoirs typically are from a depth interval of 8,200 to 11,800 feet (Montgomery and Robinson, 1997). The pay zone in the Jonah Field consists of 16 or more thin sandstones (Fig. 12). This type of sandstone distribution at Jonah illustrates why the development of the technique of multiple fracking was necessary to exploit the relatively thin tight anomalously pressured reservoir sandstones that are separated by shales.

A log profile with interpreted lithologies from the Pacific Creek well highlights the highly variable lithologic characteristics of the Lower Tertiary/Upper Cretaceous section in the BSF/NRD area (Fig. 13). The well is located in Sublette County, with Section/Township/Range coordinates 33-27N-103W in the Greater Green River Basin, (center of the BSF/NRD area). The well

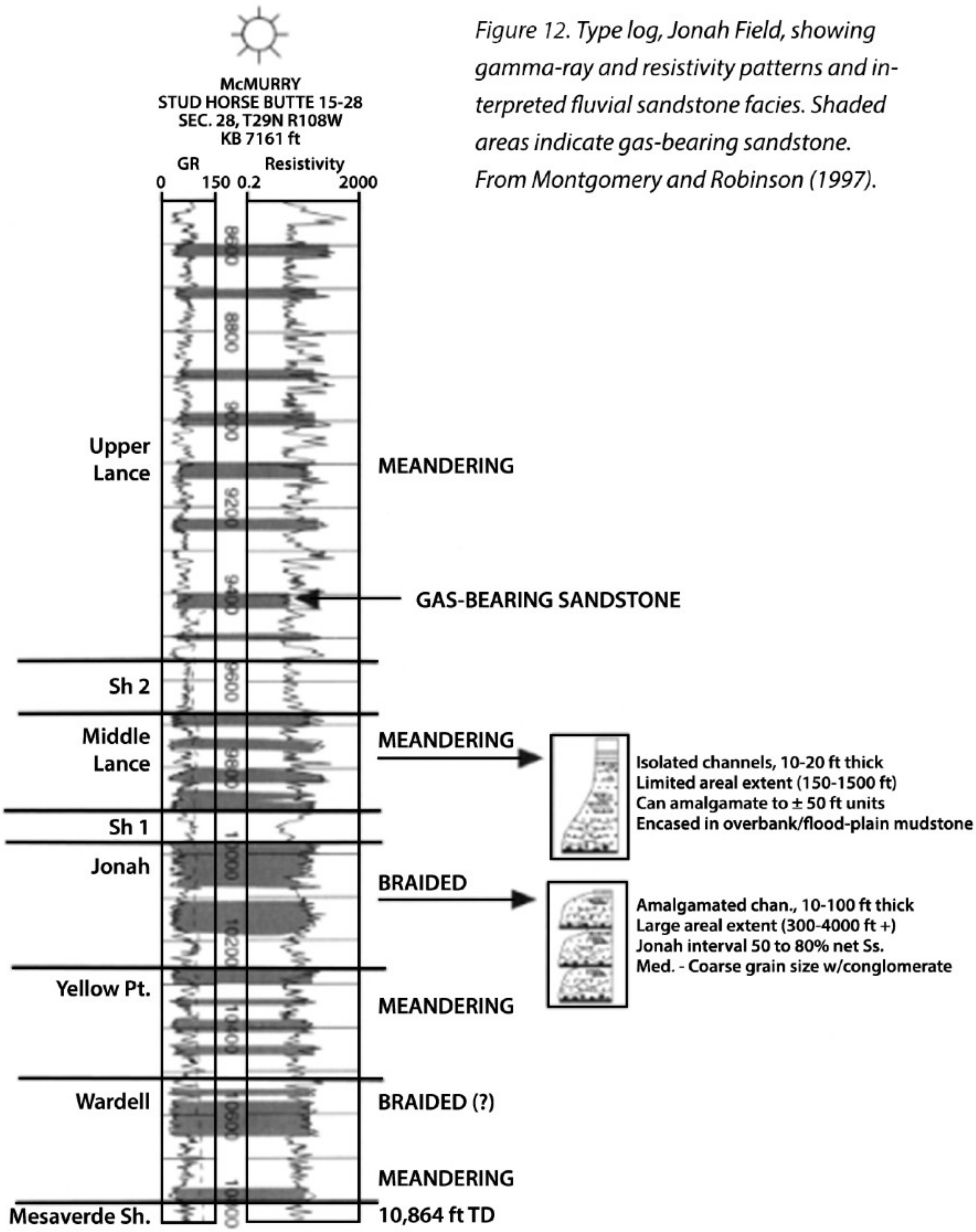


Figure 12. Type log, Jonah Field, showing gamma-ray and resistivity patterns and interpreted fluvial sandstone facies. Shaded areas indicate gas-bearing sandstone. From Montgomery and Robinson (1997).

was drilled in 1993 to a total depth of 12,900 feet and was perforated from 12,575 to 12,594 feet depth (Ericson sandstone) with no production reported. The most recently reported status of the well was that it is plugged and abandoned. To evaluate the oil and gas potential of this well in the subsurface, the following logs were digitized by hand, the gamma ray (GR), sonic transit time (DT), and deep resistivity (ILD). The velocity log was calculated from the delay times and was used for lithology identification (together with GR log), and a combination of DT + ILD logs was used to estimate organic richness using the Δ' log R' technique (Passey et al., 1990). The logged depth interval (5,000 - 12,650 feet) includes the following rock formations (in ascending order), the Cretaceous Ericson Sandstone (Ke), Almond (Kal), Lewis (Kle), and Lance (Kl), and the Paleocene Fort Union (Tfu). Consequently, the following log data interpretation includes the upper part of the Upper Cretaceous and lower part of the Tertiary (Fig. 13).

The Ericson Sandstone is chiefly composed of sandstone that is interbedded with siltstone and mudstone. The Lance Formation contains significant sandstones, whereas the older rocks are composed of interlayered sandstone, siltstone, shale, and mudstone. The differences in log features between the rock formations within the depth interval from about 9,000 to 12,000 feet depth are minor. It is noteworthy that no significant sandstone units can be observed in the Almond Formation.

Depositional patterns of lower Tertiary rocks are more complex than the older Cretaceous rocks. Relatively thicker sandstone beds are present within the depth interval from 8,000 to 9,000 feet. The Fort Union Formation is similar in both the Pacific Creek well and the Wagon Wheel No. 1 well (in the Pinedale Anticline area).

The Fort Union Formation consists of interbedded conglomerate, sandstone, siltstone, mudstone, and carbonaceous mudstone. The upper Fort Union Formation is characterized by the presence of high gamma intensity shales. No easily interpretable Cretaceous-Tertiary boundary can be identified from log data. The upper Fort Union rocks differ from the lower Fort Union rocks by the increased amount of coal seams that affect the sonic and resistivity curves by producing sharp spikes in the logs (Fig. 13).

