3D GEOLOGIC MODELING AND FRACTURE INTERPRETATION OF THE TENSLEEP SANDSTONE, ALCOVA ANTICLINE, WYOMING

by

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ABSTRACT

Alcova anticline is a Laramide-age structure on the southeast margin of the Wind River basin, central Wyoming. The Tensleep Sandstone is exposed at the core of the anticline. The North Platte River cuts across the axis of the anticline, resulting in two near-vertical walls of Tensleep Sandstone, approximately 500 m (1640 ft) wide, 100 m (330 ft) tall, separated by approximately 140 m (460 ft).

The purpose of this study is to: 1) determine the changes in fracture orientation and intensity across the Alcova anticline, 2) use the emerging technology of LiDAR to aid in the quantification of fracture orientation and intensity in an outcrop setting, 3) characterize fractures at Alcova anticline in a way that will allow the data to be used in a fractured reservoir flow model of analogous structures and, 4) complete a revised geologic map of the Alcova anticline and vicinity.

LiDAR is a laser-scanning technique that provides high-resolution (1-2 cm, 0.4-0.8 in) topography of outcrop surfaces. The LiDAR survey at Alcova anticline contains sufficient data points to resolve fracture planes ≥1 m^2 (11 ft^2) in area. LiDAR analysis has provided height, strike, and spacing data for 575 fractures with a trace length greater than 5 m (16 ft) for both outcrops. LiDAR data interpretation of fracture planes at Alcova anticline results in orientation and spacing values consistent with those measured in the field at Alcova anticline. There are 3 major and 1 minor fracture sets. Fracture height and spacing values fit simple power-law distributions.

One result of this study is a new geologic map of the Alcova area, with formation contacts constrained by GPS (global positioning system). A set of 14 balanced serial cross sections, constrained by the field map, were used to construct a 3D geologic model of the Tensleep sandstone. The model was restored using a flexural-slip unfolding algorithm. This model was tested for geometric attributes, such as dip magnitude, dip direction, rate of dip change (simple curvature), and Gaussian curvature. Strain was tracked during the restoration process. Rate of dip change (simple curvature) was found to have the greatest correlation to the location of tectonically produced fractures. Areas of elevated strain correspond directly to field-mapped transverse faults at high angles to the main thrusts.

The Tensleep Sandstone has been identified as a test candidate for carbon dioxide sequestration at the Teapot Dome oil field, 90 km (50 mi) northeast of Alcova anticline. The results of the LiDAR analysis, the 3D geologic model, and field observations at Alcova anticline provide a set of input parameters for a fractured reservoir model of the Tensleep Sandstone at Teapot Dome field. The input parameters are fracture set orientation, fracture set height, fracture set aspect ratio, fracture set spacing, and the distribution of the fracture sets over the structure.

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CHAPTER 1

INTRODUCTION

The Pennsylvanian Tensleep Sandstone, and its equivalents, the Minnelusa, Casper, and Weber, is one of the prolific oil-producing reservoirs of the Rocky Mountain foreland. The Tensleep Sandstone is an important reservoir in the Wind River and Big Horn basins, Wyoming. Some of the earliest oil production in the Rocky Mountains was from the Tensleep and its equivalents in basin-rimming anticlines and domes. Since 1978, the Tensleep and its equivalents in Wyoming alone have produced 810 million barrels of oil (WOGCC, 2005).

All of the producing Tensleep fields have completed primary recovery and many are nearing the end of secondary recovery efforts. In addition, the Tensleep Sandstone has been identified as a test candidate for carbon dioxide sequestration at the Teapot Dome oil field, also known as Naval Petroleum Reserve – 3 (NPR-3). As reservoir management plans are discussed for tertiary recovery and carbon dioxide sequestration, reservoir heterogeneities are an important factor, particularly in the modeling of reservoirs. Fundamental knowledge of the fractures and faults created during folding of these Laramide basement-involved anticlines is a key aspect of reservoir characterization.

Fractures and faults can be either barriers or conduits for fluid flow. Significant offsets in faults or low-permeability fracture fillings can create reservoir compartments. These compartments can lead to stranded oil and form reservoir heterogeneity that can hinder hydrocarbon recovery. Faults and fractures can also be escape pathways for sequestered carbon dioxide. The prediction of areas of increased fault and fracture intensity within anticlinal structures is a key understanding to use during the management of the production and development phases of a field.

1.1 Purpose of Study

The purpose of this study is to characterize the fracture distribution in the Tensleep Sandstone exposed at Alcova anticline, Natrona County, Wyoming. This model should provide constraints for fracture prediction in a reservoir flow model of the Teapot Dome (NPR-3) oil field. The research objectives of this study are:

- Determine the changes in fracture orientation and intensity across the Alcova anticline.
- Use the emerging technology of Lidar to aid in the quantification of fracture orientation and intensity in an outcrop setting.
- Characterize the fractures at Alcova anticline in a way that will allow the data to be used in a fractured reservoir flow model of Teapot Dome (NPR-3).
- Complete a revised geologic map of the Alcova anticline, a popular field trip location.

1.2 Research Contributions

- The new geologic map of Alcova anticline is based upon GPS-controlled formation tops and faults.
- The new structural interpretation of the Alcova anticline includes basement corners formed by the intersection of high-angle transverse faults with the underlying thrust. These features were not recognized by previous workers.
- A set of 14 balanced serial cross sections establishes the nature of the structure and provides control for a 3D geologic model.

- The analysis of the 3D geologic model indicates that attributes, such as Gaussian curvature and strain can identify areas where high-angle transverse faults are present.
- LIDAR data interpretation of fracture planes at Alcova anticline results in interpretations that are consistent with those measured in the field at Alcova as well as for other analogous Laramide-age Tensleep Sandstone structures.
- The distribution of fracture height and fracture spacing values exhibit simple power-law distributions. These distributions can be used for modeling in analogous, Laramide-age Tensleep Sandstone outcrops and reservoirs.
- The Teapot Dome (NPR-3) fractured reservoir model constraints are consistent with those observed at Alcova anticline and other analogous subsurface anticlines.
- The study demonstrates the value of LiDAR data for fracture characterization in outcrop. Fracture orientations, spacing, and height can be quantified by observing planar features in LiDAR digital elevation models. Such data provide the essential input for 3D geologic and flow models.

CHAPTER 2

BACKGROUND

2.1 Study Location

The Wind River basin is a Laramide-age foreland basin located in central Wyoming. Covering approximately 8,500 mi^2 (22,000 km^2), the basin is bounded to the east by the Casper Arch, to the west by the Wind River Mountains, to the north by the Washakie, Owl Creek, and Big Horn Mountains, with the Granite Mountains (Sweetwater Uplift) to the south (Figure 2.1). The basin is asymmetric with the structurally deepest area in the northeast, near the location where the Owl Creek Mountains, Big Horn Mountains and the Casper Arch intersect (Keefer, 1965a). The margin of the Wind River basin is ringed by Laramide-age anticlines and domes.

The Alcova anticline is a Laramide-age basement-involved asymmetric anticline on the southeast margin of the Wind River basin, on the flanks of the Granite Mountains (Sweetwater Uplift). The structure is located approximately 35 mi (58 km) southwest of Casper, Wyoming along Wyoming State Highway 220 (Figure 2.2). The study area is located within the Alcova, Bear Spring, Benton Basin, and Pathfinder Dam USGS 1:24,000 scale quadrangles (Figure 2.3). Figure 2.4 outlines the study area. The large body of water is the Alcova Reservoir, created in 1935 by the construction of the Alcova dam at the northern mouth of Alcova canyon, impounding the waters of the North Platte River (Knittel et al., 2004). The anticline forms the northern terminus of the reservoir. The town of Alcova is just north of the dam site. The majority of the lands within the study area are under the control of the Bureau of Land Management or the United States

Bureau of Reclamation. The deeply cut canyon to the south is Fremont Canyon, named after J. C. Fremont, one of the early explorers and surveyors of the region.

The Pennsylvanian Tensleep Sandstone is exposed for approximately 4 mi (6.5 km) along the trend of the anticline and the complete stratigraphic section from the Precambrian basement to Upper Cretaceous shales are exposed at this location. The North Platte River cuts across the axis of the anticline, resulting in two near-vertical walls of Tensleep Sandstone (Figure 2.5). At the rivercut, one is essentially looking at an analog to the interior of a petroleum reservoir (Figure 2.6). This provides an excellent location to describe and characterize how the frequency and orientation of fractures change across the structure.

2.2 Previous Work

The Alcova area first attracted geologic interest due to the hot springs in the canyon. Knight (1900) described the area in his review of Wyoming artesian basins. In a subsequent volume, Knight (1901) described the major fault as a thrust and named it the Fremont fault in honor of J. C. Fremont. For his study of the Paleozoic and Mesozoic of Wyoming, Darton (1908) included a brief description of the anticline and with a photograph of the canyon prior to dam construction.

Hares (1916) included a description of the Alcova anticline in his review of anticlines in central Wyoming. Hares (1916) contradicted the earlier works of Knight (1901) and Darton (1908) by claiming that the formations from the Chugwater through the Niobrara can be traced continuously from the eastern limb, around the nose and off to the west until they are buried by the overlying Tertiary, stating that there is no Fremont fault. Hares (1916) also came to the conclusion that the region surrounding the Alcova anticline had no future as an oil territory due to the degree of erosion of the oil-bearing formations.

Lee (1927) measured a section near the anticline and provided the first detailed description of the local stratigraphy. In a brief abstract, Beckwith (1933) characterized the structure of the area. Beckwith (1933) described the block of Tensleep and Embar (Goose Egg) as an overthrust to the south along a fault dipping at a low angle. He also described subsidiary thrust faults branching off tangentially from the main and subsidiary thrust faults. In some cases, they rejoin the main fault and form a series of crescentic blocks. He also noted minor faults striking at right angles to the thrusts that show no offset and die out in the incompetent beds. Thomas (1934) measured a section through the Goose Egg (Phosphoria and Dinwoody of his nomenclature) and lower Chugwater for a study of the Permian rocks through central and southeastern Wyoming.

Bradley (1935) studied the canyon and area immediately to the southwest of the canyon as a part of the investigation for the selection of a suitable site for the Alcova dam. He detailed the stratigraphy of the Amsden and Tensleep outcrops of the canyon walls and mapped the locations of the hot springs. Bradley (1935) also published the first detailed map of the geology along the southwest limb of the anticline. This is of great importance due to the construction of the dam in 1935 and the subsequent flooding of the valley floor. Bradley (1935) showed a series of normal faults parallel to the fold axis that terminate against a younger east-west normal fault. Bradley (1935) is the only author to describe the motion on the fault as normal. However, his placement of faults and formations on the surface appear to be consistent with those observed in this study and will be discussed in a subsequent chapter. The Wyoming Geological Survey (1935) published a county map of the geology of Natrona County as mapped by J. D. Love.

Hares et al. (1946) published a geologic map of the southeastern part of the Wind River basin. Alcova anticline was included, but not mapped in detail. 1946 was the first year in which the anticline was featured in a field guide by the Wyoming Geological Association. Since then, numerous road logs and field trip guides have been compiled and published through this association.

Sheffer (1951) mapped the area from the North Platte River and Alcova Reservoir west to the first occurrence of Tertiary sediments as a thesis project for the University of Wyoming. Sheffer (1951) mapped the geology on 1:27,700 scale aerial photographs. He measured and described approximately 5,000 ft (1,523 m) of stratigraphic section from the Precambrian to the Tertiary. Mitchell (1957) completed the geologic mapping of the Alcova area with his thesis covering the area east of the North Platte River and Alcova Reservoir. Mitchell (1957) also measured and described the stratigraphic section from the Precambrian to the Tertiary. Together, these two studies comprise the most detailed work done over the entire Alcova area prior to this study.

A revised Natrona county geologic map was included in the water-supply paper by Christ and Lowry (1972). Van Burgh and Strube (1974) published a natural history field guide to the Alcova area that contains a detailed road log that encircles the reservoir.

Sando and Sandberg (1987) included a measured section in Fremont canyon for their work on Paleozoic stratigraphy in southeast Wyoming. The section is from the basal, Cambrian Fremont Canyon Sandstone (which they are the first to identify) into the lower Tensleep/Amsden Formations. Hornbacher (1990a,b) started a Ph.D. study from Texas A&M, but never completed his work and did not publish a map. He described the nature of the main faults and measured thinning due to strain within the stratigraphic formations.

Vealy (1991) completed a thesis that used the Tensleep exposure at the Alcova anticline as an outcrop analog to the South Casper Creek oil field. The primary goal of this study was to determine the scale of heterogeneities that would affect the well spacing at South Casper Creek. Vealy (1991) measured three stratigraphic sections, with outcrop gamma ray, on the west wall of the Alcova Anticline. Vealy (1991) described 10 genetic lithostratigraphic units based on 9 lithofacies interpreted in the field. These lithostratigraphic units were used to identify flow units based upon permeability and porosity. Vealy (1991) also measured fracture intensity and orientation by field traverses and through photo interpretation.

In 2004, Knittel et al. (2004) published a revised edition of the Van Burgh and Strube (1974) natural history field guide. Included in this guide are updated color photos and a geologic map based upon the mapping of Curry (1970), Love (1970), Love et al. (1979), and Love and Christiansen (1985). No additional field mapping was included in this new geologic map.

2.3 Stratigraphy

This section describes the regional stratigraphic framework of the Wind River basin and the local stratigraphy present at Alcova anticline. Figure 2.7 is the regional stratigraphic column of the Wind River basin.

2.3.1 Regional Stratigraphy

The mountain ranges encircling the Wind River basin are composed of igneous and metamorphic rocks of Precambrian age. These rocks are composed predominantly of granite, granite gneiss, and schist with local areas of mafic dike populations (Keefer, 1970).

By the end of the Precambrian, the region that would become the Wind River basin was tectonically stable and reduced to a broad, level plain by extensive erosion (Keefer, 1970). This formed the base for the next 540 million years of sedimentation. With the exception of the Silurian, sedimentary rocks from every time period are present in the Wind River basin. In general, most formations deposited during the Paleozoic and Mesozoic are thicker and more complete in the western portion of the basin when compared to the same units in the eastern portion of the basin. This is due to the mainly shallow-marine deposition of the Paleozoic and Mesozoic sediments, with the result that slight changes in base level due to sea-level fluctuations or tectonic activity led to widespread unconformities and changes in patterns of sedimentation (Keefer, 1965a).

The Transcontinental Arch influenced Early to Middle Paleozoic sedimentation. The Transcontinental Arch was a major, broad, southwest-northeast trending basement high that extended from present-day northeastern Arizona to southern Minnesota (Snoke, 1993). Central Wyoming was located on the northwestern flank of this broad feature and its Cambrian and Ordovician depositional history are reflected in the progressive west-to-east marine transgression during that time (Snoke, 1993). The Flathead Sandstone is the oldest known Phanerozoic stratigraphic unit in Wyoming. The Flathead Sandstone is a quartz-rich sandstone that represents the first advance of the Paleozoic seas (Keefer, 1965a, Snoke, 1993). The Flathead Sandstone is the base of a well-defined Cambrian transgressive sequence of marine sandstones, shales, and limestones that includes the Gros Ventre Formation and the Gallatin Limestone. The contacts between the formations are gradational and the boundaries become younger eastward across the Wind River basin. Cambrian time ended with the sea retreating and a period of exposure and erosion (Keefer, 1965a).

The Middle and Upper Ordovician Bighorn Dolomite lies unconformably on the Cambrian formations. With the exception of a thin, lenticular sandstone known as the Lander Sandstone, the Big Horn Dolomite consists of massive, relatively pure dolomite (Burke, 1956; Keefer, 1965a; Boyd, 1993). The Lower Devonian Beartooth Butte Formation, consisting of lenses of conglomerate and dolomite overlie the Big Horn Dolomite. Two later Devonian formations are also present in the Wind River basin. The marine dolostones, limestones, and shales of the Darby Formation were deposited in the northwestern part of the basin (Keefer, 1965a). The transgressive Fremont Canyon Sandstone was deposited near the Devonian-Mississippian boundary in the southern portion of the basin (Sando and Sandberg, 1987; Boyd, 1993).

The Early Mississippian Madison Limestone occurs extensively throughout central Wyoming. Near the end of the Mississippian, much of Wyoming was exposed during a major regression. Widespread karstification occurred on the exposed shelf (Boyd, 1993). A period of transgression resulted in deposition of the Amsden Formation, which consists of marine shales, limestones, and sandstones (Keefer, 1965a). Overlying the Amsden is the Pennsylvanian Tensleep Formation. The youngest Paleozoic formation consists of the Permian Phosphoria/Goose Egg formation.

Mesozoic deposition began with the siltstones and carbonates of the Dinwoody Formation, followed by the tidally dominated redbeds of the Triassic Chugwater Group. The Chugwater Group consist of sandstones, shales, and limestones, including the prominent Alcova Limestone member (Keefer, 1965a; Picard, 1993). The earliest Jurassic is represented by the eolian sandstones of the Nugget Formation. Sea level once again rose and the Middle Jurassic formations are composed primarily of carbonates, evaporites, red siltstones, and marine shales and sandstones. The formations are the Gypsum Spring and Sundance, respectively. At the end of the Jurassic, the sea regressed and the variegated fluvial shale and sandstone channels of the Morrison were deposited (Keefer, 1965a; Picard, 1993).

The fluvial conglomerates of the Cretaceous Cloverly Formation were deposited uncomformably over the Jurassic Morrison before giving way to the Early Cretaceous seas that resulted in the black marine-shale deposition of the Thermopolis and Mowry Formations with the Muddy Sandstone. To the west, propagation of the Cordilleran thrust belt eastward and rapid subsidence resulted in a shift of the Upper Cretaceous seas to the east and deposition of the extensive nonmarine sandstones and marine shales of the Frontier Formation (Keefer, 1965a; Kuuskraa et al., 1999). The marine Cody Shale was deposited as transgression continued and the Frontier sand source was cut off. Mesaverde Group deposition is marked by the first regression after Cody deposition. The nonmarine sandstones, shales, coals and carbonaceous shales are the remnants of a large alluvial plain or low coastal plain. The Mesaverde is primarily found in the western portion of the basin. In the east, this unit interfingers with shales of the Cody Formation (Keefer, 1965a; Steidtmann, 1993; Johnson et al., 1996). Overlying the Mesaverde is the Lewis Shale and its partial equivalent, the Meeteetse Formation. The Lewis is the last marine interval and is composed of marine shales and sandstones. Multiple transgressions of the

Late Cretaceous sea resulted in interfingering of the Lewis with the non-marine sandstones, siltstones, shales, carbonaceous shales, and coals of the Meeteetse Formation (Keefer, 1965b, Johnson et al., 1996).

The Late Cretaceous to Early Tertiary Laramide Orogeny resulted in uplift of the mountain ranges surrounding the basin, and subsequent downwarping of the basement. The uplifts provided large amounts of eroded sediment, deposited in the basin in a series of wedge-shaped accumulations of clastic sediments. These sediments, which formed the Lance Formation, represent the last Mesozoic rocks deposited in the Wind River basin (Keefer, 1965a; Keefer, 1965b; Johnson et al., 1996).

Continuation of the Laramide Orogeny kept a constant supply of sediment available. Major fluvial systems led to deposition of the Tertiary Fort Union Formation. The Fort Union Formation is composed of conglomerates, sandstones, shales, and coals. The Fort Union was the last formation deposited during the time of active tectonism. Strata of the Late Tertiary, including the Wind River and White River Formations, were deposited unconformably over the Laramide-deformed strata of Paleozoic and Mesozoic age.

2.3.2 Local Stratigraphy

The stratigraphic section that crops out in the Alcova study area totals approximately 6,000 ft (1,818 m) from the Devonian Fremont Canyon Sandstone to the Upper Cretaceous Cody Shale and overlying Tertiary units. Figure 2.8 is the local stratigraphic column for the Alcova study area.

The stratigraphic section of the Alcova area rests unconformably on top of Precambrian granite. This granite is exposed in the extreme southern portion of the study area. Where exposed, the granite is pink-weathering, poorly foliated, and is composed mainly of pink orthoclase feldspar, biotite, and quartz. Pegmatite veins are common. The rock weathers to form massive, rounded outcrops that are highly fractured.

The Devonian Fremont Canyon Sandstone lies unconformably on the granite. The Fremont Canyon is a newly recognized stratigraphic unit with its type section at Fremont Canyon in the southern portion of the field area. Previous workers have described this unit as the Cambrian Flathead Sandstone. Sando and Sandberg (1987) completed a study of the Paleozoic stratigraphy in the Northern Laramie Range. The authors concluded, based upon detailed petrographic analysis and stratigraphic position, that the basal sandstone exposed in Fremont Canyon was correlatable with the Parting Formation of Colorado. Because the sandstone in Wyoming cannot be physically traced into the areas where the Parting is exposed, a new name was given to the strata (Sando and Sandberg, 1987). Additional evidence for this change of age to the Fremont Canyon Sandstone includes Devonian conodonts in the conformably overlying strata, as well as paleomagnetic pole determinations that suggest a pole closer to that of the Devonian rather than to the Cambrian and Ordovician pole positions (Sando and Sandberg, 1987). The Fremont Canyon Sandstone is a quartz arenite composed of angular to well-rounded, well-sorted grains. Sando and Sandberg (1987) proposed that the Fremont Canyon Sandstone represents a nearshore-marine environment and suggested that it was sourced from the Transcontinental Arch to the east.

