Naturally Fractured Tight Gas Reservoir Detection Optimization

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1.0 3D P-WAVE ALTERNATE PROCESSING

Standard processing of the 37 square mile 3D survey was completed during the last quarter. Final data volumes were shipped to the Owner/Operator for loading on their work station by Palantir, and also shipped to Lynn, Inc. An analysis was made of the N/S and E/W volumes at the lower Fort Union, and a number of anomalies in the gradients were observed. In order to fully evaluate these anomalies, it was necessary to review the velocities that were used to stack the final data. On inspection of the velocity picks, it was determined that velocities that were too fast had been used. Western therefore re-picked the velocities and re-stacked the data with special attention paid to the differences with the new velocities. After the corrected velocity field was applied to the NS and EW datasets, new Final Stack data volumes were generated, and from these volumes, the AVO gradient and SAVI were recalculated, and difference volumes (NS azimuth data minus EW azimuth data) for each were generated.

During interpretation of the difference volumes, it was noted that a time slice taken through the dataset showed a banded appearance with parallel, linear features trending NNE. These features could not be explained structurally, and could not be attributed to the acquisition. After analysis by Western, the problem was isolated. Generally, difference volumes are generated from datasets which have the exact same geometry and trace count. This enables the difference (or subtraction) routines to begin at trace one in the Volume A, subtract from it trace one of Volume B, output the result, and move on to trace two of Volumes A and B. This process is repeated for all traces in the volume.

On the alternately processed 3-D dataset, the EW azimuths were stacked for "Volume A" and NS azimuths were stacked for "Volume B". By using this azimuthal approach, the shape of the EW volume is elongated in the East-West direction, and the shape of the NS volume is elongated in the North-South direction. Thus, it can readily be seen that the shapes of Volumes A and B will be different, and as "Trace 1" for both volumes is located at a specific corner of the survey, "Trace 1" for the NS volume will be in a different physical location than "Trace 1" for the EW volume. As a result of the location difference, the subtraction process had to be indexed by Northing and Easting rather than trace number. After the problem was isolated, new difference volumes were delivered for loading on the Owner/Operators workstation and to Lynn, Inc.

2.0 INTERPRETATION OF 3D P-WAVE ALTERNATE PROCESSING

Interpretation of the 3D data began on both the Owner/Operator's work station and on the Lynn, Inc., work station in the first quarter of 1996. The interpretation has been completed for the Top Waltman Member of the Fort Union formation, and the Lower Fort Union formation. Further descriptions of this work are given below.

2.1 Top Waltman Member of the Fort Union Formation

2.1.1 *Geologic Description*

The Fort Union Waltman member is a thick, widespread unit of the Tertiary section in the Wind River Basin. It consists of pro-delta or lacustrine shales in the deepest parts of the basin, grading both upwards and laterally into shoreline deposits (delta fans, braided streams, fan-plains).

2.1.2 *Geophysical Description*

As the Waltman member overlies the Lower Fort Union member, (the primary unit of study for this project) it affects seismic transmission to the Lower Fort Union and its interpretation is therefore important to the project.

Depth control for the Top Waltman is given by 39 wells within the 3-D survey. Figure 2-1 shows the depth to Top Waltman as contoured from this well control. The dashed line indicates the northernmost limit of the Top Waltman as picked by the Owner/Operator.

Seismic time calibration is provided by 16 wells for which sonic logs exist through the Top Waltman. These sonic logs have been used to calculate synthetic seismograms, which were then tied to the seismic data from the 3-D survey.

The reflection at the Top Waltman unit is characterized by a change from higher velocity in the overlying Indian Meadows/Wind River formation to low velocity in the Top Waltman. The seismic signature of the Top Waltman on the 3-D dataset is a peak. Internally the Top Waltman unit is characterized by a general lack of seismic reflections, as is commonly the case for massive shale units. Figures 2-2 and 2-3 show a representative inline (dip line 90) for the NS and EW volumes, respectively. A seismically blank zone is seen within the Top Waltman unit in the crestal areas while the structural flanks show more continuous reflectors. This is interpreted to be due to the interfingering of more laterally continuous sandy beds deposited on the flanks (Ray, 1982). As a general observation, better signal-to-noise at the Top Waltman reflector was seen north of the faulting shown on Figures 2-2 and 2-3 (the fault block farthest north has the best signal-to-noise ratio.)

The 3-D time interpretation map for the Top Waltman, as taken from the NS volume is given in Figure 2-4.

2.2 Top of Lower Fort Union (TLFU)

2.2.1 Geologic Description

In the area of the 37 square mile 3-D the Lower Fort Union consists of interbedded sandstones and silty shales. The sandstones are typically very fine- to medium-grained, light gray to brown and tan, glauconitic, silty and argillaceous. The interbeds of shale are brown to tan, silty and soft. The sands are of fluvial origin. Where it is possible to make correlations, the individual sands and larger units appear to have a general East-West trend.