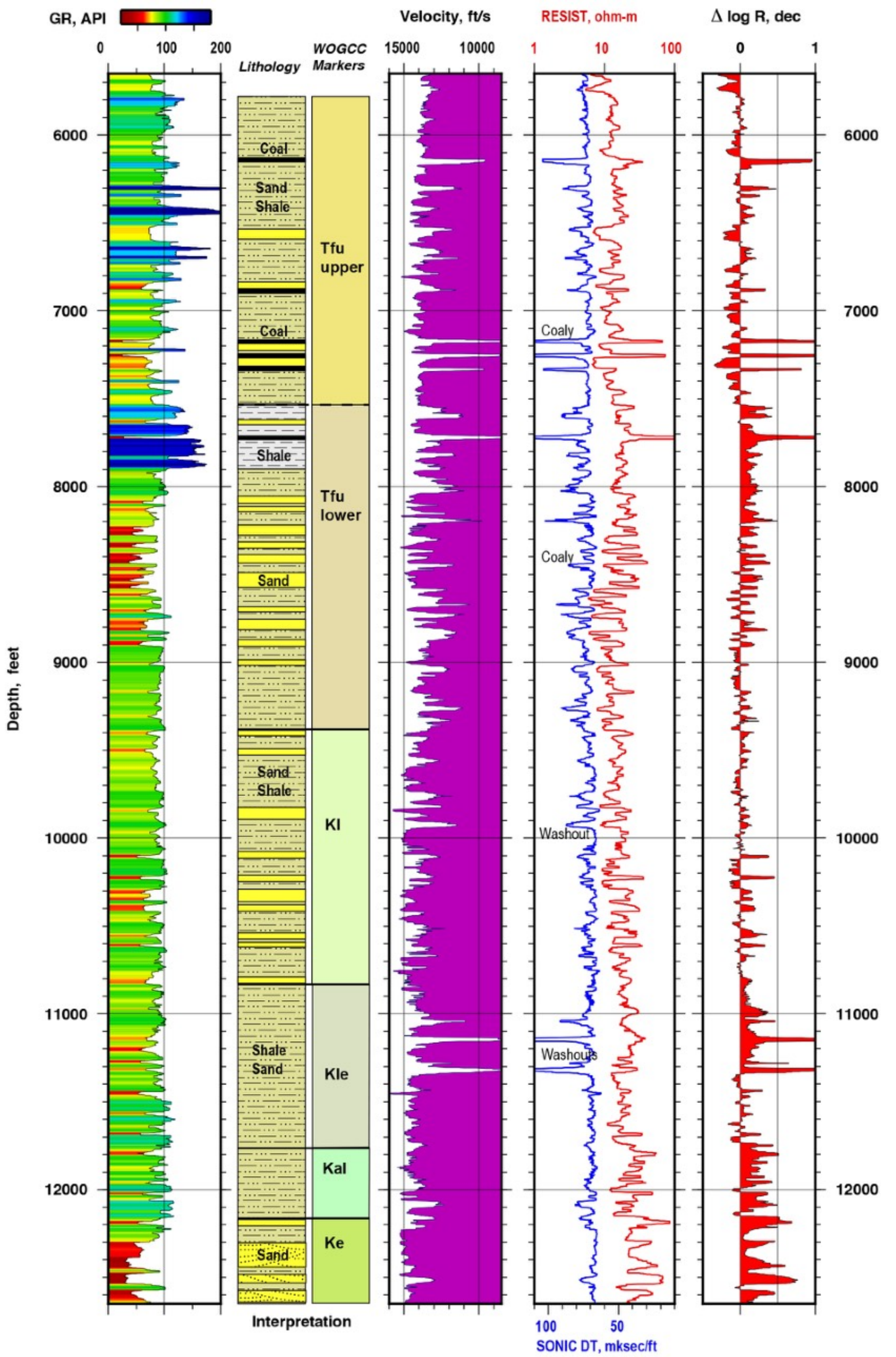


Figure 13. Log profile for the Pacific Creek 1-33 well. Lithologies are interpreted from well log information.

These observations demonstrate the highly complex nature of the potential reservoir/source rock relationships in the BSF/NRD area. It is in the context of this brief summary of the geology, stratigraphy and lithology that the potential for the discovery of new oil and gas resources in the BSF/NRD area will be discussed. The following sections will examine the potential for new (1) conventional oil and gas fields; (2) unconventional anomalously pressured oil and gas accumulations; (3) shale gas; and (4) coalbed methane resources.

Conventional Oil and Gas Fields

Figure 14 shows the distribution of seismic lines in the BSF/NRD area. The density of seismic lines suggests that the area has been well explored for conventional oil and gas accumulations associated with structural and/or stratigraphic traps. As a consequence of this exploration activity, as is apparent from the numerous seismic lines, numerous wells have been drilled (Fig. 15). Most of the successful drilling has been contained in a relatively narrow band adjacent to the northern edge of the Rock Springs Uplift (Fig. 16). This relationship between the northern edge of the Rock Springs Uplift and oil and gas accumulations is illustrated by the present location of active, abandoned and marginal (1 or 2 well) gas fields in the Northern Red Desert area (Fig. 16). The best explanation for this spatial relationship is that there are numerous faults and folds associated with and probably caused by the tectonic activity associated with the northern edge of the Uplift (Figs. 17 and 18).

These folds and faults supplied the required structural trap, seals, reservoir enhancement, and fluid migration routes required for normally pressured conventional oil and gas accumulations. Moreover, these oil and gas accumulations at the northern edge of the Rock Springs Uplift were at a depth where the oil and gas resources could be discovered and developed by utilizing readily available standard exploration and extraction techniques.

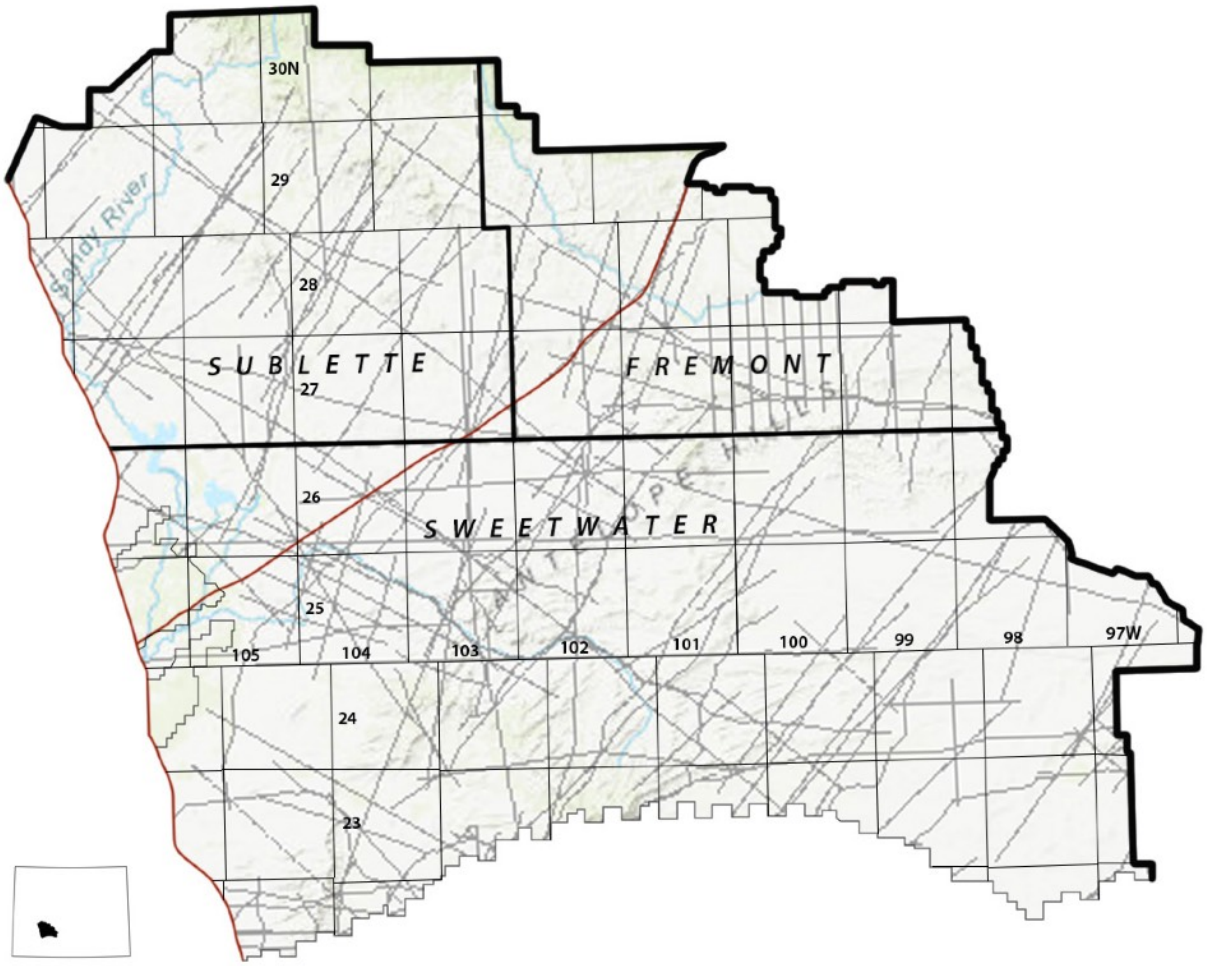


Figure 14. Figure shows the location of previously shot seismic surveys in the study area. Seismic survey locations are from WyRIT (Wyoming Reservoir Information Tool) from the Enhanced Oil Recovery Institute, Wyoming.