The Fremont Canyon Sandstone is the oldest Paleozoic unit preserved in the Alcova area. Unlike other parts of the Wind River basin, there are no Cambrian or Ordovician units. As in the rest of the Wind River basin and most of Wyoming, there are no Silurian rocks present, either. Missing units in the Cambrian include the basal Flathead Sandstone, the shales of the Gros Ventre Formation, and the limestones of the Gallatin Group. The massive Bighorn Dolomite of the Ordovician period is also absent. Following deposition of the Bighorn Dolomite, sea level dropped and Wyoming was subaerially exposed. Ordovician and Cambrian rocks were completely removed from southeastern Wyoming, including the Alcova study area (Boyd, 1993).

Following deposition of the transgressive Fremont Canyon Sandstone, Wyoming was once again covered by the sea during the Mississippian. During this time, thick carbonate sequences were deposited across all but the extreme southeast corner of the state. These units are named the Madison Formation and thicken irregularly to the north and west, up to thicknesses greater than 1,000 ft (305 m) (Boyd, 1993). The lack of Mississippian strata to the southeast is due to the continued presence of the Transcontinental Arch (Maughan, 1993). Continued deposition was terminated by a major regression that moved the shoreline to the western border of the state (Boyd, 1993). Subaerial exposure and abundant meteoric-water influx resulted in a well-developed karst topography that marks the boundary with Pennsylvanian strata. This surface is well exposed in the goosenecks of Fremont Canyon on the south margin of the study area.

Locally, the Mississippian-Pennsylvanian Pathfinder uplift resulted in the Alcova area being subaerially exposed for a much greater period of time than the rest of the state. Evidence for this includes thin Amsden beds at Fremont Canyon. The Amsden is thicker to the west and onlaps the flanks of the Pathfinder uplift. The Amsden at Alcova reservoir is limited to two thin units, a red mudstone that fills karstic sinkholes and a thin sandstone bed.

The Tensleep Sandstone represents the second depositional sequence of the Pennsylvanian, initiated by the Ancestral Rocky Mountain diastrophism. The Tensleep sequence can be correlated to the Quadrant Sandstone of Montana, the Casper and Minnelusa of eastern Wyoming, the Weber Sandstone of southwestern Wyoming and the upper member of the Fountain Formation in Colorado (Maughan, 1993). Middle Pennsylvanian uplift provided a large supply of quartzose sand from an unknown source to the north. This sand formed a major component of the well-sorted, fine- and medium-grained Tensleep Sandstone (Maughan, 1993).

The Tensleep Sandstone is characterized by interbedded layers of sandstone and dolomite at its base, to large, thickly bedded dune sets at its top (Figure 2.9). The sand sea that formed the Tensleep Sandstone prograded across the Wyoming shelf from the north or northwest during the Middle Pennsylvanian (Maughan, 1993). During migration of the sand dunes, fluctuations in sea level due to Pennsylvanian glaciation caused the dunes to be flooded by shallow seas that reworked the previous deposits and resulted in deposition of sandy dolomitic layers (Boyd, 1993). Deposition of the Tensleep sequence ended during the Late Pennsylvanian to Early Permian uplift of the Wyoming Arch (Maughan, 1993).

The uppermost Tensleep consists of sandstones reworked during transgressive flooding. Overlying the Tensleep sands are the redbeds of the Permian Goose Egg Formation. The formation can be divided into the Opeche Shale, Minnekahta Limestone, Glendo Shale, Forelle Limestone, Difficulty Shale, Ervay, Freezeout Shale and Little Medicine members (Keefer, 1966). This study did not differentiate members of the Goose Egg Formation. The Goose Egg is composed of interbedded layers of anhydrite, red to yellow sandy shales and siltstones, thin limestones, and dolomites. The Goose Egg is the landward equivalent of the Phosphoria Formation of the central Wind River basin. Periods of transgression and regression resulted in the interfingering of the two facies (Boyd, 1993).

The Chugwater Group at Alcova anticline has traditionally been divided using the nomenclature of the of the Laramie, Hanna, and Shirley basins, as opposed to the Wind River basin as defined by the Wyoming Geological Association's Nomenclature Committee. The lower Chugwater unit, the section below the Alcova Limestone, is the Red Peak Formation and the section above is called the Jelm Formation. The Red Peak Formation is Early Triassic in age, and is composed primarily of brick red shales, siltstones, and sandy siltstones. Generally, there is an upward increase in the abundance of coarser grains and an upward increase in the number and thickness of coarser beds (Burke, 1956; Picard, 1993). The Red Peak was deposited in an arid, shallow-marine environment. The youngest Red Peak beds indicated a higher amount of sand available and the beds are variegated in color. A transgression from the west to the east flooded most of Wyoming, resulting in the Wyoming shelf being one of the most stable, quietest places of the Mesozoic era (Picard, 1993). During this time, the Alcova Limestone was deposited over 50,000 mi^2 (1.3 x 10^8 km^2), generally at a thickness of 10-20 ft (3-6 m) and rarely over 25 ft (8 m) (Burke, 1956; Picard, 1993). The Alcova Limestone is composed of gray or tan to pinkish, dense, hard, finely-crystalline limestone with a lower stromatolitic unit. At Alcova anticline, and across Wyoming, the Alcova Limestone is a prominent ridge-former. The Jelm Formation was deposited in a fluvial and fluvial-lacustrine environment in southeast Wyoming. The Crow Mountain Sandstone and Popo Agie Formation of central and western Wyoming are approximate time-equivalents to the Jelm (Picard, 1993). The Jelm is composed dominantly of cross-stratified, channel-filling, red sandy siltstone and sandstone with rare conglomeratic and shaly limestone (Picard, 1993). These sediments were deposited on a generally westward-prograding deltaic plain (Picard, 1993).

The Jurassic Nugget Sandstone and Gypsum Spring Formation are absent at Alcova anticline. The Jurassic Sundance Formation unconformably overlies the Jelm. Missing section may be due to local uplift and erosion of the Nugget and Gypsum Spring in the eastern Wind River basin during the Jurassic (Keefer, 1965a). The Canyon Springs Sandstone, the lowermost member of the Sundance Formation, lies directly on the Jelm Formation at Alcova anticline. The Sundance Formation represents a marine-dominated environment and is characterized by green and yellow shales with interbedded resistant sandstones and thin-bedded limestones (Picard, 1993). The Sundance can be divided into a lower and upper interval, each representing a major transgression/regression sequence. At Alcova anticline, the lower Sundance can be broken out into the Canyon Springs Sandstone, Stockade Beaver Shale, Hulett Sandstone, and Lak Redbeds members. This sequence consists of gray to pale green shales, oolitic limestone, and fine-grained pink to gray sandstone (Burke, 1956). The upper interval, composed of the Pine Butte Sandstone, Redwater Shale, and Windy Hill Sandstone, is also present at Alcova anticline and consists of glauconitic green to pale-green shales, calcareous sandstones, and thin-bedded limestones.

The regression of the Sundance seas led to deposition of the terrestrial Morrison Formation. The Morrison is composed of low-energy stream-deposited sandstones, siltstones, and conglomerates at the base and an upper unit characterized by variable-colored claystones, mudstones, and siltstones. Within this upper unit are sandstone channel lenses and sheet sands of braided-stream deposits. Also included are lacustrine carbonates, representative of small lakes that formed on the Morrison alluvial plain (Burke, 1956; Picard, 1993). Dinosaur bones can be found in sandstone channels throughout the study area.

The basal Cretaceous unit in this portion of the Wind River basin is the Cloverly Formation. The Lakota Conglomerate member of the Cloverly is a coarse-pebble conglomerate that is well cemented, and is locally a ridge former in the Alcova reservoir area. The Lakota Conglomerate was deposited as fluvial gravels in a broad east-northeast directed stream system that flowed from the fold-and-thrust belt across the foreland basin (Burke, 1956; Steidtmann, 1993).

Other Cretaceous rocks of the Alcova area are the Thermopolis Shale, Muddy Sandstone of the Lower Cretaceous, and the Mowry, Frontier, and Cody Formations of the Upper Cretaceous. The Thermopolis Shale consists of black to dark-gray, soft, fissile marine shales. Following Thermopolis deposition, sea level dropped, which formed a regional lowstand surface of subaerial exposure and erosion. This led to the development of an incised valley system into which deposition of the Muddy Sandstone occurred (Steidtmann, 1993). The Muddy Sandstone is a varied unit of marine and nonmarine strata that filled the valleys. Traditionally, the Muddy is a fine to coarse-grained sandstone that is locally argillaceous and streaked with black, carbonaceous shale (Burke, 1956). As transgression continued, the area was once again submerged and the Mowry Sea formed. The Mowry Sea was bordered to the south by the Transcontinental Arch. This broad, high feature prevented the Mowry Sea from communication with the proto-Gulf of Mexico. This isolation led to an increase in stagnation as the sea deepened, which formed black shale and hydrocarbon source beds (Steidtmann, 1993; Johnson et al., 1996). The marine sandstones, nonmarine sandstones, and marine shales of the Frontier Formation formed as a series of deltas, barrier islands and costal-plain deposits as the sea transgressed and regressed (Steidtmann, 1993; Johnson et al., 1996). The thick overlying Cody Shale is the last Cretaceous unit observed in the Alcova reservoir area. The Cody Shale is composed of marine sandstones and shales.

Following the Laramide Orogeny, the Eocene Wind River Formation and the Oligocene White River Formation were deposited over the deformed Paleozoic and Mesozoic strata. The Wind River Formation is composed of gray to white arkosic sandstone and conglomerate. The formation was deposited as streams flowed from the adjacent Laramide highlands. The White River Formation is composed of siltstones, claystones, and sandstones with a variegated gray-to-white coloration. The White River Formation is also composed of sediments shed from the surrounding highlands (Love, 1970; Knittel et al., 2004). The Wind River and White River Formations had completely covered the study area until the Late Cenozoic when a regional uplift elevated the Wind River basin and the surrounding mountains 3,000–4,000 ft (915-1,220 m). This resulted in the erosion of the Wind River and White River Formations and the exhumation of the Alcova anticline (Keefer, 1965a).

2.4 Structural Geology

This section describes the tectonic framework of the Wyoming foreland and its relationship to the Wind River basin. Structures in the southeastern corner of the Wind River basin, including Alcova anticline, are also described.

2.4.1 Regional Structural Geology

The present-day form of Wyoming and the Wind River basin is dominated by the highlands of the Rocky Mountains and the intermontane basins. Wyoming is situated along the eastern margin of the U.S. Cordillera. The Rocky Mountains are the easternmost expression of the horizontal compression associated with the Sevier and

Laramide orogenies that occurred during the Early Cretaceous through Eocene. In the past, the Sevier and Laramide orogenies were assumed to be separate events. However, Snoke (1993) provided structural and stratigraphic evidence to suggest that, at least in Wyoming, Sevier deformation extended through the end of the Laramide. Tectonic interactions at the western boundary of the North American plate are credited for the horizontal shortening that is responsible for both styles of deformation.

The Sevier and Laramide orogenies are characterized by two distinctly different styles of deformation. Sevier deformation is dominated by basement-detached folding and thrusting. In Wyoming, only sedimentary rocks were affected, with the thrust faults merging into a decollement near the top of the crystalline basement. Sevier faults dip to the west, are listric in shape, and cut upsection in the direction of transport in a stairstep trajectory (Snoke, 1993). Folds are generated primarily by the bending of sedimentary layers above fault ramps. The Sevier fold and thrust belt is located at the Wyoming/Utah/Idaho border, to the west of the Laramide deformation. Laramide deformation is dominated by basement-rooted faults and associated deformation. Laramide faults tend to be steeper than Sevier faults. Folds result from the propagation of faults through the sedimentary section.

Sevier and Laramide structures also differ in the amount of internal deformation related to the ratios of horizontal shortening to vertical uplift. Laramide structures are characterized by discrete areas of intense deformation near principal faults or tightly folded domains. The structures of the Sevier fold and thrust belt are characterized by widespread deformation throughout the structure (Zahm, 2002). The amount of uplift in Laramide thick-skinned structures is greater than the uplift in Sevier thin-skinned structures. Conversely, the amount of horizontal shortening of Sevier structures is much greater than that of Laramide structures. This results in Laramide structures that have a low shortening-to-uplift ratio, and Sevier structures that have a high shortening-to-uplift ratio.

Figure 2.10 shows the basin-bounding, or primary structures of the Wyoming Laramide foreland are primarily oriented NW-SE or E-W. Examples of primary structures include the Owl Creek uplift, the Casper Arch, and the Wind River Mountains uplift. This variation in orientation has been examined by various workers with two resulting hypotheses. The first hypothesis involves two phases of deformation with a shift in shortening direction from a SW-NE orientation during the Late Cretaceous to a S-N shortening direction during the Eocene (Gries, 1983; Chapin and Cather, 1983). This model proposes that faulting is dominated by dip-slip movement. The contrasting model is centered around a hypothesis of an extended phase of deformation with the shortening direction being oriented SW-NE (Figure 2.11). Structures with an E-W or N-S orientation are proposed to have formed from faulting with a significant amount of oblique-slip movement (Stone, 1969; Blackstone, 1990; Paylor and Yin, 1993; Erslev, 1993; Molzer and Erslev, 1995; Erslev, 2005).

The numerous anticlines that ring the margins of the Laramide basins formed by the primary structures can be considered as secondary structures. These secondary structures formed by four different mechanisms (Figure 2.12) as defined by Erslev et al. (2001):

1. Basement backthrusting can cause rotation and folding in the hanging wall of basin-bounding thrusts.
2. Stratal wedging can cause detachment and backthrusting of sedimentary strata in the hanging wall of basin-bounding thrusts.
3. Footwall thrusting may develop on splays that extend from basin-bounding thrusts, which commonly have large hanging-wall rotations. This indicates shallow-level detachment in the basement.
4. Synclinal tightening can form in the backlimb of asymmetrical arches, which can be attributed to rotational fault-bend folding on curved master thrusts at depth.

When these secondary structures form 3D closure, they provide the most common hydrocarbon traps in the Rocky Mountain foreland, and specifically the Wind River and Big Horn basins. 3D closure is achieved by three main mechanisms, also defined by Erslev et al. (2001). Large-displacement gradients of faulting along strike result in structural closure. Closure is also achieved when thrusts intersect with other transversely oriented basement-rooted structural elements. The final mechanism for forming structural closure is the development of tear faults. The structural closure of Alcova anticline can be described within the terms of these mechanisms.

2.4.2 Local Structural Geology

The Wind River basin is defined by a series of major faults and their resulting uplifts. The basin is bounded to the west by the Wind River thrust and Wind River Mountains, to the north by the east-west trending Owl Creek fault system, to the east by the Casper Arch and to the south by the Granite Mountains (Sweetwater Uplift). The vertical offset within these fault zones is as high as 20,000 to 30,000 ft (6,100-9150 m) (Kuuskraa et al., 1999). Structures within the Wind River basin are generally oriented NW-SW. However, Casper Mountain (and the Casper Mountain Fault) is an east-west trending structure at the extreme southeastern corner of the basin.

During most of the Paleozoic and Mesozoic, the area now known as the Wind River basin was a stable shelf northwest of the Transcontinental Arch and to the southeast of the Cordilleran foredeep. Structural deformation of this area was minimal, yet a localized uplift occurred during the Pennsylvanian in the northern Laramie Mountains and westward into the Alcova and Pathfinder reservoir areas. This is termed the Pathfinder uplift (Maughan, 1993). This uplift resulted in erosion of the existing Paleozoic strata. Across the uplift, the Amsden and Tensleep Formations onlap the lower Madison Limestone, and in some cases the Precambrian basement. The Amsden

Formation, as observed in Fremont Canyon, includes only two thin units, whereas to the west it is considerably thicker (Maughan, 1993).

The Wind River basin began to take its current structural form during the Late Cretaceous with the start of the Laramide Orogeny. The eastern boundary of the Wind River basin formed first with the uplift of the Casper Arch (Gries, 1983). Evidence for this timing includes the thick sections of Paleocene sediments against the Casper Arch, which indicate early basin subsidence (Figure 2.13a). The Owl Creek Mountains formed shortly afterwards, to separate the Big Horn basin from the Wind River basin. Thick sections of Eocene sediments at the base of the Owl Creek Mountains indicate uplift and subsequent erosion at that time. Uplift of the Casper Arch also continued during that time (Figure 2.13b).

The Alcova anticline is located at the extreme southeast corner of the Wind River basin, on the northeast flank of the Granite Mountains (Sweetwater Uplift) (Figure 2.14). Local structural features include the Casper Mountain Uplift, the North Granite Mountains Fault Zone and the Bates Park anticline. Casper Mountain is a prominent, east-west trending Laramide uplift. Stone (2002) attributed the east-west trend of Casper Mountain to the influence of pre-existing fabric in the basement. The uplift developed along an existing Precambrian structure that was reactivated during Laramide time.

The Granite Mountains, also referred to as the Sweetwater Uplift or Arch, consist of an asymmetric, doubly plunging anticline that is cored by Precambrian basement, and trends N70˚W (Blackstone, 1991). The Granite Mountains are unique when compared to the other basement-cored ranges of Wyoming in that they remain partly buried by upper Cenozoic sedimentary deposits. Other mountain ranges have been more completely exhumed (Keefer, 1970; Love, 1970). Paleozoic and Mesozoic strata, where exposed by exhumation, dip uniformly 8-15˚ off the north flank of the uplift. These strata are broken by the east-trending North Granite Mountains fault system (Keefer, 1970; Love, 1970). These nearly vertical normal faults formed as the result of Tertiary extensional tectonism. The fault zone is approximately 60 mi (100 km) long and begins in the extreme southeast arm of the Wind River basin, cuts obliquely across the north flank of the Granite Mountains, through the Rattlesnake Hills volcanic field and back to the southern margin of the Wind River basin where it terminates. The pre-existing Laramide structures have been cut with little deviation from the east-west trend of the fault zone (Love, 1970). The average displacement is approximately 800 ft (243 m) on normal faults that dip to the south (Blackstone, 1991). In the terms of Figure 2.12, the Alcova anticline can be described as a back-limb tightening structure formed on the backlimb of the Granite Mountains (Sweetwater Uplift). It is presumed to have formed from the synclinal tightening associated with rotational fault-bend folding on a curved master fault at depth (Figure 2.15). As will be shown later, structural closure of the Alcova anticline results from a decrease in displacement along strike and intersection with transversely oriented basement-rooted structural elements.

2.5 Petroleum System

The first oil field in Wyoming was discovered in 1884 at Dallas Dome on the western flanks of the Wind River basin (Willis and Groshong, 1993). Since that time, the basin has become one of the important petroleum-producing provinces in the Rocky Mountains (Keefer, 1969). The success at Dallas Dome prompted thorough exploration of the numerous anticlinal structures that surround the western, northern, and eastern edges of the Wind River basin, as defined by mappable exposures of pre-early Eocene rocks or as delineated by geophysical surveys in covered areas (Keefer, 1969; De Bruin, 1993). As defined by Magoon and Dow (1994), a petroleum system consists of source rock, reservoir rock, seal, trapping mechanism and maturation-migration-accumulation components. Each of these individual components will be addressed for the Wind River basin.

2.5.1 Source Rocks

Source rocks are organic-rich sediments that have undergone periods of sufficiently high temperatures and pressures to generate and release hydrocarbons. Gries et al. (1992) identified three separate time-stratigraphic source-rock intervals in the Rocky Mountain foreland area. Figure (2.16) shows these source-rock intervals. Group I source rocks were deposited in a passive-margin setting, Group II within a foreland basin, and Group III in partitioned basins of Tertiary age (Gries et al., 1992). All three of these source-rock groups are found in the Wind River basin.

Group I source rocks are Late Precambrian through mid-Jurassic in age and formed primarily within the passive-margin setting present in Wyoming throughout all of the Paleozoic and early Mesozoic. The source rocks of this interval formed primarily in marine condensed sections or lagoonal shales that accumulated during sea-level highstands or as anoxic shales and evaporites associated with basin starvation during periods of relative sea-level lowstands (Gries et al., 1992). The primary source rock within this interval, and by some accounts, the source rock for all Paleozoic oil in the Big Horn and Wind River basins, is the Permian Phosphoria Formation (Stone, 1967; Keefer, 1969; Gries et al., 1992). Two phosphatic shale members within the Phosphoria have total organic carbon (TOC) values that range up to 4.9%, with 0.5% widely considered to be adequate for hydrocarbon generation (De Bruin, 1993).

Group II source-rocks are Jurassic and Cretaceous in age and were deposited in a foreland setting. There are both marine and nonmarine source rocks contained within this interval. The transgressive marine shales of the Skull Creek/Thermopolis, Mowry, and Cody Shales contain Type I and II marine kerogens that average 1-2% TOC and locally average as high as 3-4% TOC (Gries et al., 1992). These formations are the primary hydrocarbon source for the Jurassic Nugget reservoirs of southwestern Wyoming and reservoirs in the Cretaceous Muddy, Dakota and Frontier formations. Thick coal measures in the Frontier and Mesaverde are dominated by Type III terrestrial kerogen and may be local sources of natural gas when buried sufficiently to have undergone thermogenic generation (De Bruin, 1993).

