ANALYSIS OF FAULTS AND FRACTURES, 
AND THEIR IMPACT ON A TIGHT GAS SAND 
RESOURCE PLAY IN THE UINTA BASIN.

by
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ABSTRACT

Tight gas sand field development plans need to incorporate new strategies to include the role of fault/fracture systems. This thesis characterizes the fault/fracture systems for the main reservoirs in the Natural Buttes gas field within the Uinta Basin in the eastern Utah. The data base included a 3D seismic survey processed for azimuthal velocity; volume seismic attributes; electric logs; core samples; production and geomechanic analyses. A fracture prediction model, with interpreted faults as input was generated applying the Elastic Dislocation Method in TrapTester software.

The seismic interpretation defined the major faults present in the study area, with a general fault strike of N70°E, W-E and N50-70°W. The curvature attribute shows orientations of negative curvature at different stratigraphic levels: At basement level W-E, N60°E, N25°E, and N-S; at intermediate levels N75°W, N-S to N25°E, N60°E and W-E lineaments; and at shallower levels W-E, N25-60°E, N-S, and a predominant group oriented N50-80°W.

The dipole sonic log information provided two kinds of information: Actual present day state of stress direction (\( \sigma_h = 101-281^\circ \)), and the fracture analysis, where 69 partially healed fractures strike 110-290°; and a few low angle shear fractures striking 20-200°. Nine hundred (900) feet of examined core contained few fractures; those restricted to sandstone levels are joints, and in the mudstone layers there are break outs and irregular fractures filled with residual oil.

Production histogram data from wells in the Price River Formation with at least one year of production correlated to gas EUR indicate highest production in the fault/fracture influenced production zones.

In this dissertation the fractures generated at different stratigraphic levels by Elastic Dislocation Method are oriented as follow:
- Basement Level N40-85°E and N45-75°W, with minor W-E and N-S.
- Price River N25-65°E and N40-75°W, with minor W-E.
- Wasatch Formation W-E, N25-70°W, N40-65°E and scarce N-S.

Generated fractures show a good correlation with curvature lineaments for the intervals of interest. The cluster of fractures predicted exhibit the same patterns as the curvature time slices, and also show a good correlation with the highest production wells in the Price River Formation.
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CHAPTER 1

INTRODUCTION

This chapter introduces the scope of this study, objectives, data available, a brief geological background research, and ends with a general conclusion.

1.1 Purpose of This Work

There is a need to understand faults and fractures at the Great Natural Buttes Field (GNB), and their relation to production from tight oil/gas sand reservoirs. Seismic interpretation in the area (2D lines and recent 3D surveys), has revealed deep vertical faults affecting the most basal section (here and after called deep basement faults). These basement faults are mainly oriented East-West and they reach the lower part of Mancos Shale Formation, where they lose their continuity and are apparently decoupled from higher fault structures. Fault picking in the upper section is difficult as seismically resolvable faults are irregularly distributed in the section from Mancos Shale up to the Mesaverde Formation. In the Tertiary section from North Horn (Paleocene) to the surface, there is a combination of faults from the Basement (E-W oriented faults) and those oriented parallel to the Gilsonite Dikes (N60-80°W). In summary, there is an uncertainty about the interrelation, genesis and behavior of these fault sets. Fault and fracture characterization modeling is performed in this project in order to understand three basic phenomena: Linkage faults associated with deep faults decoupled at the Mancos Shale Formation; the relationship between deep and shallow faults; and association of shallow faults and Gilsonite Dikes at the surface.

A tectonic model based on fault interpretation and complemented by a fracture generation and characterization model, is required to understand the impact of faulting-fracturing on a tight gas resource play. This analysis has important implications for other
tight gas plays, particularly in areas of poorly resolved faulting where fracture modeling may be an important part of any analysis.

1.2 Research Objectives

The main goal of this project is to perform a detailed analysis of the fault/fracture network through a 3D survey (Coyote Wash), including information from key wells. This is in order to derive a comprehensive tectonic model that will be compared to the current day stress field of these fault/fracture systems, and study their impact on a tight gas sand resource play.

1.3 Study Area (Field Location)

The study area is a prolific hydrocarbon zone located in northeastern Utah, within the Uinta Basin (figure 1.1). The Uinta basin has a number of different hydrocarbon fields in development. One of them is the Greater Natural Buttes (GNB) or Natural Buttes (NB) field, where this study is focused. Due to confidentiality agreement between the parties a detailed study location is not available. However, figure 1.1 taken from the USGS (2002) represents a general map location of Uinta and Piceance Basins separated by the Douglas Creek Arch. The yellow circle shows the approximate location of the study area.

1.4 Data Set

The available information in the area of interest is enormous, but has been limited in order to reach the objectives of the proposed thesis. This study is therefore limited to the GNB Field, around the Coyote-Wash 3D survey.

Available Information:

- 3D Volume. A 3D survey of 80 square miles, processed for azimuthal velocity attribute. The 3D survey was acquired in 2004 as a wide azimuth survey within the GNB Field. Since its acquisition, the volume has been interpreted by EOG Resources Inc., and their associated company Kerr McGee Corp.
Figure 1.1 Location of hydrocarbon prolific basins in eastern Utah Uinta Basin and western Colorado Piceance Basin. The area of interest is located by the yellow circle (USGS 2002).

The 3D volume has been processed in order to enhance fault detection; nevertheless each processing algorithm has different results that cannot be adopted as the unique answer. Several comparisons were made between different volume processes in order to have the most consistent interpretation. In this study, the basic interpretation was performed in the amg_prestack_fx_tvsw volume; other versions were used as support.

- Horizons. Eight horizons were taken from the previous company interpretations. Horizons and well markers were tied, and additional horizon interpretation was done to reach the 3D boundaries. Only at lower levels was some horizon completion required at the split ends of the volume; a complete horizon description is presented in chapter 3.
- Faults. All faults included in this interpretation were interpreted by the author. A comprehensive description and interpretation is presented in chapters 3, 4 and 5 of this thesis.

- Seismic Attributes. A complete set of seismic attribute analyses was performed by a group at Houston University on the original azimuthal velocity volume. Dr Kurt Marfurt and two of his students performed meticulous volumetric attribute calculations. The results were sent back to EOG Resources offices, where they were incorporated in the interpretation. This set of attributes will be described and analyzed in chapter 3.

- 2D Seismic Lines. Selected conventional 2D seismic lines were initially considered to be incorporated in the interpretation. There are a number of 2D surveys shot by several companies during different years around the area of interest. The majority of the lines were not tied to the 3D volume by the time this study was done. Consequently a decision to work only in the 3D survey was made.

- Well Information. Three wells with Oriented Dipole Sonic Scanner information was provided and the interpretation incorporated in this study. Additional well information was provided in terms of geomechanical analysis from three wells. Chapters 3 and 4 exhibit the analyses and results.

- 900 feet of core were recovered from the same well located within the 3D survey. After the core was slabbled, a visit to the warehouse was undertaken in order to perform a fracture characterization study, and the results are summarized in section 3.5.

- Depth Conversion. All horizons and faults were interpreted in time and finally converted to depth using constant velocities and volumetric functions. The procedures and results are discussed in chapter 4.

- EUR Maps. An estimate of expected ultimate recovery (EUR) Map at the Price River Formation was calculated by EOG Resource’s Group and provided for
fault/fracture network vs. production comparisons. The definition and applicability of EUR Map is presented in chapter 5.

- Actual State Stress Field. Information about orientation of actual state stress field was received from three wells in the area of interest. Complementary well information like Density, Pore Pressure, Leak-Off Tests and Formation Integrity Tests were also provided. This information was part of the input for fracture network prediction.

- Geomechanic measurements from three wells were received and processed in order to obtain Young’s Modulus and Poisson’s Ratio by stratigraphic level. This information was the input for elastic dislocation modeling presented in chapter 5.

- Software. During the development of this project EOG Resources provided a complete set of software tools for interpretation on a work station. 1) Landmark platform, the applications used were: Seiswork, Syntool, Geo-Probe for seismic 3D visualization, and Depth Team Explorer and TDQ for time depth conversion. 2) Petra package was used for general geologic maps, well interpretation, and log analysis. 3) The Department of Geology and Geological Engineering of Colorado School of Mines provided software specialized in structural geologic modeling: 3D Move 4.2 developed by Midland Valley, and Trap Tester 5.3 by Badley Geoscience Limited.

1.5 Previous Research

The area of interest has been drilled and produced during the last decade. The geoscientist teams have been collecting data to understand the influence of faults/fractures on production. New information has been acquired including the 3D survey processed for azimuthal velocity. Many efforts have been made and are in progress in order to understand fault/fracture influence on a tight gas resource play. Part of that effort generated this thesis research project. By the time this study was proposed,
there were several questions that need an explanation in terms of fault/fracture influence (personal communication, Robert Kidney 2006):

- Are shallow faults (section from surface to Price River Formation) associated with Gilsonite Dikes?
- Are deep basement faults associated or disassociated with shallow faulting?
- Is there a decoupled zone at Mancos Shale Formation level?
- Are linked faults associated with deep basement faults?

In order to accomplish the objectives of this research project it was important to integrate published information with the new results acquired from this study.

All the information available is important to realize the goals of the study. Fault interpretation is the major input to obtain fracture network in an appropriate geological model for the area of the Coyote Wash Survey. Complementary information like present day stress field and geomechanic data from wells and production data constrain the postulated fracture system to a geological model, accomplishing the major goals of this analysis.
CHAPTER 2

GEOLOGICAL OVERVIEW

This chapter summarizes the stratigraphy and structural geology from a regional context. The conclusions presented at the end of this chapter are focused on the area of interest within Uinta Basin.

2.1 Stratigraphy

Stratigraphic knowledge in the Uinta Basin has been increased in the recent years by hydrocarbon drilling and the enormous set of data collected during more than 50 years of exploration. This part of the chapter summarizes the stratigraphic sequence in the area of interest, and uses the nomenclature presented by Fouch et al. (1992) and detailed by the USGS (2002). The tectonostratigraphic systems for Cretaceous and Tertiary periods in the area can be summarized as follows: Latest Cretaceous through Tertiary uplifts on San Rafael Swell, Uinta Mountains, Uncompahgre Uplift, and White River Uplift, which disrupted the former depositional pattern of primarily marine and marginal-marine Cretaceous sedimentation in the Uinta Basin, and ultimately produced a Tertiary continental lacustrine basin with internal drainage (Fouch 1975; Johnson 1985). Lake Uinta contained different subenvironments including; deep lacustrine, interdeltic, lake-margin carbonate-flats, alluvial deposits and sediments deposited lateral to marginal lacustrine that prograded over the lake. These subenvironments produced a wide variety of lithofacies: organic rich claystones, mud supported carbonates, claystones, sandstones, and conglomerates beds sourced from nearby highlands (USGS 2002).