2.2.2 Geophysical Description

The reflection present at the TLFU is characterized by a trough, as the seismic wave passes from the slower shales of the Top Waltman to the faster sandstones of the TLFU. The overall structure of the TLFU follows the structure of the Top Waltman. The well control used to calibrate the Top Waltman from depth to time with sonic logs was also used to calibrate the TLFU. The TLFU horizon has been interpreted on both the NS and EW volumes, and the 3-D time interpretation map for the TLFU, as taken from the EW volume is given in Figure 2-5.

Interpretation of the azimuthal differences is currently underway. The main attributes to be examined are:

- Azimuthal Variation of Velocity.
- Azimuthal Variation of Amplitude Variation with Offset (AVOA).
- Azimuthal Variation of Reflection Amplitude.

2.3 Figure Captions

Figure 2.1

Depth to Top Waltman below seismic datum (5,000ft.a.s.l.). Control provided by the indicated 39 wells.

Figure 2.2

N-S seismic line generated from the N-S data volume.

Figure 2.3

N-S seismic line generated from the E-W data volume.

Figure 2.4

Top Waltman time interpretation from N-S azimuth data volume.

Figure 2.5

Time interpretation from E-W data volume, Top Lower Fort Union.

Figure 2-2

Figure 2-3

— Cross sections shown in figs 10-17

Figure 2-4

Top Waltman Time Interpretation
from N/S Azimuth ABC Volume
April 1996
K.M. Simon

Top Lower Fort Union Time Interpretation

3.0 3-D 3-C PROCESSING

The processing of the 3-D 3-C dataset began in April, 1996, at Western Geophysical in Denver, CO. Western will process both the P-P and P-S datasets. Western was chosen on the basis of several factors, the most important being: (1) their familiarity with the 37 square mile 3-D and the processing requirements already established in the DOE project; (2) their technical capability.

3.1 P-P Processing

The basic processing flow for the P-P portion of the 3-D 3-C dataset was modeled closely after the processing sequence performed on the 37 square mile 3-D data. A new methodology of processing has been proposed for post-NMO data to take full advantage of the insights gained in the 37 square mile 3-D, and the relatively complete azimuth and offset distribution available in the 3-D 3-C survey. The processing flow is outlined below. Processes performed during this reporting period are shown in boldface type.

- I. Geometry Description for V, H1 and H2 Components
- II. Amplitude Recovery Using $T^{1.5}$ Exponential Gain Function
- III. RAAC (Residual Amplitude Analysis/Compensation)
- IV. Surface Consistent Deconvolution
- V. Refraction Statics
- VI. Velocity Analysis
- VII. MISER Reflection Statics
- VIII. Iterations of Steps VI and VII to Convergence
- IX. Dip Moveout Application
- X. DMO Velocity Analysis
- XI. Stack
- XII. Migrate

A methodology was proposed to allow the *azimuthal* variation in the orientation of the anisotropy in the 3-D 3-C P-P data to be more finely delineated than +/- 45 degrees.

The methodology in the initial processing of the 37 square mile volume allowed the assessment of the data NS compared to EW; thus only these two azimuths were evaluated. If the orientation of the anisotropy is N45E or N45W, then we would not expect to identify such zones as anisotropic, since they should look the same NS as EW.

With the newly proposed processing flow, four azimuth volumes (+/- 22.5 degrees) will be taken through NMO-Stack-Time Migrate, using (a) full fold stack, (b) near offset half fold stack and (c) far offset half fold stack. This process will leave twelve volumes available for azimuthal velocity variation analysis. The AVO gradient for each azimuth will be computed on migrated data, so it will tie the structure maps.

The structure maps will be made using DMO-Stack-Migrate using all offsets for the NS and EW volumes.

3.2 P-S Processing

The processing flow of the P-S wave data is given below. As the DOE project is the first converted wave processing attempted by Western, many modules of the processing flow are still under development. The steps that were accomplished during this quarter are shown in boldface type.

- I. **Geometry Description for V, H1 and H2 Components**
- II. **Rectification of Trace Polarity with Azimuth**
- III. **Amplitude Recovery Using $T^{1.5}$ Exponential Gain Function**
- IV. **RAAC (Residual Amplitude Analysis/Compensation)**
- V. Zone Anomaly Processor (Used to Attenuate Noise Bursts)
- VI. FXCNS (Coherent Noise Suppression Performed in f-x Space)
- VII. Surface Consistent Deconvolution (Operators Calculated Using Limited Azimuth Windows)
- VIII. Velocity Analysis
- IX. CCP Binning
- X. Statics Calculation
- XI. Iteration of Steps VI, VII and VIII Until Convergence is Reached

Western has completed testing of their CCP (common conversion point) binning, and the results were presented at a meeting with Blackhawk Geometrics, Lynn, Inc. and Palantir.

