STRUCTURAL COMPARTMENTALIZATION AT CAVE GULCH FIELD, WIND RIVER BASIN, WYOMING

by

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ABSTRACT

Cave Gulch field is located in the Wind River basin, Natrona County, Wyoming. The field has an estimated recovery of 600 billion cubic feet (BCF) of gas from sandstones of the Paleocene Fort Union (thickness = 1,500 ft, 457 m), and Upper Cretaceous Lance (thickness = 2,500 ft, 762 m), Meeteetse (thickness = 1,500 ft, 457 m), and Mesaverde (thickness = 2,000 ft, 610 m) Formations. Cave Gulch field is a structurally complex reservoir due its origin as a faulted anticline that lies in the footwall of the Owl Creek thrust (18,000 ft, 5,486 m in vertical offset). The purpose of this study is to determine the depths of subseismic-scale faults in wells with borehole image logs, and to calculate the size of fault-bounded compartments based upon a 3D stochastic model.

Formation MicroImager (FMI) logs covering 62,000 ft (18,898 m) of vertical section are available in 11 wells in Cave Gulch field. These logs were interpreted for bed boundaries, fractures and microfaults. Bed boundaries in interbedded shales were used to create cumulative dip, dip azimuth vector, and statistical curvature analysis technique (SCAT) plots. Inflection points on these plots are interpreted as subseismic-scale faults. 320 subseismic-scale faults were identified from 11 FMI logs, with an average of 3.9 faults per 1,000 ft (304 m) of vertical log depth.

Published structure maps of the top of the Lance and Meeteetse Formations were digitized and used to build a 3D geologic model. This model includes 3 deterministic seismic-scale faults. Subseismic-scale faults were generated using a grid-based fracture generator within 3D Move software. The model was constructed based on microfault orientations interpreted from FMI logs, and the depths to subseismic-scale faults interpreted from dip-domain analysis of FMI data. After subseismic-scale faults were generated, a horizontal plane was cut through the model at the middle of the Lance Formation. For the purpose of this study, subseismic-scale faults were assumed to be no-flow boundaries. Area sizes for fault-bounded compartments ranged from <1 to 387 ac (<0.004 to 1.6 km^2). Well spacing templates of 5, 10, 20, 40, 80, and 160 ac (0.02, 0.04, 0.08, 0.16, 0.32, and 0.65 km^2) were superimposed on the model to determine the drainage efficiency of various infill-drilling programs. Comparison of compartment size with ideal well spacing has identified the most efficient development strategy. A well spacing of 30 ac (0.12 km^2) is recommended, with a closer spacing (5 ac, 0.02 km^2) needed in proximity to seismic-scale faults. This study does not address stratigraphic compartmentalization, which adds another layer of complexity because of the abundance of stacked fluvial sandstones in the reservoir.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The Wind River basin, Wyoming, is an asymmetric intermontane basin and is bounded by the Washakie, Owl Creek, and southern Big Horn Mountains on the north, the Wind River Mountains on the west, the Granite Mountains on the south, the Laramie Mountains on the southeast, and the Casper Arch on the east (Figure 1.1) (Keefer, 1965a and b). Oil and gas exploration in the Wind River basin dates back to the mid 1950's with the discovery of Madden field. Today, the Wind River basin has an estimated recoverable resource value approaching 1 TCF (trillion cubic feet) (Montgomery et al., 2001). Drilling in the Owl Creek thrust area was periodic until the early 1990's, when Barrett Resources discovered Cave Gulch field (Figure 1.2). Cave Gulch was a significant gas discovery, and has generated renewed interest in sub-thrust targets in the Wind River basin. The field is producing from several formations and has proven reserves of approximately 600 BCF (billion cubic feet). Cave Gulch field, located at the northern edge of the Wind River basin, is an intensely faulted anticline in the footwall of the Owl Creek thrust (Kuuskraa, 1999; Natali et al., 2000; Montgomery et al., 2001). This study explores the structural development of Cave Gulch field.

1.2 Purpose of Study

The purpose of this research is to study Cave Gulch field using borehole image logs, structural analysis, and 3-D modeling. Cave Gulch field has 11 borehole image logs used for interpretation of bedding planes, fractures and microfault orientations. Sherwood (2002) interpreted 5 of these logs, analyzed production data, and examined a 3-D seismic survey as part of his M.S. thesis.

The objectives of this study are:

- Interpret the remaining 6 borehole image logs.
- Identify subseismic-scale faults using dip-domain analysis of image-log data using cumulative dip plots, dip azimuth vector plots, and the Statistical Curvature Analysis Technique (SCAT).
- Compare previously interpreted 3-D seismic data with log-defined subseismic-scale faults.
- Correlate and compare subseismic-scale faults, microfaults, fracturing, and fracture density interpreted from borehole image logs with production anomalies, structural position, and well performance.

- Incorporate subseismic-scale faults from Sherwood (2002) and this study into a 3-D stochastic model, which shows how the subseismic-scale faults affect compartmentalization in Cave Gulch field.

1.3 Research Contributions

Eleven borehole image logs were interpreted for bed boundaries, fractures and microfaults. The Cave Gulch #4-19 well is a deep test and was interpreted, but not included in any further analysis. Once these data were collected, they were used as the constraining parameters for a 3D model. This project gives an increased understanding of fractures and faulting in the field, and reservoir compartmentalization, and it provides a structural model of Cave Gulch field.

- Dip domain analysis of 6 wells drilled in Cave Gulch field led to the identification of 166 subseismic-scale faults.
- Borehole image analysis of 6 wells resulted in the interpretation of 1,290 open fractures, 1,083 healed fractures and 2,717 microfaults.
- A total of 320 subseismic-scale faults have been interpreted in the reservoir interval from 10 borehole image logs (4 in Sherwood, (2002) and 6 in this study).
- Better production is associated with less faulted areas in Cave Gulch field.

- Poles to microfaults used to generate faults in the 3D stochastic model have an average dip direction/dip of 357°/58°.
- The fault model provides a 3D visualization of bed geometries and subseismic-scale fault intensity.
- Assuming that fault surfaces in the 3D model act as no-flow barriers, the drainage efficiency of wells spaced at 160 ac (0.65 km^2) is 31%; 80 ac (0.32 km^2) is 43%; 40 ac (0.16 km^2) is 78%; and 20 ac (0.08 km^2) is 131%. Some values exceed 100% because more than one well can occur in the same fault-bounded compartment.
- Subseismic-scale fault intensity is higher in the vicinity of seismic-scale faults. Drainage efficiency for fault-bounded compartments near a fault at 40 ac (0.16 km^2) is 30%; 20 ac (0.08 km^2) is 36%; 10 ac (0.04 km^2) is 63%; and 5 ac (0.02 km^2) is 103%.

CHAPTER 2

GEOLOGIC FRAMEWORK

2.1 Location of Study Area

The Wind River basin is an 8,500 mi^2 (22,000 km^2) asymmetric Rocky Mountain foreland basin located in central Wyoming. The basin is 180 mi (290 km) long from northwest to southeast and 75 mi (121 km) wide (Keefer, 1965a). Much of the Wind River basin is an underexplored region, with good prospectivity for oil and gas production (Sprauge, 1983). A foreland basin is defined as a sedimentary basin that is found encased between mountain fronts and the nearby craton (Allen et al., 1986). The Wind River basin is a unique example; it is a retro-arc foreland basin, which is adjacent to a magmatic arc and associated with subduction of oceanic crust beneath a continent (Jordan, 1981; Allen, 1986). The basin is bounded by the Washakie, Owl Creek, and southern Big Horn Mountains on the north, the Wind River Mountains on the west, the Granite Mountains on the south, the Laramie Mountains on the southeast, and the Casper Arch on the east (Figure 2.1) (Keefer, 1965a). Cave Gulch field is located on the northeastern edge of the basin in Natrona County, Wyoming, along the leading edge of the Owl Creek thrust, near the axis of the Wind River basin (Figure 2.2) (Montgomery et al., 2001).

2.2 Stratigraphy

Figure 2.3 is a stratigraphic section of the Wind River basin. Cave Gulch field is productive from multiple lenticular, stacked sands that range from 25-125 ft (8-38 m) thick within the Fort Union, Lance, Meeteetse, Mesaverde, Frontier, Muddy and Cloverly Formations (Natali et al., 2000; Montgomery et al., 2001). The focus of this study is on the Upper Cretaceous Lance and the Cenozoic Fort Union Formations. Fluvial, lenticular sands with porosities that range from 9-19% and permeabilities that range from 0.1-50 md account for the bulk of the production at Cave Gulch field (Montgomery et al., 2001).

2.2.1 Regional Stratigraphy

The regional stratigraphic sequence in central Wyoming contains numerous reservoir intervals that range from Mississippian to Eocene in age (Figure 2.3). During the Precambrian, a thick succession of sedimentary rocks was deposited and later metamorphosed. These metasediments are exposed in the cores of surrounding mountain ranges and represent the oldest rocks in central Wyoming. During the late Precambrian extensive erosion occurred and the region became a broad, nearly level plane (Keefer, 1965a).

The Wind River basin during the Paleozoic was a stable shelf. The flat plane of the Precambrian rocks acted as a platform for accumulation of Phanerozoic rocks. Cambrian rocks consist of the Flathead Sandstone, Gros Ventre Formation, and the Gallatin Formation. This sequence of rocks defines the first transgression of the Paleozoic seas, with subsequent minor regressions, until the Late Cambrian when the sea fully retreated, followed by a period of erosion. The Flathead Sandstone is a transgressive sand that represents the initial deposition of the Cambrian sequence, and is nonconformable with the underlying Precambrian basement (Burke, 1956). The Gros Ventre Formation consists of interbedded glauconitic shales, siltstones and limestones that conformably overlie the Flathead Sandstone. The Gallatin Group is a dense gray micritic and oolitic limestone that conformably overlies the Gros Ventre Formation. The Gros Ventre Formation and Gallatin Group in central Wyoming are intensely sheared and attenuated in fault zones (Keefer, 1965a; Paylor and Yin, 1993).

Ordovician deposits are separated from Cambrian rocks by an unconformity. The Middle and Upper Ordovician Big Horn Dolomite is a very resistant, structurally liff former. The base of the dolomite is a thin lenticular sandstone that was deposited during a transgression of the Paleozoic sea. The sea regressed at the close of the Ordovician, and a period of erosion ensued during the Silurian and Early Devonian. Deposition began again during the Early to Middle Devonian with the Darby Formation in the northwestern part of the basin. The Darby Formation consists of marine dolostones, limestones, and shales (Keefer, 1965a).