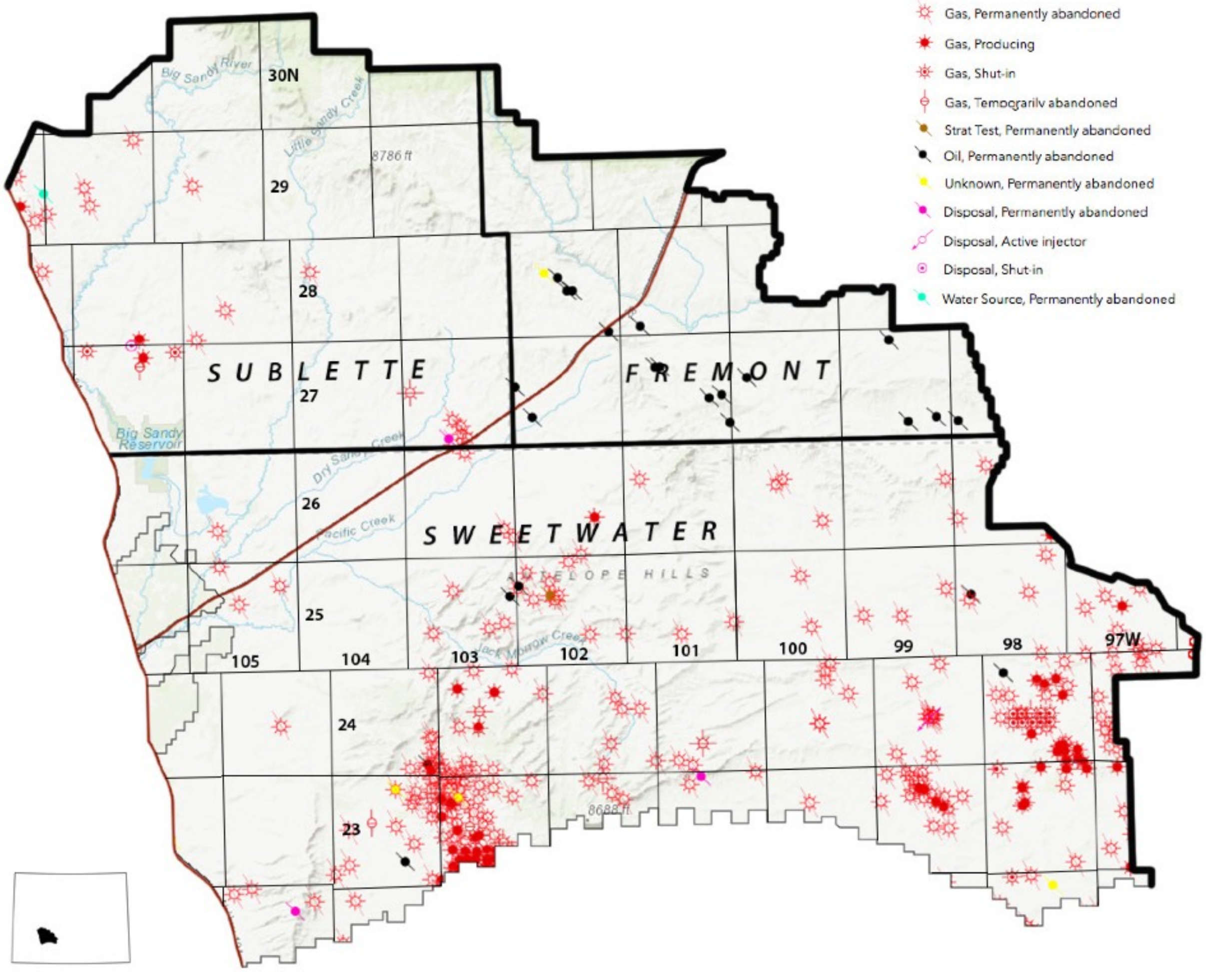


Figure 15. Figure shows the location of wells drilled in the BSF/NRD area. Data is from WyRIT (Wyoming Reservoir Information Tool) from the Enhanced Oil Recovery Institute, Wyoming.

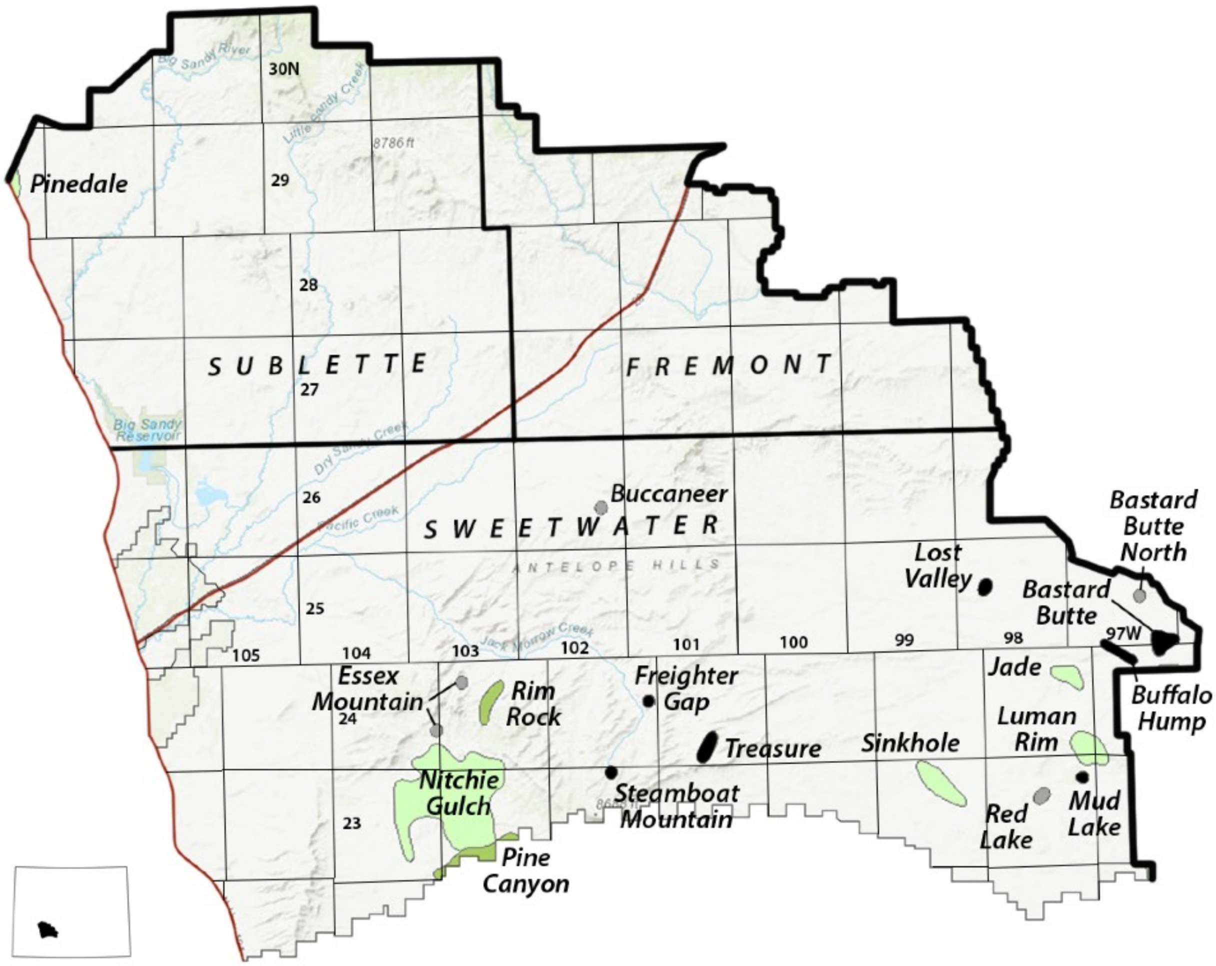
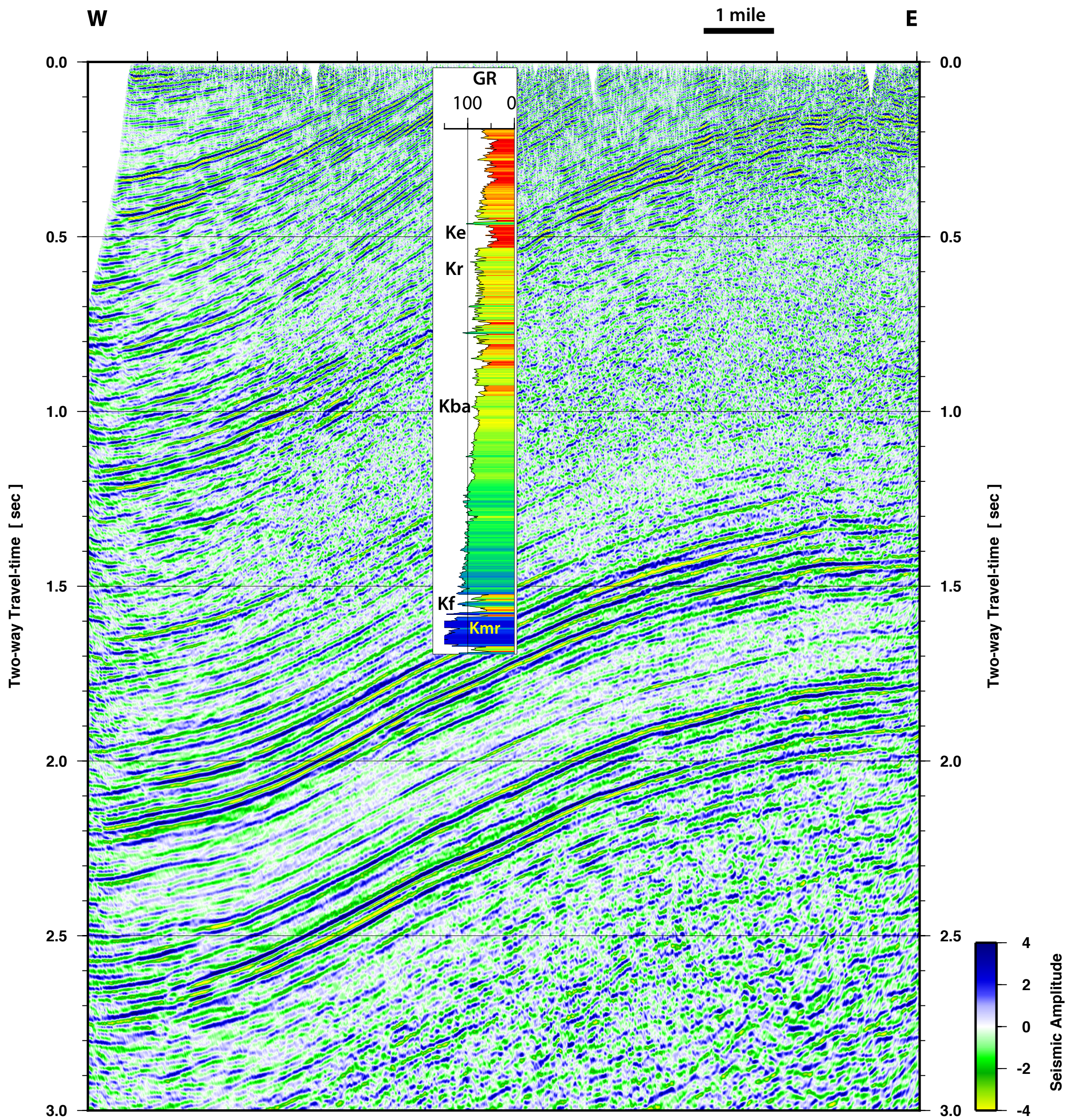


Figure 16. Figure shows the location of oil and gas fields in the study area. Green is for active fields; gray is for 1 or 2 well fields; and black is for abandoned fields. Data is from Interactive Oil and Gas Map of Wyoming from the Wyoming State Geological Survey.