In the context of this brief depositional overview; it is important to review one of the deepest wells drilled in the area, the Conoco 22-1 Fed. This well reached sediments older than Cretaceous age, and encountered the tops of the Morrison and Carmel Formations from the Jurassic; Navajo/Nugget Sandstone from the Jurassic; the Webber Sandstone from Permian to Pennsylvanian; and the Redwall-Leadville Limestones of
Mississippian age. In this study, the horizon termed Basement could be equivalent to the limestones of Redwall-Leadville Formations. Therefore, a description of each formation is presented afterwards from published literature (section 2.1.1). Nevertheless, the main objective of this stratigraphic section is to understand the lithological interrelations and depositional setting.

Fouch et al. (1992) includes a stratigraphic cross section for the Cretaceous rocks along the north flank of the Uinta Basin south of Vernal Village. The stratigraphic cross section is included in figure 2.1.

The stratigraphy in this cross section begins with Morrison Formation (Jurassic); overlain by the Cedar Mountain Formation (Cenomanian) and Dakota Sandstone (Upper Cenomanian); covering these sandstone deposits is the Mowry Shale Formation, and on top, the Frontier Formation. In the middle of the cross section, at the right side of the vertical exaggerated figure 2.1, the Mancos Shale Formation represents the thickest deposit in the basin (approx. 4500 feet). It is composed mainly by mudstone rocks. On top of the Mancos Group, the Buck Tongue and Sego Sandstone formations interfinger with the lower members of Mesaverde Group. This cross section illustrates the relative thickness of each formation; the local interfingering levels; and the stratigraphic position of each member from the Jurassic through the Cretaceous section.
Figure 2.1 Stratigraphic diagram of the Cretaceous section in the area of interest. (Modified from Fouch et al. 1992).
As a complement to the stratigraphic distribution, another cross section for the Tertiary age units is included as figure 2.2. In the upper left corner of the cross section, a sketch of the location map is shown, pointing out the location in the central part of the basin and giving the actual direction of the cross section in a V shape. The sedimentary section closest to the area of interest is named the Green River point.

In figure 2.2, the formations present (from bottom to top) are North Horn, Wasatch (Colton Formation), Green River, Uinta and Duchesne River Formations. Markers like Flagstaff Marker of Green River Formation, Carbonate Marker equivalent to Uteland Butte Limestone or Long Point Bed, and Mahogany Oil Shale Bed are emphasized. The environment for the Upper Paleocene to Upper Eocene corresponds to closed lacustrine system due to the calcium sulfate salts, halite, sodium bicarbonate salts, and kerogen-rich shales deposits (Bradley 1925, 31; Johnson 1985; Fouch et al. 1992, 94).

A general stratigraphic column for the Uinta Basin, Douglas Creek Arch and Piceance Basin is included in figure 2.3 from the USGS (2002). In figure 2.3, the principle oil systems known in the area are differentiated by colors and for GNB the important ones are Green River (yellow) and Mesaverde Systems (green).

In the following paragraphs a brief description of each unit drilled in the area is presented from oldest to youngest; figure 2.3 integrates all general stratigraphic groups, formations and members:

2.1.1 Redwall or Leadville Limestones

The Redwall or Leadville Limestones are correlative units of Early Mississippian age. These limestones are generally light to dark gray, fine to medium grained, thick and unevenly bedded, cherty limestone and dolomitc limestone that is sparsely fossiliferous. This corresponds to the lower most formation reached by well Conoco 22-1 Fed (Sprinkel et.al. 2000).
Figure 2.2 Stratigraphic diagram of the Tertiary section at west side of the area of interest. (Fouch et al. 1992).
2.1.2 **Webber Sandstone**

The Webber Sandstone (Middle Pennsylvanian to Lower Permian) ranges in thickness from 650-1500 feet (200-275 m), and "consists mostly of fine to very fine grained, well cemented quartz sand". It is generally tan to cream colored to light or yellowish gray. Very thick, sweeping cross-beds indicate mostly eolian deposition in a beach and sand dune environment (Hansen et al. 1980, 83; Rowley, Dyni et al. 1979; Rowley et al. 1985). Locally, interlayered limestone beds with fossils that indicate a close marine association.

2.1.3 **Navajo Sandstone**

The Navajo Sandstone is composed of very fine to fine grained sandstones, with trough cross beds exhibiting its eolian sand dune origin in the early Jurassic.

2.1.4 **Carmel Formation**

The Carmel Formation (Middle Jurassic) thickens westward and pinches out towards the east, ranging from 130 to 60 feet, at the eastern side of the area. The Carmel Formation is composed of sandy shale, fine to medium grained sandstone, siltstone and mudstone. Probably deposited in a shallow marine depositional environment (Hansen et al. 1980, 83; Kinney et al. 1979; Rowley et al. 1985).

2.1.5 **Morrison Formation**

The Morrison Formation (Jurassic to Albian) is divided from bottom to top into the Salt Wash and Brushy Basin Members. The Morrison Formation consists of varicolored red, green, gray mudstones with interbedded siltstones and sandstones (McGookey 1972). In the southern Uinta Basin, the Morrison Formation is 680–730 ft thick, and underlies the Cedar Mountain Formation (Hintze 1988).
Figure 2.3 General Stratigraphic Column for Uinta Basin (USGS 2002).
2.1.6 Cedar Mountain Formation

The Cedar Mountain Formation (Cenomanian) is 200 to 1000 feet thick, and is recognized by the basal conglomerate or sandstone bed (the Buckhorn Conglomerate Member), which overlies the predominantly shaly upper part of the Morrison Formation (Molenaar et al. 1991). According to Young (1960), the Cedar Mountain Formation consist of a massive basal conglomerate or a conglomeratic sandstone overlaying by gray-green to purple mudstone containing scattered lenticular beds of sandstone.

2.1.7 Dakota Sandstone

The Dakota Sandstone (Moretti Jr. 1992) ranges in thickness from 230 to 270 ft; it consists of medium to coarse grained sandstones and scattered conglomerates deposited by braided streams in the lower part; in the middle, light gray and greenish gray mudstones with some medium grained trough cross bedded sandstone units, and local coal beds at the base, deposited in a coastal plain environment of low lying swamps and marshes with an intermittent stream channels; finally, the upper section corresponds to coarsening upward sequences with subhorizontal laminae, extensive bioturbation, small scale trough cross beds, cut and fill structures and common ophiomorpha burrows deposited in a thick complex of shoreface to foreshore marine sandstones and distributary channels sandstone beds.

2.1.8 Mancos Shale Formation

The Mancos Shale Formation (Turonian to Santonian) varies in thickness from about 1,700 ft in the westernmost part of the basin to about 5,000 ft in the middle part of the Uinta Basin. It is formed from base to top by the following members: Tununk Shale, Ferron Sandstone, Lower Blue Gate Shale Member, Emery Sandstone and Upper Blue Gate Shale Member (Montgomery 2003; and Edwards 2005). The Mancos Shale, in general, comprises a thick sequence of marine shale, which interfingers with several eastward-prograding sandstone tongues that reflect episodes of deltaic sedimentation along the western margin of the Cretaceous western interior seaway. The Mancos ranges
in lithology from black organic-rich shale to siltstones and sandy siltstones. A brief description of each member is presented below.

**Tununk Shale**

   The Tununk Shale is made up of dark brown shale and sandy mudstone deposited during a marine invasion.

**Ferron Sandstone**

   The Ferron Sandstone is a sequence of interbedded fluvial-deltaic sandstone, shale, and coals. Near its base the Ferron sandstone contains iron rich nodules; at the top it exhibits extensive bioturbation.

**Lower Blue Gate Shale Member**

   The Lower Blue Gate Shale Member comprises siltstones and shales from a marine invasion.

**Emery Sandstone**

   The Emery Sandstone consists of 500–1,000 ft of interbedded sandstone and laminated mudrock that was apparently deposited on a depositional ramp/shelf during the Santonian and early Campanian. The Emery sandstones comprise bioturbated or hummocky cross-stratified well-sorted, fine to very fine-grained sandstones arranged in upward-coarsening and thickening bed sets.

**Upper Blue Gate Shale Member**

   The upper most Upper Blue Gate Shale Member exhibit siltstones and shales.

**Buck Tongue Shale**

   The Buck Tongue Shale is about 100 ft (31m) thick in the eastern GNB and thins to zero going westward under the western part of GNB, (Osmond 1992).
Sego Member

The Sego Member according to Willis et al. (2003) is composed of tidally deposited sandstones interbedded with intervals containing marine shales and thin wave-deposited sandstones. The tidal sandstones have been interpreted to comprise multiple amalgamated estuarine valley fills above a major sequence boundary that is incised into distal marine deposits of the underlying Buck Tongue Shale. The Sego deposits constitute the base of a thick transgressive succession within the Sevier foreland clastic wedge. Alternatively, lower Sego sandstones have recently been interpreted by the authors to be tide-dominated river delta deposits in an overall regressive interval of the foreland succession.

2.1.9 Mesaverde Group

The Mesaverde Group is 2200 to 2900 ft (670 to 885m) thick. The Mesaverde Group (Campanian) is divided in Star Point Sandstone, Blackhawk Formation, Castlegate and Price River Formation. It is part of a wedge of alluvial fan and plain and deltaic sandstones deposited as a belt along the western margin of the epicontinental sea as it regressed (Osmond 1992). A brief description of each member is presented below:

Star Point Sandstone Formation

Star Point Sandstone was named and regarded as the basal formation of the Mesaverde Group by Spieker and Reeside (1925); Clark (1928); and Fisher et al. (1960). The formation spans a 350 feet stratigraphic interval at Price Canyon, Utah, and becomes finer grained eastward and grades into the Mancos Shale in the vicinity of the Price and Soldier Canyon areas. Young (1960) described the Star Point Sandstone as consisting of predominantly littoral marine and marine deposits.

Blackhawk Formation

The Blackhawk Formation is the dominant coal-bearing unit in the Mesaverde Group, is more than 900 feet thick in the southwestern part of the Uinta Basin and northern Wasatch Plateau (Fisher et al. 1960).
**Castlegate Sandstone Formation**

The Castlegate Sandstone 350 feet (107m) thick, is an upward coarsening delta plain deposit of very fine to coarse grained sandstone locally overlain by coal. In the eastern GNB the top of the Castlegate comprises about 20 feet (6m) of delta front sandstone. The lower approximately one-third of the main body of the Mesaverde, the Neslen Formation contains coal and carbonaceous shale interbedded with siltstone and very fine to fine grained quartzose and quartz lithic-sandstones deposited in deltaic environments. To the west of the Green River, the Neslen Formation grades laterally into fluvial units of the Castlegate Sandstone with thickness ranging from 250 to 500 feet, (Fouch et al. 1992), figure 2.3. The transition upward into the undifferentiated Tuscher and Farrer Formations represents the change from deltaic to alluvial conditions as the facies tracts followed the eastern regression of the sea (Osmond 1992).