Normal-marine deposition took place in the Wind River basin during the Early Mississippian in the form of extensive marine carbonates of the Madison Limestone. The Madison Limestone is comprised of structurally competent cliff-forming limestones and dolomites. The Madison Limestone conformably overlies the Devonian Darby Formation, and disconformably overlies the Ordovician through the Cambrian rocks to the southeast in the basin. Near the end of Madison Limestone deposition, central Wyoming was exposed and karstification occurred (Keefer, 1965a; Paylor and Yin, 1993).

An Early Pennsylvanian shallow sea spread across the Wind River basin, and deposited the Amsden Formation, which unconformably overlies the Madison Limestone. The Amsden is comprised of interbedded red shales, siltstones, limestones, and sandstones that fill in the karsted surface of the Madison Limestone. Overlying the Amsden Formation is the Tensleep Sandstone. The Tensleep is a medium-grained cross-stratified, marine-eolian sandstone. The formation is well exposed in the Owl Creek Mountains (Keefer, 1965a; Paylor and Yin, 1993).

At the beginning of the Permian, a highland occupied the central Wind River basin, and seas lay on the east and west sides of the high. The seas began to encroach from the east and west, and by the Late Permian the basin was flooded. The Permian Phosphoria Formation was deposited unconformably on the Tensleep Formation. The

Phosphoria is composed of redbeds and evaporites to the east and carbonates to the west (Keefer, 1965a; Paylor and Yin, 1993).

The Early Triassic there was deposition of siltstones and carbonates of the Dinwoody Formation. The overlying Chugwater Formation consists of sandstones, siltstones, and limestones. Limestones in the Permian Phosphoria and Triassic Chugwater Formation are commonly folded near major fault zones (Keefer, 1965a; Paylor and Yin, 1993).

The Nugget Sandstone represents continental Early Jurassic sediments. The Nugget is an eolian cross-bedded sandstone. During the Middle Jurassic, shallow seas invaded and deposited carbonates, evaporates, and siltstones of the Gypsum Springs Formation. The Gypsums Spring Formation contains beds of gypsum and anhydrite more than 100 ft (33 m) thick. The Jurassic Sundance Formation consists of marine shales and sandstones. During the Upper Jurassic, the sea regressed and the vari-colored shales of the Morrison Formation were deposited in a fluvial and lacustrine environment (Keefer, 1965a).

Unconformably overlying the Jurassic Morrison Formation are the Lower Cretaceous, tan to brown, well-cemented, sideritic sandstones and shales of the Cloverly Formation. The Cloverly Formation is fluvial and lacustrine in origin. After the termination of Cloverly deposition, Wyoming was flooded and black marine shales of the Cretaceous Thermopolis and Mowry Formations were laid down. The Thermopolis and Mowry Formations are black, fissile shales that contain numerous beds of bentonite and a few fine to medium-grained sandstones. The Mowry Shale has an organic content of 1.5-2.5%, and is a potential source rock in the area. As the seas shifted to the east, extensive nonmarine sandstones and marine shales of the Frontier Formation were deposited. The Frontier consists of fine to medium-grained cross-bedded lenticular sandstones and fissile, silty to sandy carbonaceous shales. The dark-gray marine Cody Shale was deposited as the Cody sea transgressed across Wyoming. During the next regression, the basal sandstones of the Mesaverde Formation were deposited (Keefer, 1965b). The Mesaverde is a non-marine sequence of sandstone, shale, carbonaceous shale, and coal. The fluvial lenticular sandstones of the Mesaverde are white, fine to coarse-grained, with thin shale, siltstone, and carbonaceous shale beds. The upper sandstone in the Mesaverde Formation, named the Teapot Sandstone, is a massive light-gray ledge former. The complete transgression of the Cody sea gave rise to a surface of low relief, characterized by floodplains, swamps, deltas, and lagoonal deposits of the Meeteetse Formation. The Meeteetse is interbedded nonmarine sandstone, siltstone, shale, and coal. Sandstones are fine to coarse-grained lenticular fluvial channel sands. Multiple transgressions of the Late Cretaceous sea caused interfingering of marine shales and sandstones of the Lewis Shale with non-marine strata of the Meeteetse Formation (Keefer, 1965a, b; Johnson et al., 1996).

During the Late Cretaceous Laramide Orogeny, a major downwarping of the basin occurred. Uplift occurred in the mountain ranges that surrounded the basin. Fine-grained sediments were eroded from surrounding uplifts. Lenticular fine-grained fluvial sands and interbedded shales and coals of the Lance Formation were deposited during this time (Keefer, 1965a, b).

During the Paleocene, the Laramide Orogeny continued, and clastic sediments were shed from the surrounding mountain ranges into the basin. Fort Union conglomerates, sandstones, shales, and coals were deposited by major fluvial systems in the basin. During the Late Paleocene, the central part of the Wind River basin was flooded by Lake Waltman, which deposited the black organic-rich Waltman Shale of the Fort Union Formation. During the Early Eocene, uplift and basin subsidence came to a halt. Deposition of red shales and mudstones of the Wind River Formation continued until the middle Eocene. During the Late Cenozoic, regional uplift occurred, elevating the surrounding mountains and Wind River basin 3,000 to 4,000 ft (915-1,220 m). This uplift began a period of erosion that continues today, and only the lower Eocene and older rocks remain (Keefer, 1965a, b; Ray and Keefer, 1985).

2.2.2 Local Stratigraphy

Cave Gulch field is located along the axis of the Wind River basin and has over 25,000 ft (7,622 m) of sediments from Cambrian to Late Cenozoic in age. Most of these sediments (87%) are Cretaceous and Cenozoic in age (Figure 2.4) (Kuuskraa, 1999). The stable craton of the Cordilleran shelf was the setting for Paleozoic and Lower Mesozoic sediment deposition. At the beginning of the Cretaceous, the development of a foreland basin is reflected by sedimentation and east-west progression of the Sevier thrust belt. The Cloverly, Thermopolis, Muddy, and Mowry Formations are sourced from the emerging highlands to the west. The Upper Cretaceous Frontier, Cody, Mesaverde, Lewis Shale, and Meeteetse Formations represent the foreland-basin sediments. Subsequent to the filling of the basin, basement uplift began during the Late Cretaceous. This movement segmented the earlier foreland into a series of intermontane basins and uplifts. The Laramide Orogeny (Campanian - Middle Eocene) controlled the fluvial and fluvial-lacustrine deposition of the Lance and lower Fort Union Formations and the upper Fort Union Formation and Waltman Shale, respectively (Figure 2.5). Sand packages are thickest along the developing axis of the basin, which is to the northeast. Uplift increased along the Owl Creek Mountains and Casper Arch, and the Wind River Formation was deposited in depressions along the basin margins by alluvial fans (Montgomery et. al, 2001).

Fields within the Wind River basin produce from Mississippian through Cenozoic age strata. Cave Gulch field is productive from multiple stacked fluvial sands within the Upper Cretaceous Mesaverde, Meeteetse, Lance and Paleocene Fort Union Formations. Most of the production is associated with the Lance and Fort Union. Thickening of the Lance and Fort Union Formations is associated with depositional fairways controlled by the axis of the basin, just downdip of Cave Gulch field. The orientation of the basin is roughly parallel to the emerging Casper Arch.

In the Cave Gulch area, the Lance and Fort Union are interpreted as meandering to braided fluvial environments. This is in accordance with the interpretation of vertical beds exposed in the field (Keefer, 1965b; Keefer and Johnson, 1993) (Figure 2.6). The Lance and lower Fort Union contain numerous lenticular sands that are 25-125 ft (8-42 m) thick, with porosity greater than 10% and permeability in the range of 0.01- 50 md, in a vertical section of 4,500-4,800 ft (1,371-1,463 m) thickness (Montgomery et al., 2001).

The Lance Formation can be divided into the lower, middle, and upper intervals at Cave Gulch field. A stratigraphic cross section through several adjacent wells shows the lenticular nature of this productive sand (Figure 2.7). The lower and middle sections have a greater percentage of sandstone compared to the upper section, which contains significantly higher amounts of shale and mudstone. Well logs indicate that individual sandstone lenses range from 10-30 ft (3-9 m) in thickness, and are separated by thin shales (Montgomery et al., 2001).

Lance sandstones are very fine to fine-grained (0.062-0.25 mm), moderately well sorted, 80-90% quartz, 12-20% lithic fragments, and 6-9% clays by weight. Cements include slightly ferroan dolomite, authigenic clays and quartz overgrowths. Clay analysis by X-ray diffraction specifies 31-55% of total clay weight is kaolinites, 10-49% is illite/smectite, 13-28% is chlorite, and 8-14% is smectite (Montgomery et al., 2001).

2.3 Structural Geology

Cave Gulch field is located in the northeastern portion of the Wind River basin. The Wind River basin is an asymmetric depression in the Rocky Mountain foreland. The uplifts surrounding the Wind River basin are the Washakie, Owl Creek, and southern Big Horn Mountains on the north, the Wind River Mountains on the west, the Granite Mountains on the south, the Laramie Mountains on the southeast, and the Casper Arch on the east (Figure 2.1).

2.3.1 Regional Tectonics

The Atlantic Ocean opened during the Jurassic and the western North American craton progressed from a passive to an active subducting margin. During the Late Jurassic to Early Cretaceous, the Farallon plate was subducted beneath the North American plate. This created an Andean-type orogeny on the western Cordillera continental margin. Wyoming is part of the Rocky Mountain foreland basin, which is a retro-arc foreland basin. Retro-arc is defined as a basin situated behind a magmatic arc and linked with subduction of oceanic lithosphere (Jordan, 1981). The foreland basin was created because of the Sevier and Laramide tectonic activity during the Jurassic though the Early Eocene (Baars et al., 1988). The convergence of the Farallon and North American plates resulted in thin-skinned, low-angle thrust faults and horizontal shortening of the Sevier Orogeny (Late Jurassic though Late Cretaceous) in Utah, Idaho, Nevada and Wyoming. Continued plate subduction into the Eocene generated basement uplifts of the Laramide Orogeny (Late Cretaceous though Middle Eocene) (Figure 2.8) (Coney, 1978).

The Sevier thrust belt is a thin skinned structure style. The Laramide tectonic events, consisting of asymmetric basement-cored basins and uplifts bounded by thrust faults, were superimposed on the Sevier foreland basin. The Laramide deformational period is separated from the Sevier thrust belt by decollement-style folding and thrusting of the Paleozoic-Mesozoic sediment found in western Utah and Nevada, which evolved during the Sevier Orogeny (Coney, 1978).