Line 91_7x Vertical exaggeration = 4.25x

Figure 17. Migrated time section over seismic line GRB91-7X (W to E). The insert shows the gamma ray (GR) log from the Boars Tusk well (see Plate 1 for well location). This seismic line crosses over the northern edge of the Rock Springs Uplift. Note that the most elevated area (crest of the anticline) is located at the eastern-most part of the section where most of the gas production on the south edge of the BSF/NRD area has occurred. (Seismic data from https://walrus.wr.usgs.gov/namss/survey/w-2-91-wy/dataset/)

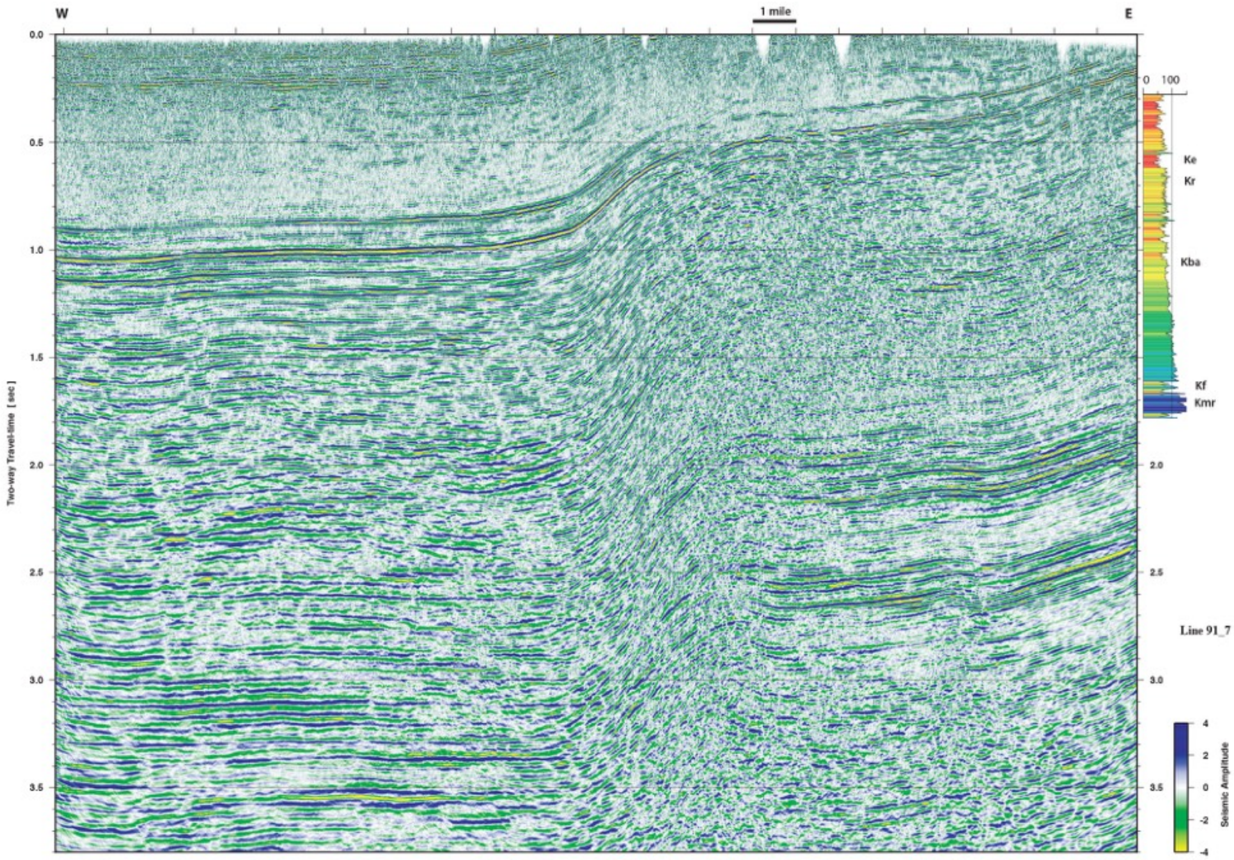


Figure 18. Seismic section along the 91-7X line. Note fault complex at west edge of the anticline shown in Figure 17. (Seismic data from https://walrus.wr.usgs.gov/namss/survey/w-2-91-wy/dataset/)

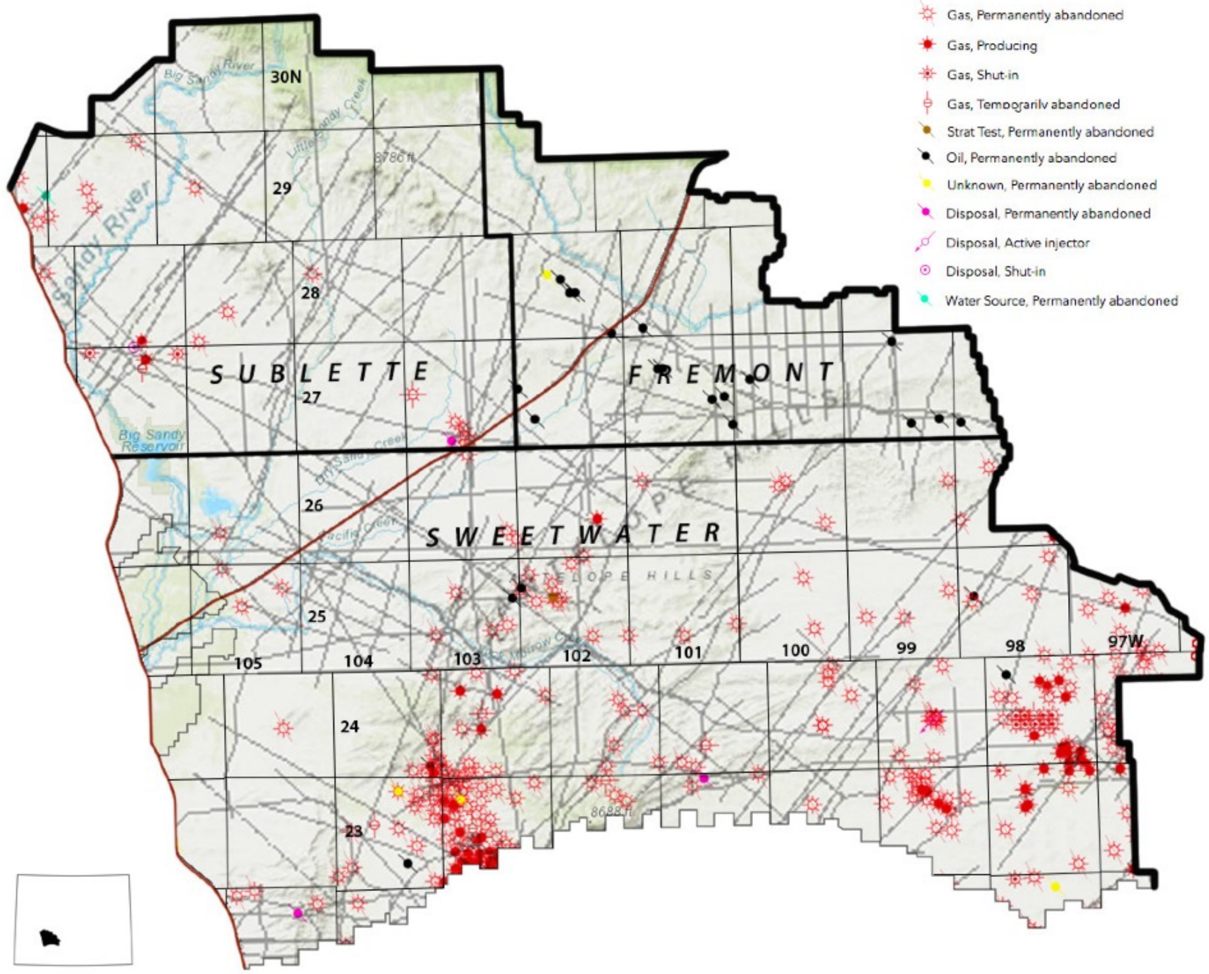


Figure 19. Map of the BSF/NRD area showing the overlap of seismic lines and wells drilled. Data is from WyRIT (Wyoming Reservoir Information Tool) from the Enhanced Oil Recovery Institute, Wyoming.