Group III source-rock sediments were deposited on a regional unconformity, which separates the Paleocene (Fort Union Formation) and Late Cretaceous regressive sediments. The Waltman Shale member of the Fort Union Formation consists of organic-rich lacustrine sediments that provide source and seal for Group III hydrocarbons in the Wind River basin. In general, traps for Group III hydrocarbons are deep basin structures. The Madden field in the northeastern Wind River basin produces hydrocarbons sourced from Group III sediments (Gries et al., 1992).

2.5.2 Reservoir Rocks

Important producing formations of the Wind River basin include the Mississippian Madison Formation, Pennsylvanian/Permian Tensleep Formation, Permian Phosphoria Formation, Triassic/Jurassic Nugget Sandstone, Lower Cretaceous Muddy Sandstone, the Upper Cretaceous Frontier Formation, Shannon Sandstone, Lance Formation and the Tertiary Fort Union Formation (De Bruin, 1993). These represent a full spectrum of depositional settings that include eolian, coastal, fluvial, deltaic, shelf, and deepwater. Of these producing formations, most oil production is from the Phosphoria Formation and the Tensleep Sandstone (De Bruin, 1993).

2.5.3 Seals

The red shale and evaporite beds of the Triassic Chugwater Group form particularly effective seals for the Paleozoic reservoirs of the Wind River basin. Additionally, the redbeds and evaporites of the Goose Egg Formation, present in the eastern portion of the basin, provide excellent seals for the underlying Tensleep Sandstone. These seals fail when they are cut by major faults, or when the

Phosphoria/Goose Egg Formations are eroded (Stone, 1967). Traps in the Jurassic and Tertiary section are primarily stratigraphic in nature. Therefore, the seals are not regionally extensive and are provided either by unconformities or interbedded shales (Gries et al., 1992).

2.5.4 Traps

Structural closure and combination stratigraphic/structural trapping configurations are the prevalent trap type. There are no large stratigraphically controlled fields, like the Cottonwood Creek field of the Big Horn basin, found in the Wind River basin (Gries et al., 1992). Anticlines along the eastern and western edges of the basin with reverse faulting on the steeply dipping flank are the primary structural traps (De Bruin, 1993). These structural closures formed during the basement-block uplift that occurred during the Cretaceous through Oligocene Laramide orogeny. Combination traps are common along low-relief structural noses and flank-position traps (Gries et al., 1992).

2.5.5 Maturation-Migration-Accumulation

Maturation of the source rocks in the Wind River basin and the Rocky Mountain foreland occurred with the onset of the Laramide Orogeny and the subsequent deposition of thick Laramide Eocene sediments. The Cretaceous and older source rocks were buried to a depth with sufficient temperature and pressure to begin hydrocarbon generation. Group I Paleozoic and early Mesozoic sediments were buried deep enough to enter the dry-gas window in the deeper Laramide basins (Gries et al., 1992).

The basin-margin anticlines that formed as a result of the Laramide Orogeny provided structural and combination traps for oil and gas generated from the Cretaceous and younger source rocks. As a result, these hydrocarbons probably only migrated a short distance. Stone (1967) predicted that Paleozoic hydrocarbons migrated long distances, possibly through the thick Pennsylvanian Tensleep section. Love (1960) determined that Paleozoic-sourced oil did not accumulate in Paleozoic reservoirs until the Late Cretaceous to the Paleocene, which indicates that the Paleozoic oils must have migrated from earlier accumulations to new locations as a result of the Laramide deformation.

2.5.6 Local Oil Fields

Figure 2.17 shows the location of oil fields in the vicinity of the study area. No economic accumulations of hydrocarbons have been discovered to date within the study boundaries. Just outside of the study area, approximately 6 mi (10 km) north of the Alcova dam, are the Tipps, Government Bridge, and Schrader Flats oil fields. These three fields have produced a combined 4,424,299 barrels of oil from lower Cretaceous and upper Jurassic reservoirs in combination structural-stratigraphic traps (WOGCC, 2005). Local Tensleep Sandstone producing fields include Oil Mountain, Poison Spider, and South Casper Creek. Of these, South Casper Creek is the most significant with 17,321,323 barrels of oil produced from the Tensleep Sandstone since its discovery in 1919 (WOGCC, 2005). South Casper Creek is a doubly plunging asymmetric Laramide-age anticline (Figure 2.18) (Montgomery, 1996).

2.5.7 Theoretical Original Oil-in-Place Calculation for Alcova Anticline

The Alcova anticline provides a useful example for the visualization of a typical oil accumulation of the Rocky Mountain Laramide foreland. Three of the largest oil fields in Wyoming produce from the Tensleep/Phosphoria reservoirs in anticlinal closures. One of these, Hamilton Dome, in the southwest corner of the Big Horn basin, has produced approximately 261 million barrels of oil since its discovery in 1918. Table 2.1 reports the reservoir data for the Tensleep reservoir at Hamilton Dome field. These numbers are fairly typical for Tensleep reservoirs and will be used in a simple original oil-in-place calculation for the hypothetical "Alcova Oil Field."

We can suppose the situation where the Alcova anticline was buried to a depth where the Tensleep was charged with hydrocarbons and capped with a competent seal. For the sake of visualization, we will assume that the Alcova reservoir level is the oil/water contact. Additionally, we will assume that the reservoir is bounded by a fault where Lakeshore Drive cuts across the Alcova anticline. Figure 2.19 is the theoretical structure map of the reservoir. With this information and the reservoir parameters from Hamilton Dome, the amount of oil that could be held in a structure of this size can be calculated by the following equation:

$$OOIP = 7758\frac{Ah\phi(1-Sw)}{Boi}$$

This is a standard volumetric calculation where: OOIP = original oil in place, A = area in acres, h = formation pay thickness in feet, Φ = porosity, S_w = water saturation, B_{oi} = formation volume factor, and 7758 is the conversion factor from acre-ft to barrels. This calculation was made for the area of each structural closure and an h value of 100 feet with the exception of the top-most area, for which an h value of 50 feet was used. This resulted in an OOIP of 154 million barrels of oil. If we assume a 15 to 20% recovery factor, 23 to 31 million barrels of oil could be recovered from our theoretical "Alcova Oil Field."

CHAPTER 3

LIDAR ACQUISTION AT ALCOVA ANTICLINE

3.1 LiDAR Principles

LiDAR is an acronym for LIght Detection and Ranging. The LiDAR process uses a low-energy laser pulse and sensor to determine range (Jennette and Bellian, 2003). It is also known as ladar, optical radar, laser radar, or 3D laser scanning (Bellian et al., 2005). LiDAR technology was first developed in the 1960's for use in atmospheric studies (Bellian et al., 2002). Since its inception, LiDAR technology has slowly been making its way into geologic research. Terrestrial laser scanning creates a 3D data point cloud of outcrop surfaces in a rapid, accurate manner. This point cloud can be converted into a virtual 3D surface using digital surface construction in visualization software programs. These techniques can help to reduce the use of difficult, time-consuming, and potentially hazardous traditional methods of gathering outcrop data.

LiDAR uses laser light to measure distance in the same way that sonar uses sound waves or radar uses radio waves. In all three methods, a highly accurate clock records the time-of-flight for the energy pulse to strike the target and return to the source. Figure 3.1 shows the principles of LiDAR. A source emits a laser pulse, which travels to and reflects from the target and returns to a receiver. The two-way travel time is divided by 2 and multiplied by the speed of light. This gives the range, or distance, to the target. By knowing the exact location of the scanner, the location of the data point on the target can be calculated. An intensity value, i, is also recorded. This value is a measure of the amount of the original laser energy reflected, or conversely, how much of the laser energy is absorbed by the target surface. This can be affected by the color or moisture content of the surface that the laser pulse strikes (Bellian et al., 2005). This information can be related to the mineralogy of the rock unit and can aid in the determination of lithology (Bellian et al., 2002). Most scanners can collect several thousand data points per second. The collected data are stored on a portable PC for post-processing in the office.

LiDAR instruments are active scanners. This means that they generate their own signal necessary to make measurements. This is different from passive instruments, such as cameras and spectral satellites. Passive instruments rely on the present lighting and atmospheric conditions. This key difference means that LiDAR data can be collected with any amount of light, including complete darkness, and in all but the most extreme of weather conditions (Bellian et al., 2005).

3.2 Previous Ground-Based LiDAR Studies

LiDAR-derived 3D outcrop models have been used for several years for the purpose of creating large stratigraphic models. The Texas Bureau of Economic Geology (BEG) at the University of Texas – Austin has pioneered the methods used for this type of modeling on outcrops in West Texas and northern Spain (Bellian et al., 2002; Jennette and Bellian, 2003; Bellian et al., 2005). From LiDAR point-cloud data, a 3D Digital Outcrop Model (DOM) is created through creation of a triangulated irregular network (TIN) surface. Digital photomosaics and rock-property attributes can be applied to this surface and interpretations can be digitized directly on it. The BEG has built models from many square kilometers of outcrop data. Other sedimentary modeling work has been documented by Nagihara et al. (2002), Xu et al. (2002), and Loseth et al. (2003). Recently Ellison (2004) used LiDAR data to create a 3D model of fluvial channel-body geometries in the Williams Fork Formation in the Piceance basin, Colorado. The purpose of this model was to examine the effects of stratigraphic and petrophysical heterogeneity on fluid flow and storage within fluvial point-bar deposits.

Some of the first published work using LiDAR-derived 3D models to determine fracture orientations was by Ahlgren and Holmlund (2002) and Ahlgren et al. (2002). The authors collected a LiDAR survey of a fractured rock outcrop in an Arizona mine pit. The surface scanned for this study had an area of approximately 500 m^2 (5,380 ft^2). They processed the data using a proprietary semi-automated algorithm that extracted fracture geometries, intersections, trace lengths, and orientations based upon a user-defined lower threshold for fracture-plane size. These parameters provided the necessary input to generate a 3D synthetic fracture model. This model was analyzed for attributes such as fracture connectivity and drainage area. This is a powerful relationship because the modeling carried the data into the third dimension and was able to make predictions on key attributes that are very important when it comes to producing hydrocarbons from fractured reservoirs.

Work has been done by geotechnical engineers and highway engineers studying fracture and joint spacing in small highway cuts in Europe and the United States. Slob et al. (2004) proposed an approach for automated identification of discontinuity sets using clustering techniques. Their approach is based upon the assumption that the geometry of the visible rock surface is primarily determined by the discontinuity structures within the rock mass. Alternatively, every surface of the created point-cloud model is a small part of a discontinuity set and should represent a certain discontinuity set. Using a clustering algorithm, the orientation of each surface can be displayed on a stereonet where the data clusters represent discrete orientations of joint sets. This technique provides no information on joint spacing. Additionally, this method can only be applied to small-scan areas and datasets with small file sizes.

The study at Alcova anticline combines the outcrop scale of stratigraphic work that the BEG has conducted with the level of detail of the surveys of Ahlgren and Holmlund (2002) and Ahlgren et al. (2002) and Slob et al. (2004). The size and resolution of this dataset required the development of new techniques and workflows for LiDAR data manipulation and modeling. These methods may apply to future studies of this size and scope.

3.3 Previous Work with Scan-line Surveys and Fracture Data

In fracture surveys, three geometric properties are of interest: density (i.e., spacing, frequency), size (i.e., trace length, area), and orientation (i.e., strike and dip of fracture plane) (Baecher, 1983). Scan-line surveys are a quick and systematic way of collecting these data (LaPointe and Hudson, 1985).

3.3.1 Fracture Analysis Using Scan-line Techniques

For scan-line analysis, a measuring tape is laid out across the outcrop of interest (e.g., a fracture-pavement or vertical outcrop) (Figure 3.2). Along the line, spacing is measured between the intersections of adjacent fracture traces, either for individual sets of sub-parallel fractures or for all fractures. Trace length is measured as the linear distance between the end points of a fracture trace intersection with the scan line (Baecher, 1983). The orientation of the fracture traces should be recorded for use in calculating the true spacing distance and for the determination of fracture sets.

Terzaghi (1965) noted that fracture sets are progressively under-sampled as the angle between the scan line and the fracture set decreases. Terzaghi (1965) proposed a correction factor for dealing with data sets with this problem. The correction factor is related to the inverse cosine of the angle between the scan line and the normal to the fracture. La Pointe and Hudson (1985) used data from two orthogonal scan lines to reduce the bias introduced by the situation proposed by Terzaghi (1965). La Pointe and Hudson (1985) used the spacing results from the two scan lines to produce a range of possible fracture spacing, on what they called a fundamental rosette. Hudson and Priest

(1983) suggested that a survey should consist of a minimum of three orthogonal boreholes or scan lines so that no fracture sets are missed.

3.3.2 Fracture Populations

Hudson and Priest (1983) studied fracture distributions from scan-line data and concluded that the intersected trace lengths resemble a log-normal distribution. Ruf et al. (1998) concluded that in rocks without systematic mechanical discontinuities, such as granite, the fracture spacing followed an approximate log-normal frequency distribution. Ruf et al. (1998) also reported that with increasing mechanical boundaries, such as bed partings in sedimentary rocks, the distribution is more clustered around the mode than a perfectly log-normal distribution. Malmanger and Teufel (1997) conducted a geostatistical analysis of fracture network maps and scan-lines of sandstone outcrops in Wyoming, Colorado, and Texas. Based upon this analysis, Malmanger and Teufel (1997) concluded that fracture spacing and length can be approximated by a log-normal distribution.

As opposed to a log-normal fracture distribution, Marrett (1996) concluded, based upon empirical studies, that the individual attributes of both faults and extensional fractures follow power-law relationships. Cladouhos and Marrett (1996) referenced eight field studies from a variety of tectonic settings of fault length versus frequency and concluded that the population followed a power-law distribution. Cladouhos and Marrett (1996) suggested in a fault population with a power-law length distribution, the number of faults (N) of length ≥ L is

$$N_{\geq L} = (L/L_{max})^{-C}$$

where L_{max} is the length of the longest observed fault and $-C$ is the slope of a line fitted to fault length (L) vs. fault cumulative frequency (N) on a log-log graph. One of the data sets used was from Blackstone (1988). This data set represented a Laramide compressional setting. Marrett et al. (1999) concluded that lengths of natural faults and fractures exhibit a simple power-law distribution, regardless of rock-type or movement mode. This conclusion was based on data from Cladouhos and Marrett (1996) and new field and core studies.

3.3.3 Recent Wyoming Fracture Studies

Vealy (1991) reported on the fractures he observed while completing his stratigraphic interpretation at Alcova anticline. Vealy (1991) interpreted two major fracture directions with orientations of N80˚E and N75˚W. He found the N80˚E set to be prevalent on the back limb of Alcova anticline and noted several large fracture zones of N80˚E orientation that he believed could be interpreted across the canyon to the opposing outcrop. Vealy (1991) noted the N75˚W orientations primarily along the fold axis. He noted orientations of NW and NNE and observed that the orientations were constant through all stratigraphic horizons. Hickman (1989) found the same major fracture directions and lumped the N80˚E and the N75˚W into a general east-west set. Vealy (1991) estimated that 95% of the fractures were open, uncemented, unmineralized, and unfilled.

Maraj (2003) built a 3D geologic model of the CEPO/Powder Mountain area, Washakie basin, Wyoming, to examine the varied production from wells in the Lewis Shale. Borehole image logs and cores provided the input for fracture orientation and intensity. Maraj (2003) used this geologic model to create two 3D fracture models. One fracture model was generated using a method that related fracture occurrence to curvature, a geometric attribute of the bedding layers. The other model used the fracture orientation and intensity data collected from the core and borehole-image work. Doupe (2005) examined faults and microfaults and their role in compartmentalization of the reservoir at Cave Gulch field, Wind River basin, Wyoming. Doupe (2005) examined borehole image logs from the field and interpreted bed boundaries, fractures, and microfaults. She then built a 3D model of the reservoir section. Using the fracture and fault data from the borehole image logs as input parameters, Doupe (2005) generated a fracture model throughout the reservoir interval. This model was used to predict the size of fault and fracture-bounded compartments within the Cave Gulch field and the effects they would have on production.

3.4 LiDAR Acquisition Program at Alcova Anticline

We collected the LiDAR dataset at Alcova anticline during one week in June, 2004. Western Mapping of Tucson, Arizona, did the LiDAR data acquisition and processing. Prior to data collection, we provided outcrop photos, maps, aerial photos, and outcrop dimensions to Western Mapping. There are several 3D laser scanners on the market today with a variety of optimal scanning ranges, each with strengths and weaknesses. Based upon the estimated distances in the study area and the requirement of resolving planar features 1 m^2 (11 ft^2) and greater, Western Mapping selected the most appropriate scanner and designed the survey before they went to the field.

Initially, two members of Western Mapping arrived at Alcova anticline to prepare the site for LiDAR acquisition. The Western Mapping team completed a regional surveying project of the vicinity. This was necessary to place the LiDAR data into the local coordinate system. The local coordinate system chosen for this survey is UTM Zone 13N, NAD 1983 to remain consistent with the coordinate system used for the geologic mapping. The Alcova LiDAR dataset was referenced to Bureau of Reclamation benchmarks on the Alcova dam and the southeast outcrop. Additionally, Western Mapping placed and surveyed four (two on each side of the river) survey nails into the outcrop (Figure 3.3). As discussed in Section 3.1, it is necessary to know the precise location of the scanning unit to accurately determine the position of the target, in this case, the opposing canyon wall.

Upon completion of the local survey, the outcrop was prepared for LiDAR data acquisition. Targets, approximately 12 x 12 cm (5 x 5 in) were placed by boat along the water's edge at the base of the outcrop and along the top of the outcrop. These targets have a highly reflective surface that returns a high intensity value to the scanner. This intensity value is much higher than any of the surrounding rocks or vegetation and is clearly visible in the unprocessed, raw data. The locations of these targets are precisely surveyed and provide the basis for georeferencing the LiDAR data to the local coordinate system as defined by the initial surveying.

Once the site preparation was complete, the third member of the Western Mapping team arrived with the LiDAR laser scanning unit. The scanning setup consisted of a laser scanning unit with tripod, a laptop running the scanner's acquisition software and a generator to provide power for the scanning unit and PC (Figure 3.4). The entire set up was extremely mobile and could be moved to different locations on the outcrop with minimal difficulty. The operator entered parameters for each scan into the PC. These included the maximum angle of rotation and declination for the scanner, which fixed the amount of outcrop to be scanned. The amount of outcrop scanned in each pass was limited by the range of the scanner. Additionally, each scan had to include at least four of the highly-reflective targets and overlap the adjacent scan. This is necessary for processing and georeferencing the dataset. Once the scan was initiated, no additional input was necessary and when the scan was complete, the scanner was packed up and moved to the next location on the outcrop. Each scan took between one and two hours, depending on the size of the outcrop panel being collected. Each outcrop was covered with five overlapping scans, with additional scans being made from the dam itself. It took less than three days for the scanning portion of the survey.

The scanner used for this survey was the Trimble GS200 3D Laserscanner. This specific scanning unit has a recommended range of 1-200 meters and is capable of collecting data at rates up to 5,000 points per second. The scanner has a 360˚ horizontal field of view and a 60˚ vertical range.

After acquisition, Western Mapping post-processed the raw data. This occurred over a period of seven months in their Tucson facilities. The processing was necessary to remove any errant data points caused by vegetation or anthropogenic sources. When these sources of noise were removed, the raw data were georeferenced using the surveyed targets. Western Mapping delivered to CSM cleaned, processed ASCII files containing X, Y, and Z coordinates measured to the 10^{-6}m for each panel of the outcrop scans. The total number of data points for both sides of the river is approximately 12 million. The data points have an average spacing of 1 cm (0.4 in) and the total scanned area is approximately 73,000 m^2 (785,500 ft^2) These ASCII files are the basis for the interpretation of fractures at Alcova anticline. Western Mapping georeferenced and draped high-resolution digital photos of the outcrop over the data set. The draped digital photos were used to create an animation of the canyon walls for promotional purposes. ASCII files of the LiDAR point cloud data, the digital outcrop photos, and the animation file are included in the "LiDAR DATA" folder on the accompanying DVD-ROM.

3.5 Fracture Analysis from LiDAR Dataset

This section describes in detail the interpretation and analysis methods used on the LiDAR dataset acquired at the Alcova anticline.

3.5.1 Interpretation Methods

The method of fracture interpretation is diagrammed in Figure 3.5. The first step in the interpretation process was to load the panels of point-cloud data delivered from Western Mapping into Midland Valley Exploration's 3DMove4.1 structural interpretation software package. This program is run on an SGI Octane2 with 2 gigabytes of RAM. Several software packages on PC, UNIX, and Linux platforms were tested to determine their ability to handle the size of dataset the LiDAR data gathering method delivers.