The development of these two different modes of deformation may have been caused by changes in plate movement along the western continental margin. Convergence of the North American plate and the Farallon plate, during the Late Jurassic through Late Cretaceous, occurred at approximately N72°E at a rate of 3.2 in (8 cm) per year. Direction of convergence rotated to N40°E and subduction increased to 5.5 in (14 cm) per year at the beginning of Laramide deformation. The change form thin-skinned Sevier deformation to the basement uplifts of the Laramide deformation is a result of the increased rate of subduction (Figure 2.9) (Coney, 1978).

The Wind River basin, an asymmetric basin, actively formed during the Late Cretaceous to Early Eocene. The Rocky Mountain foreland was downwarped from the Arctic to the Gulf of Mexico, with later basinal divisions caused by localized uplifts due to the Laramide Orogeny (Hogle and Jones, 1991; Johnson et al., 1996). The Wind River basin is an asymmetric basin, with its axis parallel to the Owl Creek thrust, and located 3-5 mi (5-8 km) basinward. The deepest portion of the basin occurs to the northeast, near the intersection of the Owl Creek Mountains, Big Horn Mountains, and Casper Arch (Figure 2.10) (Ray and Keefer, 1985; Hogle and Jones, 1991).

Uplift in the eastern Wind River basin took place during the Early Jurassic. This uplift occurred along the northern and eastern edges of the basin, which caused depositional thinning of Jurassic sediments. During the Late Cretaceous, the basin had an evolving surface of low relief, which became tectonically active during the Laramide Orogeny. The onset of activity had a significant influence on the sediments deposited during this time. At the beginning of the Laramide uplift, upwarping occurred along the southern and northwestern edges of the basin, which are now occupied by the Granite Mountains and the Washakie Range, respectively. During the Paleocene, the Wind River Mountains began to rise to the west and folds formed along the present site of the Owl Creek Mountains in the north. Folding and uplift started during the Early Eocene and this caused reverse faulting to occur in the north. The Big Horn Mountains and the Casper Arch were uplifted along extensive reverse faults. Thrusting of Precambrian granite over Paleozoic strata occurred on the Casper Arch. Sediments along the margins to the north and east of the Wind River basin are commonly vertical to overturned, due to the intense faulting and folding of the Casper Arch (Ray and Keefer, 1985). During the middle Eocene, the movement of the Laramide Orogeny was coming to a stop. During the late

Tertiary, regional uplift and erosion occurred (Keefer, 1965a, b; Gries, 1983a).

The deformation style responsible for the structures seen in the Rocky Mountain foreland has been the center of debate for many years. How do the basement uplifts and faults relate to the overlying strata? Is the dominant structural style due to vertical or horizontal forces? One proposed interpretation of Laramide deformation is vertical forces, which resulted in high-angle faults and drape folds (Prucha, 1965; Stearns 1978). Berg (1962) and Brown (1983) stressed involvement of thrusted uplifts of basement-involved foreland structures by regional horizontal compression in the form of many low-angle reverse faults. Another model was proposed by Stone (1984) and Erslev (1991) that involves fault-propagation folding caused by horizontal stresses (Figure 2.11).

Gries (1983a) suggested that a rotated regional stress field was responsible for east-west and northwest-southeast structural trends. The change in orientation of horizontal compression from northwest-southeast to north-south allowed the development of east-west trending mountain ranges in the foreland (e.g., the Owl Creek Mountains). Gries (1983a) also proposed that the older north-northwest structures were overprinted by younger east-west oriented structures. The Wind River basin supports northeast-southwest compression because the faults and folds are dominantly oriented N 40° W.

Paylor and Yin (1993) suggested that the east-west striking portion of the Owl Creek thrust has dominantly left-lateral strike-slip offset, due to the non-orthogonal relationship of the east-striking Owl Creek thrust and the regional compressional direction. This model suggests a single phase of horizontal compression, causing northeast-southwest oriented faulting during the Laramide. This compression is responsible for the dip-slip (perpendicular to arch) and oblique-slip (oblique to arch) that occurs in faults and folds in the area (Figure 2.12) (Molzer and Erslev, 1995).

2.3.2 Regional Structure

The Wind River basin is bounded on all sides by uplifts and thrusts related to movement of the basement. Cave Gulch field, located at the northern edge of the Wind River basin, is an intensely faulted anticline in a subthrust environment beneath the Owl Creek thrust (Montgomery et. al, 2001). The Owl Creek thrust is a major zone of basement reverse faults that continuously override the northern and eastern margins of the basin. Activation of the Owl Creek thrust began after deposition of the Fort Union Formation (Paleocene). Conglomerates eroded from the thrust plate are readily found along the basin edge at the unconformity at the top of the Fort Union Formation. Thrusting continued through the lower Eocene, and concluded prior to deposition of the Wind River Formation (Keefer, 1965a, 1970; Gries, 1983a; Hogle and Jones, 1991). In the Owl Creek thrust, Precambrian granite is thrusted over the underlying Mesozoic and Paleozoic sediments. Cave Gulch field was formed during the Mid-Late Eocene when the area was affected by NNE-SSW regional compression. Gas was trapped beneath the

Precambrian in the upper plate of the Owl Creek thrust (Swan et al., 2002). Figure 2.13 shows a general cross section across the north edge of the basin. Along the Owl Creek thrust, offset is 1-12 mi (2-19 km) horizontally and 2,000 – 30,000 ft (610 – 9,146 m) vertically. Maximum offset of the fault occurs at the change in strike direction, which is located at the center of the thrust at the northeast corner of the Wind River basin. The displacement at Cave Gulch is 3-4 mi (5-6 km) horizontally and 18,000 ft (5,488 m) vertically (Montgomery et al., 2001).

The Waltman Arch, a pre-Laramide asymmetric fold, is a trans-basinal arch that trends northward across the basin. Cave Gulch is located on the northeast terminus of the Waltman structure, where the leading edge of the Owl Creek thrust overrides the arch (Figure 2.14). The Waltman Arch is restricted to the west by a major basement reverse fault with a vertical offset of 2,000 ft (610 m). Thinning of several beds over the arch implies sporadic activity throughout the Pennsylvanian to Tertiary. The Waltman structure trends southwest of Cave Gulch for 20 mi (32 km) or more, and is responsible for production in multiple fields in the basin (Montgomery et al., 2001).

Cave Gulch is a complex structure with faulting and folding due to its position at the junction of the Waltman Arch and the Owl Creek thrust. Paleozoic and Mesozoic structural elements appear to be tectonically overprinted by younger northwest-southeast Tertiary elements. Paylor and Yin (1993) proposed that a single period of northeast-southwest compression of the Laramide might also be accountable.

2.3.3 Local Structure

Production in Cave Gulch field is related to structure and is found in the subthrust anticline developed along the northeastern terminus of the Waltman Arch. Structural position determines well productivity, but is complicated by the presence of normal and reverse faults, which compartmentalize the field. Wells in the field were drilled through vertical and overturned beds into reservoir rocks in the footwall of the Owl Creek thrust (Figure 2.6).

3-D seismic data, along with subsurface well control, has led to the interpretation of the Cave Gulch structure as a subthrust footwall anticline. Two structures, the Waltman fault and the Waltman Arch, bounded by faults 1–2 mi (2-3 km) to the west, control the location of the anticline (Figure 2.15). Overall, the crest of the Cave Gulch anticline migrates to the south-southwest as one moves up section (Montgomery et al., 2001).

The Cave Gulch anticline developed above a secondary basement reverse fault that has vertical displacement of 2,500-3,000 ft (762-915 m). This secondary basement reverse fault splays into the Paleozoic-Lower Cretaceous section, stopping in the Cody Shale (Figure 2.16) (Montgomery et al., 2001). Numerous high-angle reverse faults cut up to the Fort Union Formation, with 700-750 ft (213-229 m) of displacement (Figure 2.17). It has been suggested by Montgomery et al. (2001) that these faults are from multiple generations, because they cut different stratigraphic levels in the Cretaceous.

The shallow structure is segmented by reverse faults into several culminations (Figure 2.17 and 2.18). The most significant of these faults is the east-west trending fault zone, with the main fault being the master footwall fault seen in Figure 2.18. This fault zone is confined to the crest of the Cave Gulch anticline and bisects the field. Production in Cave Gulch field declines away from the crest of the anticline within this fault zone, which has an offset of 700 ft (213 m). The Waltman #1 and #16 and Barrett Resources #1 wells in Cave Gulch field all show outstanding production (>10 BCF), whereas the Barrett Resources #4 well was a marginal producer. The Barrett Resources #9 well drained a small fault-block reservoir rapidly (Figure 2.18) (Montgomery et al., 2001).

2.4 History of Field

Barrett Resources Corporation, now Bill Barrett Corporation, discovered Cave Gulch field in the early 1990's. The discovery well, Cave Gulch Federal Unit #1, produced from the Cenozoic Fort Union and Cretaceous Lance Formations with initial rates of 9.7 MMCFD and 117 BCPD (Dea et al., 1998; Montgomery et al., 2001). The Cave Gulch discovery has prompted renewed interest in the subthrust belt in Wyoming (Siguaw et al., 2004). The concept of sub-thrust prospects was first presented in 1959, and Cave Gulch field was first identified in 1971 (McPeek et al., 1997, 1998). One reason that this prospect went undrilled for 35 years was the unreliable 2-D seismic data. Significant velocity variations occur within the sediments and Precambrian granite.

A strong lateral variation in the velocity beneath the Owl Creek thrust results in a pull-up effect and complicates the interpretation of the structure at Cave Gulch (Skeen and Ray, 1983). This is a problem at Cave Gulch field because dips on time-migrated data are reversed and the crest of the structure is shifted as much as 1 mi (1.6 km) to the northeast (Natali et al., 2000). To eradicate these effects, check-shot surveys have been obtained in many wells. These surveys were used in a velocity model, which was progressively updated. The 3-D seismic volume, acquired after Cave Gulch #1 was drilled, is an iterative interpretation of multiple post-stack depth migrations. Figure 2.19 accurately places the major faults, but also shows depth pull-up to the north, in the form of an anticlinal high (Skeen and Ray, 1983; Natali et al., 2000; Montgomery et al., 2001)

The acquisition of 3-D seismic data, just after initial discovery in 1994, was crucial to the imaging and growth of the field (Figure 2.20) (Siguaw et al., 2004). The survey covered a 21.5 mi^2 (55.7 km^2) area. Two 40 acre (0.16 km^2) offset wells, the Cave Gulch #4 and #9, were drilled before processing of the data. The Cave Gulch #4 and #9 wells were unsuccessful due to structural difficulties in the field. Depth migration of the seismic data made it clear why these two wells failed. Cave Gulch #4 was drilled into a downthrown fault block, which at the time was suspected to be 250 ft (76 m) high, in a separate structure to the #1 well. Cave Gulch #9, with initial production of 12

MMCFGPD, was unsuccessful because it was drilled into a small fault compartment that was drained quickly (Figure 2.21). Cave Gulch #7 was the first successful offset well. The 3-D seismic survey has reduced the risk of drilling subthrust wells in Cave Gulch (Natali et al., 2000; Montgomery et al., 2001).