**Price River Formation**

The Price River Formation described by Guiseppe (1998) is approximately 200 m thick at its type locality (Price Canyon) and consists of cliff-forming sandstone and siltstone. Sandstone sheets, 6 to 30 m thick, are separated by numerous, poorly exposed siltstone intervals 2 to 10 m thick. The sandstone deposits are composed of medium-grained, generally trough-cross-bedded, sandstones with some mudstone breaks and sparse pebble horizons (Lawton, 1983). The Price River Formation is divided into five members (Olsen et al. 1995); Of these, the Willow Creek Member, defined as a 25-m-thick, laterally continuous sandstone sheet, lower contact of the Price River Formation is conformable with the Castlegate Sandstone. The Price River Formation is overlain by the North Horn Formation of latest Maastrichtian to Eocene age, which is recognized by its reddish sandstone and limestone beds. At Price Canyon, the contact separating the Price River Formation and the North Horn Formation is a disconformity, representing a 2 m.y. hiatus (Lawton 1983). The top of the Mesaverde is an unconformity, which increases in magnitude eastward toward the Douglas Creek Arch, which forms the eastern margin of the Uinta Basin (Osmond 1992).
2.1.10 North Horn Formation

The North Horn Formation of latest Maastrichtian to Eocene age, is recognized by its reddish sandstone and limestone beds. The North Horn Formation in Price Canyon consists of thin lacustrine shales and lime wackestones overlain by variegated floodbasin mudstones and fine-grained fluvial sandstone lenses with thin granule horizons.

2.1.11 Wasatch Formation

The Wasatch Formation is about 3000 feet (915m) thick in the western GNB and thins to about 1000 ft (305m) in the eastern part (Osmond 1992). The thinning is caused as the lower part pinches out on the eastern and southeastern margins of the basin. A Paleocene basal conglomeratic zone is characterized by black chert pebbles and is recognized in the subsurface where it has been called erroneously the “Ohio Creek Conglomerate” (Johnson and May 1980). Fouch and Cashion (1979) named these the beds at Dark Canyon. Varicolored shales, palludal limestones, carbonaceous shales and coals, and conglomeratic sandstones in the lower part of the Wasatch Formation in GNB are equivalent to the Paleocene North Horn Formation and the Flagstaff member of the Green River Formation in the western part of the basin. These beds are transitionally overlain by alluvial red shales and siltstones enclosing scattered, lenticular channel-form sandstones. Formation contacts are easily recognize by the obvious color changes from the reds and browns of the Colton Formation to the green and light buff colored rocks of the Green River Formation and the Flagstaff Member.

Flagstaff Member

The Flagstaff Member is made up of feldspathic-lithic, very fine to fine grained and occasionally medium grained sandstones deposited by streams, which flowed northwest into the Uinta Basin from newly formed highlands in Colorado.

Colton Formation

The Colton Formation thins northward and westward, where the main body of the Green River Formation conformably overlies the Flagstaff Member, forming a continuous lacustrine sequence (Ryder et al. 1976). Rocks of the Colton Formation
represent a progradational fluvial-deltaic wedge of red and green sandstones and mudstones which built out into Lakes Flagstaff and Uinta from the SE (Ryder et al. 1976; Remy 1991).

2.1.12 **Green River Formation**

The Green River Formation thickens from 2200 feet (671m) in the southeast corner of the field to 3800 feet (1600m) in the northeast corner; the Formation consists of lacustrine dark brown marlstone (oil-shale) with interbedded light gray, oil stained water-bearing sandstones of the Parachute Creek and Evacuation Creek Members. The richest oil shale is the mahogany oil-shale bed. The base of the Middle Eocene part of the Green River Formation is lacustrine ostracodal coquina limestones, gray to tan with some oil staining. They are in sharp contrast with the red beds of the Wasatch Formation directly below. The lower approximately 1/3\textsuperscript{rd} of the Green River Formation, below the ostracodal limestone H Marker, is marginal-lacustrine dark gray shale with interbedded ostracodal and oolitic limestone and feldspathic lithic sandstones which were deposited along the northeast trending shores of Lake Uinta and in northwestward meandering deltaic distributary channels, (Osmond 1992). The lake episodically enlarged and contracted during deposition of the lower Green River strata so that the areal and stratigraphic positions of the limestones and sandstones vary greatly. This part of the Green River Formation is traditional Douglas Creek member of Bradley (1931) and Cashion (1967) and the black shale facies of Picard (1957).

2.1.13 **Uinta Formation**

As described by Osmond (1992), the Uinta Formation (late Eocene) forms the surface over most of the GNB and is up to 1700 feet (518m) thick in the northern part. It consists predominantly of greenish-gray to yellow-gray, red and purple variegated shale sand siltstones with lenticular, channel-form sandstones and beds of volcanic tuff less than 5 feet (1.5m) thick. The sandstones are coarse grained, conglomeratic, arkosic and thicker in the upper part of the formation. They become fine grained, thinner and more widely scattered in the lower 400 feet (122m). The lower contact is transitional from the
lacustrine rocks of the Green River Formation to the alluvial / fluvial strata of the Uinta Formation.

2.1.14 Duchesne River Formation

The Duchesne River Formation (Eocene-Oligocene) consists of more than 3,000 feet of fluvial conglomerate, sandstone, and fine-grained rocks. It is the standard section of the latest Eocene Duchesnean Stage. The Duchesne River Formation is subdivided into four lithostratigraphic units (from oldest to youngest): the Brennan Basin, Dry Gulch Creek, Lapoint, and Starr Flat Members (Andersen et. al. 1972).

2.1.15 Nomenclature for This Research

This research preserves the seismic horizons and well marker names used in the oil industry for the area of interest. Eight horizons were recommended and interpreted by Robert (Bob) Kidney across the whole 3D volume; the horizons used are tied to the wells and controlled by biostratigraphic and petrographic analyses. The eight horizons copied, renamed and extended to the whole 3D volume from bottom to top, are Basement; Base and Top of the Mancos Formation; Sego Sandstone; Price River Formation; Mesaverde Formation; Wasatch; and H Marker level from the Green River Formation. These horizons represent the main lithological changes in the area, and they are designated according to the operational names.

Most of the wells drilled in the area do not reach the deeper levels; common depths range between 7000 and 11000 feet (figure 2.4). For correlation purposes the well Conoco 22-1 Fed, located approximately 12 miles towards the west of the volume, was included in this report. The well was drilled by Conoco in June 1972 at total depth of 20053 feet in the deeper stratigraphic section of the GNB. The tops reached by this well had been published by USGS (2002), and summarized in figure 2.4. The stratigraphic equivalences between the tops reached in the well and the tops read from the synthetic log, performed by EOG Resources in 2001, were included. A time depth conversion table
Figure 2.4 Tops of well Conoco 22-1 Fed. drilled by Conoco in June 1972, located 12 miles towards the west of the area of interest. Two wells are representing the common depths drilled in the basin.
from the synthetic log mentioned for the same well was the input for the velocity model applied in this study. There are not significant differences between the published horizon tops and those in the synthetic log for the whole section.

The total thickness of the stratigraphic column is unknown due to the amount of sediments between the horizon termed basement and the lower stratigraphic sequences in the area. The basement in this research does not represent igneous or metamorphic rocks; it is equivalent to the limestone deposits of Mississippian age drilled by the well Conoco 22-1 Fed (Oral communication of Robert Kidney 2006).

2.2 Structure

Tectonics is the major interest and focus of this study and in this section the regional tectonic history of Uinta Basin is synthesized and illustrated from published information, in order to understand the principal features that affected the basin through geological time.

2.2.1 Regional Tectonic History

Marshak et al. (2000) suggest that structures oriented west to northwest and north to northeast in the Rocky Mountains, Colorado Plateau, and Midcontinent regions of the North American Cratonic Platform, for the late Paleozoic Ancestral Rockies event and/or Mesozoic - Cenozoic Laramide event, were generated by inversion of Proterozoic extensional fault systems. Proterozoic rifting events formed weak faults in the cratonic platform crust, and these faults were reactivated by stress transmitted during Phanerozoic compressional orogenies. Their suggestion assumes the control and influence of previous tectonic regimes through time. If their model is correct, the pattern of ancestral Rockies and Laramide contractional structures reflects the trends of Proterozoic extensional faults. In figure 2.5, the same authors presented a map of United States showing the location and trend of the faults in the Cratonic Platform. In this figure, the position and limits of Rocky Mountain-Colorado Plateau province (RM-CP), OA-Oklahoma aulacogen; LCFZ-Lewis and Clark fault zone, TWL-Texas-Walker line, MSM-Mojave-Sonora megashear, and MCR-Midcontinent rift are emphasized as major tectonic provinces.
The center of the yellow circle points out the area of interest. Marshak et al. (2000), based on the previous cratonic platform map of United States calculated two rose diagrams illustrating the dominant fault trends for two different regions: A) The Rocky Mountains Colorado Plateau province (RM-CP) with 96 samples plotted at left side of figure 2.6; the plot shows a main north-south orientation followed by a random population orientation. B) The United Stated Midcontinent (USA Midcontinent) with 143 samples plotted at right side of figure 2.6 and exhibiting a predominant northwest-southeast direction with minor orthogonal trends. These diagrams were included as the first fault orientation data in the area of interest.

Figure 2.5 Map of United States showing location and trend of faults. Rocky Mountain-Colorado Plateau province (RM-CP) is shaded. Other features are OA-Oklahoma aulacogen; LCFZ-Lewis and Clark fault zone, TWL-Texas-Walker line, MSM-Mojave-Sonora megashear, and MCR-Midcontinent rift. The yellow circle points out the area of interest. (Modified from Marshak et al. 2000).

Marshak et al. (2000) pointed out that the stress necessary to initiate sliding on preexisting faults is less than that needed to form new faults in intact rock, partly because frictional resistance is generally less than shear rupture strength under the same confining
pressure" (Etheridge 1986); and finally, they mention the stress state in the craton during marginal orogenies in the range of only 20 - 40 MPa; less than the experimental failure strength of rock under confining compression at shallow crustal levels (cf. Handing 1966). In their proposal of tectonic evolution of North America cratonic platform Marshak et al. (2000) suggest that after cratonization, two or more extensional events between 1.3 and 1.1 Ga and between 0.9 and 0.7 Ga, produced basement penetrating faults. These faults remained as permanent weaknesses in the upper crust. Late Proterozoic exhumation stripped away the rift fill in all the deepest rifts. Phanerozoic continental margin orogenies inverted the weak faults, causing reverse transpressional displacements that generated basement cored uplifts and associated monoclines. Because not all faults were oriented appropriately to deform by dip slip deformation, regional deformation was partitioned between reverse, oblique and strike slip movements (Varga 1993; Karlstrom and Daniel 1993; Tindall and Davis 1999).