3DMove4.1, running on the UNIX platform, performed best during testing and was chosen for data analysis. Additionally, 3DMove4.1 is the software package used for the creation of the 3D geologic model over Alcova anticline and thereby allows for comparison of results on the same platform. The point-cloud file size did not allow for the interpretation to be conducted on the whole dataset for each outcrop. The interpretation was divided into the five panels delivered by Western Mapping. At the end of the interpretation, the files were merged to cover each outcrop. Figure 3.6 is an example of the loaded point-cloud data. During the loading process 3DMove4.1 allows the user to decimate the dataset. This decimation simply skips subsequent data lines from the ASCII file according to the decimated degree desired. For this study, decimation to 20% of the original data density provided an acceptable balance of data resolution compared to computer processing speed. With data points at spacing of approximately 1 cm (0.4 in), loading every fifth data point will still result in an overall resolution of approximately 5 cm (2 in). Due to the presence of numerous small-scale planar features, I only interpreted fractures with a trace length greater than 5 m (16 ft) for this study.

Once I loaded the data points for each panel, a triangulated irregular network (TIN) algorithm was run to generate a surface over the data points. A TIN surface is created by forming a series of triangles between each data point and all of its neighbors (Figure 3.7). The reason for choosing this algorithm is that it honors all data points. Figure 3.8 is a side-by-side comparison of the TIN surface created from the 20% decimated data point-cloud and a high-resolution digital photograph of the corresponding region on the outcrop. The majority of the features that can be seen on the photo can be seen on the TIN surface. On this TIN surface, linear features are traced (Figure 3.9). Based upon comparison to outcrop photos, these linear features are expressions of fractures. 3DMove4.1 allows the user to trace lines on a surface by picking two endpoints. Where appropriate, fracture traces on either side of covered zones were connected to form one fracture. 3DMove4.1 saves these endpoints in a data file, thereby creating a unique feature that can be manipulated later. These endpoints can be exported in an ASCII file, important for later analysis. These methods result in an interpretation that provides the basis for a detailed analysis of fracture height and spacing; however, the same could be done on a georeferenced outcrop photo mosaic. Determination of the corresponding orientation of each fracture, which can only be done using the LiDAR data, requires further processing and interpretation steps.

Once all of the TIN surfaces were generated, I removed the point-cloud data from the surface file to save memory. The next step in the interpretation process was to assign an orientation to each triangle in the TIN surface. An algorithm in 3DMove4.1 generates the azimuthal strike and dip value for each triangle of the TIN surface. The orientation is stored as an attribute of the TIN surface to which a color map can be applied. Figure 3.10 shows a 0-360 degree color map applied to a panel from the northwest outcrop. Features of similar strike have the same color. The majority of orientations on the outcrop are roughly parallel to the outcrop face, which results in the dominant blue/green coloration, which corresponds to strikes between N40˚E and N60˚E. This orientation range is approximately that of the river cut. However, areas of different color are observed. Figure 3.11 is a close-up view of a panel near the northwest outcrop crest. The linear bands of yellow are presumed to be fracture planes with the yellow corresponding to an orientation of between N50˚W and N60˚W. This relationship provided the basis for the interpretation of fracture orientation.

I created a set of four custom color maps in 3DMove4.1. These color maps illuminated orientations between 0-89˚, 90-179˚, 180-269˚, and 270-359˚. Only features within these orientation groups are visible when the color map is applied to the TIN surface. The other orientations of the surface are blacked out (Figure 3.12). Within these color maps, orientation values are divided into 30 degree bins. Assigning data to a 30 degree bin of possible orientations is acceptable based on the decimated nature of the data and the effects of erosion on the outcrop. This bin of data was compared to the outcrop measurements collected in this study as well as to those of Hickman (1989) and Vealy

(1991). From this comparison, a final orientation was assigned. Based upon average strike azimuth readings, the fracture sets were named: N10˚E, N50˚E, N80˚E, and N55˚W. Additionally, the N55˚W set was divided into two subsets depending on observed direction of dip, either to the northeast or the southwest.

I assigned orientations to the previously interpreted linear features by loading each of the four custom color maps and determining the best fit of orientations to each interpreted linear feature. The lines were color-coded based upon the assigned orientation (Figure 3.13). This was a time-consuming process that had to be done several times for each data panel. In most cases, it was necessary to toggle back and forth between the various color maps and black and white views to complete the interpretation.

When all of the fractures had been assigned an orientation, the line files were combined into a single file for the northwest outcrop and a single file for the southeast outcrop. The resolution of the TIN surfaces was decreased to save file size. For each line, a plane was projected from each linear feature in the direction of the orientation assigned to it (Figure 3.14). This surface, which represents the fracture plane, creates the three-dimensional planes that are required to determine fracture spacing and frequency. Intersection of these planes on a surface, either flat or curved, allowed analysis using traditional scan-line techniques.

3.5.2 Analysis Methods

3DMove4.1 has a built-in planar-feature analysis tool that allows the user to examine planar features in different regions of the model. Rose diagrams and stereonets are generated based upon the planar data. These tools provide a quick look at the general relationships of the fracture sets, but a more detailed analysis is required for fracture spacing, frequency, and height data. Fracture spacing is the perpendicular distance between fractures of the same set. Fracture frequency is the number of fractures intersected per unit distance along a scan line. Fracture height is the length of the line of intersection of a fracture plane with a vertical plane that is oriented perpendicular to the fracture plane. Two separate analyses were required to determine the fracture spacing and the fracture height.

Spacing values were calculated for all fracture sets and for a combined set. Frequency was only calculated for the entire population. To examine the changes in fracture frequency and spacing in a geologically significant manner, curved scan lines were created in the middle of lithologic bedding boundaries. The flow units that Vealy (1991) delineated were used for comparison to his lithologic descriptions to determine what, if any, correlation there was to lithology in the fracture frequency and spacing. Vealy's (1991) boundaries were interpreted by hand onto the outcrop photomosiac (Figure 3.15) and transferred to the LiDAR dataset. Curved scan lines were picked in the middle of Vealy's (1991) Flow Units 10, 9, 8, 7, 6, and 5.

3DMove4.1 has functions that allow the user to export data files of the lines created by the intersection of planar features with a horizontal plane. These lines, which represent the fracture planes, are necessary to perform the scan-line analysis. Because 3DMove4.1 can only calculate the intersections on a horizontal plane, the curved scan lines must be flattened in a structurally correct way. Structural restoration algorithms within 3DMove4.1 were utilized to achieve this goal.

Planes were projected from the scan lines out of the outcrop in the direction of the axis of the anticline (Figure 3.16). The plane-projection algorithm in 3DMove4.1 creates the new surface using a densely spaced network of data points used to create a TIN. The density of these created data points is greater than necessary for the flattening procedure and increases processing time. For that reason, the curved scan-line planes were resampled to 25% of the original data points. This creates a smooth surface, defined by fewer triangles, and increases processing efficiency.

The flattening of the curved scan-line plane used the Flexural Slip Unfolding restoration module in 3DMove4.1. This module allows the user to input a surface to be flattened and surfaces that are considered passive objects. Passive objects move along while the target surface is flattened. The curved scan-line surface for each flow unit was flattened to a target elevation of 1780m. This elevation was arbitrarily chosen and had no effects on the results of the flattening process. To complete the flattening process, the user must select a transport plane and a pin plane (Figure 3.17). The transport plane is a vertical plane that defines the unfolding direction. The strike of the transport plane should be oriented perpendicular to the hinge of the fold. The strike of the transport plane was determined using the π-method of plotting poles (Marshak and Mitra, 1988). The pin plane is the plane from which the unfolding occurs. Points of the template surface which intersect the pin plane are not translated horizontally. The pin plane should be oriented parallel to the axial plane of the fold. The axial plane of the fold was also determined using the π-method of plotting poles (Marshak and Mitra, 1988). The pin plane was placed on the back limb of the fold. Tests were conducted with varied placement of the pin plane on the structure. The results were identical for placement on the back limb and on the crest of the fold.

The unfolding algorithm allows the fracture planes to unfold as passive objects. As a result, the locations at which they intersect the scan line remain unchanged (Figure 3.18). Using the Cross Section tool in 3DMove4.1, a horizontal section can be created at 1,780 m. The fracture planes are now represented as a series of 2-D lines. Fractures that belong to the same set are parallel and have the same color (Figure 3.19). This section is exported as a DXF file and opened in Midland Valley Exploration's 2DMove3.8 structural analysis software. I drew a scan line oriented roughly parallel to the river cut. I used various line orientations to try to intersect as many interpreted fracture planes as possible (Figure 3.20). The fracture traces are extended to intersect this line, and marks are placed along the scan line every 10 m (33 ft). These marks are used to calculate moving-average values along the scan line. A function in 2DMove3.8 calculates the locations of the intersections of the fractures along the scan line. These are exported as an ASCII data file with the X, Y, and Z locations, and color-code listed. This file is opened in Microsoft Excel. The X and Y locations are used to calculate spacing along the scan line for the bulk fracture population using the formula:

$$S_d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

where S_d is the distance between fractures (Figure 3.21a).

For the bulk fracture population, a moving average was calculated along each scan line to show changes in spacing values and frequency across the structure. An average was calculated at a station every 10 m (33 ft), using all values +/-10 m (33 ft). This moving-average calculation was made for both the spacing between fractures and the frequency, in fractures/m, for each scan line. This process was completed for a total of 12 scan lines.

For the N10˚E, N80˚E, and N55˚W fracture sets, the same scan-line orientations used to calculate of the bulk fracture sample were used to calculate the spacing of the individual fracture sets. The same method was used with the addition of a step to correct for the true spacing value because the orientation of the scan line is not perpendicular to the fracture-set orientation (Figure 3.21b). The correction is as follows:

$$S_t = S_d \sin\theta$$

where S_t is the true (perpendicular) spacing value, S_d is the calculated spacing value along the scan line, and θ is equal to the angle between the scan line and the fracture-set orientation. This data can be presented as a series of frequency distributions for each fracture set from each scan line. Due to the fact that the orientation of the N50˚E fracture set runs almost parallel to the scan-line orientation, alternate scan lines were needed to determine the spacing of this fracture set. Scan lines of 70˚ and 210˚ were drawn over as many of the N50˚E set fracture traces as possible. This allowed calculation of the true fracture spacing, as described previously. Fracture height is calculated using the X, Y, and Z locations of the endpoints of the user-defined linear features. 3DMove4.1 allows the user to export the endpoints as an ASCII file. This ASCII file was loaded into Microsoft Excel. Because the outcrop is not completely smooth and the face is not vertical, the distance between the two endpoints is not equal to the true fracture height. This relationship is shown in Figure 3.22a. To determine the true fracture height, a series of geometric transformations must be made. This process is outlined in Figures 3.22b & 3.22c. The fracture heights were kept as a bulk population for both the northwest and southeast outcrops and were not divided according to structural position.

3.6 Results

This section presents the results of the interpretation and analysis for the LiDAR dataset. The results are divided into sections for bulk fracture population analysis, individual fracture set spacing analysis, and fracture height analysis.

3.6.1 Bulk Fracture Analysis

This study resulted in the identification of three major fracture populations and one minor fracture population from LiDAR data analysis. The major fracture orientations are N80˚E (oblique to the anticlinal axis), N50˚E (perpendicular to the anticlinal axis), and N55˚W (parallel to the anticlinal axis). The minor fracture orientation is N10˚E (oblique to the anticlinal axis). Figure 3.23 shows the relationship of the fracture orientations to Alcova anticline. Figure 3.24 is a stereonet of poles to the fracture planes for all fractures from both outcrops. The N55˚W fracture set can be divided into subsets, one that dips to the southwest and one that dips to the northeast. The magnitude of dip ranges from 55˚ to 81˚ for the fracture sets. Figure 3.25a shows a series of rose diagrams created at various structural positions across the northwest outcrop. Figure 3.25b shows a series of rose diagrams constructed by Hickman (1989) from fracture measurements across the top of the structure. There is good correlation between the LiDAR-derived fracture orientations and those measured by Hickman (1989). Figures 3.26a – 3.26l show the spacing and frequency values for the bulk fracture population in relation to structural position on Alcova anticline. Figures 3.26m – 3.26n show the spacing and frequency values for the N55˚W fracture set in relation to structural position on Alcova anticline for Scan Line 8. Fracture spacing values greater than 20 m are most likely the result of covered sections due to erosion. The fracture spacing generally decreases and the frequency generally increases from the back limb to a maximum on the crest and decreases on the forelimb. The exception is a series of fracture swarms on the back limb. These fracture swarms can be traced across the canyon to the opposing outcrop and have an orientation of N80˚E. The fracture spacing value rapidly decreases from averaging over 5 m to less than 2 m in a short distance at these locations. As a result, the fracture frequency at these locations is greater than at the crest.

3.6.2 Individual Fracture Set Spacing

For the calculation of the individual fracture set spacing, the results from the same scan lines on either outcrop were combined. This was done to increase the sample number. Priest and Hudson (1976) suggested that at least 200 individual measurements were required to fit a distribution curve to fracture spacing or length data. It is unlikely that the majority of the individual fractures identified on the northwest outcrop are long enough to reach the southeast outcrop (the fracture swarms are composed of many smaller fractures, which forms a much larger linear feature). The increase in sample number is necessary to fit curves to the data and determine the style of distribution (power-law or exponential) that the data may follow. Figure 3.27 show cross-plots of the arithmetic and geometric means of each fracture set, for each scan line. The 1:1 correlation line is drawn and for the most part, there is not a great deviation from it. The exceptions are the N10˚E set and the southwest-dipping subset of the N55˚W set. The N10˚E set has a very low sample number. There appears to be an outlying data point in the N55˚W set that is skewing the distribution. The outlier is most likely the result of a covered section of the outcrop. Because there is no systematic difference between the two data sets, the scan line results from the same stratigraphic level on either side of the river can be combined for later analysis.

Spacing-distance histograms and cumulative frequency vs. spacing plots for each fracture set from Scan Line 8 are shown in Figures 3.28a-3.28e. The data were divided into 2 m (6.5 ft) bins for distribution analysis. I chose to present the results for Scan Line 8 because it is the longest scan-line with no extensive covered regions. The cumulative-frequency graphs are plotted on log-log scales to check for power-law relationships using the methods of Marrett (1996), Cladouhos and Marrett (1996) and Marrett et al. (1999). The remaining plots are located in Appendix A on the included DVD-ROM. A Microsoft Excel file of the fracture spacing data is located in Appendix B on the included DVD-ROM. Examination of the histograms indicates that the fracture spacing values for all of the data sets are not normally distributed. There are a greater number of smaller spacing values than large spacing values. For this reason, an arithmetic mean may not be the most accurate representation of the spacing. Instead, the geometric mean is calculated for each data set. The geometric mean is the *n*th root of the products of the *n* observations, or equivalently, the arithmetic mean of the logarithms of the observation. The geometric mean is used for asymmetrical, or skewed, frequency distributions (Davis, 1986). Table 3.1 reports the arithmetic and geometric means for each fracture set, for each scan line. Figure 3.29 is a plot of the geometric mean of each fracture set for each scan line.

Trend lines, with their respective equations and regression coefficients (R^2 values), are plotted on Figures 3.28a - 3.28e. A log-normal distribution function was applied to the spacing-distance histogram. A power-law distribution function was applied to the cumulative frequency vs. spacing plot. The maximum and minimum data points were removed to eliminate end effects. In all cases, the power-law function was a better fit to the data. The implications of this will be discussed in a later section.

3.6.3 Fracture Height

For the same reasons used for fracture-spacing data, the fracture-height samples were combined for the northwest and southeast outcrops. Figures 3.30a – 3.30f show height-distribution histograms and cumulative frequency vs. height plots for all fracture sets and for a combined set. For both the histogram and cumulative frequency vs. height plots, any fracture-height values less than 5 m (16 ft) were removed from the data set. This is because a lower threshold value of 5 m (16 ft) was used when picking the data. Some fractures less than the threshold were inadvertently picked. As a result, it is an under-sampled population and should be removed. After removal of fractures with height < 5 m (16 ft), a total of 575 fractures remained. As with the spacing values, log-normal and power-law distribution trend lines were fitted to the data. The power-law distribution was the better fit in all cases. Table 3.2 displays the arithmetic and geometric mean fracture heights for each fracture set. The fracture height is not a normal distribution, so again, the geometric mean is the preferred average value. Table 3.3 reports the power-law exponent, or the slope of the trend line, *-C* of Cladouhos and Marrett (1996), on a log-log plot. A Microsoft Excel file of the fracture height data is located in Appendix C on the included DVD-ROM.

<u>3.7 Discussion</u>

In general, the results of the LiDAR interpretation for fracture orientation are consistent with those determined by outcrop studies (Hickman, 1989; Vealy, 1991). The major exception is that this study found a greater population of the N50˚E fracture set. This may be due to the accessibility of the outcrop. This particular fracture set is best observed at the base of the outcrop, near the water's edge. This is in contrast to the top of the outcrop, where most of the outcrop fracture data were collected by previous workers.

3.7.1 Advantages for LiDAR Analysis of Rock Outcrops

LiDAR methods of analysis allow geologists to gather rock-surface data without having to get near the surface of the rock face. Scan-line surveys and cell mapping are the traditional methods of determining discontinuity properties. However, all manual field survey methods have three main disadvantages: large errors are often introduced due to sampling difficulties and human bias, safety risks are considerable on steep and unstable slopes, and direct access to rock faces is often difficult or impossible (Kemeny and Post, 2003). These disadvantages exist at Alcova anticline. LiDAR analysis also allows the geologist to bring the outcrop back to the office and work without the limitations of field work, such as daylight and adverse weather. To recreate the analysis performed at Alcova anticline by hand would require at least a team of two, armed with ropes and a boat and enough time to traverse both outcrops while suspended from the top of the cliff.

The TIN surface created from the LiDAR data has the advantage of being a surface with relief vs. the flat surface of an outcrop photo. The TIN surface is three dimensional and the interpreter can manipulate a variety of attributes to analyze the data. The outcrop can be viewed from any angle the interpreter chooses. The lighting angle can be changed to illuminate features that might not be clear on the photograph. No matter what the resolution of the outcrop photo, it still only captures a 2D view of the outcrop, specific to lighting conditions and angle of photography at that moment.

3.7.2 Potential Bias with LiDAR Analysis

A major disadvantage of using traditional scan-line techniques to analyze fractures is the bias introduced by the data collector. Unfortunately, the human bias element was not removed from this study. The method of assigning an orientation to the fracture traces is highly subjective. Similar to working with seismic data, the interpreter, consciously or subconsciously, allows preconceived notions and views to affect the interpretations. While it is necessary to check the LiDAR interpretations with the field observations with this method, it would be preferred to compare results after interpretations are complete. Hopefully, future work at Alcova anticline will lead to the reduction of this bias through the development of automated methods of LiDAR interpretation.

3.7.3 Significance of Spacing and Frequency Moving Averages

This data set can be directly compared to geometric attributes of bedding such as dip, rate of dip change, and curvature. Additional steps allow it to be compared to dynamic attributes, like strain. These attributes are derived from a 3D geologic model of the structure, the topic of the following chapter.

The location of increased fracture development provides an important insight into how effectively a reservoir might drain. Vealy (1991) reported that, at least at the surface, 95% or greater of the fractures were open with no apparent sign of mineralization or cementation. List (1995), in a study of the Tensleep reservoir at South Casper Creek field, determined that 75% of the fractures were open at depth. This is significant because open fractures are initially going to allow rapid drainage of the reservoir. When the field matures and secondary and tertiary recovery plans are designed, the engineer needs to know where the greatest number of fractures is going to be found. Fractures are high-permeability zones that act as preferential flow paths and lead to fast breakthrough times of flooded water or CO_2. If the location of these fractures can be related to a geometric attribute, such as dip, rate of dip change (simple curvature), or Gaussian curvature, this will provide a greater insight into the efficiency of the design. Dip, rate of dip change, and Gaussian curvature are values that can be calculated from a horizon created from seismic data or well tops.

3.7.4 Fracture Spacing Data Trends

For all fracture sets, the geometric mean spacing values of fractures with a height greater than 5 m (16 ft) are less than 10 m (33 ft). The N50˚E fracture set has the smallest spacing value at approximately 1 m (3.3 ft). The N80˚E fracture set is the next most closely spaced set at approximately 2 m (6.5 ft). The N10˚E and N55˚W fracture sets have a range of geometric means of approximately 5 to 8 m (16 to 26 ft). For all fracture sets, there does not seem to be a systematic increase or decrease in fracture spacing between scan lines (Figure 3.29).

The observation that the range of fracture spacing values appears to be consistent with a power-law distribution is significant in that a power-law distribution for fracture spacing has not been discussed in the literature. Marrett (1996), Cladouhos and Marrett (1996) and Marrett et al. (1999) provided evidence for other fracture and fault attributes that exhibit power-law relationships, such as length, displacement and kinematic aperture. Ruf et al. (1998) and Malmanger and Teufel (1997) presented data that supported a log-normal distribution for fracture spacing. Log normal and power-law functions are similar and it is reasonable that the distributions of Ruf et al. (1998) and Malmanger and Teufel (1997) could be reinterpreted as power-law distributions.