Cave Gulch field is 440 acres (1.8 km^2) in size, and includes more than 50 active wells as of late 2000. The field produces from the Paleocene Fort Union, Cretaceous Lance, Meeteetse, Mesaverde, Frontier, Muddy, Lakota and the Jurassic Morrison and Sundance Formations. Deeper Madison and Tensleep prospects are likely, but continue to be undeveloped. Depths of drilling are 5,000 ft (1,524 m) to top of the Lance, 17,000 ft (5,183 m) to the Frontier, 19,000 ft (5,793 m) to the Lakota, and 21,000 ft (6,402 m) to the Mississippian Madison (Montgomery et al., 2001).

Development of the field has focused on the Lower Fort Union and Lance reservoirs. Barrett drilled these wells on 40 acre (0.16 km^2) spacing, and they commonly have a net pay of 250-1,000 ft (76-305 m). Each well has reserves ranging from 2-25 BCF, with an average of 7.5 BCF. Reserves for the entire Fort Union and Lance interval is 300-400 BCF. Fracture stimulation is required due to low permeability, which ranges from 0.1-50 md. Three to six sands are perforated for every 50-300 ft (15-91 m) of gross pay interval. Gas quality from the Lance and Fort Union reservoirs is 1,130 BTU/MCF and 1,140 BTU/MCF, respectively (Montgomery et al., 2001).

Deeper development in the field is in progress. Recent wells in the Frontier and Muddy are showing excellent potential with initial production rates of 10 MMCF and 38

MMCF per day, respectively. Overpressuring is common in the Cody Shale, which may be a factor in the preservation of porosity at these depths. Supported by the substantial success at the nearby Madden field (25 mi, or 40 km northwest), prospectivity of the Mississippian Madison Limestone reservoir is highly likely (Montgomery et al., 2001).

CHAPTER 3

ANALYSIS AND INTERPRETATION OF BOREHOLE IMAGE LOGS

3.1 Borehole Images

The borehole image logs from Cave Gulch field are Schlumberger Formation MicroImager (FMI) logs. The FMI is an openhole high-resolution microresistivity-imaging tool with a maximum temperature and pressure of 350 °F (177 °C) and 20,000 psi (1.39 kPa) (Figure 3.1). The tool has 24 closely spaced microresistivity electrodes with insulated backing mounted on each of eight orthogonal pads and flaps. The FMI log provides images of the borehole wall at a resolution of 0.2 inches (5.1 mm). Coverage is a function of borehole size, number of pads, and width of the electrode array. FMI coverage is approximately 80% in an 8 in (20.3 cm) borehole (Hurley, 2004; Schlumberger, 2002; Prosser, 1999; Safinya et al., 1991).

Electrodes on the FMI tool are 0.2 in (5.1 mm) in diameter and are positioned as two rows 0.15 in (3.8 mm) apart (Figure 3.2). The pads and flaps are pressed against the borehole wall during a logging run. As the tool is pulled up the hole, a current is emitted from each electrode and forced into the rock. The remote sensors record the data as the current interacts with the rock. Other measurements of the tool are azimuth, inclination, caliper readings, accelerometer and magnetometer readings and depth. These provide borehole orientation and deviation. The sample rate is 0.1 x 0.1 in (2.5 x 2.5 mm) horizontally and vertically. The current produces both a low-frequency signal and a high-resolution component. The low-frequency signal provides petrophysical and lithological information. The high-resolution component provides the microresistivity data, which is used for the imaging and dip interpretation and is presented as 8 strips in the log. The strips are presented as a two-dimensional unrolled cylinder along true North (Figure 3.3) (Hurley, 2004; Prensky, 1999; Prosser et al., 1999; Safinya et al., 1991; Bourke, 1989).

The high-resolution image allows a qualitative and quantitative investigation of features such as bedding, fracture, and microfault orientations. Because the FMI is an electrical tool, conductive fluids must be used. The maximum resistivity of the mud is 50 ohm-m (Hurley, 2004; Schlumberger, 2002). The identification of features is due to changes in conductivity. The more conductive features are assigned dark tones and the more resistive features are in lighter tones (Prensky, 1999). Drilling mud helps identify features by filling open fractures during drilling. The fractures appear as highly conductive (dark) streaks on the FMI log (Hurley, 1994). The FMI's sensor size and assembly is able to resolve small features that are ideal for fault and reservoir characterization.

3.2 Data Available

Eleven borehole image logs are available in this study (Table 3.1). Locations for these wells are shown in Figure 3.4. Interpreted logs serve as the input for fracture and fault analysis and a 3-D structural model. All images used are FMI logs. The Cave Gulch #2, 3, 6, 7, 10, 11, 13, 4-30, B-4 and B-5 wells focus on the lower Fort Union and Lance Formations. The Cave Gulch #4-19 deep was logged deeper in the structure, evaluating the Frontier, Muddy and Cloverly Formations, and was not used in the analysis in this study.

3.3 Borehole Image Log Processing

In this study, FMI logs are processed using Baker Atlas RECALL/REVIEW software. There are three basic steps in processing an image log: first, data restoration, second, image generation, and third, image enhancement.

Data restoration involves magnetic declination, accelerometer corrections and depth correction. Accelerometer corrections first confirm that the accelerometer data are on depth with the resistivity curves (Hurley, 2004). Next, the tool's 192 microresistivity curves are used to create a matrix, which is processed into the image. Image enhancement pertains to static and dynamic normalization of the images. Static normalized images are represented by the entire log dataset, which has had one setting applied to the entire well. Dynamic normalized images have moving contrast adjustments throughout the well, highlighting only a sample population of the data values (Figure 3.5). Dynamic normalization enhances the contrast between bedding and structural features. In this study, combinations of both static and dynamic images are used for interpretation.

3.4 Methods of Borehole Image Log Interpretation

FMI interpretation was done in Baker Atlas RECALL/REVIEW. FMI logs are presented as unrolled cylinders in two dimensions. Any planar feature that intersects the borehole at an angle other than horizontal appears as a sine wave (Trice, 1999). The amplitude of the sine wave is a function of the dip magnitude. Dip azimuth is represented by the intersection of the low point of the sine curve with the borehole (Figure 3.3).

Each FMI log was viewed digitally on a computer workstation, with both static and dynamic images adjacent to each other. All dips are manually picked, so the dip quality values are all 1.00, reflecting high confidence. In order to create plots needed for structural analysis, an ASCII file was extracted from each well with dip type, depth, dip direction, magnitude, gamma ray, and dip quality values (Table 3.2). Structural analysis of the data started with the identification of dip domains. Dip domains are determined using cumulative dip, dip azimuth vector, and Statistical curvature analysis techniques plots. Dip domains are intervals of relatively constant dip magnitude and direction. Cumulative dip plots are cross plots of the cumulative dip magnitude vs. an arbitrary bedding plane number. Such plots are made to recognize domains of constant dip magnitude. Dip azimuth vector plots are projections in the horizontal plane that are made by plotting oriented unit vectors end-to-end. Such plots are constructed to recognize domains of related dip azimuth (Hurley, 1994). SCAT plots are a combination of 6 cross plots used to determine the maximum information about structural orientation. Such plots are prepared to pick out dip domains and complement information gained from the other plots (Bengtson, 1981). Inflection points between dip domains are generally interpreted as faults. However, stratigraphic reasons such as crossbedding, unconformities, or soft-sediment deformation can cause dip domain boundaries. In the Cave Gulch field, stratigraphic reasons were generally ruled out because microfaults and fractures are associated with the depth of the faults.

Dips related to faulting are differentiated from stratigraphic changes by constructing cumulative dip plots, dip azimuth vector plots and SCAT plots for shale beds (Hurley 1994; Bengtson, 1981). The differences in the dips that showed evidence of faulting are compared with fractures and microfaults from the borehole image logs, which contain bed boundaries that include sand-on-sand, sand-on-shale and shale-on-shale. To eliminate the stratigraphic constraints on dip variation, any dip in a sandy interval was eliminated from the plots. This was accomplished by a gamma-ray cutoff, a number that is variable due to the ratio of sand to shale. Gamma-ray values are assigned to each tadpole (bed boundary). In this study, tadpoles in sandstones that fell below 80 API units were removed from structural analysis (Figure 3.6). This method assumes that shale layers were originally deposited horizontally. For that reason, shale-bed orientation was used for interpretation of structural features. Dip domain boundaries between shale layers in Cave Gulch are probably a result of faulting.

3.4.1 Fracture and Microfault Interpretation

Poles within each identified dip domain were plotted on equal-area lower-hemisphere Schmidt plots. A mean dip and dip azimuth are calculated for the whole population. Then, a 10° cone is drawn about that mean, and a new mean is computed. This eliminates the outliers. The poles to the planes of each fracture and microfault (minor offset visible in an image log) are plotted on stereonets and Kamb contoured in order to determine the total number of fracture sets and calculate the vector mean for strike azimuth and dip magnitude. Kamb contours represent standard deviations away from the expected density for a random sample (Kamb, 1959). Strike azimuth rose diagrams were plotted for fractures and microfaults in each well.

Fracture frequency histograms were created for each well using depth versus frequency of fractures and microfaults. The fracture and microfault data were obtained from FMI log interpretation for each well. A depth interval was then determined from the FMI intervals, and the number of fractures and microfaults for that interval was calculated. Fracture frequency histograms were plotted for all fractures (opened and healed) in each well, and microfault frequency histograms were plotted for each well.

Fault drag is a common feature seen in FMI logs. Fault drag is ductile deformation of a zone located in the hanging wall and footwall near the fault plane (Figure 3.7) (Ramsey and Huber, 1987). Fault drag was identified from a visual change in dip direction on the vector plots and was checked against the image logs. The data were then plotted on a stereonet. A great circle was fit to the points, and the pole to the great circle is the strike orientation of the fold axis and the dip-slip fault. Microfaults and fractures are usually associated with fault drag. Figure 3.8 illustrates microfaults seen in the zone of deformation adjacent to subseismic-scale faults.

3.4.2 Quality of Borehole Images

The borehole image logs interpreted in this study are graded in terms of quality, with the majority of the results being good to excellent. The Lance and the Fort Union section of the FMI logs are of excellent quality in the Cave Gulch # 2, 4-30, 7 and 13 logs. Wells 6 and B4 are of slightly lesser quality, with some intervals not being interpretable. The data cover the Fort Union, Lance and Meeteetse Formations, where the Fort Union and Lance Formations are the reservoir intervals.