![Figure 2.6 Rose diagrams illustrating approximate dominant fault trends in Rocky Mountain-Colorado Plateau province (RM-CP) and United Stated Midcontinent by cratonic platform times. (Modified from Marshak et al. 2000).](image)

In the following section, a general tectonic evolution of the foreland basin and its effects over the area of interest is summarized and explained according to major tectonic events published.
2.2.1.1 Sevier Thrust Belt

Currie (2002) cites different authors opinions in terms of tectonic evolution during Sevier deformation. Currie’s interpretations are based on stratigraphic determinations (thickness, composition, and lateral facies variations). His adopted definition of the Sevier Thrust Front is the eastern margin of thin-skinned deformation in the North American Cordillera (Burchfield and Davis 1975). In Utah, the thrust belt is divided into four major segments: the Utah-Idaho-Wyoming segment, the Nebo salient, the central Utah segment, and the southern Nevada-southwestern Utah segment (Lageson and Schmitt 1994). Each segment is structurally decoupled from adjacent segments along east-west oriented transverse zones and consists of different thrust systems (Mitra 1997). A USGS (2002) publication defines the Sevier Orogeny as eastward thrusting along the Sevier Orogenic Belt, where thrusting occurred in response to active subduction along the west margin of the North American continent. Subsidence, related to thrust loading (Price 1973) and possibly subduction-induced mantle flow (Mitrovica et al. 1989; Stern and Holt 1994; Pysklywec and Mitrovica 1998, 2000), created the Rocky Mountain foreland basin east of the thrust belt. Thrusting along the Sevier Orogenic Belt is generally thought of as “thin skinned” because of the low angle of the thrust faults and because the thrusting generally does not involve Precambrian crystalline rocks. Currie (2002) described a generalized paleogeographic map of the Sevier Thrust Belt and foreland basin, based on sedimentological and stratigraphic relations in the lower Cretaceous section. His map is shown in figure 2.7, illustrating the main division of the foreland basin into foredeep, forebulge and back-bulge areas. According to Currie’s map the area of interest was mainly in the forebulge zone of deposition in the foreland configuration by Albian age.

A general configuration of the foreland deposits in the basin, from west - east is shown in figure 2.8. A compressional history was interpreted by the USGS (2002), initiating in Late Cretaceous time with an epicontinental sea extending from the Arctic Ocean to the Gulf of Mexico. In the area of interest, the sea was bordered to the west by tectonically active highlands of the Sevier Orogenic Belt, which supplied sediments to eastward-flowing streams. The eastern shore was on the stable craton, topographically
low and supplied little sediments (Molenaar and Rice 1988; Williams and Stelck 1975). During Late Cretaceous time, the sea repeatedly advanced and retreated across the western part of the basin resulting in a complex pattern of intertonguing marine and nonmarine deposits (figure 2.8).

![Map of Sevier Thrust Belt and Foreland-Basin system](image)

Figure 2.7 Generalized paleogeographic map of the Sevier Thrust Belt and Foreland-Basin system in Utah and Colorado during Albian time. The Sevier thrust belt during the Aptian is shown at west side of the figure. Isopach contours represent the original thickness of Lower Cretaceous rocks in southwest Utah north of zero isopach contour are unknown. The yellow circle shows the area of interest (Currie 2002).

The marine deposits are represented by westward-thinning tongues of marine shales and siltstones. The nonmarine deposits are represented by eastward-thinning clastic wedges of sandstone, siltstone, shale, and coal. The yellow circle pointing out the area of interest is approximate, and was located based on the stratigraphic nomenclature (forebulge zone), in figure 2.7. In conclusion, the basin configuration shown in figure 2.8 is restricted to Sevier Belt Thrust times and differs significantly with the actual configuration of the basin as it is discussed in section 2.2.1.4.
Figure 2.8 Sketch of a Regional Stratigraphic Cross Section of Cretaceous rocks extending from western Utah to western Colorado showing stratigraphic relation between marine and non-marine strata. The yellow circle points out the approximate location of the area of interest. (USGS 2002).

2.2.1.2 Laramide Orogeny

The following Laramide orogeny summary was extracted from USGS (2002). It is characterized by thick skinned deformation manifested by reverse faults extending deep into basement rocks, and affecting only the central part of the Rocky Mountain region (figure 2.9). In this area, rising Laramide uplifts divided the foreland basin into smaller Laramide basins from latest Cretaceous through Eocene time. Several tectonic models related to changes in subduction along the western margin of the North American continent have been proposed to explain why compressional forces during the Laramide were concentrated in a fairly restricted area of the central Rocky Mountain region. The style of deformation appears to have occurred during a time of unusually rapid convergence between the Farallon and North American plates. The deep troughs of Laramide basins typically developed adjacent to thrust-bounded uplifts, and thrust loading has been proposed as the principal mechanism for inducing subsidence (Beck 1985; Beck et al. 1988). A deep trough formed to the south of the southward-thrusting Laramide Uinta Uplift, creating the Uinta Basin.
Theories about regional evoution of Laramide Orogeny were summarized as follows by Tikoff and Maxson 2001. The prevailing model for contraction during the Laramide orogeny entails a change at ca. 85 Ma. in the angle of subduction of the oceanic Farallon plate beneath North America. Dickinson and Snyder (1978) proposed that Late Cretaceous shallowing of subduction beneath the western margin of the North American plate transmitted tectonic stresses into the foreland and caused the Laramide block uplifts. An alternative plate-tectonic model for the Laramide orogeny involves collision and subsequent northward transpression of an assemblage of exotic terranes.

Figure 2.9 Laramide structures of Rocky Mountain-Colorado Plateau Province delineated by diagonal pattern lines; showing variations in vergence of Laramide structures. The yellow circle shows the area of interest (Tikoff and Maxson 2001).
Tikoff and Maxson (2001) presented a map showing the orientation of major structures (figure 2.10), and the interpretation that sinistral strike-slip motion occurred on east-west structures, particularly in the northern Rocky Mountains of the United States.

Figure 2.10 Major structures formed during Late Cretaceous through Paleocene time. The north-south-striking structures generally show dextral relative separation, whereas east-west-striking structures generally show sinistral separations. Strike-slip zones occur throughout the orogen, from coastal batholiths to the foreland arches. Abbreviations: IB, Idaho batholith; SN, Sierra Nevada batholith, yellow circle shows the area of interest (Tikoff and Maxson 2001).
Paylor and Yin (1993) documented approximately four kilometers of left-lateral slip along the South Owl Creek fault system, along the south side of the Owl Creek Mountains. Farther west, along the same fault system, 10 km of sinistral offset was inferred by Sundell (1990). These sinistral faults are consistent with physical models of Laramide uplifts that involve both folding and sinistral faulting (Sales 1968). Dextral deformation is also seen directly within the Front Range in Colorado. The most thoroughly documented fault analysis comes from measurements on flanks of the Front Range uplifts by Erslev (1993). This work demonstrated that the area is typified by oblique-slip faults, which describe a consistent contraction direction of N60°E. This orientation of contraction, combined with the overall N10°W trend of the Front Range, suggests a dextral component of deformation. Stated differently, if the contraction direction of faults is not perpendicular to the uplift (e.g., Front Range), a component of transcurrent movement is induced. A similar dextral shear component, as discerned from oblique-slip vectors, may describe other Rocky Mountain arches (Erslev 1993).

2.2.1.3 Regional Strain and Stress Maps

The tectonic history of western North America in Cretaceous-Tertiary time is explained by Bird (2002), and condensed in figure 2.11. Bird divided his studies by periods related to major tectonics events. Starting at 85 to 50 Ma., the most compressive horizontal stress azimuth σ1H was fairly constant at 068° in United States, where the Sevier Orogeny involved eastward thrusting of thick sedimentary sheets, which may have been driven by lateral expansion of a thick and elevated crustal welt created by subduction at the Pacific margin. The Laramide orogeny, in which shortening expanded eastward and involved Precambrian basement, was probably driven by an episode of horizontal subduction of the Kula and/or Farallon plates. During 50 to 35 Ma, both counterclockwise stress changes (in the Pacific Northwest) and clockwise stress changes (from Nevada to New Mexico) are seen, but only with about 50% confidence.

Eocene extension in metamorphic core complexes of the Pacific Northwest may be related either to early rollback of horizontal subduction in this region, or to formation of dextral faults in British Columbia that absorbed a portion of Pacific/North America
relative motion (Bird 2002). A major stress azimuth change of 90° occurred at 30 ± 2 Ma in the western United States. This was probably an interchange between σ1 and σ3 caused by a decrease in horizontal compression. The most likely cause was the rollback of horizontally subducting Farallon slab from under the southwestern United States and northwest Mexico, which was rapid during 35–25 Ma. After this transition, a clockwise rotation of principal stress axes by 36° - 48° occurred more gradually since 22 Ma, affecting the region between latitudes 28°N and 41°N.

Miocene extension of the Basin could be a kinematic result of the formation of the Pacific/North America transform margin, if the former margin trended more northerly than the relative plate velocity and/or a dynamic result of slab rollback in the southern latitudes (Bird 2002).

The Pliocene-Quaternary phase of mixed dextral shear and extension in the northern Basin and Range clearly represents a fraction of Pacific/North America relative motion, and localized orogeny in the Transverse Ranges of southern California is apparently due to a transpressive left step in this transform boundary. Each of these hypotheses presumes that deviatoric stresses in the lithosphere provide a link between plate tectonic causes and their distant effects. Therefore these hypotheses can be tested by examining the quasi-independent record of paleostress directions contained in dikes, veins, and mesoscale structures (Bird 2002).

**Principle Strain Map**

The following section summarizes the Principle Strain Axes for each stage, from the late Cretaceous to Present in North America (figure 2.11), Bird (2002):

A) Sevier/Hidalgo Orogeny; the strike of the thrust belt varied so significantly (more than 90°) with latitude. Only 5 data are relevant to the period 85–75 Ma (one in Washington, one in California, one in Arizona, and two in Texas), and all data show σ1H in the azimuth range 045°-067°, figure 2.11A.
B) During the Laramide Orogeny about 75 Ma, basement-involved thrusting began further east and formed the Rocky Mountains of the United States (Figure 2.11B). The mean $\sigma_{1H}$ azimuth in the United States was 068°.

Figure 2.11. Schematic and qualitative tectonic history of western North America. No palinspastic restoration is attempted. Regions of highest strain rate at each epoch are shown with shading. Only the strain rate axes in the northern part of western North America (b) and the southern part (c) result from formal computations; other axes are drawn perpendicular to the mean trend of dip-slip faults active at that time. Distribution of high strain rates (e) is based primarily on historical seismicity. Yellow circles show the location of the area of interest. (Bird 2002).

C) Eocene extension in the Pacific Northwest; the Eocene data together would suggest that $\sigma_{1H}$ only rotated 45° counterclockwise (from 065° azimuth during the
Cretaceous-Paleocene to 020° in the Eocene). The least compressive principal stress σ3 must have had an azimuth of 290° - 320°, (Figure 2.11 C).

D) Oligocene Extension in the Basin and Range; the most dramatic stress occurred in the early Oligocene, and it affected all of the western United States. Changes of principal horizontal stress (σH) from roughly WSW-ENE to roughly NNW-SSE are almost everywhere over 60° and in more than half the area are 75° to 90° (Almost everywhere, there is 90% confidence that the change is significant).