3.7.5 Fracture Height Data Trends

The geometric mean of the fracture height values ranges from 14 m (47 ft) to 24 m (79 ft) (Table 3.2). This is a tight spread of data considering the number of data points and the different fracture orientations. The thickness of the Tensleep Sandstone at Alcova could influence the maximum fracture height. If this the case, then the fracture height distribution could be used to predict fracture height across the entire anticline, regardless of fracture orientation.

Knowing the fracture height, fracture length can be estimated by using an aspect ratio. The aspect ratio is the fracture height divided by the fracture length. In this case, the height distribution is known. If there is a reasonable range of possible aspect values, the distribution of possible lengths can be calculated. This is highly useful for discrete fracture modeling.

In the fracture models generated by Maraj (2003) and Doupe (2005), the greatest unknown was the fracture length. Both Maraj (2003) and Doupe (2005) had borehole image logs and core, which provide accurate orientation and spacing data, but results are limited to the width of the borehole. Maraj (2003) used outcrop data from a study by Harstad et al. (1995) of the Frontier Formation at Muddy Gap, Wyoming. Maraj (2003) calculated an aspect ratio from the average bed thickness of the Lewis reservoir at CEPO/Powder Mountain field and the average fracture length from Harstad et al. (1995) to use in the fracture modeling. Doupe (2005) determined fault lengths from the equation presented by Cladouhos and Marrett (1996) with the exponential coefficient *(-C)* of -1.11, as determined from the Blackstone (1988) study and fault-length data consistent with Cave Gulch field. Doupe (2005) selected the default aspect ratio in 3DMove4.1 of 0.5. This aspect ratio constrained the fault heights to within the reservoir boundaries at Cave Gulch field.

Marrett et al. (1999) proposed that fractures lengths exhibit a simple power-law distribution, regardless of rock type. If that is the case, the equation of Cladouhos and

Marrett (1996) could be used in conjunction with the *C* values determined from this study as inputs into fracture models.

The C values determined for fracture heights from this study range from -1.61 to -2.85 for the individual fracture sets and -3.03 for the combined data set. This is considerably higher than the -1.11 for fault lengths determined by Cladouhos and Marrett (1996) to describe the Blackstone (1988) dataset for a Laramide setting. However, the fault lengths used from the Blackstone (1988) data range from 5 to 50 km (3 to 30 mi). Cladouhos and Marrett (1996) noted that the power exponent for smaller faults will be equal to (C + 1), which implies that the power exponent will increase as the fault length decreases. All the fracture heights determined from the LiDAR data are less than 100 m (330 ft), which could explain the elevated C values at Alcova anticline. It is possible that inhomogeneities caused by rock layering will yield different C values for fracture heights than fault lengths, as seen in map view.

3.7.6 LiDAR Data Acquisition

The data of highest quality in this study occurred in the regions where panels overlapped. Workers at the Texas Bureau of Economic Geology have determined that 10% overlap provides an effective amount for their stratigraphic studies. This was one factor considered in designing the LiDAR data acquisition. Smaller overlap helps to keep the file sizes smaller, as well. However, the work of the Texas Bureau of Economic Geology focused on analysis of digital photographs overlain on the outcrop model. The Alcova study was entirely dependent on the outcrop model. This type of work in the future should have 100% overlap. Each portion of the outcrop should be scanned from at least two scanner locations.

CHAPTER 4

GEOLOGIC MAPPING AT ALCOVA ANTICLINE

4.1 Purpose

The purpose of geologic mapping at Alcova anticline has been to obtain accurate X, Y, and Z locations for formation contacts, outcropping faults, bedding attitudes, and general field observations. This level of detail is necessary to aid in the construction of a 3D geologic model of the study area. The mapped area is outlined in Figure 2.4. This work can help test the validity of interpretations of previous workers (Bradely, 1935; Sheffer, 1951; and Mitchell, 1957).

Field mapping was completed during three field sessions in June, October, and December, 2004. During the December field session, the water level in the reservoir was approximately 4.5 m (15 ft) lower than in June and October. This allowed for more detailed mapping along the shoreline of the reservoir.

Field data were used to calibrate aerial photo interpretations for areas not visited in the field, primarily due to access issues. Examples are formation contacts at the extreme western and eastern boundaries of the map area. In these cases, interpretations were made from field data overlain on an aerial photo. In some cases, such as the Tensleep/Goose Egg contact, it was easier to map from the aerial photo due to a pronounced color variation that is apparent in the photo, but is not clear in the field.

4.2 Faults at High Angles to Thrusts in Laramide Basins

Numerous faults at high angles to Laramide thrusts have been documented in both subsurface and outcropping anticlines. These faults range in scale from 1 – 10 m (3-33 ft), with right- or left-lateral offsets of sedimentary units to other, large throughgoing faults that offset anticlinal hinge lines 100's of meters. Several Laramide structures are apparently abruptly terminated against features at high angles to basement thrusts. A review of pertinent studies is necessary to help understand the possible mechanisms behind deformation at Alcova anticline and the resulting surface expression.

Stone (1969) used the term "trapdoor" structure to describe an arcuate uplift formed by the syngenetic development of a wrench fault and a high angle thrust fault (Figure 4.1). From this model, Stone (1969) suggested the following fundamental principles: 1) faults are finite objects and separation and slip must range from zero to a maximum and back to zero again, 2) a component of vertical separation and slip must accompany lateral movement along wrench faults, 3) separation and slip can vary considerably in both magnitude and direction, and 4) wrench faulting is initiated at some depth below the surface but gives way to other compressional features at the surface including folds and thrust faults. Stone (1993) provided an outcrop example of a trapdoor structure at Beer Mug anticline in the eastern Hanna basin, Wyoming. Beer Mug anticline is an asymmetric fold bounded to the south by an approximately east-west oriented high-angle fault. Vertical and lateral separation placed easily eroded Cretaceous shales against the Tensleep Formation in the core of the anticline, resulting in the apparent abrupt termination of the anticline.

Hennings and Spang (1987) examined the development of the Dry Fork Ridge anticline on the northeastern margin of the Bighorn Mountains, near the Wyoming/Montana border. Of particular interest was the northern termination where the underlying thrust fault of the Dry Fork Ridge anticline is interpreted to intersect two transversely oriented (N40˚E), steeply dipping basement faults. Local dip changes in the

Madison Limestone along the hinge of the anticline pinpoint the location of these faults. This abrupt change in hanging-wall displacement forms two basement corners. Figure 4.2 is a block diagram of the basement that illustrates this concept. The difference in hanging-wall displacement decreases along trend for 6 km (3 mi) until the backlimb is unfaulted. The abrupt change in structural relief at the basement corners is dissipated gradually in the sedimentary column. As a result, folding continues away from the basement corner with faults fully contained within the Paleozoic and Mesozoic layers (Hennings and Spang, 1987).

Approximately 100 km (60 mi) to the south along the Bighorn Mountain front, Stone (2003) examined the Piney Creek thrust and its interaction with the Granite Ridge tear fault. The Piney Creek thrust had previously been interpreted to terminate against a high-angle transverse fault. Based upon detailed subsurface data and structural balancing techniques, Stone (2003) determined that the Piney Creek thrust did not terminate, but instead lost displacement across the Granite Ridge tear fault. Figure 4.3 is a block diagram that illustrates the development of the Piney Creek thrust. As shown, the Granite Ridge fault originates in the Piney Creek thrust and propagates and loses displacement upward and westward into the backlimb. According to Stone (2003), tear faults: 1) form by differential movement within the hanging-wall of a thrust, 2) strike in the general direction of tectonic transport along the underlying thrust, and 3) dip at high angles. Stone noted that the Granite Ridge tear fault terminates against the Piney Creek thrust, forming a basement corner and the footwall is not affected. Stone (2003) determined ~4,750 m (15,000 ft) of net left-oblique slip of the basement.

Brown (1988; 1993; 1997) described basement faults at high angles to underlying thrusts to explain offset anticlinal hinges. Brown (1988; 1993; 1997) called these compartmental faults. According to Brown (1997), compartmental faults: 1) are of limited areal extent, oriented transverse to a fold trend with a decrease from maximum vertical separation to zero at the finite ends, which results in a net oblique slip, 2) may terminate folds abruptly and result in apparent lateral offset of folds between compartments, 3) changes in direction of fold asymmetry and vergence may occur abruptly across compartmental faults, 4) structural balance is maintained across adjacent compartments. Brown (1988; 1993) used an example from five basement-involved anticlines in the Bonanza-Zeisman Dome area of the Big Horn basin. Brown (1988; 1993) interpreted the structures to be part of a single shortening event with compartmentalization resulting from oblique slip along faults formed by the reactivation of zones of weakness in the Precambrian basement during Laramide deformation. Figure 4.4 is a block diagram of Brown's (1993) interpretation of the basement and a map of the surface traces of the anticlines. From well log and production data, Woolf (2005) interpreted compartmental-style faults cutting the footwall and hanging wall of Hamilton Dome, Big Horn basin, Wyoming.

Locally, Mitchell (1957) recognized high-angle faults at Bates Park anticline, the next structure to the northeast of Alcova anticline. Bates Park anticline is an asymmetric, doubly plunging fold with an orientation of N35˚W. Mitchell (1957) mapped two east-west oriented faults that cut the Cretaceous formations at the crest of the structure. Figure 4.5 is a map of Bates Park anticline. The southernmost fault has 160 m (525 ft) of net slip. The axial trace is offset by 152 m (500 ft) to the west. The northern fault has a measured slip of 128 m (420 ft) and an axial trace displacement of 91 m (300 ft).

Faults at high-angle to the main thrust have also been identified at the two analogous oil fields to Alcova anticline. At South Casper Creek field, detailed 3D seismic interpretation indicated the presence of two transverse, east-west oriented faults that cut across the axis of the anticline at the Nowood Member (Goose Egg Formation) level (Montgomery, 1996) (Figure 2.18). Well data and seismic analysis have shown the Tensleep reservoir at Teapot Dome to be compartmentalized by a series of northeast-oriented faults (Figure 4.6). The southern fault, near the structurally highest part of the field, exhibits apparent left-lateral slip.

4.3 Geologic Mapping Methods

This section describes the methods used to collect and analyze the data gathered at the Alcova anticline study area. Traditional field mapping techniques combined with modern technologies, including global positioning system (GPS) and geographic information systems (GIS), were used to construct the new geologic map.

4.3.1 Global Positioning System

A global positioning system (GPS) unit was used to collect field data. GPS systems are an efficient tool for collecting the coordinates of structural, bedding, and location data. The efficiency, combined with the portability of the unit allows, one to collect a large amount of data to be collected over a large area in a small amount of time. Parts of the following section are modified from Ciftci (2001).

Initially a program of the Department of Defense, the NAVSTAR Global Positioning System can locate any point on the earth's surface by using a system of 24 orbiting satellites. These satellites orbit the earth at an altitude of 20,200 km (12,120 mi) in nearly circular orbits. The geometry of the orbits provides 4 to 8 observable satellites, 15° above the horizon, at any point, at any time of the day (Hofmann-Wellenhof et al., 2001).

The satellites furnish accurate timing pulses and error information to users with receivers for the determination of positions, velocities, and time (Logsdon, 1995). The satellites constantly emit a pseudo-random binary code, a code that appears to be a random generation of 1's and 0's but is in fact generated by precise mathematical relationships with total predictability (Logsdon, 1995). A user receiver is synchronized with the satellites to generate the same code at exactly the same time. When a receiver picks up a code signal from a satellite, the satellite code will be shifted with respect to the user's receiver. This shift represents the time delay for the satellite signal to travel from the satellite to the receiver. Radio waves travel at the speed of light, a constant, thereby allowing the receiver to calculate the exact distance to the satellite that sent the code.

Location on the earth's surface is determined by using multiple satellite signals. The principle of triangulation is used to fix the position based on distances, but because electronic signals are used to determine distance, it is referred to as trilateration (Hofmann-Wellenhof et al., 2001). Theoretically, 3 satellites can fix a location on the earth's surface. The geometry of three intersecting spheres leaves two possible positions, with one having unreasonable attributes (high above the earth's surface or an impossibly high velocity). The receiver's computer can generally determine which is the correct point (Hurn, 1989). However, it is generally preferred to collect data with four or more satellite signals.

There is a certain amount of error in a location determined by a GPS receiver due to several sources. There are three main sources of error in GPS locations, not counting user receiver malfunction. These are satellite, atmosphere and multipath errors (Hurn, 1993).

Accurate timing is the basis for all location determination. The GPS satellites are equipped with extremely accurate atomic clocks. However, slight inaccuracies in their timekeeping can lead to inaccuracies with position measurements. Because radio waves are traveling at the speed of light, 310,000 km/second (186,000 mi/second), errors of as little as 1/1000 of a second can lead to a position being off as much as 310 km (186 mi). These errors are mitigated when the user takes measurements with 4 or more satellites. If there is a timing error, the receiver will be unable to calculate an intersecting point for the distances given. It will then run through a series of algorithms to add and subtract fractions of a second until it can calculate an intersection point (Hurn, 1989).

The atmosphere can delay the transmission of radio waves, thereby interfering with transit time. While it is assumed that the speed of light is a constant, that is only true in a vacuum. As the radio waves travel through the earth's atmosphere, they can be slowed by charged particles in the ionosphere and water vapor within the troposphere.

Again, this delay in transit time can result in a position being wrong by many kilometers or miles.

The last source of error occurs after the radio signal has arrived at the earth's surface. Multipath errors occur when the signals reflect from local obstructions before they reach the receiver's antenna. The antenna receives the direct signal from the satellite and the reflected signal arrives later, resulting in noisy results. These errors can be mitigated by avoiding large bodies of water and other highly reflective surfaces, if possible, during data collection. Alcova reservoir can be considered a large body of water. However, mulitpath conditions are easily recognized while data is being collected. In a multipath situation, the real-time location readout on the GPS receiver will erratically change positions by many meters or feet in short amount of time when the user's location has remained static. When these conditions are recognized, data collection should stop until the satellites have changed position and the reflection off the water is reduced.

Differential GPS is a technique that was developed to correct for the sources of error described in the previous section. The technique requires using two ground-based receivers, a stationary "base" station and a mobile "rover" station. If the receivers are within 500 km (300 mi) of each other, it can be assumed that the rover and base stations receive data from the same satellites and experience the same atmospheric conditions. Both receivers will be subject to the same delays. However, the exact location of the base station is known. By differentiating between the known coordinates of the base station and those calculated from the GPS satellites, a correction factor can be determined for any time during data collection. This correction factor can be applied to the remote receiver. It is assumed that the base and rover stations experience the same amount of error so the same amount of differential correction will be valid for both receivers (Hurn, 1993; Hofmann-Wellenhof et al., 2001).

The Trimble Pathfinder PRO/XRS GPS receiver system was used to collect field data (Figure 4.7). The PRO/XRS is a backpack-mounted, 12-channel GPS receiver. The system is composed of three main parts: an antenna to receive the signals, the GPS receiver that interprets the signals, and a hand-held computer unit, the TSC1 datalogger, to provide an interface between the GPS and the user. The datalogger can store up to 1.7 megabytes of field data and has software capabilities for system configuration, data collection, data editing and navigation. Pathfinder Office version 3.1 provides communication between the datalogger and a PC. This system is capable of supplying sub-meter accuracy after differential correction.

4.3.2 Data Collection

Prior to data collection in the field, steps must be taken to provide for an organized data collection. Using the Pathfinder Office software, a data dictionary is created to organize the typical data types that will be collected, such as bedding contacts, strikes and dips, and faults. The dictionary, when uploaded to the datalogger, allows the user to assign identification and attributes to each measured GPS data point. For instance, the location of a strike and dip can be stored with the measurements as well as the geologic formation. The entire system runs on two 12-volt camcorder batteries. The batteries provide enough power to collect data for half of a day.

Accurate data can only be collected when there are more than 4 satellites within line of sight of the antenna. This is relevant when working in areas with deep canyons or cliffs that limit the amount of the sky visible to the antenna. How well the satellites are distributed in the sky can also affect the ability to collect data. If the satellites are tightly grouped in the sky, this results in less accurate position data. This is defined by Trimble as the Position Dilution of Precision (PDOP). PDOP is a dimensionless value that is calculated from the configuration of the satellites in the sky. Lower values of PDOP result in more accurate location determination. Trimble recommends that data not be collected when PDOP is greater than 4.0. With PDOP less than 4.0, the accuracy will be submeter in the X,Y and Z directions. However, at times, collection of data above 4.0 cannot be avoided, particularly when working in a region with steep canyons and cliffs that will always block out a portion of the satellites in the sky. The datalogger notes the PDOP for each data point collected. During post-processing, if the user decides this data is unacceptable, it can be deleted.

4.3.3 Data Processing

Each day, a new data file was created to store the day's work. At the end of each field day, data were downloaded from the datalogger to a PC. After returning from the field, these data files were differentially corrected using correction factors from the National Geodetic Survey's Continuously Operating Reference Station (CORS) in Casper, Wyoming. This provides the base station necessary for differential correction of the data. The station is located 58 km (35 mi) from the field site, well below the 500 km (300 mi) limit. The Pathfinder Office software provides an interface for the user to navigate, through the internet, to the CORS base station and retrieve the necessary correction factors for the exact time data was collected in the field. Once all of the field data were differentially corrected, the files were combined to form one data file. This data file was exported from Pathfinder Office in ArcView shapefile format in UTM, NAD83 coordinates. This field data provided the basis for the creation of the new Alcova geologic map in ArcView3.2a.

4.3.4 Field Mapping

The top of Precambrian basement is mapped at the contact between granite and the sandstone of the Fremont Canyon Formation. The contact between the Fremont Canyon Formation and the overlying Madison Formation is located at the first occurrence of marine limestone. The top of the Madison Formation is defined by a well-developed karst surface. For this study, the Amsden Formation and Tensleep Formation are undifferentiated and mapped as a single unit. The top of the Tensleep Sandstone is defined as the contact of eolian sandstone with the reworked sediments of the basal Goose Egg Formation. From an aerial view, this relationship is marked by a pronounced color change from the buff-tan color of the Tensleep Sandstone to a distinct yellow and red coloration of the Goose Egg Formation. The top of the Goose Egg Formation is defined as the last resistant, gray to pink, silty limestone ledge present. This unit is overlain by redbeds typical of the lower Chugwater Group. This contact definition is also readily observed in color aerial photographs. The top and base of the Alcova Limestone is one of the most recognizable contacts throughout the entire study area. The base is a sharp contact between limestone and the underlying redbeds. The top is mapped at the last appearance of stromatolitic beds before the redbeds of Jelm Formation. The base of the Sundance Formation and top of the Jelm Formation is defined at the base of the Canyon Springs Sandstone member of the Sundance Formation. The Canyon Springs Sandstone member is a 5 m (16 ft) thick white, massive sandstone that separates the redbeds of the Jelm Formation from the gray to green marine shales of the Sundance Formation. The top of the Sundance Formation is mapped at the top of the Windy Hill Sandstone member. The Windy Hill Sandstone member is the last continuous marine sandstone before the fluvial shales and isolated channels of the Morrison Formation. The top of the Morrison Formation and base of the Cloverly Formation is also an easily identifiable contact. The Lakota Conglomerate member of the Cloverly formation lies directly on the shales of the Morrison Formation and provides a distinct lithographic contrast to map. All of the Cretaceous marine shales above the Lakota Conglomerate member are mapped as undifferentiated. The contact between the deformed undifferentiated Cretaceous shales and undeformed Tertiary alluvial sediments is an angular unconformity throughout most of the study area.

The top of Precambrian basement, top of Tensleep, top of Alcova, and the top of the Morrison/base of Cloverly (Lakota Conglomerate) were the formation contacts selected for detailed mapping in the field (Figure 2.8). In addition, other formation tops were mapped for later use in air-photo interpretation. These units were selected because they form prominent ridges in the field. These are rigid lithologic units that allow interpretations of the more ductile units to be made. Due to the rigidity of these lithologic units, faults are readily recognized and measured. These units also provide surfaces to collect orientation data. For the top of Tensleep and top of Alcova contacts, the GPS was set to automatically gather a datapoint every 10 seconds and the contact was walked. Data gathering paused when an additional data point, such as a fault or bedding orientation, was collected. The top of Morrison and top of Precambrian basement contacts were often exposed at the base of cliffs with vertical faces often higher than 10 m (33 ft). This blocked the line of sight to most satellites in the sky, resulting in large areas where GPS data gathering was impossible. To gather data in these instances, an alarm on the GPS was set to go off when the PDOP dropped below a value of 6.0. When the alarm went off while walking at the base of the cliff, a data point was taken over a period of 30 seconds. These data points were loaded into ArcView3.2a and connected using digitizing functions within the software program.

All of the post-field interpretations and digitzations were completed on color digital orthophoto quadrangle (DOQ) photographs. DOQ's are computer-generated images of aerial photographs that are georeferenced. The state of Wyoming has available for free download almost a complete coverage of 1 m (3.3 ft) resolution color photographs shot in 2002. DOQ's were downloaded for the USGS 1:24,000 quadrangles covering the field area. These photographs are readily imported into ArcView3.2a and the field data points overlie the correct placement on the photo (Figure 4.8). Available for free download from the USGS are 30 m (100ft) resolution digital elevation models (DEM) of the field area. DEM's consist of a raster grid of regularly spaced elevation data. These data are primarily derived from USGS quadrangle topographic maps. Using functions in ArcView3.2a and ArcGIS9.0, the DOQ can be draped over the elevation data from the DEM, creating a 3D image (Figure 4.9). The field mapping data points are inserted and formation contacts can be accurately mapped in areas inaccessible to field work.