3.4.3 Dips

A total of 62,000 ft (18,897 m) of FMI log was interpreted manually. Bed boundaries are indicated by green sine waves, and the dip magnitude ranged from 1°-82°. Bed boundaries are selected by contrasts in the amplitude of the static and dynamic images (Figure 3.9). Color palette adjustments and vertical depth-interval changes enhanced the resolution of the structural and bedding features.

In addition to picking bed boundaries, other planar features such as healed (Figure 3.10) and open fractures (Figure 3.11), scours (Figure 3.12), microfaults (Figure 3.13), and drilling-induced faults (Figure 3.14) are also defined. Healed and open fractures are interpreted with yellow and red sine waves, respectively. Open fractures are easily distinguished from healed fractures because open fractures are filled with drilling mud and are more conductive (darker tones). The more resistive healed fractures are filled with cements (lighter tones). Healed fractures are cemented, which produces a “halo effect” caused by changes in resistivity (Thompson, 2000). Scours are indicated by blue sine waves and represent erosional events that are incised into the underlying strata. Microfaults are shown by magenta-colored sine waves. By definition, minor offsets are seen where microfaults are interpreted. Drilling-induced fractures, usually parallel to the borehole axis, are shown by brown sine waves. Drilling-induced fractures are commonly 180 degrees apart and appear as darker tones, because they are filled with highly conductive drilling fluid (Rider, 1996).

3.4.3 Cumulative Dip Plots

Cumulative dip plots, described by Hurley (1994), are useful for the interpretation of significant structural and stratigraphic boundaries, e.g., faults, unconformities and sequence boundaries (Prosser et al., 1999). In this study, cumulative dip plots are used to help determine the depths of faults. Interpretation of bedding-plane orientations from FMI logs was the first step in structural interpretation, allowing the depth of each fault to be correctly positioned.

Cumulative dip plots are cross plots of cumulative dip magnitude vs. an arbitrary bedding plane number that is a function of depth. The ASCII file containing the bedding-plane orientation information can be organized in a spreadsheet and sorted by depth. Dip magnitudes are color coded in each of the four compass quadrants. All dips interpreted are assigned an arbitrary number, ranging from the shallowest to the deepest dip. Dip magnitudes of bedding planes are summed sequentially to give cumulative dips (X-axis) and are plotted against sample number (Y-axis). The result is a cross plot where inflections occur at boundaries between dip domains. This approach can define complex fault-controlled compartments. Sample numbers are used in place of depth due to the irregular distances between picks. Plotting by depth can result in false inflection points.

Cumulative dip plots appear as straight-line segments and inflection points. Inflection points represent changes in dip magnitude that can be interpreted as faults or unconformities. Color-coding the samples based on their compass quadrant allowed for easier interpretation of changes in dip azimuth. The plots identify zones of constant dip, and changes in dip represent structural or stratigraphic boundaries.

3.4.5 Dip Azimuth Vector Plots

Dip azimuth vector plots are projections in the horizontal plane made by plotting one oriented unit vector for each observed shale bedding plane. Each vector points in the dip direction of the observed bed. Vectors are plotted end-to-end from deepest to shallowest reading. Inflection points that occur between straight-line segments can be used to classify tops and bottoms of dip domains, which are generally interpreted as faults or unconformities (Hurley, 1994).

3.4.6 SCAT Plots

Statistical curvature analysis techniques (SCAT) are helpful in structural interpretation of dip data. In the study of Cave Gulch field, SCAT plots are used to help determine fold geometry, fault planes and orientation of faults. SCAT plots are 6 data displays that extract the maximum information from the dipmeter or FMI data. The six plots are: (1) dip versus azimuth (DVA), (2) tangent, (3) azimuth versus depth, (4) angle of dip versus depth, (5) the transverse (T) dip component versus depth, and (6) longitudinal (L) dip component versus depth. One issue with the use of the SCAT technique is if a well passes through a fault or an unconformity, the portions of the plot above and below the structural discontinuity should be treated as separate units (Bengtson, 1981). Data in Cave Gulch field were separated into the hanging wall and footwall of the Owl Creek thrust.

Tangent and DVA plots are used together to determine the T (direction of greatest structural change) and L (direction of least structural change) directions and the pattern that is related to the specific structural setting of the area (structural bulk curvature). Structural bulk curvature suggests that each individual stratigraphic bed of a structure shares a certain curvature property with other stratigraphic beds in the same structure. This information is then incorporated into the four types of depth plots. The purpose of the four different depth plots is to help eliminate uncertainty and obtain structural dips from irregular data. The structural information interpreted from the depth plots is a structurally representative dip along the wellbore, the kind of fold present and evidence of faults. These data can help determine separate dip domains in the well (Bengtson, 1981).

3.5 Results

Structural interpretation of dip domains involves the construction of cumulative dip plots, dip azimuth vector plots and SCAT plots. Table 3.3 shows all fractures, microfaults, and faults interpreted from the structural analysis. The goal is to identify fault-defined reservoir compartments (Hurley, 1994). Figures 3.15 and 3.16 are cross sections that illustrate the faults interpreted from dip-domain analysis. These two cross sections show reservoir zones, and faults interpreted from cumulative dip, vector and SCAT plots. Individual results from Cave Gulch # 2, 4-30, 6, 7 and B4 are discussed and can be found in Appendices A-E. To facilitate the interpretation of the fractures and microfault orientation of the wells, a combination of cumulative dip plots, dip-azimuth vector plots, SCAT plots, lower-hemisphere Schmidt plots, stereonets, strike-azimuth rose diagrams, and fracture frequency diagrams were constructed and are shown for the Cave Gulch #13 well. This well was chosen because of the completeness of the FMI log and interesting features seen throughout the interval. Similar data for all other wells appear in Appendices A-E.

3.5.1 Structural Analysis

Figure 3.17 is a cumulative dip plot from the Cave Gulch #13 well. Inflection points represent faults interpreted at given depths. Figure 3.18 is an example of a dip azimuth vector plot from the Cave Gulch #13 well. There are 6 dip domains on the plot, 3 of which correspond to the same depths as dip domains interpreted from the cumulative dip plot. The number of dip domains varies from the cumulative dip plot because some of the inflection points have a change in dip magnitude and not a change in dip azimuth. Conversely, a change in dip azimuth may occur, with no change in dip magnitude.

Tangent and DVA plots were the precursors to the remaining 4 cross plots for SCAT analysis. Table 3.4 summarizes the strike and dip for the 6 wells, divided into hanging wall and footwall orientations. Figure 3.19 shows an example of tangent and DVA plots from the hanging wall of the Cave Gulch #13 well. The tangent and DVA plots show a plunging anticline for the hanging wall and provide no structural information for the footwall, which contains the reservoir interval (Figure 3.20). The footwall structure was reinforced by plotting the strike and dip data from the tangent and DVA plots (Table 3.4) on a structure map of the footwall interval. Figure 3.21, a structure map on the top of the middle Lance Formation, confirms the consistency of the data obtained from the tangent and DVA plots for 6 wells and the structural contours. Figure 3.22 is an example of an interpreted segment of a Cave Gulch #13 SCAT plot.

3.5.2 Fractures and Microfaults

Figure 3.23 shows stereonets and rose diagrams of microfaults and fractures plotted for the entire Cave Gulch #13 well, as well as for hanging wall and footwall intervals. The fracture data were sorted into open and healed fractures above and below the Owl Creek thrust. The different components are plotted separately to aid in the identification of the field structure (Figures 3.24, 3.25, 3.26). Strike orientation is also discerned from the rose diagrams. Figures 3.27-3.30 are structure contour maps with strike azimuth rose diagrams superimposed. This was done to observe the relation of fractures and microfaults to the seismic-scale faults.

Figure 3.31 shows Schmidt plots for dip domains for a portion of the Cave Gulch #13 well. Table 3.5 gives the mean dip azimuth and dip for a cone of 10° drawn about the mean pole, which is automatically calculated from the plot. These dip domains are associated with microfaults and/or fractures in the borehole image logs. Figures 3.32-3.35 are examples of dip domains with microfaults and fractures associated with the interpreted subseismic-scale fault. These data are used as input for the 3-D structural model. Tables for all wells, including wells from Sherwood (2002), can be found in Appendices A-E and on the CD-ROM.

Figure 3.36 shows a frequency histogram for the Cave Gulch #13 well, with the number of fractures per 100 ft (304 m) vs. depth. The plot shows the number of fractures per reservoir zone and includes faults interpreted from dip-domain analysis. Figure 3.37 is a diagram with fracture-frequency histograms superimposed on the Lance structure contour map. Microfault data are also shown. Figure 3.38 is a frequency histogram of the microfaults for the Cave Gulch #13 well, with the number of microfaults per 100 ft (304m) vs. depth. The plot shows the number of microfaults in each reservoir zone and is compared to the subseismic-scale faults interpreted from dip-domain analysis. Figure 3.39 shows the frequency histograms overlain on the Lance structure contour map. These figures were done to observe the number of fractures and microfaults in relation to nearby faults and the structural position of the well.

3.5.3 Fault Drag

Fault drag is seen in two of the wells (Cave Gulch #2 and #6) in this study. Figure 3.40 is an example of fault drag in the Cave Gulch #2 well. Results for the Cave Gulch #6 well are in Appendix B. This process uses analysis of the cumulative dip and vector plots. Curvature in the plots can be associated with fault drag. I plotted the dips 50 ft (15.2 m) above and below the interpreted fault on a stereonet and fit a great circle to the data points. The pole to the great circle provides the strike of the dip-slip fault. The outcome was compared with the structure map at a similar depth, which in this case was the Meeteetse (Figure 3.40).

3.6 Discussion

This section discusses pitfalls and assumptions used in the interpretation of the data in this chapter. Pitfalls occur due to local poor quality of data and incompleteness of the data, whereas assumptions are made about the deposition and deformation of the beds.

3.6.1 Pitfalls and Assumptions

Some pitfalls occur in the interpretation and analysis of the data. Some FMI logs contain sections of poor quality data, which can be due to pads not touching the borehole wall, sensors not working, thick mud cake, and/or acceleration of the ascending tool. The data provided was also sporadic. FMI intervals do not cover the entire reservoir interval and/or are segmented, which was probably done during the time of acquisition to save money.