4.0 CORRELATION MATRIX

A correlation matrix was designed by the Owner/Operator, Blackhawk Geometrics, Lynn, Inc., and Palantir in an effort to determine which criteria could be directly linked to gas production from fractures in the study area. Seven wells were chosen in the study area whose gas production ranged from "excellent" to "no gas". It is hoped that several of the criteria from the correlation matrix will show trends that follow the amount of gas production in the seven wells. The criteria were divided into four subsets:

- (i) Production Criteria.
- (ii) Geologic Criteria.
- (iii) Engineering/Well log Criteria.
- (iv) Seismic Criteria.

The complete list of criteria are listed in Table 4-1 with the specific criteria to be analyzed by the DOE project shown in *italic* type.

Table 4-1

Criteria for Correlation Matrix

Production Characteristics:	
◇	Initial flow rates
◇	Cumulative production - life of well
◇	<i>Cumulative production - normalized for the six months prior to 3D acquisition</i>
◇	Gas versus water
◇	Production for 3, 6, and 12 months following the 37 square mile seismic acquisition
Geologic Criteria:	
◇	Distance (North or South) from structural axis
◇	Producing from T.O.M.S. interval?
◇	Sand thickness, possibly sand:shale ratio
◇	Structural elevation relative to the highest point in field
Engineering/Well Log Criteria:	
◇	Mud log results
◇	Fracture log results
◇	<i>Shear wave anisotropy - VSP</i>
◇	Borehole elongation
Seismic Criteria:	
◇	<i>Shear wave anisotropy from converted wave data</i>
◇	<i>Stack amplitude difference between EW and NS azimuth volumes</i>
◇	<i>Dix velocity difference between EW and NS azimuth volumes, both for discrete intervals and the entire LFU-Base interval</i>
◇	<i>Instantaneous frequency difference between EW and NS azimuth volumes</i>
◇	<i>Reflection time difference between EW and NS azimuth volumes</i>
◇	<i>Coherence difference between EW and NS azimuth volumes</i>
◇	<i>Gradient difference between EW and NS azimuth volumes</i>
◇	LFU to Base Marker interval velocity
◇	Presence of amplitude anomaly, i.e., bright spots, dim spots
◇	Presence of patch coherence anomalies
◇	Density of coherence anomalies, NS and EW coherence volumes
◇	Proximity to major faults, distance and azimuth
◇	Position with respect to major faults, footwall or hanging wall
◇	Instantaneous phase characteristics

Analysis of the specific criteria has begun, and the results of this analysis will be presented at meetings with the OWNER/OPERATOR, Blackhawk Geometrics, Lynn, Inc., and Palantir during the third quarter of 1996.

5.0 MODELING

Three types of modeling were advanced during this quarter. These are listed below.

5.1 Converted Wave Validation

The purpose of this modeling is to create synthetic P-S "shot records" to input into the converted wave software being developed by Western. Horizons have been developed for four different layers, simulating the structure at the study area, and these will be submitted to the Aims 3D raytracing package for creation of converted wave response. This data will go to Western for validation of their converted wave software.

5.2 Paraxial Ray Tracing

This modeling will be used to address which anomalies in the P-P data can be attributed to gas filled fractures, and which anomalies can be attributed to other causes. The intent is to use Dr. Richard Gibsons paraxial ray tracing code, which he, and others, developed at MIT. Blackhawk Geometrics has been in contact with MIT and modeling is expected to start in the third quarter of 1996.

5.3 Converted Wave Well Log Modeling

Modeling was initiated on five wells within the boundary of the DOE study area. The modeling of these wells had three goals. The first was to characterize the P-wave seismic response to tie existing data. These P-wave synthetic seismograms are generated as a by-product of the converted wave effort. The second goal was to provide a synthetic converted wave seismic response. These will be available for quality checking the processed P-S data from the 3-D 3-C survey, as well as correlation to the final processed data set. The third goal was to establish a baseline from which to perform crack or fracture perturbations to the wellbore cases and evaluate the AVO response with and without cracks. Here the elastic parameters developed as a part of the modeling process will be available for the paraxial ray tracing and modeling in the Aniseis package.

6.0 WIND RIVER BASIN GEOLOGY

6.1 Summary

The Wind River Basin, located in the center of the Rocky Mountain Foreland, was formed during the Laramide tectonic cycle, and began with a linear, east-west downwarping of the northeastern corner of the present-day basin. Downwarping began before uplifting was initiated. Subsequent downwarping and infilling of the basin, and folding and uplift of the flanks, continued through the lower Eocene. Deposition in the basin, indicating continued downwarping, continued through the Miocene (Table 6-1).