E) Miocene-Present stress rotation between the time steps from 30 Ma to the present; there is a noticeable tendency for a progressive clockwise rotation of σH. As the Pacific plate came into contact with North America along a lengthening transform boundary, northwest directed traction was exerted on a lengthening segment of North America plate margin by the Pacific plate. This gradual addition of vertical-plane area with dextral shear traction parallel to the coast caused regional-average σH to rotate clockwise until they reached orientations of approximately E-W, (figure 2.11 D and E).

**Principle Stress Map**

In the World Stress Map different types of stress indicators are used to determine the present day tectonic stress orientation. They are grouped into four categories: Earthquake focal mechanisms, well bore breakouts and drilling-induced fractures, in-situ stress measurements (overcoring, hydraulic fracturing, borehole slotter), and young geologic data (from fault-slip analysis and volcanic vent alignments).

The stress map displays the orientations of the maximum horizontal compressive stress (σH). The information was available in internet www.world-stress-map.org from Reineck et al. 2005. The map presented in figure 2.12 corresponds to the Basin and Range Region, where the Utah State is included as well as the study area. The tectonic conventions used in this map are NF for normal faulting, SS for strike-slip faulting, TF for thrust faulting, and U for an unknown regime. The length of the stress symbols represents the data quality, and around Uinta Basin the symbols could have a deviation of
15°-20°. A general orientation of the principal horizontal stress (σ_H) could be 115°-285° emphasized by normal faults, drilled induced fractures, strike slip movements and focal mechanisms. (Locally, there is a direction 175°-355° in the middle of the area).

Figure 2.12 World Stress Map for the Basin and Range Region from Reinecker (2005). The yellow circle points the area of interest.

2.2.1.4 Evolution of Uinta Basin

The genesis of the Uinta Basin (Johnson et al. 1990) can be summarized in five distinct phases of basin development and type of sedimentation (Johnson et al. Include the Uinta and Piceance basins as a province - UPBP, in the same evolution history). This summary condenses the previous literature in five stages:
(1) The UPBP formed part of a continental platform shelf on the northwestern flank of North America during the early and middle Paleozoic. Cambrian through Mississippian strata consist mainly of carbonate rocks, shale, and quartzite contain major unconformities and thicken westward.

(2) Pennsylvanian-Permian uplifts of the ancestral Rocky Mountain orogeny segmented this continental platform shelf into the Eagle, Paradox, and Oquirrh basins. Basin margin tectonics and cyclic eustatic climatic fluctuations strongly controlled deposition of the clastic, carbonate, and evaporitic fill of these basins.

(3) During the early Mesozoic, the UPBP formed part of a slowly subsiding continental platform. Triassic-Jurassic rocks include eolian, alluvial, and lacustrine deposits that thicken and grade westward into marine facies.

(4) Paleozoic and early Mesozoic strata in the westernmost part of the UPBP were thrust eastward during the late Mesozoic Sevier orogeny, causing subsidence in the adjacent foreland basin. The history of the UPBP part of this foreland basin is recorded by thick nonmarine deposits within and adjacent to the thrust belt that grade eastward into thinner accumulations of marine rocks.

(5) The geometry and style of regional compressional deformation changed markedly with onset of the latest Cretaceous-Paleogene Laramide orogeny. Laramide uplifts segmented the UPBP foreland basin into the Uinta and Piceance intermontane lacustrine basins. The geometry of these lacustrine basins is notably different from that of the late Paleozoic basins. Locally, the evolution of the Uinta Basin is clearly related to the Uinta Mountains uplift. The south limit of Uinta Mountains is the Uinta thrust, which became active in latest Cretaceous to Paleocene (Montgomery et al. 1998). The axis of the Uinta Basin, as defined by Eocene deposits, lies directly in front of, and parallel to the Uinta Basin Boundary and Asphalt Ridge thrusts. This relationship is typical of a foreland basin developed at the leading edge of a thrust sheet. If so, then the major period of activity of the system of north-dipping thrusts along northern margin of the Uinta
Basin was early Eocene in age (Montgomery et al. 1998). The actual configuration of the basin is shown in figure 2.13 with a gently southern flank and steeply northern flank limited by the Uinta Thrust. A general description of Uinta Basin is presented in the following section.

2.2.2 **Uinta Basin - Main Structural Features**

The Uinta basin is an asymmetrical, structural depocenter roughly 9300 mi² (24,000 km²) in areal extent that underwent subsidence as part of the Laramide orogeny in the latest Cretaceous-Eocene, (Osmond 1964; Fouch 1975; Ryder et al. 1976), figure 2.13.

The present form of the Uinta Basin is genetically related to uplift along the southern flank of the Uinta Mountains block. The basin has a steep northern flank and a gentle southern flank with an axis adjacent to, and closely parallel with, the thrust zone marking the northern margin with the Uinta uplift (Montgomery et al. 1998). The Uinta Basin is filled by as much as 17,000 ft of Maastrichtian and Paleogene lacustrine and fluvial sedimentary rocks (Bradley 1925; Cashion 1967; and Fouch 1985). Uppermost Cretaceous and lowermost Tertiary strata dip 4° to 6° toward the north. The younger Uinta and Duchesne River Formations of late Eocene to earliest Oligocene age dip less steeply.

The cross section shown in figure 2.13 is located in the northwest part of the Uinta Basin, oriented southwest to north as indicated in the central lower part of the figure. The cross section was created for the Tertiary sedimentary section starting with the North Horn Formation (Paleocene). The section orientation emphasizes the asymmetry of the basin, as well as the lateral relationships between different stratigraphic units. Several oil wells were included in the cross section as well as oil field names for localization.
Figure 2.13 Cross section showing the most common stratigraphic markers for the Tertiary section and the asymmetry of the Uinta Basin. (Fouch et al. 1992).

Several major structural features surround the Uinta Basin, and a variety of minor structural elements lie within its boundaries. The Uinta Basin roughly parallels and is bounded on the north by the Uinta Mountains; on the west by the Wasatch Mountains, Charleston Nebo Thrust and the Wasatch Plateau; on the east by the Douglas Creek Arch, and on the south by the Uncompahgre uplift and the San Rafael Swell. These main structures are displayed in figure 2.14 and briefly described in the following section:

Wasatch Plateau

The Wasatch Plateau lies near the northwestern margin of the Colorado Plateau in the transition zone to the highly extended Great Basin segment of the Basin and Range province to the west. The transition zone has experienced multiple episodes of fracturing, the most pronounced of which formed steeply dipping normal faults that dissected the
Wasatch Plateau into several roughly north trending horsts and grabens (Tingey et al. 1991).

Figure 2.14 Main structural features surrounded Uinta Basin: From north, clockwise direction, the Uinta Mountains; Douglas Creek Arch, Uncompahgre uplift, San Rafael Swell, Wasatch Mountains, and Charleston Nebo Thrust. Some surface structures are located in the map as Duchesne fault zone and Gilsonite Dikes (G). The area of interest is pointed out by a yellow circle. (Fouch et al. 1992).
Charleston Nebo Thrust

The Charleston transverse zone of northcentral Utah is an east-west trending corridor of faults and folds that forms the boundary between the Provo salient of the Sevier foldthrust belt and the Uinta-Cottonwood arch. The zone trends nearly 90° to the regional structural grain of the fold-thrust belt. Structural analysis and mapping in American Fork Canyon, near the western margin of the Charleston transverse zone, demonstrates that the zone contains an array of low-angle thrust faults and high-angle reverse and normal faults. Crosscutting relations indicate that the low-angle thrust faults formed first, followed by the reverse faults and possibly selected normal faults, and then by the majority of normal faults. Locally, normal faults reactivate reverse faults. (Paulsen, and Marshak 1998).

The overall pattern of faulting and folding in the Charleston transverse zone suggests that the zone is a left-lateral strike-slip flower structure superimposed on an imbricate thrust fan. Trends of normal faults in the transverse zone suggest that many formed during a later phase of oblique extension that had a component of right-lateral shear. Preliminary paleomagnetic data support a left-lateral strike-slip accommodation zone suggesting the Charleston transverse zone locally rotated counterclockwise about a vertical axis. Laramide uplift of the Uinta-Cottonwood arch tilted structures of the Charleston transverse zone to the south and may have locally reactivated faults within the zone. Subsequent extensional tectonism reactivated the Charleston transverse zone with an oblique component of right-lateral shear.

Uinta Uplift

The Uinta uplift trends east-west at the northern limit of the basin. It is 36 miles (48 kms) wide by 155 miles (250 kms) long extending from the cordillera Sevier thrust belt on the west to the axial basin arch. The uplift changes orientation slightly at its eastern end as it merges with the Grand Hogback and White River Uplift, from its dominant east-west trend to an east-southeast orientation (Stone 1986; Bradley 1995; Gregson and Chure 2000). The Uinta uplift represents reactivation of a pre-existing structure. This uplift coincides with an east-trending Middle to Upper Proterozoic
sedimentary trough that accommodated deposition of 7 to 10 kms of Uinta Mountain Group sediments (Hansen 1986; Stone 1993). The main uplift of the Uinta Mountains occurred during the Cretaceous end Early Tertiary, overlapping with both the Sevier and Laramide orogenies. The Uinta uplift also records a significant sinistral strike-slip component, as constrained by field observation (Gregson and Ersley 1997; Johnston and Yin 2001), and consistent with paleomagnetic data from the Colorado Plateau (Livaccari 1991; Wawrzyniec et al. 2002). The sinistral component of offset is thought to have occurred in the Eocene (Jonhston and Yin 2001), the same timing as for sinistral motion on other east west trending features in the region (Tikoff and Maxson 2001). Figure 2.15 shows a sketch of displacement between Rock Spring Uplift and Douglas Creek Arch through the eastern part of Uinta Mountains. Clockwise rotation of the Colorado Plateau and right lateral slip on the features near the Colorado Front Range also require 8 to 12 kms of left lateral slip along the Uinta trend.

Figure 2.15 Cartoon showing the sinistral offset along the Uinta Uplift considered to have occurred during the Eocene during relative movement of Rock Spring Uplift and Douglas Creek Arch. (Mederos et al. 2005).
Douglas Creek Arch

Douglas Creek Arch is a north south trending, anticlinal structure exposing Upper Cretaceous rocks in its core and Paleocene to Eocene rocks along the flanks. (Kopper 1962; Tweto 1975; Gries 1983; Rowley et al. 1985). The Douglas Creek Arch terminates southward into the Uncompahgre uplift (Stone 1977), and its separate the Uinta Basin from the Piceance Basin. Isopach mapping and stratigraphic studies in the Douglas Creek Arch indicate that the arch was formed during the Late Cretaceous (Campanian) through the Eocene (Kopper 1962; Tweto 1975; Johnson and Finn 1986).