The assumptions made in the techniques used to manipulate and analyze the data are that the shales show true structural dip and any deformation after deposition is related to structure. Post-depositional effects other than those that are related to structure can occur. Shales in fluvial systems can be affected by a variety of different stratigraphic variations, such as rooting and differential compaction. This was considered and ruled out by examining the image logs. The argument that dip-domains picked are separated by faults is strongly enhanced by seeing these breaks on multiple plots and by the fractures and microfaults nearby on the image logs (Knight, personal communication, 2004). A change in dip domain can also be caused by a sequence boundary. This is ruled out by the microfaults and fractures, which are present near the dip domain picks (Figures 3.32-3.35). Fracturing and microfaulting are closely associated with seismic-scale faults. Other reasons that suggest that these are faults, not related to stratigraphic variance, is the drag seen on a few of the faults picked (Figure 3.40). For the purpose of the model built in this study, dip-domain boundaries interpreted from shale-bed orientations will be treated as faults.

3.6.2 Discussion of Results

Borehole image logs form the basis for all structural analysis in the study. No cores are available from the field. Faulting and fracturing interpreted from FMI logs are related to proximity to major faults. Table 3.3 shows the number of open and healed fractures and microfaults in each well. Figure 3.4 is a map showing location of the wells and their proximity to the major seismic-scale faults in the field. These relate to the pitfall of the limited amount of data, in that not all image logs were acquired over the same intervals. Dip-domain analysis was integrated into cross sections to enhance the interpretation of the structure at Cave Gulch field.

3.6.3 Dip Domains

Cross sections (Figures 3.15 and 3.16) show the 166 subseismic-scale faults determined from dip-domain analysis in this study. All interpreted faults were found to be below seismic resolution, except for the Owl Creek thrust. Approximately 19 of the faults interpreted from dip-domain analysis are evidenced on all three of the dip domain plots: cumulative dip, dip azimuth vector and SCAT plots. 51 of the faults are interpreted on two of the three plots, and 96 faults were found on only one of the three plots. Approximately 85% of the faults interpreted from structural-analysis techniques correspond to interpreted fractures and or microfaults in the borehole image logs. This was a comparative visual analysis of the interpreted subseismic-scale fault depths with the corresponding depth in the borehole image logs to see if fractures and microfaults were associated with that depth. Figures 3.32 -3.35 are examples of fault-separated dip domains. Notice the numerous microfaults and fractures that are associated with the faults. Faults can constitute an important structural control on reservoir performance. The ability to see faults from multiple interpretation methods and the fact that they are associated with fractures and microfaults in image logs gives a high level of certainty that they are real and not a stratigraphic change.

Dip-domain changes in the footwall of the Owl Creek thrust were difficult to see in the SCAT analysis technique. This was due to the low dip of the beds. This hindered the selection of the T and L directions needed for the 4 cross plots. To solve this problem, the data obtained from the tangent and DVA plots were used to check with inconsistencies of the SCAT plots. This was accomplished by plotting orientation (Table 3.4) data on a structure map of the reservoir interval (Figure 3.20). Strike and dip symbols plotted from shale bedding-plane orientation obtained from tangent and DVA plots are consistent with the structure contours for the field. The strike and dip symbols represent orientation data obtained from borehole image data. The data in the hanging wall are consistent with a plunging anticlinal structure, whereas the footwall seems to have low dip. Berg (1962) called this model the fold-thrust uplift (Figure 3.41). Similar cross sections presented by Montgomery et al. (2001) and Natali et al. (2000) show this same sort of model (Figure 3.41).

3.6.4 Fractures and Microfaults

Fracture and microfault data were obtained from FMI interpretation. Stereonets, strike-azimuth rose diagrams, Schmidt plots, and frequency histograms were constructed for fractures and microfaults. The fracture and microfault orientation data from the FMI logs, as plotted on stereonets and strike-azimuth rose diagrams are consistent with the data interpreted from Sherwood (2002), and nearby seismic-scale faults. Fractures and microfaults plotted suggest a predominantly NW-SE to E-W orientation (Figures 3.27-3.30). These zones of weakness are associated with the major fracture and/or microfault sets and trend the same way as nearby major faults. Stearns and Friedman (1972) stated that fractures associated with faults are generally a product of the same stress state that caused the fault. Orientations of the fault can be deduced from fractures and microfaults, and the converse is also true.

Fracture and microfault populations give a descriptive picture about fracture and microfault frequency in the reservoir zones. In Cave Gulch field, fracture and microfault frequency varies for each stratigraphic interval. The X axes were normalized to the Cave Gulch #B5 well. It is difficult to discern any relation of fracturing and faulting to structure and proximity to seismic-scale faults. The middle to lower Lance Formation tends to have abundant fractures and microfaults compared to other parts of the well. The amount of fractures and microfaults seen in the Cave Gulch wells do not have an explicit clear relationship to structure, proximity to seismic-scale faults, or to lithostratigraphy. Fracture and microfault frequency histograms show that fracturing and microfaulting in the Lance Formation are abundant. The fracture and microfault frequency histograms show that there is an increase near the targeted production zone, which is the middle and lower Lance Formation. This could enhance the recovery of hydrocarbons from this zone, if open fractures contribute to flow. These intervals also have the highest porosity and net sand.

3.6.5 Subseismic-Scale Faults

Multiple subseismic-scale faults have been interpreted in each well, from structural-analysis techniques. There are more subseismic-scale faults in the wells closer to the seismic-scale faults (Table 3.3). This is due to the fact that microfaulting and fracturing occurs before the offset of the subseismic-scale fault, and the minor faults and fractures dissipate with distance from the fault (Figure 3.8) (Nelson, 2004). These zones of weakness are associated with the major fracture and microfault sets and trend the same way as nearby major faults. As previously noted, (p. 111) Stearns and Friedman (1972) stated that fractures associated with faults are generally a product of the same stress state that caused the fault. Orientations of the fault can be deduced from fractures, and the converse is also true.

CHAPTER 4

INTEGRATED ANALYSIS

4.1 Introduction

Barrett Resources (now Bill Barrett Corporation) acquired a 3-D seismic survey over Cave Gulch field immediately after discovery. This chapter compares published seismic-scale interpreted faults with faults interpreted from dip-domain analysis. Cross sections are constructed to demonstrate the effect of the anticlinal structure, faulting, and thickness of sand on production in Cave Gulch field.

4.2 Data Available

3-D seismic data from Natali et al. (2000) were used for the integrated analysis. Issues with seismic processing are discussed in Chapter 2. The 21.5 mi^2 (55.7 km^2) 3-D survey (Figure 4.1) was acquired in late 1994, immediately following the drilling of the discovery well in Cave Gulch field. Due to long offset distances needed to image dipping beds, only 6 mi^2 (15.5 km^2) was imaged in the subsurface. Bin size is 110 ft x 110 ft

(33.5 m x 33.5 m) with a source of 24 pounds of dynamite spaced at 65 ft (19.8 m) intervals (Natali et al., 2000).

Production data were acquired from the Wyoming Oil and Gas Commission website (http://wogcc.state.wy.us/). Acquired data included perforation intervals, cumulative production, treatment types, and initial and monthly production rates of oil, gas, and water.

4.3 3-D Seismic Data

Figure 4.2 is a map showing the location of the two section line, F-F’ and G-G’. Two lines (Figures 4.3, and 4.4) illustrate the 3-D seismic results. Figure 4.3 is a southeast-northwest trending seismic line, and Figure 4.4 is a west-east trending seismic line. A cross section that bisects the field is used to depict the complex Cave Gulch structure. The depth-migrated seismic lines show reservoir intervals, major faults and well locations. Figure 4.5 shows the 3-D seismic interpreted faults and horizons overlain by the faults interpreted from dip-domain analysis of each well. Figure 4.3 shows wells on both sides of the master footwall fault (MFF) that bisects the field.

4.4 Production Data

Structure and perforation interval play a significant role in the performance of Cave Gulch wells. Wells located on top of the Cave Gulch structure have lower decline rates and higher cumulative production than wells located on the flanks of the anticline. Montgomery et al. (2001) stated that flow rates and estimated ultimate recoveries (EUR) are higher and overall decline rates are lower for wells in the central part of the field and on the crest of the structure. Cross sections in the field show lower production on the flanks and higher production on the crest of the structure (Figures 4.6 and 4.7). Wells #13 and 7 are on the updip side of the MFF. These two wells have produced over 17.4 BCF and 16.6 BCF, respectively, over the last 9 years. In contrast, Cave Gulch B4, which is off the crest to the south, has only produced 0.5 BCF. Wells #2 and 6 are on the downdip side of the MFF, which bisects the field. They are still high on the anticline, and they have produced 10.7 BCF and 5.2 BCF, respectively, over 9 years of production history.

Pay distribution for the major reservoir intervals, the Fort Union and Lance Formations, were studied for thickness of sand and its influence on production. Figures 4.8 and 4.9 show the sand distribution of the Fort Union and Lance Formations, respectively. Both figures are isopach maps on top of the Lance Formation structure contour map. Pay cutoffs are defined as sandstone with more than 10% log porosity and greater than 40 ohm-m of resistivity. Significant gas shows from mud logs correspond to these cutoffs (Montgomery et al., 2001).

Fort Union Formation thickness drops off significantly as it crosses the MFF fault, ranging from > 300 ft (91 m) on the updip side to < 200 ft (61 m) on the downdip side. The greater thickness corresponds to structural highs. The Fort Union Formation also becomes non-productive over this fault. The Owl Creek thrust (Montgomery et al., 2001) likely breaches this section of the Fort Union Formation.

The thickness of the Lance Formation is similar on both sides of the MFF with > 300 ft (91 m) at the highest point on the structure. To the north of the MFF, the Lance Formation has excellent production, unlike the Fort Union Formation. This is possibly due to fracture enhancement and better reservoir quality (Montgomery et al., 2001). The Fort Union Formation's porosity could have been affected by diagenetic factors.

Wells higher on structure have the highest initial flow rates. Faulting throughout the field plays a significant role. However, some fault compartments have limited production, an example of which is Cave Gulch #9, drilled prior to the 3-D survey. The well was drilled into a small compartment, which has cumulative production from the Fort Union and Lance Formations of 2.15 BCF over 9 years of production. Production rate decline curves for oil, gas and water for the Cave Gulch #2, #6, #7, #13, #4-30 and #B4 wells are shown in Figures 4.10, 4.11 and 4.12, respectively.

4.5 Discussion

Seismic data are an integral part of understanding Cave Gulch field. Combining seismic and borehole image interpretation helps develop a more complete structural picture of fracturing and faulting, as well as revealing effects on production.