The Rocky Mountain Foreland was created by northeast-southwest directed compression caused by the indentation of the Colorado Plateau into the North American Craton. The process of indentation created a system of related thrust and strike-slip faults which, in turn, gave rise to the deep linear basins paired with basement uplifts. The elongated linear basins are separated from the uplifts by major strike-slip faults.

The Owl Creek fault system, which bounds the basement-cored Owl Creek mountains on north and south, forms the northern boundary of the Wind River Basin, and has been identified as an east-west trending left-lateral strike-slip fault system. The evidence for the strike-slip nature of the fault is convincing:

- Juxtaposition of linear basement uplift and deep basin; 35,000 ft. of relief on the granitic basement.
- Similarity with uplift/basin pairs of the San Andreas fault system of southern California.
- Fits with strain accommodation due to the northeast-southwest directed stress which created the Wind River and Casper Arch thrusts.
- Subsurface faulting patterns determined from seismic surveys across the Owl Creek mountains similar to "positive flower" or "palm tree" structures.
- Minimum of 10 km. left-lateral movement mapped on North Owl Creek fault zone.

The anticline was created by a minor fault which splayed to the south from the South Owl Creek strike-slip fault zone into the subsiding basin probably during deposition of the Lower Fort Union formation. Surface faulting and fractures over anticline determined from satellite imagery are consistent with faults and fractures determined by model studies of strike-slip fault systems. Fracturing in the Tertiary sediments will be determined by:

- Directions of faulting that were ongoing during deposition of the sediments.
- Effects of crustal stretching during Pliocene regional uplift.

Table 6-1

WIND RIVER BASIN

TECTONIC HISTORY

TIME	UPLIFTS					BASIN	
	Wind River	Washakie	Owl Creeks	Casper Arch	Granite Mountains	Formation	Activity
Cretaceous							
Upper	Quiet					Meteetse	Quiet
		Upwarp			Upwarp	Lance	Downwarp
Paleocene							
Early	Rise	Rise	NW Folds		Rise	Fort Union	Subsidence
Middle-Late	pC Breached	Cretaceous Eroded	Cretaceous Eroded		pC Local Breaching	Fort Union	Subsidence
Late						Waltman Shale (FU)	Central Subsidence
Eocene							
Early	Accelerated Folding and Uplift					Indian Meadows	Continued Subsidence
		Reverse Faulting					Continued Subsidence
	pC Breached	pC Local Breaching	Uplift Along Reverse Faults		pC Extensive Breaching	Wind River	Continued Subsidence
	Extensive Erosion					Wind River	ditto
Late-Early	Renewed Folding and Faulting					Wind River	ditto
						Volcano Clastics	Margins: Folding, Faulting
End-Early	Covered by Sediments 35,000 ft. Relief W.R.Basin/S. Owl Creek Mountains					Wind River	Continued Subsidence
Post-Early	Minor Folding and Faulting					Volcanic Sediments	Continued Filling
Oligocene	Erosion					Volcanic Sediments	Continued Filling
Miocene	Erosion					ditto	ditto
Pliocene	Regional Uplift						
	Erosion						Erosion
Pleistocene	Erosion						Erosion
Present	Erosion						Erosion

6.2 Tectonics

The Laramide Orogeny has been examined in great detail by Chapin and Cather (1983) who discuss the role that strike-slip faulting may have played in the tectonic development of the region. Chapin and Cather (1983) postulate that, if the Colorado Plateau converged with the North American Craton, left-lateral strike-slip faulting would occur on the west, and right-lateral strike-slip faulting would occur on the east of the Colorado Plateau. Sales (1983) suggested that the Wyoming sub-province of the Rocky Mountain Foreland was created by a left-lateral couple between the Colorado Plateau and the stable foreland in Canada, while Stone (1969) postulated a conjugate system of left-lateral and right-lateral strike slip faults throughout the Rocky Mountain Foreland. A number of authors, e.g., Harthill et al. (1996), Sales (1978), and Stone (1969) postulate that the east-west trending faults in the Wyoming sub-province should be left-lateral strike-slip faults. Harthill et al. (1996) analyzed the effects of the Colorado Plateau/North American Craton collision in detail and showed that the Wyoming sub-province is dominated by overthrusts, such as the Wind River Uplift and Casper Arch, and a linked system of east-west trending left-lateral strike-slip faults which separate the asymmetric basins from their related uplifts (Figure 6-1). The three types of thrust which are found in the Wyoming Foreland are shown in Figure 6-2. In Figure 6-2A, the classic decollement thrust is shown which involves only the sedimentary rocks; these faults are part of the Cretaceous Sevier orogeny. In Figure 6-2B, the basement involved thrust typified by the Wind River Uplift is shown in which granitic basement rocks are thrust over the sediments in a single wedge-shaped mass. In the Wyoming Foreland, the strikes of such thrusts are approximately N50°W. In Figure 6-2C, the third type of thrust which involves multiple upthrusts is shown. Such thrusts probably evolve from a single, throughgoing strike-slip fault; similar features have been mapped in Southern California by Sylvester and Smith (1976). These thrusts (Figure 6-2A) are probably a result of vertical adjustment to lateral shearing in the crust.