When the distribution of seismic lines is overlain on the distribution of wells drilled in the area, it is readily apparent that the BSF/NRD area has been well explored (Fig. 19). Moreover, it is apparent that few significant oil or gas fields have been discovered, with the exception of the small fields in the south adjacent to the edge of the Rock Springs Uplift. **These observations support the conclusion that the probability of a future discovery of a significant conventional oil or gas field in the BSF/NRD is remote.**

Unconventional Anomalously Pressured Gas Resource Potential

It is possible to delineate the general configuration of unconventional natural gas resource potential using velocity profiles from sonic logs and seismic velocity data. An example of this approach is the work at Jonah Field outlined earlier by Surdam et al. (2001). For the work at Jonah, the distribution of anomalously slow sonic and seismic velocities was used to detect and delineate high priority gas accumulation in the Lance Formation. A problem with this type of approach is that more than one parameter may affect the velocity variation. The velocity variation can be affected by burial, erosional, lithologic, pressure, and compaction effects, as well as the presence of a gas phase in the formation fluid (Surdam el al., 2005). However, if the velocity analysis is focused on a specific lithology such as sand-rich intervals in the Lance, Frontier, or Ericson Formations within the context of the anomalously pressure domain, the uncertainty of the evaluation can be greatly reduced. In this case, the gas resource potential can be evaluated by the magnitude and/or variation of abnormally slow velocity (i.e., the deviation from velocity derived from the typical regional velocity-depth trend). The gamma ray log over the same interval can be utilized to assure that the evaluation is for a constant lithology (i.e.,sandstone).

More than 30 sonic logs were collected from the BSF/NRD area and analyzed for anomalous velocities (Fig. 20). The raster logs and formation tops were downloaded from the website of the Wyoming Oil and Gas Conservation Commission (WOGCC – http://wogcc.wyo.gov). In Figure 21, three representative Lance sections from the analyzed wells are compared to the productive Lance section at the Jonah Field. On each well log both Gamma Ray (left) and sonic velocity (right) logs are plotted; a solid blue line represents the typical normal sonic velocity/depth trend for the region.

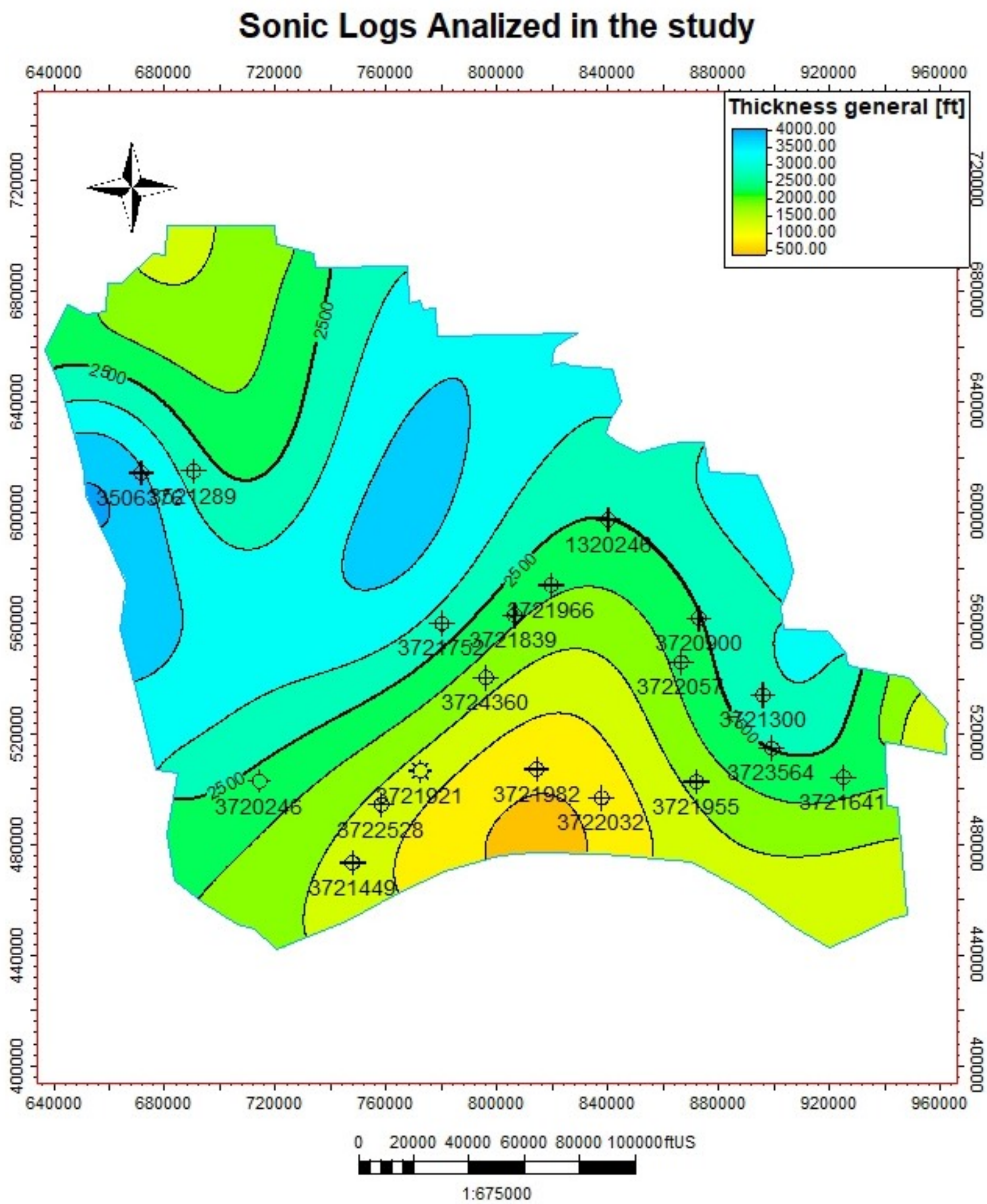


Figure 20. Available sonic logs in the study area that were analyzed to evaluate the potential gas resources based on the abnormally pressured gas resources evaluation technology developed by the Surdam Group. The contour map is the thickness of the Lance formation.

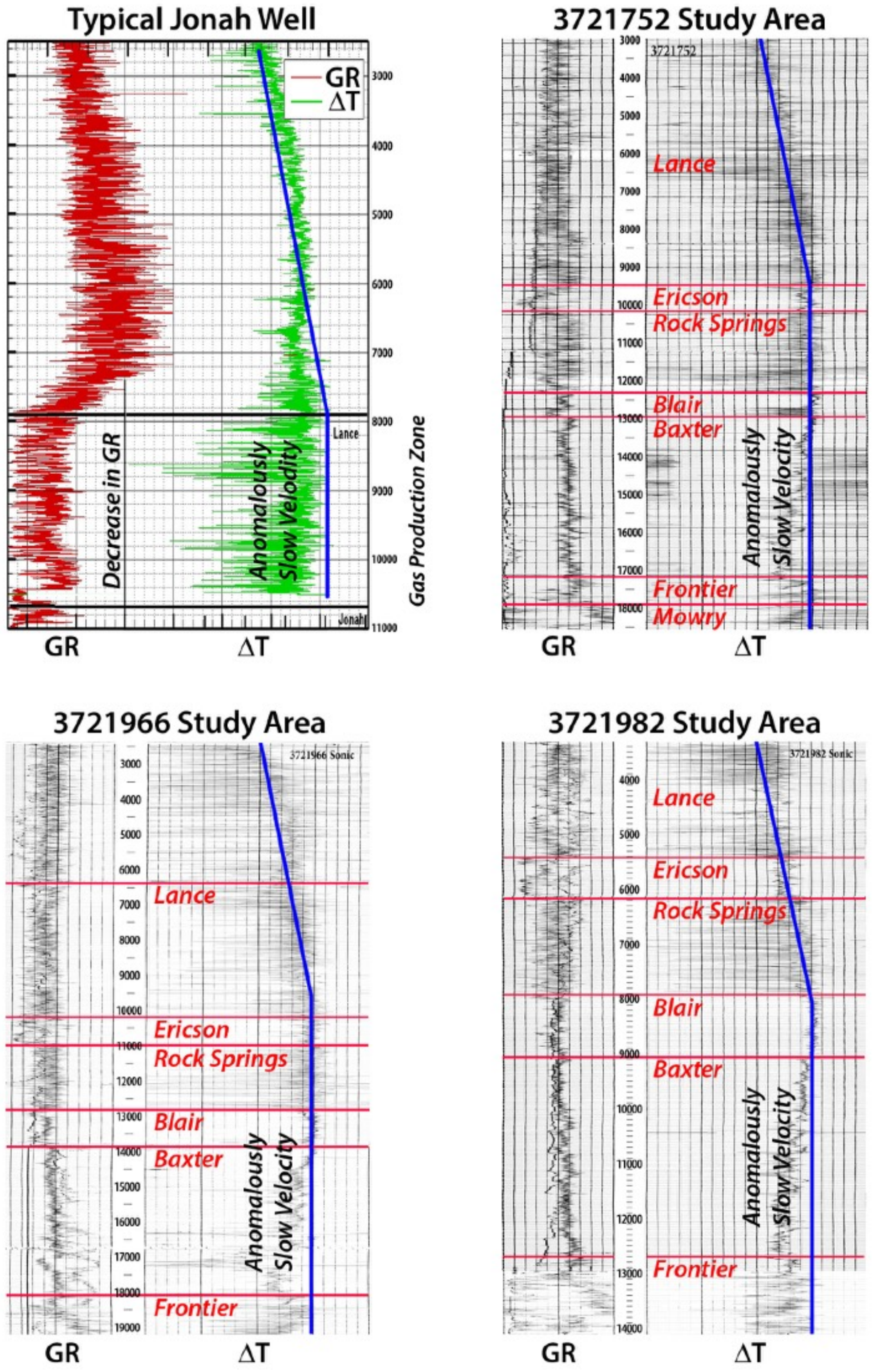


Figure 21. Comparison of the productive Lance reservoir at the Jonah Field with three of the wells studied that have the best section through Lance unit. At Jonah Field, the red lines are the values for the Gamma ray logs; whereas the green lines show the sonic velocity log. The blue lines in all four logs represent the observed regional sonic velocity/depth trend. No anomalously slow velocities were found in any Lance sections in the wells from the study area. In the three study area logs there are anomalous velocities in the Baxter Formation.