Uncompahgre Uplift

According to Stone (1977), the major uplift of this region took place during Pennsylvanian and Permian time, as evidenced by the voluminous amounts of arkosic rocks of that age that were deposited adjacent to the uplift. This period of tectonic activity culminated at the close of the Early Triassic when the uplift was eroded down to its Precambrian core. Subsequently, the uplift was covered with Mesozoic and Cenozoic deposits. Starting in the Late Cretaceous, a new period of tectonic activity associated with the Laramide Orogeny caused renewed movement along the uplift’s northeast bounding faults. The whole feature was tilted toward the northeast, and many smaller structural elements, on and adjacent to the uplift, were reactivated. The Uncompahgre Uplift is a buried tectonic feature that trends northwest and extends across the Colorado-Utah State line, (Stone 1977). The uplift is bounded on the northeast by the Garmesa fault zone and on the southwest by the Uncompahgre fault zone.

San Rafael Swell

The San Rafael swell is actually an anticline 80 miles long and 35 miles wide, limited on its eastern boundary by the San Rafael Reef. The strata consist primarily of sandstones and shales of the Wingate, Kayenta and Navajo Formations.

These major regional structures around Uinta Basin are associated with some local structures that had affected the area of interest. Those structures are described in the following two sections as deep and surface structures:
2.2.2.1 **Deep Structures**

The ancestral Uncompahgre tectonic activity might have commenced as early as the late Precambrian with postulated left-lateral movement along two basement shear zones now represented by the Garmesa and Uncompahgre fault zones. This event was mapped by Stone (1977) and presented here in figure 2.16.

![Diagram of structural features](image)

**EXPLANATION**
- Precambrian crystalline basement
- Isopach line—Contour interval 500 ft
- Anticline—Showing direction of plunge
- Fault—U, upthrown side; D, downthrown side. Opposites shown relative movement

Figure 2.16 Structural features associated with the Uncompahgre uplift. Isopach interval is from the top of the Precambrian to the base of the Shinarump Member of the Chinle Formation. Red arrows are emphasizing the relative movements of the blocks evidenced by the displacement of anticline axes. The yellow circle points out the area of interest. (Stone 1977).

A brief description of figure 2.16 is presented in order to illustrate the main structure orientations belongs Uncompahgre uplift. In Stone’s map, the southern limit of the Uncompahgre uplift is Uncompahgre Fault Zone striking N42°W and the upthrown
block is on the north side of the fault. Towards the North there are two northward plunging anticlines, slightly deviated from the Uncompahgre fault zone strike. The northern limit of the Uncompahgre uplift is the Garmeza Fault striking N80°W, which cuts some anticline structures that show left lateral movement as illustrated with small arrows in the original map, and highlighted here in a red color. The generated structures include anticlines and small splay faults that are oriented N40°W. Towards the North there are more structures parallel to Garmeza Fault, like the Seep Ridge Fault Zone and Douglas Creek fault zone. These faults exhibit left lateral movement evidenced by the displacement of anticline axes that were cut almost perpendicularly (the orientation of mentioned axes ranges between N40°W and N10°W).

2.2.2.2 Surface Structures

There are two sets of structures observed at surface in the Uinta Basin: The Duchesne Graben Fault Zone (DGFZ) and the Gilsonite dikes (figure 2.14). These two recent structures are explained below.

Duchesne Fault Zone

The Duchesne Graben (DGFZ) is a faulted trough approximately 16 km long and up to 500 m wide (Groeger et al. 2000). This structure is located at the west side of the area of interest, (figures 2.14 and 2.17). A master fault bounds the southern margin of the structural half graben, strikes East to West, dips steeply northward, and accommodates about 200 m of slip. The origin of the Duchesne Graben is uncertain, and three hypotheses are presented by Groeger et al. (2000), and summarized in the following section:

- **Basement Involved**: The length of the Duchesne Graben Fault Zone (DGFZ) suggests that a deep-seated fault or fracture zone may be developed in the underlying basement, but there is no evidence for a basement-involved structure in regional magnetic or gravity patterns.
- **Laramide Orogeny**: The Duchesne Graben breaches an open, low amplitude flexure or anticline that continues below the depth of discernible normal faulting. Beds are locally flexed by reverse drag adjacent to normal faults at some localities and tilted by block rotation between faults. This smaller scale flexing and rotation, however, does not sufficiently account for the larger scale folding in the broad anticline that persists below the depth of discernible faulting. This anticline may have originated in the southern limb of the Uinta basin syncline during compressional deformation in the Laramide orogeny. If folding and faulting were coeval, then the graben presumably initiated where beds were extended above the neutral surface of the low-amplitude fold.

- **Recent Development**: Normal faulting and jointing continued episodically during the Neogene, even if the faulting began earlier. The Neogene was marked by uplift and fracturing in the Colorado Plateau just south of the DGFZ (Chidsey and Laine 1992). Normal faulting also occurred in the eastern Uinta Mountains (Hansen 1984) and locally along the northwestern edge of the Uinta basin (Hecker 1993). An estimated 1–2 km of overburden were stripped from the DGFZ during regional uplift and erosion in the southern part of the Uinta Basin, while maturation of hydrocarbon source rocks continued to generate high fluid pressure in the Green River Formation (Fouch et al. 1992). The narrow but distinct topographic troughs and prominent photolineaments within the DGFZ have been interpreted as evidence for Quaternary faulting (Hecker 1993). These hypotheses were included to show the ambiguity in origin of some of the preponderant structures in the area.

**Gilsonite Dikes**

The Gilsonite Dikes or hydrocarbon-filled fractures are located in the northeastern part of the Uinta Basin, figures 2.14 and 2.17. They strike N 40-70 W and are almost vertical. The dikes range in thickness from a fraction of an inch to nearly 18 ft, in length from less than a mile to nearly 14 miles, and in vertical extent from a few feet to at least 3000 ft (Verbeek et al. 1992). The widespread occurrence of gilsonite sills that were injected along bedding planes indicates that fluid pressures at the time of injection frequently exceeded lithostatic load. The gilsonite dikes of the eastern Uinta Basin
originated as large hydraulic fractures from overpressured, hydrocarbon-rich source beds in the Green River Formation during early stages of post-Laramide regional tectonic extension (Verbeek et al. 1992). Emplacement depths are estimated at 2300–8200 ft.

The morphology of Gilsonite Dikes is strongly related to the host rock lithology, and they were described by Verbeek et al. 1992:

- **Dikes in Marginal Lacustrine Formations.** (Uinta and Green River Formations). Typically they are bounded by large, planar to gently sinuous fractures that display characteristics of extensile failure of fine grained, well cemented rock. Dike walls locally step to left or right at point where adjacent dikes bounding fractures overlap and are geometrically similar to the offset walls described by Delaney and Pollard (1981). The most common structure is plumose.

- **Dikes in Coarse Grained Channels.** The dikes in the Uinta formation have fairly smooth, low relief walls that lack much of the structural complexity of dike walls lower in the section.

- **Dikes in Mudstones.** Dikes of the upper fluvial part of the Uinta Formation are smaller on average than those in sandstone. Individual dikes in mudstone typically exhibit irregular, not matching walls and thus pinch and swell conspicuously along their length, in sharp contrast to the nearly constant width of many of the same dikes in sandstones.

Relationships of dikes to fracture network of the host rocks are mainly characterized in Piceance Basin according to Verbeek et al. (1992); the faults can be grouped into five (5) sets according to their strike and fault abundance: F1 (the oldest system) strikes N15-30°W and is sparse; F2 strikes N55-85°W and is very abundant; F3 strikes N60-80°E and is moderate; F4 strikes N15-40°E and is very abundant; and F5 (the youngest system) strikes N65-85°W and is sparse.

Verbeek et al. (1992) concluded that the time of formation of the first three fracture networks at 43-10 Ma; the two youngest sets date from the time of regional uplift beginning about 10 Ma. The youngest regional set, F1, records a weak fracture event;
fractures of the F5 set are similarly scarce within the study area and are far too young to have had any event on dike evolution. F5 fault striking is the most common strike for surface faults in the Uinta basin according to major structures mapped.

Fouch et al. (1992) presented a location map for the Gilsonite Dikes in Eastern Uinta Basin, including some different gilsonite systems such as Cowboy Bonanza, Rainbow, Wilson Creek and Ouray systems around the study area. Figure 2.17 shows the gilsonite systems and the location of the study area.

![Map showing the location of gilsonite systems](image)

Figure 2.17 Gilsonite systems location around the study area (Fouch et al. 1992). The yellow circle is pointed out the study area.
Other Related Structures

Morgan et al. (2005), published a poster entitled "Preliminary discussion of the Fault Styles in the southwest Uinta Basin based on the investigation of the regional stratigraphic trends in the Tertiary Green River Formation in the SW Uinta Basin". They conclude that the area is dominated by 3°-5° NE regional dip into the basin, interrupted by only a few E-W and NW-SE-trending faults. Most faults exposed at the surface in the SW Uinta Basin can be grouped into two types: shallow, hingeline, Duchesne-graben type, and oblique-slip faults.

The DFZ coincides with the southern hinge of the basin structural trough. At Sand Wash, southeast of the DFZ, another graben is exposed in several cliff faces. Faults along the southern flank of the Peters Point anticline are exposed in Cedar Ridge Canyon near the junction with Desolation Canyon. Figure 2.18 shows their published surface map and the main structures described: Sand Wash Fault zone and Cedar Ridge Fault Zone.

These parallel faults have a throw of 1 - 40 m, and a wide deformation zone indicating possible significant lateral movement. These oblique-slip faults are associated with a deeper, basement-involved movement. Morgan et al. (2005) interpret the faults to be part of a flower structure related to the Garmesa wrench-fault zone that forms the northern margin of the Uncompahgre uplift.
Figure 2.18 Surface geology of southwest Uinta Basin showing Sand Wash Fault zone and Cedar Ridge Fault Zone. Isopach contours at lower member of the Green River Formation. The yellow circle points out the area of interest. (Morgan et al. 2005).

2.3 Conclusions

The stratigraphic units in the area range from Mississippian age through the Recent as recorded in the deepest sedimentary section drilled in the area. However, this study is focused on two intervals that represent the actual major reservoirs in the area: the Price River Formation from Mesaverde Group and Wasatch Formation.

The stratigraphy in the area comprises sediments deposited in marine to marginal marine environments during Pre-Cretaceous and Cretaceous times; later, varying to a continental influence with mainly lacustrine deposits and sub-environments ranging from lacustrine, fluvial, deltaic and alluvial deposits. These varieties of sandstone deposits
have generated two kinds of oil reservoirs: Conventional and Unconventional plays. Both plays are present in the area and they will be defined in Chapter 5.

This report adopted the formational names used by the operating company in order to be consistent with the reservoirs of interest (plays).

The structural evolution in the area is complex and can be divided into major events including the North American cratonic platform (Rocky Mountains, Colorado Plateau and Midcontinent); Sevier Thrust Belt that generates in the Uinta Basin a foreland configuration oriented towards the east; Laramide Orogeny with the Uinta Mountains Uplift that influences directly the Uinta basin configuration and modified it to the actual geometry of an asymmetric syncline with the axis oriented west-east. This study is located in the gentle dipping south flank of the synclinal structure.