The tectonics of the Wind River Basin are controlled by northeast-southwest compression in the basement (Keefer, 1970), which gave rise to the Wind River and Casper Arch thrust wedges which form the west and east margins of the basin, respectively (Figure 6-3). Plate tectonics considerations indicate that the entire lithosphere must have been involved (e.g., Coney, 1972). Similar, but lesser structures, described as anticlines by most authors, occur on the northwest margin of the basin in the Washakie Mountains (Keefer, 1970). On the southern margin of the basin, there is the Rattlesnake Mountain anticline, which is thrust-faulted on its western margin. Two similar structures occur to the west, the westernmost is bounded by the Emigrant Trail thrust which has the same general northwest-southeast strike as the Wind River and Casper Arch thrusts. The north and south margins of the basin are delineated by the east-west trending South Owl Creek Mountains and the North Granite Mountains faults respectively. There is also a set of prominent east-west faults immediately south of the South Owl Creek fault in the sediments of the basin. This trend is continued across the south end of the Big Horn Mountains, approximately ten miles to the east. The isopach maps of the Tertiary formations (Keefer, 1965) show that zero thickness is reached about 20-30 miles north of the structural boundary of the basin (Figure 6-3) indicating that an east-west trending hinge line, or fault, downdropped on the north, controlled the southern limit of sedimentation. Based on seismic data, Ray and Keefer (1985) refer to this feature as a hinge line.

Minor structures developed around the basin boundaries. To the north of the north-east corner of the Wind River Basin, which was the focus of deposition during the Paleocene (Figure 6-3, Table 6-1), the first evidence of tectonic movement after deposition of the Lance formation, was the development of northwest-southeast trending folds in the South Owl Creek Mountains. Similar northwest-southeast trending folds developed in the Washakie Range and on the basin side of the North Granite Mountains fault zone, these anticlines are not reliably dated in the literature but do involve the post-Mesozoic sediments. These structures are part of the basin boundaries rather than the basin proper.

6.3 Anticline

The basement-cored anticline is the only east-west trending anticline in the Wind River basin, and persists for perhaps 20 miles at the lower Fort Union level, and 12 miles at Madison level (Dunleavy and Gilbertson, 1986), all other anticlines trend northwest-southeast (Keefer, 1970; Love and Christianson, 1985). The Anticline was investigated by Schmitt (1975), Reid (1978), and Dunleavy and Gilbertson (1986) using drilling data from petroleum exploration wells. The paper by Dunleavy and Gilbertson (1986) is by far the most comprehensive and is based on a larger drilling database including the D-2 well which bottomed in Precambrian rocks with a T.D. of 24,877 ft. Their mapping of the structure over the anticline at the top of the Lower Fort Union is very similar to Reid's structure map of the same horizon but is somewhat different from Schmitt (1975) who identified two anticlinal structures. The structure contour map of Dunleavy and Gilbertson (1986) and is superimposed on the fault map of the Wind River Basin in Figure 6-3.

The anticline is located on the basin side of the east-west trending South Owl Creek fault, and the northwest-southeast trending Casper Arch which intersect a few miles east of the structure (Figure 6-3). Other major faults which are also involved in this intersection are the east-trending fault which cuts off the southern end of the Big Horn Mountains, and the north-northeast trending fault which extends 55 miles from the intersection until it intersects the Tensleep fault (Love and Christianson, 1985; Stone, 1969). The geologic map of Wyoming (Love and Christianson, 1985) shows a large number of subsidiary faults in this area indicating that it is a highly disturbed zone (Figure 6-3). Deep reflection seismic studies (Ray and Keefer, 1985; Dunleavy and Gilbertson, 1985) show the anticline to be a thrust-fold structure developed between the South Owl Creek Mountains thrust fault to the north and the thrust directly beneath (Figure 6-3). Dunleavy and Gilbertson (1986) warn that near-surface velocity changes complicate structural interpretation from seismic data, and that such structures are usually not confirmed by drilling. A series of structure maps given by Dunleavy and Gilbertson (1985) show that the anticline decreases in size with depth. The structure contours on top of the Lower Fort Union over the anticline are closed to the west, the contours swing to the north as they coincide with a strong N25°W- trending lineament which is apparent on the satellite imagery of the Wind River Basin (Figure 6-3)

The most common explanation for the creation of the anticline is that it is part of the South Owl Creek Mountains thrust system which trends east-west immediately north of . However, the structure contours on the northeast side of the axis, trend N50°W along the border of the Bighorn Mountains, i.e., parallel to the strike of the Casper Arch, but possibly offset to the west (Love and Christianson, 1985; Figure 6-3). Gries (1983) attributed the anticline to be the result of north-south compression during the Eocene.