Production in Cave Gulch field is related to structural position in the field, faulting, fractures, perforations and the thickness of sand in the reservoir units. Production is related to structure, in that wells higher on the structure are better producers. According to the isopach map from Montgomery et al. (2001), high wells contain the thickest amount of pay sand in the two main reservoir intervals. Subseismic-scale faults may be barriers to flow. The number of faults interpreted from dip domain analysis was significantly more than the number of faults seen on 3-D seismic. Wells #7 and 13, which are on the hanging wall side of the MFF, have the least amount of seismic and subseismic-scale faults, but the highest production. Well #B4, off structure to the south, has a large number of seismic and subseismic-scale faults. From the seismic data, it appears that wells producing from the downthrown side of the MFF are not affected by significant fault compartmentalization (Figure 4.3). Wells #2 and 6, on the footwall of the MFF, are located high on the structure and have many subseismic-scale faults. Figure 4.3 shows the seismic line running SE-NW, and Cave Gulch #2 is located in a relatively unfaulted portion of the field. The possibility exists that Cave Gulch #6, 30 ft (9.1 m) down dip to Cave Gulch #2, drains the same reservoir, stratigraphic trap, or small compartment from sealing subseismic-scale faults. The high frequency of subseismic-scale faults is probably due to their close proximity to the MFF (Figures 4.13 and 4.14). The overall trend shows that faulting decreased the production in wells on the updip side of the MFF. Conversely, the trend on the downdip side of the MFF in production is not suppressed by the amount of subseismic-scale faults. Sherwood (2002) demonstrated that wells #3 and 11 have the least amount of subseismic-scale faults and have the highest production, whereas wells #10 and #B5 are off structure, and have the greatest number of subseismic-scale faults and minimal production. Faults in Cave Gulch field act apparently as permeability barriers, which restrict the migration of fluids. This can lead to compartmentalization with different fluid pressures (Knipe, 1993).

Open fractures on the other hand, as mentioned in Chapter 3, enhance permeability and can aid in production. Perforations tend to occur in highly fractured areas, but production is dominated by thickness of pay and placement of the well on the structure. Fracture stimulation treatments have an irregular history throughout the field, which could also have an effect on production.

CHAPTER 5

3-D FAULT MODEL

5.1 Introduction

In order to visualize compartmentalization in the field, and help lead to the best infill-well spacing strategy, I built a 3D model of subseismic-scale faults. The 3D stochastic model was constrained by data obtained through the use of borehole image logs. The software used to build the 3D model is 3D Move, a Midland Valley product. Assumptions were made because not all of the needed constraints could be identified from the borehole image analysis. Thus, the model is non-unique, and more than one solution is possible.

5.2 Data Available

Data available include the structural interpretation of subseismic-scale faults from the 6 borehole image logs in this study (Chapter 3) (Table 5.1). The published structure maps from Montgomery et al. (2001) and Natali et al. (2000) were used as bounding surfaces, along with 3 seismic-scale faults.

5.3 Methods: Building the Model

The first step in model construction was to digitize two published structure maps, one on top of the Lance Formation and one on top of the Meeteetse Formation. These two maps were acquired from publications by Natali et al. (2000) and Montgomery et al. (2001) (Figures 5.1 and 5.2). In Petra, the two maps were digitized and gridded. The gridding process was done to generate points over the entire area to eliminate gaps in the data. The surface on the Lance Structure map to the northeast of the Owl Creek thrust is a fictitious surface needed for 3D Move software. Two surfaces must overlap in order to generate subseismic-scale faults over the entire map area. 3D Move only generates faults in the areas where there are bounding beds present. The gridded maps were imported into 3D Move and used as the upper and lower bounding surfaces for the fault model.

Deviation surveys, supplied by Kim Vickery at the Bill Barrett Incorporated, were imported into 2D Move to create a dfx file, which is compatible with 3D Move. The well file was imported into the project that contained the 2 bounding surfaces. Three seismic-scale faults, which were visible on both bounding surfaces, were created in the model by drawing lines and then creating surfaces from those lines. Figure 5.3 is the base for the fault model.

The subseismic-scale fault model was constructed in 3D Move as discrete faults using the grid-based fracture module. Two hypothetical stochastic models were generated, one for the entire field, named "Background," and one for an area containing well in close proximity (<0.5 mi or 0.8 km) to a seismic-scale fault, named "Fault-Proximal." The vertical depth range is an average of 3,500 ft (1,067 m). This method of modeling incorporates statistical data interpreted from the borehole image logs.

5.3.1 Discrete Faults for the Background Model

This study used a stochastic fracture-generation module in 3D Move to create subseismic-scale faults. For the model to run, a grid had to be selected. The grid was fit to the exact extent of the bounding beds because when 3D Move generates faults, it uses the grid as a boundary. The bounding beds also must overlie each other. Any place where the surfaces do not overlie each other, no faults can be generated. The grid for the background model was 17,717-18,373 ft (5400 x 5600 m), the cell-size was 886-919 ft (270 x 280 m), and the cell count was 20 x 20. The grid dimensions are equal to the dimensions of the gridded structure maps, the cell size dimensions were chosen by trial and error, and 3D Move calculated a cell count from the previous two parameters. The toolbox shown in Figure 5.4 shows the parameters used for the grid-base fracture model. In the toolbox, there is a pull-down menu for intensity, length, orientation, and aspect ratio. The parameters used for each of these were:

1) Intensity value (N). N is the number of faults seeded per grid cell. The intensity number was used to match the average number of microfaults per 1000 ft (304

m). The N value used in this case is 2.25 (Table 5.2). The value of 2.25 was an average of the #13, 7, and 4-30 wells; these three wells were not in close proximity to a seismic-scale fault. The wells close to a seismic-scale fault skewed the average.

2) Length of the faults was determined by using the power-law equation: $y=ax^b$, where x (independent) and y (dependent) are scalar quantities, a is the constant of proportionality, and b is the exponent of the power law. Figure 5.5 shows a generalized graph of a power-law distribution. Data are plotted on a log-log graph. The average number of faults per 1,000 ft (304 m) is 2.25 faults, and the average thickness between the Lance and Meeteetse Formations is 3,651 ft (1,113 m) (Table 5.2). Minimum and maximum fault lengths used were 3,280 ft (1000m) and 17,717 ft (5400 m), respectively. These dimensions were chosen by comparing the distances between wells for the minimum length and using the entire length (east-west) of the field for the maximum length. Minimum fault length was chosen to simulate subseismic-scale faults that do not interact between wells or possibly compartments, whereas the maximum fault length was used because there is already evidence in the field, from seismic-scale faults, that there are faults of that length and greater. Exponent b equals -1.11. This exponent was taken from the Cladouhos and Marrett (1996) study on power-law distributions of fault lengths. They took a data set from Blackstone (1988), which is in a Laramide compressional setting. The exponent was determined by cross plotting fault length vs. frequency of occurrence on log-log scale. The slope of the best-fit line is equal to the exponent.

3) Image log microfault data were used to determine the orientation of the subseismic-scale faults. The tool box asks for a dip direction and a plunge. A mean dip direction of 357º, and a plunge of 58º were determined for the fault set. These numbers were determined by using stereonets and frequency histograms (Figure 5.6 and 5.7). A Fisher parameter was used to vary the orientation of the faults. A Fisher distribution is a spherical Gaussian distribution controlled by a mean value and a Fisher constant. The Fisher constant is a measure of the concentration of a distribution about the true mean direction (Butler, 1992). The Fisher constant used is 5.0, a number that was determined by comparing modeled faults to the microfault stereonet by trial and error. A true random sample has a uniform distribution over the sphere and a Fisher constant equal to 0 (Butler, 1992).

4) The aspect ratio is the ratio between the longest and shortest axis for modeled faults. The default in 3D Move is 0.5. This value was used to keep the faults confined between the two horizons in both models. If the aspect ratio was higher than 0.5, the faults projected above and below the bounding surfaces. If the number was lower than 0.5, the faults were contained within the bounding surfaces.

5) Area calculations for fault-bounded compartments were done by cutting 2-D-horizontal planes through the field near the top of the Lance (depth: 820 ft, 250 m above sea level), in the middle of the Lance (depth 1640 ft, 500 m below sea level) and above the top of the Meeteetse (depth: 2624 ft, 800 m below sea level). The planes were

imported into ARCMAP. Polygons were created using the Polyline to Polygon function in ARC toolbox. Polygon areas were calculated using the area equation in ARCMAP (ARCMAP online help, 2005).

5.3.2 Discrete Faults for the Fault-Proximal Model

The discrete-fault model for Fault-Proximal wells has a grid size of 6,562 x 3,281 ft (2,000 x 1,000 m), cell size of 1,047 x 1,017 ft (319 x 310 m) and a cell count of 5 x 5. This grid encompasses an area surrounding the Cave Gulch #2 well, which was chosen due to its close proximity (0.125 mi or 0.20 km) to the Master Footwall Fault (MFF). The toolbox shown in Figure 5.4 shows the parameters used for the grid-based fracture model. The parameters used in this model changed slightly compared to the Background model. The numbers used for each of the parameters were:

1) Intensity value (N). The value of N was chosen to match the average number of microfaults per 1000 ft (304 m) in a well in close proximity to a seismic-scale fault. The N value used for the Fault-Proximal model was 5.75, the average number subseismic-scale faults seen in well #2 (Table 5.3).

2) The length of the faults was determined by the same method used in the Background model, except the maximum number was scaled to fit the east-west length of the grid determined for the Fault-Proximal model. The average number of faults per

1,000 ft (304 m) was 5.75 faults (Table 5.3). Minimum and maximum fault length values are 3,280-6,562 ft (1,000-2,000 m), respectively. The value for exponent b stayed the same, -1.11 (Cladouhos and Marrett, 1996).

3) Orientation data for the Fault-Proximal model was not changed. A mean dip direction of 357º, a plunge of 58º, and a Fisher constant of 5.0 were used.

4) Aspect ratio was kept the same. This is for the same reason mentioned in the previous section.

Area calculations were done by using the same horizontal cross sections through the field near the top of the Lance (depth: 820 ft, 250 m above sea level), the middle of the Lance (depth: 1,640 ft, 500 m below sea level) and the top of the Meeteetse (depth: 2,624 ft, 800 m below sea level). The cross sections were imported into ARCMAP. Polygons were created using the Polyline to Polygon function in ARC toolbox and the polygon areas were calculated using the area equation in ARCMAP (ARCMAP online help, 2005).

5.4 Results

Each 3D stochastic model involves the construction of a grid-based fault model. Figure 5.8 shows the Background model generated for the Cave Gulch field using the parameters defined for wells far away from seismic-scale faults. Figure 5.9 shows the faults generated from the Fault-Proximal model from the parameters defined for wells in close proximity to a seismic-scale fault.

Fault-wellbore intersections compared closely to the number of faults calculated from the structural analysis in Chapter 3. Figure 5.10 show the intersections of faults with wells. The number of faults in the model was matched to the number of faults interpreted from dip-domain analysis. Tables 5.2 and 5.3 show the number of structurally interpreted faults compared to the number of faults in each model for each well.