Due to the location, the area is directly influenced by structures coming from Uncompahgre Uplift and described in this report as deep structures. The main azimuth orientation of these structures is N80°W, and they exhibit a preferential left lateral strike movement. Other structures affecting the area of interest are termed the Duchesne Graben oriented west-east and the Gilsonite Dikes oriented N50-80°W. Those structures are restricted to the shallower stratigraphic levels.

Recent published work defines faults exposed at the surface in the SW Uinta Basin grouped into two types: shallow, hingeline, Duchesne-graben type, and oblique-slip faults (Morgan et al. 2005).

To group the main structures documented in the area, figure 2.19 exhibits an overlapped map composed of the original map of figure 2.16 (Stone 1977) and a superimposed general surface map from Fouch et al. (1992), figure 2.17. This final map reveals the deeper structures associated with Uncompahgre Uplift, and the surface structures: Duchesne Graben (brown color) and the Gilsonite Dikes, these structures are oriented in general E-W and N40-80°W respectively. Structures like Uncompahgre Uplift
change its strike from N70°W to N50°W towards the west. The other structures Garmeza, Seep Ridge and Douglas Creek present the same direction N80°W, which is similar to the orientation of the Gilsonite Dikes. The only structure that strikes west-east is the Duchesne Graben. In chapters 3 and 4, the interpretation issue will help to prove the presence or relationships of some of these structural patterns.

Figure 2.19 Overlapped maps from figures 2.16 and 2.17 showing structural features from Uncompahgre Uplift versus the surface structures: Duchesne Graben (brown color) and the Gilsonite Dikes (blue color). The yellow circle points out the area of interest.
CHAPTER 3

SEISMIC INTERPRETATION

This chapter defines the problem, the hypothesis and how the final hypothesis is evaluated. All tools and procedures applied in the Coyote-Wash 3D volume are discussed and shown in the following flow chart, figure 3.1.

Figure 3.1 Flow Chart used for fault and fracture analysis.
To accomplish the results of this research the flow chart shown in figure 3.1 was followed. The input data came from 3D azimuthal velocity survey, and well information. The first analysis after the integration of these three sources was the horizon and fault interpretation. With this information, time structure contour maps including fault polygons were produced. The second input data were the volumetric attribute calculations, which were very useful in terms of fault definition (some of the previous faults were better identified and additional fault sets were relevant to postulate the structural complexity of the basin). Another complementary tool was the core taken for fracture characterization. Additionally, dipole sonic log information contributed to measure distribution, density, and orientation of fractures, and provided the azimuth for present day stress in the Coyote Wash area. The collected information was used to produce different scenarios in the fracture modeling process. A comparison between fracture model and EUR Maps will give an idea of fracture productivity. Figure 3.1, also, shows one step after fracture modeling connectivity, the reservoir simulation; that step is not part of the scope of this study.

3.1 Conventional Picking (Horizons and Faults)

The whole 3D Coyote Wash volume was interpreted by conventional methods in Seiswork of LandMark platform. The interpretation is based on the original seismic version of the volume, supported by interactive comparisons with other 3D processes.

Horizons

Eight horizons were taken from Robert Kidney’s interpretation due to the number of wells tied and the sedimentological, petrographic, and biostratigraphic control performed in the area, (figure 3.2). Horizons correspond to the main lithological changes in the area, and they were designated according to the operational names. Horizons were picked every twenty (20) lines and/or ten (10) traces, then autopicked, and smoothed (low smoothness was applied). Time contour maps were produced for each horizon interpreted, but just two contour maps will be presented in this thesis, one for the basement and another for the shallower section.
Figure 3.2 Interpreted trace seismic line located in the middle of the 3D volume showing name and relative position of each horizon. The seismic background presented was not the one used for fault conventional picking.

This study was focused on two horizons, the Price River Formation of Mesaverde Group (Upper Cretaceous), and the Wasatch (Colton) Formation of Wasatch Group (Paleocene-Lower Eocene). Figure 3.2 shows the relative position of each horizon picked in the whole volume.
The seismic line presented in figure 3.2 corresponds to a trace oriented north-south, located in the middle of the survey. The eight horizons from bottom to top are Basement, Base and Top of Mancos Shale, Sego Sandstone, Price River Formation, Mesaverde, Wasatch Group, and H-Marker level of the Green River Formation. The “basement” here is the deepest sedimentary horizon picked in the 3D volume and it is equivalent to the Mississippian Limestone layers present in the basin. All time horizons were converted to depth as it is discussed in section 4.2.

Faults

Faults were interpreted by the author in the whole 3D volume (personal communication of Dr Tomas Davis), using conventional fault picking, and defining fault cutoffs (personal communication of Dr Bruce Trudgill). One of the hardest things to do in this tectonic environment is conventional fault picking. Seismic lines at a scale of 1:1 are impractical to interpret in a work station environment; the seismic display has to be vertically stretched to obtain a better optical resolution. This issue is complemented by the complexity of faults in the area which makes the conventional picking complicated to predict due to the fault behavior itself, the quality of the seismic information, and the discontinuity of the faults observed in three dimensions.

Figure 3.3 reveals part of a seismic trace line with alternative methodologies of fault picking. In the upper left corner a trace without interpretation is presented; in the upper right corner a major single fault is interpreted; in the lower left corner, the same fault is interpreted with a series of splays; and in the lower right corner, a fault zone is delineated by two vertical faults. In this research, preferentially a major single fault was picked, and locally some fault zones were interpreted. Most of the fault picking was done in the traces (oriented north south), due to the predominant orientation and natural distribution of the faults. During fault picking, different structural aspects were observed, delineated and explained in the next paragraphs.
Figure 3.3 Detailed part of a seismic trace line showing three methodologies of fault picking. In the upper left corner the original line without interpretation; the following identical sections are differentiated by a single major fault, a major fault with splays, and a fault zone bounded by two vertical faults.

One of the requirements in this study was to identify and describe each fault or group of faults. Their associations or disruptions were used to postulate the structural fault model; from this structural model a fracture prediction analysis was performed.
3.2 Fault Description

This fundamental part of the report is divided in four sections: fault interpretation and characterization, structures associated with faulting, fault continuity and fault orientation.

Fault Interpretation and Characterization

The first fault interpretation begins with faults picked at basement level. Steep normal faults were picked as single faults or groups of faults (locally considered as fault zones as cited in figure 3.3). The trace seismic line, presented in figure 3.4, shows some weak lineaments that represent approximately vertical faults. At the lower levels, faults behave as near vertical faults with slips ranging between 40-6 ms (equivalent to 250-40 feet). Some of these interpreted faults are located with yellow arrows in figure 3.4. When those faults reach ductile sediments, they locally generate small low angle reverse faults; these splays are relatively short, discontinuous and very difficult to pick. They are locally extended between 10 and 20 lines along strike in the seismic volume, dip in different directions at low angles (less than 45°), and vertically they die out into the upper weak layers. Some of these faults are located by red arrows parallel to their apparent dips in figure 3.4. Additionally, some common pop up structures were generated above these fault terminations. These anticlines are frequent in the volume and their axes are mainly oriented W-E or parallel to the major faults (green arrows in figure 3.4).

Shallower in the seismic line, the steeply reverse faults lose their continuity, and some very steep normal faults are observed with very low slip values. At surface levels, these structures are less evident; fault slips are at minimum displacement according to the seismic vertical resolution; and small pop up structures are present on top of each fault reflecting some vertical movement. Those vertical faults become predominant with abundant splays subparallel to the major faults. The yellow arrows on top of the figure 3.4 are showing these surface features that could not correspond to the basement ones.
Figure 3.4 Seismic line pointing out some major faults and their associated structures. Yellow arrows mark vertical faults. Red arrows show low angle reverse faults; the green arrows are located on top of gentle anticlines.

**Structures Associated with Faulting**

To give a better idea about fault geometry and associated structures by stratigraphic level, a sketch from an interpretative point of view was drawn in figure 3.5. This sketch emphasizes fault style, sense of fault slip, and associated structures differentiated by levels. At the basement level, there are very steep normal faults that decouple at ductile layers, probably corresponding to Mancos Formation. These faults are the most common structures in the area. Their slips range from 6 to 40 ms. Locally, these faults develop low angle reverse faults when they reach ductile sediments; the reverse
faults are discontinuous and they die out in short distances. Some gentle pop up structures are present through the whole volume.

At intermediate levels of the stratigraphic section (Mancos to Wasatch Formation of the Tertiary), there are different structures: Lower in Mancos Formation, some low angle, reverse faults die out over short distances. In the middle part of Mancos Formation, some detachment zones were observed (very few) indicating fault reactivation in the upper levels. Vertical faults from top of Mancos Formation are displaced to the south-west in the volume, with apparent displacement towards the north-east. The traces of these upper faults are interrupted in the soft levels. In time slices, fault tips are common features as well as fault bends. Most of the fault/joints exhibit en echelon style; the longer faults are associated with parallel splays developed in brittle layers at intermediate levels, probably at the Mesaverde Formation.

At shallower levels (Wasatch Formation to surface), there are abundant, almost vertical faults striking N50-80°W. They exhibit small throws, gentle pop up structures and many splays approximately parallel to the master fault. The small pop up structures defines some vertical movement in the faults, difficult to establish due to seismic resolution.
Figure 3.5 Sketch emphasizing fault style by levels, fault throws, and their associated structures.
Fault Continuity

In this section, both vertical and lateral fault discontinuities are considered. Vertical discontinuities were discussed in the previous section and they are generally restricted to the shale layers. Lateral discontinuities are also present and they create joints, splays and linked faults. This explanation will be complemented in the seismic attribute section, due to the additional support provided by tri-dimensional attributes.

Fault Orientation

After conventional fault picking, horizon and time slices are an important tool for fault description, distribution and orientation. Some surface attributes were calculated in narrow windows of 10 milliseconds around the interpreted horizon. The first attribute run was average amplitude, with high amplitude responses (shown by bright colors) aligned with the fault strikes in a very acceptable correlation. The second surface attribute was dip-azimuth and its response was more relevant in terms of fault definition and lateral continuity. Figures 3.6 and 3.7 are examples of fault orientation emphasized by surface seismic attributes.

In figure 3.6, there are four maps from the same basement horizon. Figures 3.6 A and 3.6 B illustrate the same time contour map with interpreted fault polygons; figure 3.6 C displays an average amplitude map restricted to the basement level in a window of 10 ms. In general terms, high amplitude values correlate with the interpreted faults. Finally, in figure 3.6 D the dip-azimuth attribute emphasizes the major lineaments through the horizon slices. Two fault systems can be distinguished from this information (marked with numbers 1 and 2, for interpretation purposes). Fault System 1 corresponds to a lineament oriented N80°W and it is formed by small faults linked together; giving the impression of a continuous feature representing a major fault. The fault system 1 is located at north side of the volume en echelon style; limited fault segments are apparently intercepted by other faults oriented N40-50°E at west side and N40-50°W at east side of the fault. The fault system identified with number 2 corresponds to a fault zone, which is comprised of discontinuous faults with a general orientation N70-80°E. The fault zone is limited by two faults that are continuous and in general sense they conserve their strike.
Figure 3.6 Maps generated at Basement Level. A) Contour structural map on time; B) Structural time map with fault polygons; C) Average Amplitude map at 10 ms window; and D) Dip azimuth attribute. Numbers 1 and 2 indicate the fault zones described.