The typical sonic velocity/depth profile at the Jonah Field (upper left on Fig. 21) shows that the gas-charged Lance section is characterized by significant anomalously slow areas (i.e., productive reservoir section at Jonah). This slow sonic velocity characteristic in the Lance section at Jonah results from high gas and gas condensate saturation in the fluid as has been documented by other studies (Surdam and others, 1997, 2001, and 2005). A comparison of the typical velocity/depth trend from the Jonah Field with the sonic log velocity profiles available for the Lance Formation from the study area demonstrates a lack of significant velocity slowdowns in the examined logs (Fig. 21). No noteworthy sonic velocity slowdown intervals in the Lance Formation were found in any of the analyzed wells from the BSF/NRD area. This observation strongly suggests that there are no indications of any significant Jonah-type unconventional gas accumulation in the BSF/NRD area in the vicinity of the analyzed well logs.

In the northern half of the BSF/NRD area there is a paucity of publicly available sonic velocity logs so how is it possible to rule out Jonah type unconventional oil and gas accumulations in this area? Both the Jonah Field and the Pinedale Anticline have strong regional-scale structural controls. In the case of Jonah, the oil and gas production is strongly controlled by the structural setting (i.e. trap). Both the up-dip west and south boundaries of the Field are regional scale faults. In the case of the Pinedale Anticline, the oil and gas production is confined to a large regional structure. The large structural traps at Jonah and the Pinedale Anticline extend over surface areas of 30 and 36 square miles respectively.

In mapping the structural geology of the BSF/NRD area, no significant structural or stratigraphic traps of this magnitude and capable of trapping a regionally significant unconventional oil and gas accumulation were discovered. **Therefore there is no evidence or observations that contradict the following conclusion - the probability of discovering a regionally significant unconventional anomalously pressured oil and gas accumulation like the Jonah Field or the Pinedale Anticline in the Big Sandy Foothills and Northern Red Desert area is low.**

Shale Gas Plays

The thick Blair and Baxter shale sections in the newly analyzed well logs exhibit significant slowdowns in their sonic velocity/depth trends (Fig. 21). Most of the anomalously slow velocity zones in the Baxter and Blair Formation well logs are accompanied by parallel gamma logs that show no vertical variations. This observation suggests that the Baxter and Blair Formations are characterized by thick shale units. These typically organic-rich shales may have potential as shale-gas targets.

It is standard practice in North American shale gas play evaluation to use the ΔlogR technique published by Passey et al. (1990) to quantify total organic carbon (TOC) from porosity and resistivity logs. As was found by many authors throughout the world, this technique works accurately (about 20% uncertainty) in predicting TOC over a wide range of source rock maturity. The technique is based on the magnitude of separation of the resistivity and sonic log curves that indicate mature source rock when calibrated to TOC and level of organic maturity (LOM). The resistivity curve responds to formation fluids, whereas the sonic curve responds to the existence of low density and low velocity organic carbons. In immature source rocks, separation of resistivity and sonic curve is due solely to the sonic response. In mature source rocks, as oil and gas are being generated, the resistivity will increase and the ΔlogR separation will have both sonic and resistivity curve components (Passey et al.,1990). On the contrary, the sandstone reservoir rocks exhibit a ΔlogR separation primarily because of an increase in resistivity due to non-conductive oil or gas. For the low-porosity (tight) intervals, the ΔlogR separation is due almost entirely to the resistivity curve response as it appears in the Pacific Creek well logs on Figure 13 (Sonic/Resistivity panel). More interpretational features can be derived from Figure 22 from the original publication (Figure 12 in Passey et al.,1990).

In source rock intervals, the presence of organic carbon can be identified by using the ΔlogR technique. When the two curves are overlain in source rock intervals, the presence of organic carbon can be identified by using the ΔlogR technique. This technique is a calculation of curve separation between logarithmic scale resistivity curve in ohm-m units and normal scale transit time curve (sonic) in μs/feet units. The curves are scaled in such a way that each logarithmic cycle of resistivity curve (log R) corresponds to 50 μs/feet of transit time curve (Δ). When the two curves are overlain at this scale in one plot, it allows one to make both quantitative interpretation of a wide variety of features and qualitative estimate of TOC by calculating the separation or ΔlogR using the following equations:

(eq 1) $\Delta \log R = \log(R/R_{baseline}) + 0.02 * (\Delta t - \Delta t_{baseline})$

Equation (1) is used to calculate TOC by knowing the level of maturity (LOM) determined from vitrinite reflectance data:

(eq 2) $TOC = \Delta \log R * 10^{(2.297-0.168*LOM)}$

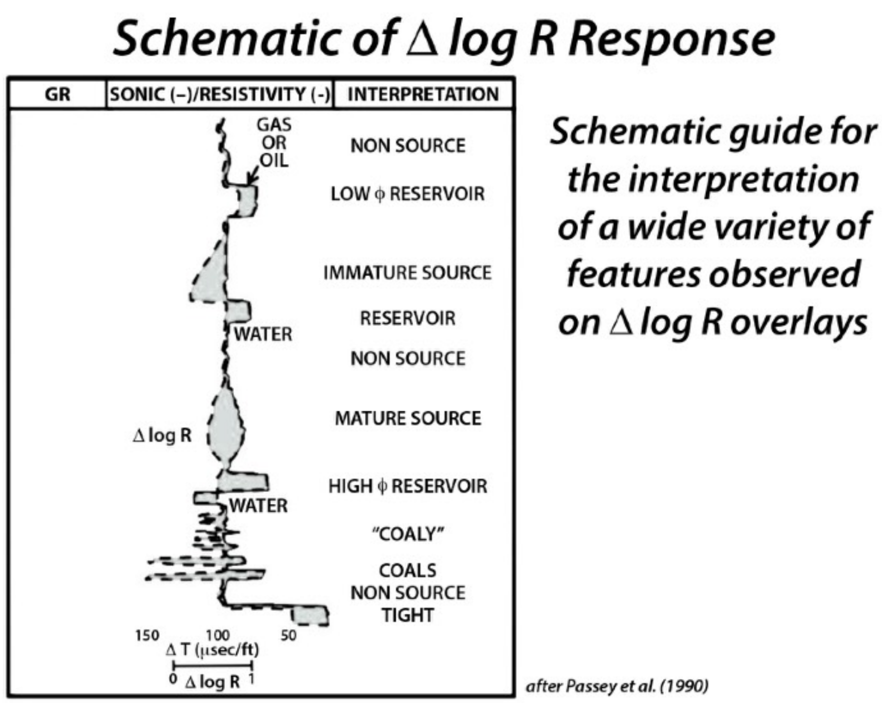


Figure 22. Schematic guide for the interpretation of a wide variety of features observed on Δ log R overlays.

Hood et al. (1975) define the level of maturity (LOM) as the level of organic metamorphism. They developed a single scale that synthesizes several existing indices of organic maturity. The scale relates LOM to vitrinite reflectance among other indicators. Vitrinite reflectance (%R_o) is used commonly in source rock evaluation to indicate whether the potential source rock is in the oil, gas, or gas condensate-producing windows. Following this scheme, the maturity of the source rock is assigned to a different production window based on the vitrinite reflectance. Vitrinite reflectance values for a potential source rock less than 0.6% are considered to be immature (LOM<9). Source rocks between 0.8 and 1.0% are in the oil zone (LOM=10). The condensate / mixed gas zone is between 1.0 and 1.4% (LOM=11-11.5). Greater than 1.4% is the dry gas window (LOM>=12). These windows are used as indicators of likely production types.

Thermal maturities at the top of the Mesaverde Group (Ericson and Almond formations) reach R_O values of 1.1 percent at the Pacific Creek well location (Figure 9 of Finn et al., 2005). Moving towards the base of the Fort Union Formation at the same location, the vitrinite reflectance decrease to R_O values below 0.8 percent (Figure 10 of Finn et al., 2005). These R_O values correspond to the range of LOM maturity values of 10-11.

Equation 1 was used to calculate the ΔlogR depth profile for the Pacific Creek well-logs with the results presented in the right-most panel of Figure 13. Excluding the spiky (washouts and coals) and reservoir intervals within the Ericson Sandstone, the calculated ΔlogR logs do not demonstrate values in excess of 0.25 decades. Using this value as an input for equation 2 results in a TOC estimate of 1.5% for the LOM parameter of 9.0, TOC = 1.0% for LOM = 10.0, and TOC = 0.7% for LOM = 11.0. As a result, the total organic carbon content within the source rocks penetrated by the Pacific Creek well ranges from 0.7% to 1.5%. It is commonly assumed that good source rocks have TOC from 3-4% to 25%. Therefore, the analyzed shale-rich rock section at the Pacific Creek Well can be characterized as organically poor with very low source rock potential for oil and gas generation.