This explanation seems somewhat improbable because, if north-south compression were the cause of the creation of the anticline, why are there no other east-west trending compression structures visible in or around the Wind River Basin? In addition, if there were north-south compression in this area, there probably would not have been the continued deposition which lasted from late Cretaceous through the Miocene. An alternative explanation for the creation of the anticline is that it is part of a left-lateral strike-slip fault system whose major southern component is the South Owl Creek Mountains fault. Paylor and Yin (1993) demonstrate that the east-west trending North Owl Creek fault in the West Owl Creek mountains has a minimum of 4 km of left-lateral strike-slip movement, and Sundell (1990) estimates a minimum of 10 km. left-lateral strike-slip movement on the same fault. The prevalence of east-west striking faults within, and bounding the Owl Creek Mountains suggests that they may all be part of the same system.

In strike-slip fault systems, not only does the crust move laterally, but tear zones form in the crust creating very deep basins with paired uplifts on the other side of the fault within a very short lateral distance perpendicular to the fault. Many examples of such structures have been mapped in southern California (Crowell, 1974; Sylvester, 1988; Sylvester and Smith, 1976). The great vertical displacements between the basin and uplifts in the Wind River basin is well documented, Keefer (1965) states that there was 35,000 ft relief between the Wind River Basin and the South Owl Creek Mountains at the end of Early Eocene time (Table 6-1). One of the signatures of such basin/uplift pairs is that very coarse alluvium is found on the basin side of the fault which grades rapidly into much finer sediments. An example of this in the area is the juxtaposition of the Waltman Shale and its lateral equivalent, the Shotgun member of the upper Fort Union formation. Alluvium containing coarse sediments up to boulder size is developed along the northern margin of the basin in all Tertiary formations.

Deep faulting in the area was defined by drilling, supplemented by reflection seismic surveys which show the and South Owl Creek faults to be low-angle thrusts dipping to the north at perhaps 30° (Ray and Keefer, 1985; Dunleavy and Gilbertson, 1986). The thrust seems to be a local phenomenon as, at the Madison level (-20,000 ft), it extends for about 12 miles along strike (Dunleavy and Gilbertson, 1986). The overthrust system is similar to those shown in Figure 6-2C. Field mapping and model studies show that when uplifts are created in a strike-slip fault, they splay upward and outward in a "palm tree", or "positive flower" structure (Sylvester, 1988). In the Wyoming foreland, such a structure was mapped on a seismic section across the Hanna Basin, Wyoming (Kaplan and Skeen, 1985; Figure 6-2C). It is very similar to structures mapped in the Painted Canyon area of the Salton Trough by Sylvester and Smith (1976). These strike-slip fault-generated thrusts are very different from the Wind River and Casper Arch thrusts (Figure 6-2; Basham and Martin, 1985; Ray and Berg, 1985). Wise (1963) mapped the Wind River canyon area of the Owl Creek mountains and developed a conceptual model for the frontal zone of the Owl Creek which is very similar to "palm tree" structures. Stone (1993) created a regional structural synthesis based on seismic data which runs across Wyoming from southwest to northeast, it crosses the South Owl Creek fault at around 109°W in the Washakie mountains. His interpretation of the Owl Creek Mountains and associated thrusts is shown in Figure 6-4. He describes the structure as a "positive flower structure" created by left-lateral movement on the Owl Creek fault system.

This interpretation is corroborated by the strike-slip fault concepts described above. An alternative explanation is that the anticline may have been created by northeast directed stress during the early Paleocene, as northwest-southeast trending folds were created in the Owl Creek Mountains at that time (Table 6-1; Keefer, 1970). The present shape of the anticline could be due to the fact that it was sheared off by the east-west trending strike-slip fault which is now called the thrust.

The anticline is a major source of hydrocarbons from reservoirs ranging from the Mississippian Madison Limestone to the Tertiary Lower Fort Union. Production from Tertiary formations is enhanced by fracturing. Therefore, any interpretation of fracturing in the Tertiary sediments of the anticline must take the mode of creation of the anticline into account.

When was the anticline created? It may have been during deposition of the lower Fort Union formation. During lower Fort Union deposition, the depocenter lay to the north of the later depocenter of the Waltman shale (Keefer, 1965) indicating, perhaps, that the anticline was rising at that time.

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6.5 Figure Captions

Figure 6-1

a) Generalized tectonic map of the Rocky Mountain Foreland (after Bayley and Muehlberger, 1968; Chapin and Cather, 1983; Gries, 1981; Stone 1969).

b) Legend.