The paper maps of Bradley (1935), Sheffer (1951), and Mitchell (1957) were scanned, digitized, and georeferenced to the same UTM Zone 13N, NAD 83 coordinate system as the field data. This allowed the interpretations of the previous workers to be directly compared with the field data collected in this study. Orientation measurements of Sheffer (1951) and Mitchell (1957) were also used to supplement the field measurements made for this study, particularly in areas that I did not traverse.

4.4 Measured Stratigraphic Sections

Figure 4.10 shows the locations of stratigraphic sections measured within the field area. There are four measured sections within the study area. Section A, located near the Cottonwood Creek campground, extends from the base of the Alcova Limestone to the top of the Morrison Formation. The section was measured using a Jacob's staff and Brunton compass. Detailed lithologic descriptions were made every 0.3 m (1 ft) of vertical stratigraphic thickness. I measured and described a total of 241 m (792 ft) of stratigraphic section at this location. In addition, I collected outcrop gamma ray (GR) data using a hand-held scintillometer. Five readings were taken every 0.3 m (1 ft) for the entire height of the stratigraphic column. The high and low reading values were thrown out and an arithmetic mean was calculated for the remaining three values. This average was the basis for construction of an outcrop GR curve (Figure 4.11a). A Microsoft Excel file with the outcrop GR values is located in Appendix D on the accompanying DVD-ROM. This GR curve can be compared to GR curves from well logs. The purpose of measuring a section at location A was to have a reference thickness of the undeformed strata between the Alcova Limestone and the top of the Morrison for later use in modeling. The structural location of Section A is on the backlimb dip slope of the Granite Mountains uplift. This area is assumed to have little or no strain associated with it (as in Zahm, 2002).

Sections B and C were measured on the plunging nose of the Alcova anticline. As with Section A, these sections were measured from the base of the Alcova Limestone to the top of the Morrison Formation. The purpose of measuring these sections was to gain insight into which stratigraphic beds, if any, had experienced thinning on the forelimb during deformation (Figures 4.11b and 4.11c).

Workers from the Rocky Mountain Oilfield Testing Center (RMOTC) measured Section D. This section extends from the top of the Tensleep Sandstone to the base of the Alcova Limestone on the backlimb of the Alcova anticline. This measured section is provided as an electronic file (Appendix E) on the accompanying DVD-ROM. The thickness provides a reference value for the units in modeling.

4.5 Results

The methods and data sources previously described provide the basis for a new, digital geologic map of the Alcova anticline and vicinity. The geologic map is shown in Plate 1. In addition, a digital copy of this map is included on the accompanying DVD - ROM. Figure 4.12 is a simplified version of the geologic map, divided into a grid to help the reader locate the areas discussed in this section.

For the purpose of reporting the results, the Alcova study area can be divided into four separate structural regions: 1) Granite Mountains uplift backlimb, 2) Alcova syncline, 3) Alcova fault system, and 4) Alcova anticline (Figure 4.13). The features of each of these structural regions will be reported in the following sections. Additionally, there is one group of features that cuts across these boundaries. This group will be discussed first.

4.5.1 Northeast-Oriented Features

There is a strong northeast structural fabric to the study area. The majority of the drainages have an orientation between N35˚E and N60˚E. The most prominent northeast-oriented features are Fremont and Alcova canyons. A straight line with the orientation of N50˚E can be drawn to connect the two canyons (Figure 4.14a). The line that connects the two canyons is completely contained within the area of the reservoir and does not cut any major formation dip slopes.

Prior to the construction of the Alcova dam, four hot springs flowed out of the rock and talus slopes of the east wall of Alcova canyon, just above the low water level (Bradley, 1935). Figure 4.14b shows the location of these hot springs. Bradley (1935) interpreted these hot springs to be of artesian origin with a hydrothermal component. The significance of these features will be discussed in a later section.

A fracture set with this same orientation has been documented in the Tensleep Sandstone at Alcova canyon. This fracture orientation is also observed propagating away from northeast-oriented drainages in the Tensleep on the backlimb of Alcova anticline. N50˚E fracture orientations are also observed in the Tensleep Sandstone exposed on the Granite Mountains uplift dip slope at Fremont canyon. This same fracture set is observed in the Cloverly Formation where Highway 220 cuts through a gap in the outcrop. This gap lines up with where the North Platte River cuts across the Alcova Limestone hogback.

4.5.2 Granite Mountains Uplift Backlimb

The southern half of the study area is dominated by the dip slope of the backlimb of the Granite Mountains uplift. The Tensleep Sandstone, Alcova Limestone, and Lakota Conglomerate of the Cloverly Formation all form prominent dip slopes. The entire stratigraphic column of the Alcova study area is exposed here. The beds dip relatively uniformly to the northeast at an average dip of 9˚. There is little deformation observed over this portion of the study area. The exception is a low horst formed by a series of normal faults that cut the Chugwater through Morrison Formations. This feature is located to the east of where the road between the town of Alcova and the reservoirs to the south pass through the Lakota Conglomerate and Alcova Limestone dip slopes, in the area of a rectangle created by corners at N10 and Q13 on Figure 4.12. Figure 4.15 is an interpreted DOQ of the area. The fault immediately to the east of the road dips steeply to the northwest and has approximately 53 m (175 ft) of apparent dip-slip separation on the Alcova Limestone. This fault trends approximately N45˚E. To the north, the fault trace is covered by surface alluvium and reappears as two normal faults with the same sense of offset at the road cut through the Lakota Conglomerate hogback. Limestone beds within the Upper Sundance Formation have less than 5 m (16 ft) of dip-slip separation and the faults appear to tip out in the Morrison Formation. To the south, the surface fault trace is buried in surface alluvium. The second fault, located approximately 335 m (1,100 ft) to the east, trends N30˚E and has approximately 23 m (75 ft) of dip-slip separation. Also present at the Alcova Limestone road cut is a small thrust fault that dips approximately 50˚ to the northeast and is oriented approximately N30˚W. There is approximately 5 m (16 ft) of throw on this fault. This fault is not observed on the east side of the normal fault.

4.5.3 Alcova Syncline

The axis of the Alcova syncline is oriented approximately N60˚W and the east nose plunges 4˚ to the southeast. The syncline is asymmetric with the gentle 5 to 9˚ dips of the Granite Mountains uplift on the southwest limb and steep dips of 30 to 60˚ on the northeast limb (Plate 1). The trough of the syncline west of Alcova reservoir is exposed in a prominent Lakota Conglomerate mesa. To the east of Alcova reservoir, the trough is exposed in the Cretaceous shales of the Mowry Shale and Frontier Formation.

4.5.4 Alcova Fault System

The orientation of the Alcova thrust fault system varies between N60W and N70W and extends across the entire field area. The fault zone is described as a system because where exposed, up to three separate fault traces are visible. The only location where the fault system is visible at the surface is at the northeast corner of Alcova reservoir, I9 through I10 on Figure 4.12. Figure 4.16 is a geologic map of the area. At this location, anhydrites of the Goose Egg Formation are juxtaposed against overturned Alcova Limestone beds (Figure 4.17). The exposed fault dips 72˚ to the northeast. This is the only known location where the thrust fault plane is exposed.

West of Alcova reservoir, the trace of the Alcova thrust fault system is buried beneath Quaternary alluvium and sand dunes (I2 through I6 on Figure 4.12). At this location, the fault zone is approximately 200 m (650 ft) wide. The Tensleep is juxtaposed against the Lakota Conglomerate across the fault zone. The primary evidence for the two-fault system is a small outcrop of Alcova Limestone located approximately equidistant from the Tensleep and Cloverly outcrops. The dip on the Alcova Limestone is 30˚. Dips on the footwall Morrison and Sundance Formation beds are between 25 and 40˚. With those dips, the most likely way for the Alcova Limestone to be in that position with that bedding attitude is for it to have been faulted in a wedge.

East of Alcova canyon, the projected surface trace of the Alcova thrust fault system is offset by the first of three transverse faults. For the purpose of discussion, the faults have been informally named, from west to east, the Cove fault, the Bradley fault and the Bear Springs fault. Fault locations and their names are shown in Figure 4.18. These transverse faults are oriented approximately N70˚E and all display apparent left-lateral slip at the surface. Away from the transverse fault zone, the bedding orientations in the Jurassic and Cretaceous units are approximately parallel to the axis of the anticline. Approaching the transverse fault zone, the orientation of the bedding units changes to roughly parallel to that of the transverse fault. The beds run parallel to the fault zone until they reach the next hanging-wall block. At that point, the beds reorient parallel to the anticlinal axis and continue in that orientation until the next fault is encountered.

The Cove fault is only visible during the winter months when the water level of Alcova reservoir is lowered 4.5 to 6 m (15 to 20 ft). During these times, the Lakota Conglomerate of the Cloverly Formation and Lower Cretaceous shales terminate against redbeds of the Permian Goose Egg Formation (Figure 4.16). The corresponding Cretaceous beds on the west side of the fault are below the water level of the reservoir, which prevents the calculation of lateral slip. Prior to termination, the beds abruptly change in orientation from N60˚W to N65˚E-N70˚E and become overturned. This same relationship is seen on the Bradley fault.

The Bradley fault is the largest transverse fault identified in the study area. The trace of the fault is readily visible. The fault begins on the backlimb with observable apparent normal dip-slip movement. There is approximately 2.5 m (8 ft) of down to the southwest displacement of the Alcova Limestone. The displacement of this fault decreases to the northeast and tips out in the Jurassic Sundance Formation. To the southwest, the sense of motion on the fault appears to change from normal to strike-slip with approximately 350 m (1150 ft) of left-lateral separation. Steeply dipping beds of the Sundance and Morrison formations are juxtaposed against the plunging nose of the Goose Egg Formation where the tear fault trace reaches the reservoir's edge (Figures 4.18 and 4.19a). The fault changes orientation slightly at the water's edge, cuts across two peninsulas and tips out in the Lower Cretaceous shales. As observed with the Cove fault, the Jurassic and Cretaceous sedimentary beds change in orientation to parallel the fault. The combination of the change in bedding orientation and the change in fault orientation may have caused the sandstones and limestones to become highly fractured and subsequently eroded. The isolated flatirons are preserved remnants (Figure 4.19b).

The Bear Springs fault is not observed at the surface and is inferred. The strongest evidence for this fault is the same outcrop expression as described for other faults. The Jurassic and Cretaceous formations change in orientation from northwest to northeast and back to northwest over a distance of approximately 300 m (984 ft). There is no surface trace for the Alcova thrust system east of the Bradley fault.

4.5.5 Alcova Anticline

The Alcova anticline is asymmetric with a forelimb that dips steeply to the southwest (40-70˚) and a backlimb that dips gently to the northeast (10-20˚). Based upon plotting poles in the π-method of Marshak and Mitra (1988), 372 field observations determined the orientation the structure within the field area to be N58˚W (122˚) with a plunge of 5˚ to the southeast (Figure 4.20).

The Tensleep is the oldest formation exposed at the crest of the anticline. The surface expression of the anticline is clearly defined by the prominent ridges formed by the resistant Alcova Limestone and the Lakota Conglomerate of the Cloverly Formation. The youngest defining units are sandstones of the Frontier Formation. To the west, the structure remains buried by Tertiary sediments. To the east, the Alcova anticline terminates against a shallow, northeast-trending syncline that separates the Alcova anticline from the Spindle Top – Bolton Creek anticline (Mitchell, 1957).

The crest of the Alcova anticline is broken and bent by the presence of the previously described transverse faults. The crest is clearly offset by the Bradley fault with a left-lateral separation of 450 m (1,476 ft). A detailed π-analysis of the different hanging-wall blocks is presented in Figure 4.21. The plunge of the anticline west of the river cut is 1˚ to the northwest with an orientation of N54˚W (126˚). East of the river cut and west of the Bradley fault, the orientation changes to N70˚W (110˚) and the plunge increases to 6˚ to the southeast. Between the Bradley and Bear Springs faults, the plunge increases to 8˚ with an orientation of N48˚W (132˚). Finally, east of the Bear Springs fault, the anticline decreases in plunge to 7˚ and has an orientation of N67˚W (113˚).

LiDAR data provides evidence for a deep-seated fault parallel to Alcova canyon. The change in the direction of plunge of the Alcova anticline is supported by observations made from the LiDAR data interpretation. The LiDAR data indicates that the southeast outcrop is uplifted approximately 2 m (6.6 ft) compared to the northwest outcrop. This relationship was based on correlation of a dolomite layer at the base of the outcrop across the river cut.

East of the Bradley fault, the plunging Alcova Limestone forms a spectacular amphitheater. Extensional faults are present within 400 m (1,310 ft) of a series of thrust faults. The forelimb of the anticline is cut by a series of small-scale tear faults and a backthrust. Figure 4.22 is a detailed view of the area with the geologic interpretation overlain. East of the Bradley fault, the Alcova Limestone in the forelimb is cut by two tear faults with offsets of 25 m (82 ft) and 5 m (16 ft) (Figure 4.23a). The forelimb is further deformed by a well-developed backthrust that runs for approximately 600 m (1968 ft) parallel to the crest of the anticline (Figure 4.23b). Seven separate reverse faults, perpendicular to the axis of the structure, are mapped with displacements of 1 to 8 m (3 – 26 ft) (Figure 4.24a). Additionally, there are much smaller, ductile deformation features observed in the Alcova Limestone (Figure 4.24b). To the east of the Bear Springs fault, the anticline remains distinctly asymmetric with dips of 30 to 65˚ in the Jurassic and Cretaceous beds. Small tear faults are observed in the sandstones and limestones of the Sundance and Morrison Formations (Figure 4.25).

Figure 4.26 shows a comparison of measured sections A, B, and C. Compared to Section A, Section B is missing 43 m (140 ft, 18%) of section and Section C is missing 55 m (180 ft, 23%) of stratigraphic section. For both measured Sections B and C, the missing section appears to be in the Upper Jelm and Lower Sundance Formations. There is no field evidence for normal faulting in this area, so this missing section is attributed to thinning of these ductile units over the forelimb of the Alcova anticline, similar to thinning described at Thermopolis anticline by Zahm (2002).

The backlimb of the structure is relatively uniform in dip with no major deformation observed. The beds dip to the northeast until they are faulted and deformed into the Bates Park anticline.

4.6 Discussion

Field data are an integral part of understanding the structural evolution of the Alcova anticline. There are no seismic lines across the structure or wells drilled through the main thrust to give an indication of the subsurface geometries. All subsurface configurations have to be inferred from the surface data and models created from other studies of producing fields and analogous structures.

4.6.1 Basement Features in Relation to the Northeast-oriented Fracture Set

The northeast structural grain may have been a pre-existing zone of weakness reactivated by the Laramide deformation that formed the Granite Mountains and the Alcova anticline. The Alcova reservoir is on the Ransome Lineament, as named by Maughan and Perry (1986). The Ransome Lineament is a major northeast-oriented lineament that cuts through central Wyoming. Fremont canyon and Alcova canyon could be the surface expressions of deeply rooted basement features related to the Ransome Lineament. The North Platte river cuts preferentially through lineaments at these locations, probably due to an increase in fracturing, as noted from the LiDAR analysis.

The presence and the specific location of the hot springs in Alcova canyon provide solid evidence for basement-involvement with these features. Bradley (1935) proposed that meteoric water entered the Amsden/Tensleep formations on the dip slope of the Granite Mountain uplift, flowed down the dipping beds, was heated, and re-emerged at Alcova Canyon. However, Bradley (1935) noted that water temperature from one hot spring measured 129˚ F (54˚ C) or 75˚ F (24˚ C) above the average river water temperature. According to his calculations of the depth of the Amsden in the footwall of the fault and the assumed geothermal gradient, Bradley (1935) could only account for an increase of 43˚ F (6˚ C) above mean river temperature. Bradley (1935) suggested that the missing temperature increase may be due to hydrothermal water rising along the Alcova fault. However, if this was the case, hot springs should be observed along the surface trace of the Alcova fault and parallel to the anticline. They are not. Instead, hot springs occur 500 m (1640 ft) away from the interpreted thrust fault trace up the river canyon and in the core of the anticline. This suggests the presence of a deep-seated fault parallel to Alcova canyon. This is further supported by the change in the plunge of the fold on either side of Alcova canyon (Figure 4.21) and the LiDAR data analysis.

4.6.2 High-Angle Faulting at Alcova Anticline

The high-angle faults to the main thrust at Alcova anticline have characteristics similar to those described by Stone (1969; 2003), Hennings and Spang (1987), and Brown (1988; 1993; 1997). In all three examples, differential movement in the hanging wall of the thrust fault resulted in the formation of a basement corner where the transverse fault intersects the thrust plane (Figures 4.1, 4.2, 4.3). I have chosen to not use “tear fault” or “compartmental fault” to describe the nature of these basement-rooted features. Instead, these features are described in more general terms as high-angle transverse faults. I believe that the transverse faults terminate at the intersections with the Alcova thrust fault zone. Faults observed at the surface on the footwall are interpreted to be contained within the sedimentary column and do not displace basement. In this matter, Alcova anticline is more like the structures described by Hennings and Spang (1987) and Stone (2003). Brown (1993), in his Bonanza-Zeisman Dome example, has the basement fault continue into the footwall. I will restrict the use of the term “tear fault” to describe offsets of 1 to 25 m (3 - 82 ft) present in the Alcova Limestone and limestone and sandstone beds in the Sundance Formation on the forelimb of the anticline.

The underlying reason for these transverse faults may be pre-existing zones of weakness in the Precambrian basement. Stone (2002) concluded that the morphology of Casper Mountain, 32 km (20 mi) to the northeast, was directly related to zones of crustal weakness. The features at Alcova anticline are on trend with the northeast fault zones that border Casper Mountain. The orientation of the transverse faults are also within 15˚ of the trend of the interpreted basement structure that caused the Fremont-Alcova canyons and the Alcova canyon hot springs.

The deformation caused by the transverse faults at Alcova anticline is limited to the crest and forelimb regions. Little or no movement is observed on the syncline and backlimb of the structure. This indicates that the controlling feature is limited to the hanging-wall of the Alcova thrust system. As Hennings and Spang (1987) noted at Dry Fork Ridge anticline, deformation of the overlying sedimentary layers cannot terminate abruptly at the basement corner. Instead, the change is gradual and deformation propagates away from the basement corner. The shales of the Chugwater, Sundance, and Morrison Formations absorb some of this offset. As a result, the more competent limestone and sandstone layers within the Sundance and Morrison Formations, as well as the Lakota Conglomerate, are contorted and deformed as they are draped over the basement corner. This results in the distinct surface expression of the changes in orientation of the sedimentary beds through the fault zone as described in Section 4.5.3.

4.6.3 Results of Field Mapping at Alcova Anticline

The field mapping program at Alcova anticline has led to a new geologic map of the area, as well as a new structural interpretation. This is the first interpretation to identify the existence of high-angle transverse faults and basement corners to explain the surface exposure of the Paleozoic and Mesozoic sedimentary units. This interpretation is consistent with those of other Laramide structures and will form the basis for the creation of a 3D geologic model of Alcova anticline.

CHAPTER 5

3D MODEL CONSTRUCTION AND ANALYSIS

This chapter discusses the construction of a 3D geologic model of Alcova anticline. The model is important for comparison of the fracture interpretation to structural attributes such as dip magnitude, rate of dip change (simple curvature), Gaussian curvature, and strain. Dip magnitude, rate of dip change, and Gaussian curvature are geometric attributes that can be measured from the modeled horizon. Strain is calculated by unfolding and tracking the dilatation of the surface horizon as the structure is re-deformed. To compute geometric attributes and strain, it is necessary to have a balanced, restorable 3D model constrained by outcrop and subsurface data.

5.1 Previous Work Involving 3D Modeling of Laramide Structures

Hennings et al. (2000) built a 3D geologic model of Oil Mountain anticline, a Laramide-age structure on the eastern margin of the Wind River basin. The purpose was to determine which attributes of the structural form and evolution of the anticline were most related to the development of important reservoir-scale structures, such as faults and fractures. Their model was constrained by serial cross sections constructed from outcrop, well, and seismic data. Hennings et al. (2000) tested the static model for geometric attributes such as dip magnitude, rate of dip change, and total curvature (Gaussian curvature). Additionally, Hennings et al. (2000) used modeling software to undeform their model and track the strain as the structure was re-deformed. From this work, they determined that the location of tectonically produced fractures at Oil Mountain correlated to the amount of total curvature and to a lesser degree to the rate of dip change. Hennings et al. (2000) also concluded that a zone of larger strain values correlated with areas of tear faulting.