Most of the well logs available for this evaluation were digitized from raster images stored at the Wyoming Oil and Gas Conservation Commission web page. Only two wells had logs available in digital LAS format (the westernmost Antelope 5-4 well and the easternmost Hay Reservoir Unit 85 well). The wells used for analyses possess significant drilled borehole length (TD over 10,000 ft), and importantly the largest and most continuous wireline depth interval well was over 5000 feet. Another well selection criterion was the availability of various log types for each individual drill hole. The use of multiple log types enabled the construction of well log correlations with the known producing depth interval(s) and also stratigraphic well-to-well correlations. Thus the geophysical logs used in this study are gamma ray (GR), bulk density, sonic P-wave velocity, and deep resistivity. Due to the overall sparsity of available wells in the study area and especially logged wells, it was possible to identify only nine wells suitable for cross-section building based on well-to-well correlation (Plates 1 and 2). Shale and mudstone are the most wide-spread lithologies present in color-coded log data from the study area (Plates 1 and 2). Green and blue colors (GR intensity above 65 gAPI), are characteristic of shale rock types; they compose over 80% of total logged intervals. Increasing clay content in shales can be visually correlated with a progressive change in color from yellow to green and blue in the color-coded log curves. Sandstone, siltstone and coal (red and yellow colors) represent the rest ~ 20% of the logged intervals. The south-north stratigraphic cross-section (Plate 1) shows the thickest clay-rich interval (within the Cretaceous Baxter Shale) in the southern part of profile, whereas the west-east cross-section (Plate 2) demonstrates an abundance of clay minerals within the Tertiary Fort Union formation in the westernmost part of the profile.

The wireline logs comprising the west-east cross-section (produced mostly over the Tertiary Fort Union and late-Cretaceous Lance Formations) are characterized by extreme variance in physical rock parameters: including density, velocity, and resistivity. These high-frequency fluctuations of logs can be attributed to laminated shales that are interlayerd with thin sandstone beds. Frequent occurrence of coal beds makes the color contrast of all geophysical logs appear harsh. In the study area, coals can be recognized by decreased GR readings (below 50 gAPI), low velocity and density, and increased resistivity. Most coal beds have a thickness under 5 ft with some individual coal-rich seams as thick as 50 feet.

The log data presented in both north-south and east-west cross sections (Plates 1 and 2) do not exhibit the well log or seismic character of gas-charged shales. The only exception to this observation are a few relatively thin sandy layers within the Mesaverde Group Lewis Shale and Frontier Formations. The two Plates are color coded according to gamma ray values in order to assist in assigning lithologies. The color coding allows the separation of shales (blue/green) from sandstone layers (red/yellow).

On both Plates 1 and 2, the depth profiles contain three types of logs - gamma ray, sonic (or density), and resistivity. In the Plate construction, the axes for the sonic (density) depth cures and the adjacent resistivity depth curves were purposely plotted using opposing axes directions. The joint behavior of sonic and resistivity depth curves allows the interpretation of gas-charged and/or gas-lean intervals.

For gas saturated intervals, a simultaneous derivation of the sonic/resistivity curves should be observed, for example the sonic curve should decrease and the resistivity curve should increase (Passey and others, 1990).

It is important to note that publicly available log data (Wyoming Oil and Gas Conservation Commission) for the BSF/NRD area do not adequately sample the preCretaceous strata. In other words, there is a very limited amount of well log data with continuous and long enough depth intervals to perform log analyses in the stratigraphic section below the Cretaceous rocks.

In several of the logs from the southern half of the basin shown in Figure 20, anomalously slow velocity intervals occur in the Blair and Baxter Shales. These velocity anomalies should not be considered as shale gas targets because the other log suites for the wells typically do not support a significant gas interpretation. There are a few locations in the BSF/NRD area where the shale-rich Cretaceous sections are characterized by sonic velocity log profiles that decrease (i.e., velocity slowdown), with no increase in the resistivity logs. For example, at the Boars Tusk and at the Essex Mountain Wells (points A and B on the N-S cross section (Plate 1); from ~ 7,000 to 11,000 feet depth there is some velocity log slowdown, but no increase in the resistivity log. These slowdowns in the sonic velocity logs may not be associated with gas that was generated and retained by the shales. In contrast, the deep resistivity log at the same depth interval demonstrates extremely low values. Relative to gas content, the two log suites (sonic and resistivity logs) contradict the retained gas interpretation. It is speculated that gas was generated in these organic-rich shales at the time of maximum burial and later migrated elsewhere through pathways created by Laramide tectonic activity. An alternate interpretation is that progressive clay diagenesis where the structure of mixed-layer illite/smectite clay changes from random to ordered structure at 8,000 to 10,000 feet (present-day depth), created an anisotropic effect was recorded by both the sonic and resistivity logs.

There are no direct observations in the present study that support the presence of a significant shale gas play in the BSF/NRD area.

Coalbed Methane

Methane producing artesian springs and shallow stock wells have long been known in the Powder River Basin of Wyoming, far to the northeast of the Big Sandy Foothills and Northern Red Desert. The regional source of this methane consists of the shallow coalbed aquifers located within the Fort Union Formation (Flores, 2004). Flores (2004) describes the U.S. Geological Survey's 1978 project that drilled 15 shallow wells to explore the gas content from the Anderson and Canyon coal beds in the Tongue River Member within the Fort Union Formation. Some of these shallow wells reported gas flow for individual wells of more than 1,000,000 cubic ft. per day (Flores, 2004). Based on this early work, a significant coalbed methane industry evolved in the Power River Basin of Wyoming. It is important to note that in the Powder River Basin, the pay zone in the Fort Union Formation is at 300 to 1000 feet depth.

In the BSF/NRD area, the Fort Union Formation, especially the upper portion, is characterized by interbedded shales, sandstone and coal beds, similar to the methane producing intervals in the Powder River Basin (Fig. 13). The critical question is: "Does the Fort Union Formation in the BSF/NRD area have any potential for coalbed methane production?" Figure 23 illustrates that the Fort Union Formation is presently buried more than 1000-1500 feet in the BSF/NRD area. Thus everywhere in the BSF/NRD area, the Fort Union Formation is buried deeper than the coalbed producing window in the Powder River Basin. Moreover, no methane producing artesian springs or shallow wells exist in the southern BSF/NRD. **The observations to date strongly suggest the conclusion that there is no potential for the development of coalbed methane resources in the BSF/NRD area.**

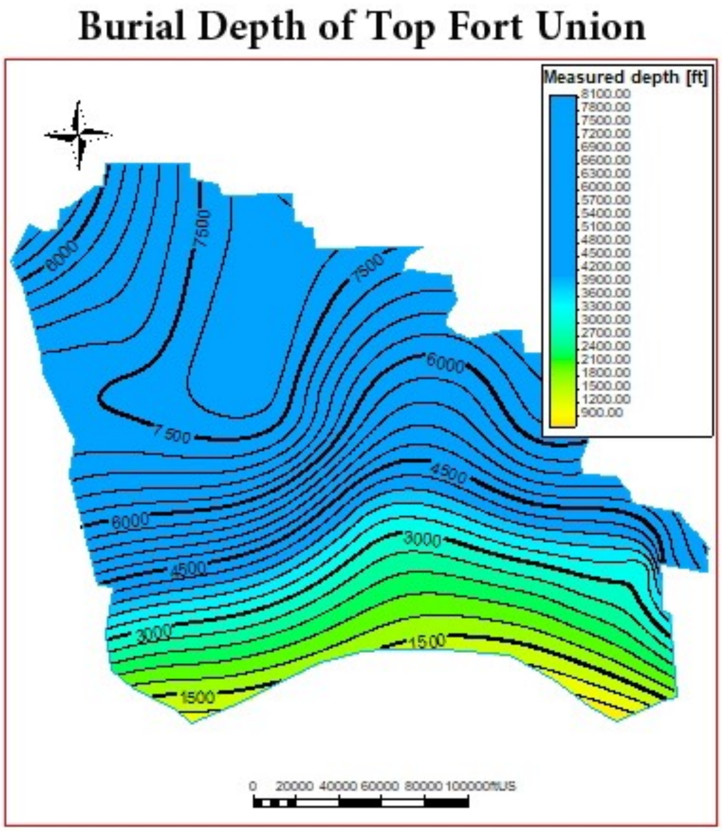


Figure 23. Burial depth of the top of the Fort Union Formation. Note that top of the Fort Union Formation is buried at depth greater than 1000 feet in the study area.

Conclusions

In order to determine the potential for significant conventional oil and gas plays, unconventional anomalously pressured gas/gas condensate fields (i.e., Jonah Field), new shale-gas accumulations, and coalbed methane development in the BSF/NRD area, a study of publicly available well logs and geophysical data was evaluated.

After careful examination of the data, it was determined that the probability of the discovery of additional conventional oil and gas fields associated with stratigraphic and/or structural traps in the BSF/NRD area is remote. The BSF/NRD area has been thoroughly explored as observed by overlaying the location of seismic lines with the location of drilled wells. This previous exploration activity had only very limited success.