Basins: BHB, Bighorn Basin; DB, Denver Basin; GDB, Great Divide Basin; GRB, Green River Basin; HB, Hanna Basin; LB, Laramie Basin; LVB, Las Vegas Basin; NPB, North Park Basin; PB, Paradox Basin; PEB, Piceance Basin; PRB, Powder River Basin; RB, Raton Basin; SB, Shirley Basin; SJB, San Juan Basin; SLB, San Luis Basin; SPB, South Park Basin; UB, Uinta Basin; WB, Washakie Basin; WRB, Wind River Basin. Uplifts: BU, Bighorn Uplift; BHU, Black Hills Uplift; BHP, Beartooth Plateau Uplift; CCU, Circle Cliffs Uplift; DU, Defiance Uplift; FRU, Front Range Uplift; GMU, Granite Mountains Uplift; HU, Hartville Uplift; LU, Laramie Uplift; MBU, Medicine Bow Uplift; MU, Monument Uplift; OCU, Owl Creek Uplift; PU, Park Uplift; RSU, Rock Springs Uplift; SCU, Sangre de Cristo Uplift; San Rafael Uplift; SW, Sawatch Uplift; UMU, Uinta Mountains Uplift; UU, Uncompahgre Uplift; WU, White River Uplift; WRU, Wind River Uplift. Cities: C, Cheyenne; CR, Casper; CY, Cody; D, Denver; DO, Durango; GJ, Grand Junction; L, Laramie; LR, Lander; P, Pinedale; PO, Pueblo; PR, Price; S, Sheridan; T, Taos; V, Vernal.

Figure 6-2

Diagrammatic examples of the three types of thrust faulting found in the Rocky Mountain Foreland. The vertical and horizontal scales are the same on each panel, there is no vertical exaggeration. Upper: Darby thrust, Overthrust Belt, classic decollement thrust, no basement involvement, overhang > 60,000 ft (after Williams and Dixon, 1985). Middle: Wind River thrust, granitic basement thrust as a single unit to thousands of feet above sea level over a thick sedimentary wedge capped by syntectonic sediments, overhang $\approx$ 40,000 ft. (after Basham and Martin, 1985). Bottom: Hanna Basin, north margin, fractured granitic basement thrust in a series of slices over a thick sedimentary wedge with coarse syntectonic sediments deposited close to the thrust, overhang $\approx$ 20,000 ft. (after Kaplan and Skeen, 1985).

Figure 6-3

Fault map of the Wind River Basin showing the relationship between the Anticline, area of Tertiary sedimentation, the South Owl Creek Mountains fault zone, and the other major faults that delineate the basin (after Love and Christianson, 1985; Dunleavy and Gilbertson, 1986; Paylor and Yin, 1993; Stone 1969).

Figure 6-4

Interpretation of seismic data across the Owl Creek Mountains west of Madden. Note that the north side (right) of the fault zone has moved away from the observer, the south side (left), towards. The structure is very similar to that observed to the east (from Stone, 1993).

FIGURE 6-1A

Uplifts	
BHU	Black Hills
BPU	Beartooth Plateau
BU	Bighorn
CCU	Circle Cliffs
DU	Defiance
FRU	Front Range
GMU	Granite Mountains
HU	Hartville
LU	Laramie
MBU	Medicine Bow
MU	Monument
OCU	Owl Creek
PU	Park
RSU	Rock Springs
SCU	Sangre de Cristo
SRU	San Rafael
SU	Sawatch
UMU	Uinta Mountains
UU	Uncom-pahgre
WRU	Wind River
WU	White River

Basins	
BHB	Bighorn
DB	Denver
GDB	Great Divide
GRB	Green River
HB	Hanna
LB	Laramie
LSB	San Luis
LVB	Las Vegas
NPB	North Park
PB	Paradox
PEB	Piceance
PRB	Powder River
RB	Raton
SB	Shirley
SJB	San Juan
SPB	South Park
UB	Uinta
WB	Washakie
WRB	Wind River

Cities	
C	Cheyenne
CR	Casper
CY	Cody
D	Denver
DO	Durango
GJ	Grand Junction
L	Laramie
LR	Lander
P	Pinedale
PO	Pueblo
PR	Price
S	Sheridan
T	Taos
V	Vernal

Figure 6-1B

TECTONIC MAP OF

SOUTH

R. R. 1
FREMONT COUNTY, WY
E. HOT SPRINGS COUNTY

T. T. 7/8
N. N.

NORTH

WIND
RIVER
BASIN

BARGE
ANTICLINE

BIGHORN
BASIN

ELEVATION
(FEET)

OWL CREEK MOUNTAINS

(POSITIVE
FLOWER
STRUCTURE)

-5,000

+5,000

0

BARGE
THRUST

TOWARDS

AWAY

BARGE QUADRANGLE

43°37'30" ANCHOR
108°45' RESERVOIR
QUADRANGLE

FIGURE 6-4

7.0 TECHNOLOGY TRANSFER

A summary of the technology transfer events in the second quarter of 1996 is given below.