Stanton (2002) constructed a balanced 3D geologic model of Sheep Mountain anticline, a Laramide-age structure on the eastern flank of the Big Horn basin, compiled from outcrop, seismic, and well data. Based upon the model results, Stanton (2002) concluded that there were two stages of deformation in the Sheep Mountain area. Additionally, evidence suggested regions of oblique-slip on the structure. Zahm (2002) built a 3D geologic model of Thermopolis anticline, on the western edge of the Big Horn basin, and the surrounding structures, constrained by outcrop and well data. The purpose of this model was to highlight areas of the outcrop where strain intensity is the highest. A second goal was to provide a calibration tool for 3D geometric attributes that can be used to predict strain distribution in analogous subsurface reservoirs. Woolf (2005) constructed a 3D model of Hamilton Dome field, west-southwest of Thermopolis anticline, from well data and serial cross sections. The purpose of his model was to define changes in fold and fault geometries and to identify faults that may occur at high-angles to the main thrust. All three studies used a version of Midland Valley's 3DMove software.

5.2 Methods

14 balanced serial cross sections formed the basis for the construction of the 3D geologic model of Alcova anticline. Dahlstrom (1969) introduced the concept of balanced cross sections as a way to compare a deformed interpretation to an undeformed geometry. The fundamental assumption of a balanced cross section is that mass is conserved, along with bed length and area (Zahm, 2002). Balancing is a method used to determine the validity of a cross section. If bed length or area is not conserved, the interpretation is invalid. If material is not introduced or removed during cross section

construction, the interpretation is valid. However, a balanced cross section is not a unique solution, only one possible solution (Elliot, 1983). Bedding geometries within serial cross sections are used to build 3D models.

5.2.1 Serial Cross Sections

In this study, serial cross section construction used multiple data sources, including surface geology, aerial photo interpretation, digital topography, and existing well data. All data were collected or projected into UTM Zone 13N, NAD83 coordinates. Having all the data in the same projection ensures that distance and direction are consistent and accurate throughout the study area. Direction is important to ensure that strikes taken from digitized geologic maps are consistent with those collected in the field. Distance is important for correct determination of bedding thickness, fault throws, and spatial relationships observed throughout the field area.

The new geologic map of Alcova anticline provided the initial parameters for the construction of serial cross sections. Using ArcView3.2a, the bedding boundaries of the top of the Morrison Formation, top of the Alcova Limestone, top of the Tensleep/Amsden Sandstone, top of the Precambrian basement, and fault traces were converted to DXF line files for importation into Midland Valley's 2DMove3.8 structural modeling software. These bedding boundaries were chosen because they were the units mapped extensively with GPS in the field. In addition, 20 m (66 ft) contour lines from the DEM of the study area were exported to create surface topography. Strike and dip information were converted to an ASCII text file for insertion into 2DMove3.8.

Tops from 12 wells in the study vicinity were used in the construction of the serial cross sections. Figure 5.1 shows the locations and the deepest formation penetrated in each well. The selected wells had all at least penetrated the top of the Cretaceous. The formation tops used for the wells were on record with the Wyoming Oil and Gas

Conservation Commission (WOGCC). When tops were not reported to the WOGCC, I picked the tops on SP/Resistivity paper logs. All wells were vertical penetrations. Text files were created containing the surface and bottom-hole coordinates. Formation tops were manually inserted in the well bores in 2DMove3.8.

The bedding contact, fault trace, bedding attitude, and well data were imported into 2DMove3.8. These data were used to construct a base map of the field area, from which to construct serial cross sections (Figure 5.2). The process of creating serial cross sections started by examining the existing data on the base map. In order for the cross sections to make the most geologic sense and balance, they needed to be oriented parallel to the tectonic transport direction (Elliot, 1983). The tectonic transport direction is inferred to be perpendicular to the trend of the fold. This orientation was determined from the π-method of plotting poles of Marshak and Mitra (1988). Figure 5.3 shows the locations of Cross Sections 1-14. Cross section line spacing values vary, but have an average spacing of 800 m (2600 ft). Cross section lines were placed to intersect as many data points as possible, as opposed to a set grid. Cross Sections 1 – 7 and 9 – 14 have an orientation of N29˚E and Cross Section 8 has an orientation of N45˚E. It was necessary to change the orientation for Cross Section 8 because the orientation of the fold changes abruptly at that location.

Cross section construction followed the methods of Zahm (2002). Intersections of the mapped bedding contacts were drawn on the section line. The topological profile was taken from the DEM-derived contour lines. Bedding attitudes near the section line were projected along strike into each section. 2DMove3.8 corrected these dips for apparent dip. Well tops were projected along strike and plunge into the line of section. Figure 5.4 shows the starting point for creating the bedding layers. The bedding attitudes and formation contacts are correctly placed at their locations on the topographic profile. I drew the formation tops for the wells along the well bore at their measured depth.

For each cross section, bedding contacts were drawn for the following formations: (1) top Morrison Formation, (2) top Sundance Formation, (3) top Jelm Formation, (4) top

Alcova Limestone, (5) top of lower Chugwater Group (Red Peak Formation), (6) top Goose Egg Formation, (7) top Tensleep/Amsden Formation, (8) top of Madison Limestone, (9) top of Fremont Canyon Sandstone, and (10) top of Precambrian basement. The stratigraphic thickness of each unit was determined from measured sections and the locations of bedding contacts and structural orientation in the field. Table 5.1 lists the various measured sections by previous workers and their results. In several instances, the nomenclature has changed. I selected a location on the back limb of the Granite Mountain Uplifts to calibrate the model thickness values. The location was chosen because the back limb of that structure is assumed to have little or no strain associated with it (as in Zahm, 2002). I created a cross section in 2DMove3.8 with the bedding contacts and bedding attitudes of the Morrison Formation, Alcova Limestone, top of Tensleep/Amsden Sandstone, and the top of Precambrian basement. Beds for all formations were created with the average thickness from the measured sections. Individual bedding thicknesses were adjusted until they fit within the constraints of the field observations. Table 5.2 lists the thicknesses used in the creation of the balanced serial cross sections.

Once the undeformed bedding thicknesses were determined, the sections were ready to be drafted. Several constraints were used to guide the geometry of the bedding contacts. The first constraint was the concept of structural style. This simply means that the structures drawn on the section are similar to those observed in the local outcrops (Elliot, 1983). For example, bedding geometry was drawn to preserve stratigraphic thickness where appropriate. Zahm (2002) and Woolf (2005) noted significant thinning of the Chugwater Formation beds over the crest and forelimb of Thermopolis anticline and Hamilton Dome, respectively. The second constraint on bedding geometry was imposed by ductility contrasts in the deforming units. Low-ductility units, such as the Precambrian basement, Fremont Canyon Sandstone, Madison Limestone, Tensleep/Amsden Sandstone, Alcova Limestone, and the Lakota Conglomerate, are restricted to more rigid deformation. Deformation will occur along discrete fault zones and thickness is not significantly changed. High-ductility units, such as the Goose Egg Formation, Chugwater Formation, Jelm Formation, Sundance Formation, and Morrison Formation can undergo extensive penetrative deformation. In the high-ductility units, significant structural thinning has been observed at the crest and forelimb and both in subsurface and outcrop examples (Zahm, 2002; Woolf, 2005).

The Alcova fault system was simplified from field observations for cross-section construction. The fault system was represented by two thrust faults to the west of the Bradley fault and one thrust to the east. The Bradley and Bear Springs faults were included, but the Cove fault and all faults in the Alcova Limestone amphitheater were excluded. There is no subsurface data on the nature of the geometry of any faults. In the study area, there is only one known location where the fault plane is exposed. At this location the fault dips 72° to the northeast. Studies of analogous subsurface structures by Stone (1993) and Willis and Groshong (1993) show an increase in the dip of a fault out of the Precambrian basement and into the overlying sedimentary beds. The basement-balancing techniques of Erslev (1986) were used to determine fault dip in the basement. A segmented fault plane was drawn to link the shallower dips in the basement with the steeper dips at the surface. The second thrust fault observed west of the Bradley transverse fault was drawn with the same dips and dip changes. Later modifications of fault geometry were imposed by balancing constraints.

To this point, all work had been done on one cross section. This was done to ensure consistency of the fault location and geometry between sections. The first test for balance applied to this section was a line-length balance. Pins were placed perpendicular to bedding on the footwall and hanging wall. Line length of overlying sedimentary layers between pins was compared with the line length of the basement. If the basement line length between pins was shorter than the overlying bed, the angle of the fault was changed to a shallower angle, if the basement line length was longer, the thrust was steepened. The Tensleep/Amsden Formation top was used for this comparison. The units between the basement and the top of the Tensleep/Amsden Formation are all inferred to have behaved similarly in a rigid manner. Therefore, the angle of the fault that cuts these beds is assumed to be constant. The fault plane was adjusted to increase in dip from the top of the Tensleep to match the surface exposure. To line-length balance the ductile units above the Tensleep/Amsden Formation, the beds were allowed to thin on the crest and forelimb of the structure and thicken on the footwall. All units were line-length balanced to +/- 5% of total balance.

Because the units above the Tensleep/Amsden Formation were allowed to transfer mass from the hanging wall to the footwall, it was necessary to area balance the cross sections as well. Area balancing ensures that no out-of-plane mass is introduced or removed while deforming the beds. As with line-length balancing, pins were placed perpendicular to bedding on the footwall and hanging wall of the structure. The total area was calculated for the units on both sides of the fault. This value was compared to the area calculated by the bedding unit's line length and its stratigraphic thickness. If the ratio of deformed area to undeformed area was within +/- 5%, the section was considered balanced. Otherwise, the amount of thickening or thinning was adjusted. The section was checked for line length balance and area balance again. This process was repeated until the section met the +/- 5% criteria and was considered balanced.

Once line-length and area balance had been achieved, the section was restored to an undeformed state using a flexural slip unfolding algorithm in 2DMove3.8. Flexural slip unfolding maintains line length and thickness while layers are unfolded through interlayer slip. Flexural slip was shown to be a dominant deformation mechanism for sedimentary layers at Sheep Mountain anticline (Stanton, 2002), and in the subsurface at Hamilton Dome (Woolf, 2005). In 2DMove3.8, the section was flattened to a target line that dips 9˚ to the northeast. This reflects the interpreted regional dip of the study area. Pin lines were drawn on the footwall, hanging wall, and fault sliver. The hanging wall, footwall, and fault sliver were unfolded separately and put back together at the basement horizon (Figure 5.5). Regions of overlap or gap of the sedimentary layers indicated problem areas. The restoration algorithm worked well for the more rigid beds from the

Tensleep/Amsden Formation down to the Precambrian basement. This is because these beds were not allowed to deform ductily. As a result, the beds above the Tensleep/Amsden Formation do not restore exactly to the regional datum. This is acceptable because of the lack of data and the lack of outcropping rock. To the west of the Bradley transverse fault, there is no outcrop and the beds are projected into the air.

When the line-length and area balance was complete for the test section, the bedding and fault geometry was copied and pasted into the remaining serial cross sections. This allowed for continuity of the fault style. The bedding geometries and displacement on the fault were adjusted to match the outcrop observations for each serial section. Each of the remaining cross sections was subjected to the same rigorous line-length and area balance. Figures 5.6a – 5.6n present the fourteen balanced serial cross sections.

If the final set of cross sections are balanced, restorable, and match surface and subsurface data, the cross sections represent a satisfactory solution. This set of cross sections then forms the basis for construction of a 3D model of the structure.

5.2.2 3D Model Construction

The 14 serial cross sections were used to create a 3D model of the Precambrian basement and the top of the Tensleep/Amsden Formation. The 14 serial cross sections were imported into 3DMove4.1 (Figure 5.7). Surfaces were created between the serial cross sections for the Tensleep/Amsden Formation horizon, the basement horizon and the faults. For the purposes of modeling, the thrust faults were linked into one system and the transverse faults were removed to simplify the model. The rationale was that faults of this magnitude in a subsurface fold would not necessarily be identified from mapping on well tops or from a seismic data cube. The Tensleep/Amsden Formation and basement horizons were joined across the transverse faults and smoothed. These changes in bedding geometry would be noted on a seismic dataset and the geometric attributes from the 3D model should indicate an area of high strain.

One of the first steps after a preliminary surface was created was to confirm that there was continuity of bedding and fault geometry between serial sections. If this was not the case, serial cross sections were edited, rechecked for line-length and area balance and reinserted. When this was satisfactory, editing of the model proceeded.

The creation of the horizons from the serial cross section lines left several gaps in the surface, particularly near the faults. In these instances, the surface had to be manually projected along bedding dip to intersect the fault plane. When all holes were filled, the model was smoothed on a 100 m x 100 m (330 x 330 ft) grid. This was necessary to smooth out local inconsistencies on the surface. Figure 5.8 shows an oblique view of the Tensleep/Amsden Formation, and basement horizons with the fault planes. The footwall surface was clipped parallel to the fault trace. The footwall to the southwest is uniform and undeformed, clipping it improved computer processing time with no loss of geometric attributes.

When the surfaces were patched and smoothed, the Tensleep/Amsden Formation and basement horizons were unfolded using a 3D flexural slip flattening algorithm in 3DMove4.1. Flexural flattening was accomplished by removing all of the dip on the surface of interest along planes parallel to the direction of tectonic transport (Figure 5.9). The target datum had a dip that is equal to the regional dip of the study area, 9˚ to the northeast as determined from field mapping. Flexural flattening was performed on the Tensleep/Amsden and basement horizons.

After the surfaces were flattened, they were fit together on the same plane to determine if gaps or overlaps existed (Figures 5.10a and 5.10b). Gaps or overlaps may indicate areas of unbalance within the 3D model. The areas of gaps or overlap were minimal and the model was considered to be balanced. The balanced, 3D Tensleep/Amsden Formation horizon was used to measure static geometric attributes, such as dip magnitude, dip direction, rate of dip change (simple curvature), and Gaussian curvature. In addition, strain was also tracked as the Tensleep/Amsden Formation horizon was restored using the flexural-flattening algorithm.

5.3 3D Model Analysis

The hanging wall of the Tensleep/Amsden Formation of the Alcova anticline 3D model was subjected to two types of analysis: geometric attributes and strain. Analysis was undertaken to: 1) better understand the deformation of the hanging wall, 2) compare the locations of fractures with geometric attributes and strain, and 3) compare mapped locations of high-angle transverse faults with geometric attributes and strain. Structure maps of Alcova anticline on the Tensleep/Amsden Formation and basement horizons, constructed from the 3D model, are shown in Figures 5.11a through 5.11d. There are edge-effects present on most of the color maps of the horizons on the northwest and southeast boundaries. These values should be ignored.

5.3.1 Dip Magnitude and Direction

Figure 5.12a is the dip-magnitude color map for the hanging wall of the Tensleep/Amsden Formation horizon. Dip-magnitude values range from 0-60˚ with a contour interval of 2˚. The steepest dips (40-60˚) are located on the forelimb of the anticline. Figure 5.12b is an enlarged view of the dip-magnitude color map for the Tensleep Sandstone outcrop at Alcova anticline. Mapped dip-magnitude values range from 0-50˚ with a contour interval of 2˚. There is a broad zone of low dip values (0-4˚) that follows the crest of the structure. The back limb is generally characterized by moderately low dip values (0-14˚). There an isolated region of steeper dip values (12-16˚) located on the back limb, west of the canyon. This area corresponds to the structurally highest portion of the anticline. Figure 5.13a is the dip-direction color map for the hanging wall of the Tensleep/Amsden Formation horizon. Figure 5.13b is an enlarged view of the dip-direction color map for the Tensleep Sandstone outcrop at Alcova anticline. Mapped dip-direction values range from 0-360˚ with a contour interval of 20˚. The majority of the dips on the back limb are oriented between 20-40˚ to the northeast. Near the anticlinal hinge, the dip direction shifts 180˚ to the southwest. An anomaly is observed on the crest of the anticline, near the location of the interpreted Bradley fault. The direction changes to 80-100˚ to the east in a very small area of the surface.

5.3.2 Curvature Analysis

The model of the Tensleep/Amsden Formation horizon was analyzed for two types of curvature, simple and Gaussian. Simple curvature gives a measure of the rate of change of dip across a structure. Simple curvature in 3DMove4.1 is measured in ˚/m. Anticlinal structures exhibit positive dip-change rates and synclinal structures exhibit negative dip-change rates. Simple curvature can imply locations where the surface is more tightly folded. Gaussian curvature, or total curvature, is a measure of the three dimensional fold shape of a surface. The Gaussian curvature of any point on a surface is equal to the product of the maximum and minimum principle curvatures, which are orthogonal to each other (Lisle, 1994). Gaussian curvature in 3DMove4.1 is measured in units/km^2. Gaussian curvature can be used as a way to imply regions of higher strain from a static geometric attribute.

Figure 5.14a shows the rate of dip change (simple curvature) color map for the Tensleep/Amsden Formation horizon hanging wall. Contoured values range from 0-0.1˚/m with a contour interval of 0.005˚/m. The back limb of the Alcova anticline exhibits minimal (0-0.01˚/m) rate of dip change values. Values increase in the hinge region of the structure and reach a maximum on the forelimb. There is little variation along the length of the hinge-line of the structure. Figure 5.14b is a close-up of the rate of dip change color map for the Tensleep Sandstone outcrop at Alcova anticline. Contoured values range from 0-0.14˚/m with a contour value of 0.0025˚/m.

Figure 5.15a shows crossplots of the fracture spacing values for the bulk fracture population versus simple curvature. Simple curvature values were extracted from the scan line planes created during LiDAR analysis. The same scan line orientation used to calculate fracture spacing in Chapter 3 was used to extract curvature values from the model surface. An average was calculated at a station every 10 m (33 ft), using all values of curvature +/-10 m (33 ft). The stations used to calculate the curvature moving averages correspond to the stations used to calculate the fracture spacing moving averages. The spacing values are from Scan Line 8 on both outcrops. Figure 5.15b shows crossplots of the fracture spacing for the N55˚W fracture set versus simple curvature. The spacing values are from Scan Line 8 on both outcrops.

Figure 5.16a shows the results of Gaussian curvature analysis for the Tensleep/Amsden Formation horizon hanging wall. Contoured values range from -0.7 to 1.5 /km^2 with a contour interval of 0.05 /km^2. As with the simple curvature, the back limb region of Alcova anticline exhibits values near zero. Along the hinge of the anticline, there are distinct areas of both maximum (positive) and minimum (negative) Gaussian curvature. Figure 5.16b is an enlarged view of the Gaussian curvature color map of the Tensleep Sandstone outcrop at Alcova anticline. Contoured values range from -0.7 – 1.6 /km^2 with a contour interval of 0.05 /km^2. The largest minimum anomaly correlates to the location of the Bradley transverse fault. A smaller minimum anomaly correlates to the location of the Bear Springs transverse fault.

5.3.3 Strain Analysis

Strain analysis was performed using the STRAIN TRACKER tool in 3DMove4.1. The STRAIN TRACKER tool calculates the dilatation, or change in area, of the triangles that compose the 3D surface horizons. Strain can be measured as the horizons are deformed or restored. For this study, the strain was measured in the hanging wall of the Tensleep/Amsden Formation horizon as it was restored to regional dip using the flexural slip flattening algorithm. The parameters were identical to those used in the flexural flattening used to check for balance. 3DMove4.1 calculates three types of strain for a surface: Current Area Dilatation, Absolute Area Dilatation and RMS Dilatation. Current Area Dilatation measures the dilatation from the surface's current state to its initial state, regardless of intermediate states. Absolute Area Dilatation sums all of the intermediate dilatations as an absolute value. That means that extension and contraction (positive and negative values) will added to one positive number. RMS Dilatation also counts the intermediate strain states, but sums them as a root mean square. As a result, Absolute Area Dilatation is always larger than RMS Dilatation. Because the restoration only involved one step, the values of Current Area Dilatation, Absolute Area Dilatation, and RMS Dilatation should be equal. The results for Absolute Area Dilatation are presented in this section, to be consistent with the results reported by Zahm (2002) and Woolf (2005).

The Absolute Area Dilatation strain map for the Tensleep/Amsden Formation horizon is presented in Figure 5.17a and Figure 5.17b. Values for Absolute Area Dilatation are dimensionless and range from 0 to 0.1. In this case, the greater the value, the more the area of the analyzed triangle has decreased, indicating an area of contraction. An area of contraction in strain that is tracked during restoration is equivalent to an area of extension in the deformed state, or the present-day outcrop.

The back limb of Alcova anticline is entirely devoid of strain. There are three areas of elevated absolute area dilatation strain present on the hanging wall of Alcova anticline. The largest area correlates to the location of the Bradley fault. A second, smaller zone of strain to the east correlates to the Bear Springs fault. Finally, further to the east is another zone of increased strain. No high-angle transverse fault has been interpreted here. However, this may be an indication that another fault should be placed there. Additional field work would be necessary to determine if this correct.

5.4 Discussion

Discussion of the analysis performed on the 3D model of Alcova anticline has two points of emphasis. The first point is a comparison of the location of fractures in the Tensleep Sandstone on the hanging wall of Alcova anticline with the modeled geometric attributes and strain. The second point compares the location of the interpreted high-angle transverse faults with geometric attributes and strain.

5.4.1 Fracture Location

Referring to Chapter 3, three major fracture orientations and one minor fracture orientation were determined from analysis of the LiDAR dataset. The three major fracture orientations are: N80˚E (oblique to anticlinal axis), N50˚E (perpendicular to anticlinal axis), and N55˚W (parallel to anticlinal axis) (Figure 3.23). A minor fracture set has an orientation of N10˚E (oblique to anticlinal axis). Referring to Figure 3.25, the N80˚E and N10˚E fracture sets are dominant on the back limb of the anticline. The N55˚W and N50˚E fracture sets are dominant in the crestal region and on the forelimb.