The lack of anomalously slow sonic velocities in the sandy stratigraphic intervals, such as the Lance Formation, suggests that finding another high-producing unconventional play like the Jonah field in the BSF/NRD area is remote. Some slow sonic velocities were noted in other parts of the stratigraphic columns, but they were not accompanied by other log suite characteristics that would have suggested the presence of reservoir quality rocks. Shale gas was evaluated in the BSF/NRD and the results were negative. In the available data, there were no direct observations supporting the presence of any significant shale gas deposits in the BSF/NRD area. Lastly, the potential of coalbed methane was evaluated and was found to be negative. The Fort Union Formation (an outstanding coalbed methane producer in the Power River Basin), is buried to a depth greater than 1000 feet in almost all of the BSF/NRD area; thus it would not be considered as a coalbed methane prospect. In summary, based on a detailed analysis of the publicly available well logs and seismic surveys, the vast majority of the observations suggest that in the future there will be no discoveries of significant oil and gas deposits in the Big Sandy Foothills and Northern Red Desert area and that known deposits are relatively insignificant.

Acknowledgments

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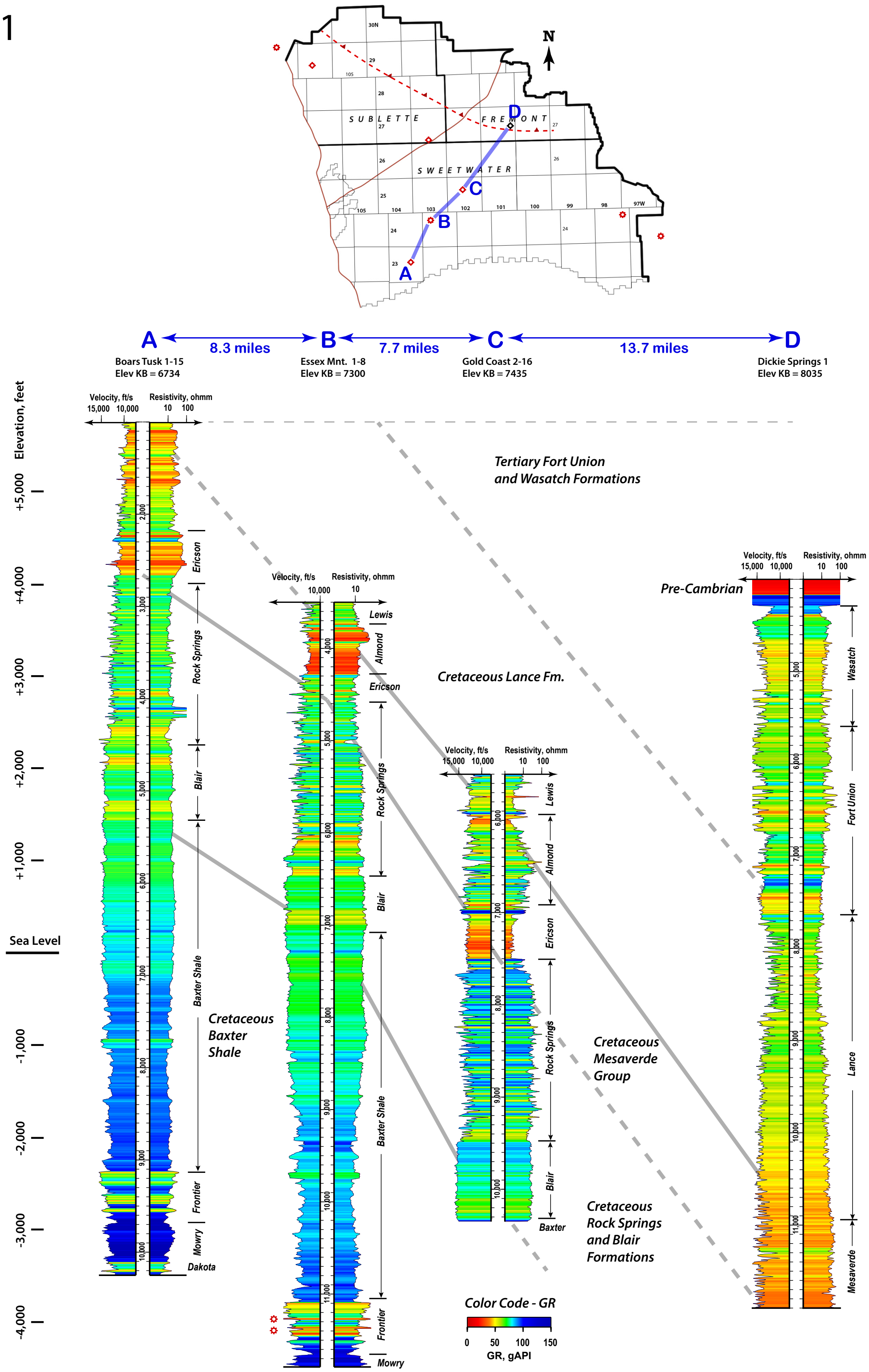
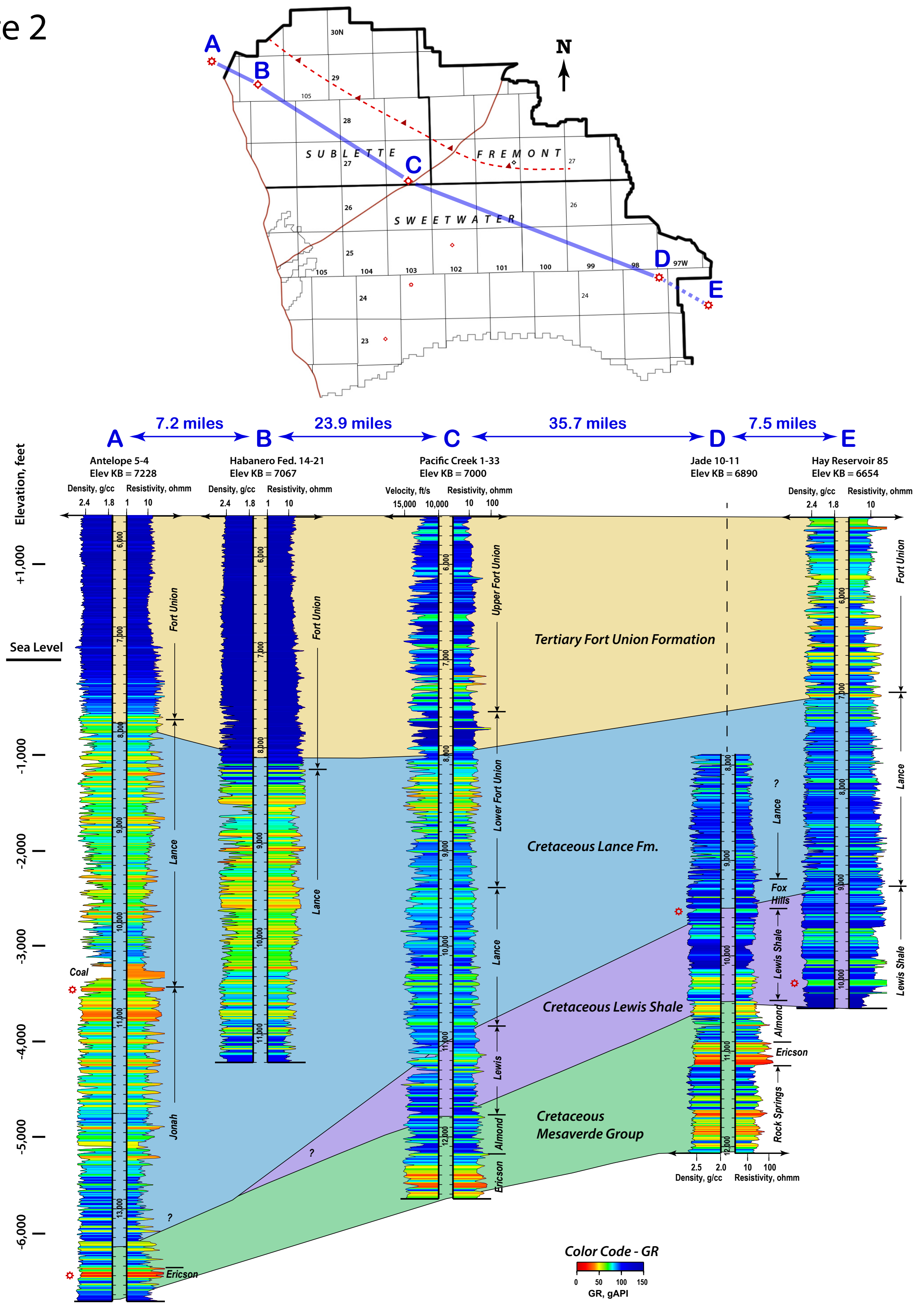
Plate 1



Geophysical log signatures of producing formations along the southwest-northeast drillhole profile. Well logs and geological markers are from the Wyoming Oil and Gas Conservation Commission web-page (http://wogcc.wyo.gov), stratigraphic interpretation is that of the authors. Note that the log curves are color-coded with gamma ray values.

Plate 2



Geophysical log signatures of producing formations along the northwest-southeast drillhole profile. Well logs and geological markers are from the Wyoming Oil and Gas Conservation Commission web-page (http://wogcc.wyo.gov), stratigraphic interpretation is that of the authors. Note that the log curves are color-coded with gamma ray values.