Abstracts were submitted in April for the 1996 Annual Society of Exploration Geophysics meeting in Denver, CO. The titles of these abstracts are "Naturally Fractured Gas Reservoirs Seismic Characterization" and "Near Surface Variability in Shear Wave Velocity Anisotropy".

The AAPG annual convention in San Diego was attended during May and a paper was presented on the Bluebell-Altamont, DOE funded project. The spring Owner/Operator partner meeting was held in May, and an update on the DOE project was given to the industry partners.

Lynn, Inc., presented an oral overview of the project in Houston at a technical work shop organized by the Geological Society of Houston (GSH), the Houston Geophysical Society (HGS), and the Society of Petroleum Well Log Analysts (SPWLA) on June 24. At this meeting, Blackhawk Geometrics also gave a poster presentation session of the Bluebell-Altamont project (DE-AC21-92MC28135) and this contract (DE-AC21-94MC31224). The workshop was attended by over 150 people. On June 27 and 28, Blackhawk and Lynn, Inc., attended and presented talks at the Wyoming Geological Association special meeting on the Wind River Basin. Over 80 delegates attended this meeting and much interest was shown in the DOE funded work. Abstracts for these presentations are attached.

Copies of two abstracts submitted for the Wyoming Geological Association meeting are attached.

Fracture Indicators for the Lower Fort Union, Wind River Basin, WY

Bates, C. R., Phillips, D.R., and Harthill, N., Blackhawk Geosciences, Golden, Colorado.

The focus of an ongoing Department of Energy funded research project is to identify zones of naturally highly-fractured rock that produce significant volumes of gas in what would otherwise be tight sand formations. This project uses a regional geological approach to initially identify potential fractured regions and their fracture patterns. This is then followed with specific seismic techniques to quantify the fracturing.

Much of the natural fracturing in Rocky Mountain basins, such as the Wind River Basin, Wyoming, was imparted to the rocks during Laramide deformation. Towards the end of the Cretaceous, the Colorado Plateau collided with the North American Craton in a North-East direction causing compression in association with strike slip tectonics. This created areas of uplift separated by broad deep basins containing massive thrusting and folding. In the Wind River Basin, a large thrust cored anticline contains the tight, but naturally fractured sands of the Lower Fort Union Formation. These sands are the target of the DOE study. The process of the collision produced fracturing patterns in Rocky Mountain Basins that are both predictable and easily mapped. A knowledge of the general trend of fracturing is important when designing and executing seismic programs that aim to identify the most productive zones of open, gas-filled fractures.

This presentation will concentrate on the regional analysis of fracture patterns conducted prior to initiation of the seismic program. Four types of study have been undertaken to identify the most likely trend of the open fractures in the Fort Union Formation, namely, the theoretical framework, basement analysis, a surface study, and borehole investigations.

Azimuthal Anisotropy in P-Wave 3D (Multi-Azimuth) Data

Lynn, Heloise B., and K. Michele Simon, Lynn Incorporated, Houston, Texas; Bates, C. Richard, Blackhawk Geosciences, Golden, Colorado; R. Van Dok, Western Atlas, Denver, Colorado.

A naturally-fractured gas reservoir in the Wind River Basin, Wyoming, is the site of a U.S. Department of Energy sponsored project to optimize seismic techniques for characterizing the natural fractures (density, orientation). The target zone is the Lower Fort Union (depth 5,500 to 10,000 ft, two way time ~1.3 to ~2 sec), a low porosity, low permeability section in which fractures are necessary for commercial gas production. Flow rates incompatible with matrix porosity and permeability are observed. To use 3D P-wave seismic to learn about fractures, additional information is required to calibrate the seismic response to the in-situ condition: wireline data giving information on in-situ stress (borehole elongation, break-out) and fracture azimuth (BHTV, 9C VSP); log data for lithology, synthetic seismograms, and seismic data polarity determination; production data indicating preferred flow direction (permeability anisotropy); and pressure data (mud weights). The primary seismic technique is P-wave amplitude variation with offset and azimuth (AVOA) using 3D multi-azimuth (vertical phones only), with corroboration from P-S 3D-3C (multi-azimuth). Fracture density is evaluated by comparing two 3D prestack-time-migrated data sets: the E/W (± 45) source-receiver (S-R) azimuths, parallel to dominant E/W fault and fracture azimuth; and the N/S S-R azimuth volume. Fracture azimuth evaluation is performed on "azimuth-bin gathers," super gathers with primary sort by S-R azimuth (10 increments), and secondary sort by offset (0-10,000').