Of the geometric attributes, no correlation can be drawn between the location of the N80˚E, N50˚E, and N10˚E fracture sets on the back limb with specific anomalies on the attribute color maps. The rate of dip change and Gaussian curvature analysis resulted in minimum values on the back limb. The major N50˚E andN80˚E fracture sets would not have been predicted from any of these attributes. The same is true for strain; the entire back limb of the structure is devoid of strain.

There is a good correlation between the maximum values of the rate of dip change (simple curvature) and the location of the N55˚W fracture orientation. The LiDAR analysis showed that frequency of N55˚W fractures increases toward the crest of the anticline. This set is interpreted to be the extensional fractures created by the folding at the crest of the anticline. However, as shown in Figures 5.15a and 5.15b, no correlation can be determined relating changes in spacing values of the bulk fracture population or the N55˚W fracture set and changes in simple curvature values. There is also a maximum Gaussian curvature anomaly in the crestal region at the river cut. These observations are consistent with the conclusions that Hennings et al. (2000) made at Oil Mountain concerning the location of tectonically produced fractures related to total curvature (Gaussian curvature) and rate of dip change (simple curvature).

5.4.2 High-angle Transverse Faults

There is a good correlation between the location of the high-angle transverse faults and the Gaussian curvature and strain color maps. The negative Gaussian curvature anomalies over the Bradley and Bear Springs faults are a good match. This is a key observation because it may indicate that Gaussian curvature can be used to indicate regions of increased strain. Strain analysis requires expensive structural restoration software to unfold structures and track strain in three dimensions. Many other analysis packages can calculate curvature from seismic or well data. Gaussian curvature could help to identify features, such as high-angle transverse faults, that may act to compartmentalize the reservoir.

The contractional strain values of the restored Tensleep/Amsden Formation horizon have an excellent correlation with the mapped Bradley and Bear Springs transverse faults. This analysis indicates that these locations are areas of extension in the outcrop setting. It is expected that these features will lead to areas of localized fracture development, parallel to the transverse fault and decreasing away from the feature. This is consistent with observations that Hennings et al. (2000) made concerning the location of faults with areas of increased strain at Oil Mountain anticline. This is useful for the prediction of high-angle transverse features in the subsurface from 3D seismic data volumes.

The relationships observed between geometric attributes and strain and fractures and faults at both Alcova anticline and from other studies, in combination with the results from the LiDAR data analysis, provide the framework for constraining fracture development in reservoir models. The next chapter addresses the proposed parameters that should be used to create a fracture model of the Tensleep Sandstone at the Teapot Dome (NPR-3) field.

CHAPTER 6

PROPOSED FRACTURE MODELING AT TEAPOT DOME

This chapter deals with taking the interpretations from field work, LiDAR data analysis, and 3D geologic modeling at Alcova anticline, and using the results to recommend input parameters for a reservoir flow model of the Tensleep Sandstone at Teapot Dome (NPR-3) anticline. Figure 6.1 shows the location of Teapot Dome (NPR-3) in relation to Alcova anticline.

6.1 Fracture Orientation

The LiDAR data analysis of the Tensleep Sandstone at Alcova anticline resulted in the interpretation of 3 major fracture orientations. The fracture sets are: 1) N80˚E (oblique to the axis of the anticline), 2) N50˚E (perpendicular to the axis of the anticline), and 3) N55˚W (parallel to the axis of the anticline) (Figure 3.23). The N80˚E and N50˚E have generally steeper dips (70-80˚) than the N55˚W fracture set (50-70˚).

The relationships of fracture orientation to anticlinal folds have been documented in outcrops by Stearns and Friedman (1972), Hennings et al. (2000), Cooper (2000), and Zahm (2002). Haws and Hurley (1992), Garfield et al. (1992), List (1995), and Hurley et al. (2003) have reported similar findings in subsurface Tensleep Sandstone reservoirs.

These relationships allow the data collected at the outcrop to be used in subsurface modeling. Stearns and Friedman (1972) separated fractures found in folds into Type I and Type II populations, classified by the orientation of the principle stress directions compared to the local structure. Figure 6.2 shows this relationship. Type I fractures consist of two conjugate shear fractures and an extension fracture, which indicates that the intermediate principle stress (σ_2) is normal to bedding, the maximum principle stress (σ_1) is in the direction of dip, and the minimum principle stress (σ_3) is in the direction of strike of the structure. Type I fractures result from the regional compressive stress that form the fold along the direction of minimum principle stress (σ_3). Type II fractures are formed along the anticlinal axis. Type II fractures also consist of two conjugate shear fractures and an extensional fracture. Opposite of Type I fractures, Type II fractures are formed with the maximum principle stress (σ_1) parallel to strike and the minimum principle stress (σ_3) parallel to dip. This reversal of principle stress orientations is formed from tensional forces along the structure (Stearns and Friedman, 1972). Zahm (2002) noted the same relationship with the location and orientation of faults in outcrop at Thermopolis anticline. Figure 6.3 summarizes his observations as a function of 3D stretch during fold development. He observed that on the crest and forelimb of the structure, both Type I and Type II fractures and faults are present. This leads to an area of increased deformation. The extensional component of Type I fractures lies generally perpendicular to the axis of the structure and the two shear components are oblique to the anticlinal axis. The extensional component of the Type II fracture set is parallel to the axis of the structure and the shear components are oblique. Type I fractures are found throughout the entire structure and Type II fractures are found primarily near the hinge of the structure. The N50˚E and N80˚E fracture sets are interpreted to be Type I fractures, and the N55˚W fracture set is interpreted to be a Type II fracture set.

This relationship is also observed in the subsurface. Garfield et al. (1992) found two major directions of fractures at Little Sand Draw field in the Big Horn basin, from core, borehole image logs, and pressure interference tests. Their results are summarized in Figure 6.4. Pressure-interference tests indicate the direction of greatest permeability, which is assumed to correspond to the orientation of an open fracture set. Haws and Hurley (1992) reported similar results from pressure-interference tests for six anticlinal fields in the Big Horn basin (Figure 6.5). These tests show a strong component of permeability in a direction approximately perpendicular to the trend of the structures.

6.2 Fracture Spacing and Intensity

The LiDAR analysis of fractures at Alcova anticline resulted in fracture spacing populations that follow a simple power-law distribution. In general, the fracture spacing for the set perpendicular to the anticlinal axis (N50˚E) and the set oblique to the anticlinal axis (N80˚E) have smaller geometric mean spacing values than the set parallel to the anticlinal axis (N55˚W). The N50˚E set geometric mean ranges between 0.5 and 1.3 m (1.6 and 4.3 ft). The N80˚E set geometric mean ranges between 1.6 and 3.9 m (5.2 and 12.8 ft). The N55˚W set geometric mean ranges between 2.8 and 8.4 m (9.2 and 27.6 ft).

Hurley et al. (2003) reported the fracture spacing results for a horizontal borehole image log interpretation of 96 m (315 ft) from the Tensleep Sandstone reservoir at Byron field, Big Horn basin, Wyoming (see location on Figure 6.5). Byron field is an asymmetric anticline with an orientation of approximately N50˚W. The horizontal well was drilled from the back limb towards the crest of the structure, approximately perpendicular to the structure. Two orthogonal sets of open-fractures were reported. Set 1 was oriented parallel to the structure with a mean orientation of N49˚W. Set 2 was oriented approximately perpendicular to the axis of the anticline with a mean orientation of N43˚E. A third population, Set 3 was oriented oblique to the axis of the anticline (N85˚E), but was healed and the spacing values were not reported. The average spacing value, corrected for the geometry of the borehole, was 2.3 m (7.5 ft) for Set 1 and 0.9 m (3.0 ft) for Set 2.

The bulk fracture spacing value will decrease in the crest and forelimb region of the structure. This is due to the intersection of the Type I and Type II fracture populations (Figure 6.3). This was observed in outcrop at Goose Egg Dome by Harris et al. (1960) and by Simmons (1990) at Sheep Mountain anticline. Garfield et al. (1992) noted a zone of highest fracture intensity along the fold hinge of Little Sand Draw field (Figure 6.4). They reported that wells drilled in this zone rapidly rose to high water cuts, probably due to the high concentration of fractures that acted as conduits to channel bottom water into the reservoir.

6.3 Fracture Height

LiDAR analysis of the fracture data at Alcova anticline resulted in fracture populations that follow a simple power-law distribution. The geometric mean fracture heights for each fracture set are very close. The lowest geometric mean height was from the N80˚E fracture set at 17.5 m (57.4 ft) and the highest geometric mean height was from the N50˚E fracture set at 24 m (78.7 ft). The largest fracture interpreted was greater than 95 m (312 ft), which is equal to the stratigraphic thickness of the Tensleep Sandstone section exposed at Alcova anticline.

There has been limited fracture length data gathered at Alcova anticline, primarily due to lack of large, uncovered fracture pavements. Vealy (1991) reported the length of the N80˚E fracture set to ranging from 5 m to >10 m (16 to >33 ft) and the N55˚W fracture set from 10 m to <5 m (33 ft to <16 ft). I measured fractures lengths of >50 m (164 ft) for the N80˚E fracture set, west of the river cut, on the crest and back limb of the structure. Time constraints did not allow for a more detailed analysis program.

6.4 Fracture Modeling at Teapot Dome (NPR-3)

Teapot Dome (NPR-3) is located on the southwestern edge of the Powder River basin, approximately 45 km (27 mi) northeast of Casper, Wyoming and 90 km (50 mi) northeast of the Alcova anticline (Figure 6.1).

6.4.1 Geology of Teapot Dome (NPR-3)

Teapot Dome (NPR-3) is a Laramide-age, basement-involved anticline, south of the much larger Salt Creek anticline field. Mesaverde Formation sandstones and shales create the surface exposure of the anticline along the western, eastern, and southern limb (Cooper, 2000). The thrust fault responsible for the formation of Teapot Dome (NPR-3) terminates within the sedimentary section and does not outcrop. Maximum dips at the surface are 30˚ on the forelimb (western limb) and 7 to 14˚ on the back limb (eastern limb) (Cooper, 2000).

The Teapot Dome (NPR-3) field produces from three formations: 1) the Upper Cretaceous Shannon Sandstone at depths of 122 to 305 m (400 to 1,000 ft), 2) the Second Wall Creek Sandstone of the Upper Cretaceous Frontier Formation at depths of 762 to 914 m (2,500 to 3,000 ft), and 3) the Pennsylvanian Tensleep Sandstone at depths of approximately 1,680 m (5,500 ft) (Curry, 1977). As of December, 2005, Teapot Dome (NPR-3) has produced 27.9 million barrels of oil (WOGCC, 2005).

6.4.2 Carbon Dioxide Sequestration at Teapot Dome (NPR-3)

In 2003, Teapot Dome (NPR -3) was designated as a National Geologic Carbon Storage Test Center. The purpose of this center is to conduct field experiments aimed at maximizing carbon storage and reducing the risk of leakage. As part of a partnership with Anadarko Petroleum Corporation, enhanced oil recovery (EOR) through carbon dioxide flooding will also be studied (RMOTC, 2005). Sequestration of carbon dioxide created from power generation and refineries has been proposed in deep oil and saline water reservoirs. Sequestration of carbon dioxide in deep geologic formations may present a low-cost, low-risk means toward reduction in the amount of carbon dioxide and other green house gas emitted to the atmosphere.

Anadarko has initiated a large commercial EOR project that will inject approximately 7,200 tons of carbon dioxide per day into their Salt Creek field, the structure immediately north of Teapot Dome (NPR-3). The carbon dioxide injection is predicted to boost oil production from 5,300 barrels of oil per day to between 26,000 and 32,000 barrels of oil per day (RMOTC website, 2005). At peak injection, 2.6 million tons of carbon dioxide is estimated to be sequestered annually. This is carbon dioxide that might otherwise be vented to the atmosphere.

A spur of the pipeline bringing carbon dioxide to Salt Creek field will be built to provide Teapot Dome (NPR-3) with a steady supply of carbon dioxide for experiment purposes. The first phase of the project is underway at Teapot Dome. Phase I, the conceptual design phase, is focused on fully characterizing the potential reservoirs at Teapot Dome (NPR-3) (including the Tensleep Sandstone), determining optimal carbon sequestration levels, and the feasibility of enhanced oil recovery. Understanding the effects that fractures will have on flow in the Tensleep Sandstone is a major part of characterizing the Tensleep reservoir at Teapot Dome (NPR-3).

6.4.3 Fracture Modeling Parameters at Teapot Dome based on Alcova Findings

The results of the fracture analysis at Alcova anticline provide the basis for fracture modeling parameters at Teapot Dome (NPR-3). The necessary input parameters are: strike of fracture set, dip of fracture set, fracture set height, fracture set aspect ratio, fracture set spacing, and distribution of fracture sets.

The orientation (strike and dip) of the fracture set was determined by comparing the interpreted fracture orientations at Alcova anticline with those determined by Cooper (2000) with his work on the Mesaverde outcrops at Teapot Dome (NPR-3) and from borehole image logs at Teapot Dome. Four fracture sets should be modeled at Teapot Dome (NPR-3): 1) N29˚W (NE dip), 2) N29˚W (SW dip), 3) N75˚W, and 4) N65˚E (Table 6.1). Figure 6.6 shows the orientation of the three main fracture sets at Teapot

Dome (NPR-3) and the three main fracture sets determined by LiDAR analysis at Alcova anticline. Figure 6.7 shows the same rose diagrams as Figure 6.6, with the anticlinal axis rotated to an arbitrary north-south orientation. When the orientation data from Teapot Dome (NPR-3) and Alcova anticline are rotated, the three main fracture sets almost overlie each other. This allows the statistics from the fracture sets to be used on the corresponding fracture set at Teapot Dome. The dip values reported on Table 6.1 are taken directly from the results of the LiDAR interpretation and analysis. In addition, these values are consistent with those reported in the subsurface at South Casper Creek field by List (1995).

The fracture height parameters for each set in Table 6.1 are reported as power-law distributions. The fracture modeling module in 3DMove4.1 allows the user to input a range of fracture heights by using a power-law distribution. This is based upon the equation of Cladouhos and Marrett (1996), presented in Section 3.3.2, that relates the maximum value, minimum value, and exponent constant (-C) of a data set. The exponent constant (-C) for each fracture set was taken from the fracture height vs. cumulative frequency plots of each fracture set presented in Chapter 3. The minimum fracture height value input should be 5 m (16 ft), the lower limit of data analyzed in the Alcova anticline study. The maximum fracture height value input should be 90 m (300ft). This is the thickness of the Tensleep Sandstone at Teapot Dome from the type log in the WGA (1981) report of the oil fields of the Powder River basin. The geometric mean of each fracture height for each set is also reported in case the modeling software chosen will not accept power law distributions.

The aspect ratio of a fracture is the ratio of the height (h) versus the length (l), (h/l). This is the input parameter with the greatest uncertainty. This is due to the lack of data sets that contain both fracture length and height data. The values suggested for modeling at Teapot Dome were determined from looking at previous fracture modeling studies in Wyoming and limited fracture length data from Alcova anticline. La Pointe et al. (2002) created a fracture model of the Permian Phosphoria Formation and Pennsylvanian Tensleep Sandstone at Circle Ridge field, a Laramide-age anticline in the Wind River basin. Based upon outcrop studies and subsurface data, they selected an average fracture length of 50 m (164 ft) and an aspect ratio of 1.0. This meant that they populated their model with square fractures. On the other extreme, Maraj (2003), based upon the outcrop work of Harstad et al. (1995) used an aspect ratio of 0.04. This resulted in very long, rectangular modeled fractures. Doupe (2005) used an aspect ratio of 0.5 in her study at Cave Gulch field. The aspect ratio for Teapot Dome (NPR-3) was determined by taking the mean fracture length of 50 m (164 ft) of La Pointe et al. (2002), which was consistent with fracture length estimations of the N80˚E fracture set at Alcova anticline. I divided the 50 m (164 ft) fracture length by the geometric mean fracture height for the N80˚E fracture set, 17.53 m (57.5 ft). This resulted in an aspect ratio of 0.35.

The spacing values in Table 6.1 for the fracture sets were taken directly from the results for Scan Line 8 of the northwest outcrop at Alcova anticline. This scan line is approximately in the middle of the Tensleep Sandstone column and in the center of the structure. This provides an average value for the whole structure. Scan Line 8 is also relatively free of debris on the outcrop, leading to no covered zones and a more accurate representation of the true fracture spacing. As with the fracture height, the fracture spacing values are reported as power-law distributions, as determined in Chapter 3. The exponent constant (-C) was taken from the spacing vs. cumulative frequency plot for each fracture set from Scan Line 8. The maximum and minimum values reported for each fracture sets were determined for the values from Scan Line 8. The geometric mean for each spacing value is also reported.

The final parameter used in the fracture model is the location or distribution of the individual fracture sets on the structure. The location of these fractures is taken from both the LiDAR interpretation and the results of the 3D model analysis at Alcova anticline, as well as from Stearns and Friedman (1972) and Zahm (2002). The N29˚W (Type II fracture set) should be located in the crestal region of the structure. A surface should be constructed on the top of the Tensleep Sandstone, ideally from the 3D seismic volume of the structure. This surface could be analyzed for simple curvature, and this fracture set should be located in the regions of elevated curvature values along the crest of the structure. As determined from the 3D model analysis of Alcova anticline, the N80˚E and N50˚E fracture sets at Alcova anticline did not have any apparent correlation to the geometric attributes analyzed. Traverses along the crest of Alcova anticline indicated, at least qualitatively, that the N80˚E and N50˚E fracture sets were fairly consistently spread over the entire structure. This is consistent with a Type I fracture set. For this reason, it is recommended that the reservoir model be set up to create the fractures from the N75˚W and N65˚E throughout the entire modeled structure area.

These parameters will provide a starting point to predict the fractures in the Tensleep Sandstone at Teapot Dome (NPR-3), based upon an analogous outcrop. As with all reservoir models, the model will have to be modified to fit the production history and updated as new data are collected.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The purpose of this study is to develop a fracture interpretation of the Tensleep Sandstone at Alcova anticline that would provide constraints for a reservoir flow model of the Teapot Dome (NPR-3) oil field. Major conclusions for this study are:

1) The new geologic map of the Alcova anticline area is based upon GPS-controlled formation tops and faults.
2) The new structural interpretation of the Alcova anticline included the recognition of transverse faults at high-angles to the axis of the anticline. These features were previously unidentified. These faults result from the formation of a series of basement corners on the plunging nose of the anticline.
3) A set of 14 balanced serial cross sections establishes the nature of the structure and provides control for a 3D geologic model.
4) The analysis of the 3D geologic model indicates that attributes, such as Gaussian curvature and strain can identify areas where high-angle transverse faults are present.
5) LiDAR data interpretation of fracture planes at Alcova anticline results in orientations and spacing values consistent with those measured in the field at Alcova, as well as for other analogous Laramide-age Tensleep Sandstone outcrops and subsurface reservoirs.

6) The distribution of fracture heights and fracture spacing values exhibit simple power-law distributions. These distributions can be used for modeling in analogous, Laramide-age, Tensleep Sandstone structures. This is significant because most of these fields are candidates for enhanced oil recovery.
7) The Teapot Dome (NPR-3) fractured reservoir model constraints are consistent with those observed at Alcova anticline and other analogous subsurface anticlines.
8) The study demonstrates the usefulness and practicality of LiDAR data to analyze fracture orientation and spacing on large, inaccessible outcrops.
9) This study is unique in that it resulted in a 3D quantification of fracture orientation, spacing, and height for a Laramide-age structure in the Rocky Mountain foreland.

7.2 Future Work

A detailed analysis of the fracture lengths at Alcova anticline should be undertaken to 1) determine the type of distribution and mean fracture length and 2) provide a range of aspect ratios for use in future modeling of the Tensleep Sandstone. There are no known large fracture pavements present on the Tensleep Sandstone outcrop at Alcova anticline, however, individual fracture traces can be followed with reasonable certainty. With several weeks of effort, 200 -300 fracture lengths could be measured at various locations around the outcrop, to provide the necessary population to perform statistical analysis of the fracture length. This will provide solid outcrop data for modeling analogous Laramide-age Tensleep Sandstone fields.

The LiDAR dataset at Alcova anticline should be further analyzed for the fractures that are less than 5 m (16 ft) in height. This will help to complete the characterization of the fracturing in the Tensleep. This is import to understand how injected carbon dioxide will travel through and eventually diffuse into the formation. This can be accomplished through gaining access to faster computers and development of automated fracture-picking algorithms. Automated fracture-picking algorithms will lead to the reduction of human-introduced bias in the analysis process.

When planning future acquisition programs for LiDAR data collection, with the intention of using the data for fracture interpretation, the survey should be designed so that each portion of the outcrop is scanned from at least two locations. The Alcova survey did not have 100% overlap. While the data was good for the portions of the outcrop only covered by one scan, the best data occurred in regions where there were overlapping scans.

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