Multiple cross sections were cut vertically through the field. These show the orientation of the subseismic-scale faults, predominantly striking east-west and dipping to the northwest. Figure 5.11 is a map that shows the location of the cross section lines. Figures 5.12-5.14 are the Background model cross sections, and Figures 5.15-5.17 are the Fault-Proximal cross sections. Notice the increased number of subseismic-scale faults in the Fault-Proximal model compared to the Background model. Examination of these cross sections revealed a problem in that subseismic-scale faults are unevenly distributed vertically. There are edge effects near the two bounding surfaces. This may cause a problem with area calculations near the top and bottom of the model.

5.4.1 Results for the Background Model

The fault-orientation data from the Background model were plotted on stereonets and rose diagrams to compare with the microfault data from FMI logs (Figure 5.18).

Horizontal planes were cut through the model to show the areas of the compartments generated by the stochastic model. Figures 5.19-5.21 are the sections cut compared to the same sections of closed compartments determined in ARCMAP. The goal is to determine the areas for the compartments (calculated in ARCMAP) generated in the field, and decide upon an infill-drilling program. For the purpose of the area analysis, the middle Lance section line was chosen because it is the only one with no edge effects, i.e., no faults were seeded due to being above or below bounding surfaces, and all compartments are assumed to be bounded by no-flow faults. Figure 5.22 is a template that surrounds the entire field, divided into a 160 ac (0.65 km^2) grid, and Figure 5.23 is the template superimposed on the compartments from the middle Lance horizontal plane. Figure 5.24 is the 40 ac (0.16 km^2) grid superimposed on the middle Lance. Figure 5.25 is a summary diagram for the drainage efficiency of each compartment area from the 10, 20, 40, 80, and 160 ac (0.04, 0.08, 0.16, 0.32, and 0.65 km^2) grids. Drainage efficiency is the percentage of compartments drained by wells on a grid. Area calculations can be found in Appendix F on the CD-ROM.

5.4.2 Results for the Fault-Proximal Model

The fault-orientation data from the Fault-Proximal model were plotted on stereonets and rose diagrams to compare with the microfault data from FMI logs (Figure 5.26). The same horizontal planes described in the previous section were used to cut the

Fault-Proximal model. Figures 5.27-5.29 show the sections cut, and the closed compartments determined in ARCMAP. Compartment boundaries are considered to be no-flow barriers, and the middle Lance section was chosen to avoid edge effects. Figures 5.30 and 5.31 show a 40 ac (0.16 km^2), and 10 ac (0.04km^2) grid superimposed on the compartments of the middle Lance, respectively. Figure 5.32 is a summary graph for the drainage efficiency of the compartments from the 40, 20, 10, and 5 acre (0.16, 0.08, 0.04, and 0.02 km^2) grids. Area calculations can be found in Appendix F on the CD-ROM.

5.5 Discussion

This section is a summary of the results obtained from the 2 models generated in Section 5.4. The discussion includes the use of parameters and assumptions for the development of the stochastic 3D model. Also, I will compare the results obtained from the two models, and recommend a development program for Cave Gulch field.

5.5.1 Parameters

The parameters needed to set up the grid-based fault model were not easy to identify. I could not calculate some of them from the available data. The power-law exponent was taken from studies in a similar type of compressional environment in another Wyoming basin (Cladouhos and Marrett, 1996).

Other parameters were determined by trial and error until the model data resembled the structurally interpreted data. For example, the Fisher constant was found this way. Figure 5.33 shows a comparison of the actual microfault data with the modeled subseismic-scale faults. A Fisher constant of 5.0 gave the closest match to the observed eigenvalues. The aspect ratio is another parameter determined by trial and error. The aspect ratio was chosen by visually looking at faults generated and trying to pick the best value to keep individual faults contained within the bounding surfaces.

The parameters determined by the aforementioned methods resemble the microfault data interpreted from the structural techniques used in Chapter 3 (Figure 5.33). These parameters also provide a similar number of fault intersections seen in each of the wells (Figure 5.9 and Table 5.1). The comparison of the model-generated data with the structurally interpreted data validates the parameters used to develop the model.

5.5.2 Assumptions

This study assumes that subseismic-scale faults are similar to microfaults interpreted in the FMI analysis. Stearns and Friedman (1972) stated that fractures associated with faults are generally a product of the same stress state that caused the fault. Orientations of the fault can be deduced from fractures, and the converse is true.

The faults generated in the models are assumed to be no-flow barriers for the purpose of compartment-area calculations. This presents a worst-case scenario for hydrocarbon recovery. Although this assumption was made, there is limited evidence to suggest that fault-bounded compartments are sealing. Cave Gulch #9, for example, was drilled into a fault-bounded compartment and it has been a poor producer (Montgomery et al., 2001). In general, faults can be no-flow boundaries, baffles, or conduits for fluid flow. Each compartment intersected by a well is assumed to be drained by that well.

5.5.3 Interpretation

Results seen in the stochastic 3D fault models are plausible for the subseismic-scale faults in Cave Gulch field. Fault intensity varies throughout the field. Due to limitations of the software; this parameter could not be varied. The model built in this study identified a pattern of compartmentalization in the Lance Formation. The middle Lance plane is used to calculate areas because the top of the Lance and top of the Meeteetse planes experienced edge effects. Near the edges of the model at these depths, there were no faults seeded. The aspect ratio selected did not allow faults to be seeded near the boundaries, so the number of subseismic-scale faults is vertically somewhat unevenly distributed through the model.

Area analyses for well templates are summarized in Figure 5.34. There is approximately a 40% decrease in hydrocarbon recovery near seismic-scale faults. More subseismic-scale faults are found near the seismic-scale faults, which increases the number of fault-bounded compartments. More closely spaced wells are needed to efficiently drain the hydrocarbons near a seismic-scale fault. Analysis of multiple templates that are 5, 10, 20, 40, 80, and 160 ac (0.02, 0.04, 0.08, 0.16, 0.32, and 0.65 km^2) in size illustrates that the 20-ac (0.08 km^2) template intersected the same compartments with multiple wells, thereby making it inefficient. Somewhere lower than 40 ac (0.16 km^2) and higher than 20 ac (0.08 km^2) will be the ideal development spacing for Cave Gulch field, whereas a finer grid of 5 ac (0.02 km^2) is needed near the major faults in the field. This does not take into account the wells already present in the field or the stratigraphic compartments that occur in the fluvial Lance Formation.

Stratigraphic trapping is related to the stacking of fluvial sand bodies surrounded by floodplain mudstones. In an analogous outcrop, one point bar sand has a lateral extent of 2,475 ft (750 m), meander amplitude of 990 ft (300 m), and an amalgamated sand-body thickness of 25 ft (7 m) (Ellison, 2004). Lithologic variations within a point bar, specifically lateral-accretion surfaces, cause further compartmentalization within the reservoir. Based on the stratigraphic complexity of the sand body, and the continuity of shale-draped accretion surfaces, optimized placement of vertical wells may be difficult.

The value of understanding the degree of compartmentalization in a field is underscored by Pavillion and Muddy Ridge fields in the Wind River basin. These two fields were thought to be depleted, with production at 2.8 MMcfd in 1991. The reservoir is now thought to be compartmentalized. The demonstration of compartmentalization at

Cave Gulch field sparked a renewed interest in development of the Fort Union sands at Pavillion/Muddy Ridge. The implementation of a more closely spaced development grid has increased production at Pavillion/Muddy Ridge to 28 MMcfd, which significantly increased the EUR for the field (Kuuskraa, 1999).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The purpose of this study was to build a 3D fault model of Cave Gulch field using borehole image logs as input data for fault orientation and intensity. The data set includes 11 borehole image logs. Major conclusions for the study are:

1) FMI interpretation of 6 wells resulted in 1,290 open fractures, 1,083 healed fractures, and 2,717 microfaults.

2) Dip domain analysis of 6 wells led to the identification of 166 subseismic-scale faults. A total of 320 subseismic-scale faults are seen in 10 wells, from Sherwood (2002) and this study. Wells closer to seismic-scale faults contain more subseismic-scale faults.

3) Wells higher on structure and with fewer subseismic-scale faults have produced more gas than wells off structure with numerous subseismic-scale faults.

4) Compartmentalization plays a major role in Cave Gulch field, but subseismic-scale faults may not be the only feature contributing to compartmentalization. Stratigraphic reasons and fracturing may also play an important role.

5) Subseismic-scale faults could be important controls on production, effectively limiting the connectivity of the fluvial sandstones in the Fort Union and Lance Formations at Cave Gulch field.

6) More subseismic-scale faults are found near the seismic-scale faults, which increases the number of fault-bounded compartments.

7) Vertical wells provide an effective development strategy to exploit these fluvial Ft. Union and Lance reservoirs. Well spacing plays a significant role in the intersections of compartments. Recommended well spacing is approximately 30 ac (0.12 km^2) based on structural analysis alone, with a more closely spaced grid (5 ac, 0.02 km^2) near seismic-scale faults. From analysis done in this study, 20 ac (0.08 km^2) drainage efficiency is 131%; 40 ac (0.16 km^2) is 78%; 80 ac (0.32 km^2) is 43%; and 160 ac (0.65 km^2) is 31% for the entire field. In the Fault-Proximal model, 5 ac (0.02 km^2) drainage efficiency is 103%; 10 ac (0.04 km^2) is 63%; 20 ac (0.08 km^2) is 36%; and 40 ac (0.16 km^2) is 30%.

6.3 Future Work

The main reservoir, the Lance Formation, crops out in Cave Gulch field (Figure 2.6). The Lance is a lenticular, fluvial sandstone. The bars can be mapped and measured to create a stratigraphic model. Mapping can be done by using aerial photos or LIDAR data, if acquired. The stratigraphic model could be integrated with the structural model to expand the existing interpretation of Cave Gulch field.

Analysis of the compartment areas in the vertical plane can add another dimension to the work done in this study. The analysis of compartments with another software package could make it possible to calculate compartment volumes, not areas, for an improved analysis.

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APPENDIX A: Cave Gulch #2 well

APPENDIX B: Cave Gulch #6 well

APPENDIX C: Cave Gulch #7 well

C.1. Cumulative dip plot.

C.2. Dip azimuth vector plot.

C.3. Table of dip domains.

C.4. Lower hemisphere Schmidt projection for all fractures and microfaults.

C.5. Lower hemisphere Schmidt plots for healed fractures.

C.6. Lower hemisphere Schmidt plots for open fractures.

C.7. Lower hemisphere Schmidt plots for microfaults.

C.8. Fault frequency histogram.

C.9. Microfault frequency histogram.

APPENDIX D: Cave Gulch #B4 well

APPENDIX E: Cave Gulch #4-30 well