Weakly defined en echelon geometry defines the fault zone. The fault zone includes convergent and divergent splays, linked faults, connecting splays and undifferentiated faults/joints. There are also minor lineaments that are not discussed in this section.
Following the same methodology of the last figure, a seismic trace line from the shallow stratigraphic level figure 3.7, is included to show the geometry of the interpreted faults.

Figure 3.7 A includes a seismic trace line with white arrows locating some of the faults identified with numbers 3 and 4 (for description purposes).

Figure 3.7 B presents the time contour map with fault polygons and the yellow dashed line represents the location of the seismic trace line.

Figure 3.7 C exhibits an average amplitude map restricted to a shallower level in a window of 10ms.

Figure 3.7 D shows the dip-azimuth attribute restricted to the same level and emphasizes the strike orientation of more recent structures in the area.

The fault analysis reveals vertical faults with small throws and local pop up structures (3.7 A). Fault system 3 corresponds to vertical faults oriented N50-80°W with a new consistent lineament restricted to the shallower levels. Fault system 4 represents the same fault system oriented N70-80°E with a very irregular continuity and a possible tip by the middle of the horizon slice view.

The lineaments observed in horizon slice maps correspond to vertical faults interpreted in the seismic lines. A general observation reveals two fault systems at each level with approximately similar orientations (H-Marker level fault systems 1 and 2; and at basement level fault systems identified as 3 and 4).
Figure 3.7 Maps generated at shallower Level. A) Seismic trace. B) Time structural map with fault polygons. C) Average Amplitude map at 10 ms window below the level. D) Dip azimuth attribute. Numbers 3 and 4 represent fault systems.

The fault polygons were the input for two rose diagrams presented in figure 3.8 for the basement and the shallower levels respectively. On the left side, the basement level presents a 060-070° (N60-70°E) striking fault system identified as number 2; and another fault system striking W-E fault system identify as number 1. The rose diagram
also exhibits two set of faults striking 070° (N70°E) number 2 and 265° (N85°E) number 1. On the right side of the figure 3.8, the shallower level exhibits a predominant 300/320-130/150° (N60/40°W) strike of the fault system (number 3); and another fault system oriented 070° (N70°E) number 4; the random oriented faults with similar distribution as the basement level is also present.

The rose diagrams presented in figure 3.8 were generated from the interpreted fault polygons.

Figure 3.8 Time contour maps of the Basement Level on the left side, and the shallower level on the right one. A rose diagram was calculated for each map.
3.3 **Seismic Attributes (Curvature)**

A brief classification of seismic attributes from Roberts (2001) was incorporated in the following paragraphs in order to understand their origin. The term surface is taken to mean any surface or window from which a volume attribute can be extracted. Surface-related attributes can be grouped into three main categories (Roberts 2001):

- Surface-associated attributes use a surface to extract values from a secondary data source, e.g., seismic amplitude, coherency cube, complex trace and AVO data.

- Surface-derived attributes are computed directly from the surface itself. The common attributes are the first derivative type, which include the dip, edge and azimuth attributes as well as other map derived attributes such as isochore, trend and residual maps.

- Surface-rendered attributes or the second derivative attributes, are those which can be portrayed in three dimensions. The obey the procedures and workflows implemented by Marfurt and his colleagues. The course given by Marfurt (2006) on Seismic Attribute Mapping of Structures and Stratigraphy was a terrific help during the development of this chapter, and some of the procedures implemented here were adopted from the cited manual in the references. In the following items, a brief definition of each attribute is condensed and the results will be explained afterwards. The attributes were named by Marfurt (2006) as d_pc_filt_cp, Outer product, cross line gradient, in line gradient, energy 00, energy r2, d_mig, frac_d_amp, and negative and positive curvature.

**Analysis of Seismic Attributes**

Marfurt (2006) in his course taught about geometric attributes and the most recent development algorithms used to calculate 3D volumes of reflector dip-azimuth to define local reflector surface and detect discontinuities. The second geometric family is coherence and related measures of similarity between adjacent seismic waveforms (low coherence can indicate faults, fractures, etc.). The third family of attributes mentioned is
curvature. Most of the attributes were obtained in the Coyote Wash volume with the following results.

The objective of this analysis is to choose the best seismic attribute, in terms of fault/fracture identification, to be used as a complementary tool. With this objective in mind, a horizon slice view for every kind of attribute was collected at the same stratigraphic level and presented in figure 3.9. This quick visual analysis shows the following conclusions.

Figure 3.9 A presents the gradient attribute performed in two directions, inline on the left and cross line on the right; this attribute display was relatively good at basement levels and diffuse at shallower ones. The lineaments observed are straight forward, and they are more frequent in cross line sections than in in-lines due to the character and natural direction of the faults. This gradient attributes (in this volume) give a general fault tendency but disregard fault/fracture details.

Figure 3.9 B shows on the left side an Outer Product, which is showing rectilinear features with wavy forms, apparently identifying channel forms; there is not much details in terms of faults and fractures. On right side, the fract-d-amplitude enhances some rectilinear features without details.

Figure 3.9 C represents energy attributes performed in two different stages, but the selected time slices are not defining the structural setting. Major features are clear but continuity and fault details are not present.

Figure 3.9 D presents positive curvature attribute on the left side with a red color scale and negative curvature at right side with green color scale. Over these two time slices, there is more structural definition of major features and their interconnections. Additionally, smaller secondary faults and there are small lineaments indicating third order faults or possible fracture features. The good definition observed here and the possibility to generate analysis in time slices was much clearer than in the other attribute time slices. As a conclusion, the curvature analysis attribute was selected for further structural analysis in this report. A brief explanation of how curvature is calculated is shown in the following paragraph.
Figure 3.9 Time slices generated at the same depth level from different attributes.
Curvature

"Curvature is a two dimensional property of a curve and describes how bent a curve is at a particular point on the curve i.e. how much the curve deviates from a straight line at this point. The two dimensional concept of curvature can be extended into three dimensions. The intersection of a plane with the surface describes a curve from which the curvature can be calculated at any point along the curve. Curvature is a second derivative based method and it is sensitive to any noise. The most positive and most negative curvatures can be calculated, and they indicate an edge type display. Faults and lineaments can be discriminated taking on a polygonal appearance; the magnitude of the lineaments is also preserved, allowing better lineament discrimination" (Roberts 2001). Positive curvature is highlighted by color red while negative curvature by color green. Comparing both volumes there is not a significant difference; some of the structures are displaced little bit in north to south direction. For well drilling purposes a detailed positioned study has to be undertaken.

3.4 Fault Description from Seismic Attributes

To give a better idea of fault presence and characterization, structures associated with faulting, fault continuity and fault orientation described in conventional interpretation; some attributes were used to reconsider and complement the description of these topics in tri-dimensional way.

Fault Interpretation and Characterization from Seismic Attributes

One of the purposes of the volumetric curvature attribute is to clarify fault interpretation. In this example (figure 3.10), the seismic line displayed (positive curvature, red color scale) shows vertical basement lineaments defined as faults. Consecutive time slices were included to present the initial fault variation through depth (time slices A to D). Blue arrows point out some of the major structures presented on both displays. In the seismic line, there are some vertical faults cross cut by the time slices. The good resolution of the fault traces can be seen in the lower section compared to the shallower one. This analysis shows how different each level is, and how the evolution of the fault system is influenced by lithological changes.
Figure 3.10 Time slices through positive curvature volume attribute and its appearance in a positive curvature line oriented west to east. The blue arrows point common structures by levels.
To clarify the fault interpretation task, a coherence attribute (Outer Product, according to Marfur 2006) was used to match faults from seismic lines and the attribute feature. In figure 3.11, the direction of the trace is shown by a dotted line in figure 3.11A (north south direction). In the time slice, there are some features that can be either correlated to interpreted faults or none evident in the seismic lines. Two complementary seismic traces are presented in figures 3.11B (without interpretation) and 3.11C (interpreted line); some numbers were included for identification purposes.

In 3.11A, the number 1 shows irregular features oriented approximately West-East that was interpreted in the seismic line as a major fault.

The green arrow on 3.11A shows a discontinuous, wavy, feature oriented east-west that in the seismic line is not a significant structure. Does it correspond to a small channel or a secondary fault structure?

Figure 3.11A presents two more lineaments (numbers 2 and 3), that correspond to vertical faults. These faults are limiting a possible fault zone matching the interpretation. In general, these two faults are vertical, subparallel, with splays; in map view, the faults are composed of small faults with rotation towards the east (the general orientation is approximately N80°E).

The feature pointed out with number 4 is a vertical fault that on time slice is oriented N50-60°W.

The red arrow points where seismic information is not clear (no record zone).

The coherence (Out Product attribute) emphasizes the major lineaments and they basically correspond to vertical faults. Small features in time slices could be paleo channels. There are many small features that were not correlated to the vertical seismic line information.
Figure 3.11 A Outer Product attribute time slice showing some sedimentary and structural features in the upper part of the figure (A). A dotted line represents the interception of the seismic line. B shows a seismic line without interpretation, and C the same line with fault interpretation. Structures are differentiated by numbers and colored arrows.

**Structures Associated with faults from Seismic Attributes**

A 3D display was chosen to describe the fault behavior and evolution through the whole volume. A chair style view is be used in figure 3.12. The first description is always in a vertical sense (traces) from the bottom of the volume; and the second description refers to the horizontal views or time slices (lower time slice first and top one secondly). There are normally two sets of lines and time slices in each figure.
Figure 3.12 contains four displays A, B, C and D of the same volume, with different top trace in a progressive movement to the east.

Figure 3.12A shows almost the whole volume; the front trace (lower one) presents some discontinuous dark zones to the south, where the seismic information is poor and the stratification pattern is well defined towards the north. The lower time slice (1) view presents a very well defined rectilinear fault with no projection to the main trace. In the main trace, there is no clear information. One of the fault zones in the right side of the main trace is continuous through the upper most time slice. This fault zone converges to a single wavy fault oriented towards the east.

Figure 3.12B presents the same volume with the main trace displaced towards the east. The front trace does not change. The time slice 1 shows two linked faults en echelon style. In the main trace the linked faults shows a vertical trace decoupled where the black arrow is. At this level, pointed by the black arrow, three different fault zones can be observed (numbers 1, 2 and 3 for identification purposes). Some vertical discontinuities are observed in at least three points of the main trace, apparently due to lithological changes and different rock mechanical conditions. The time slice (2) looks similar to figure 3.12A.

Figure 3.12C presents the front trace and time slice (1) with no changes; however the main trace was moved towards the east; the fault zone 1 is slightly moved towards the north, while faults 2 and 3 are almost at the same position. Fault 2 has a better definition in the shallower section.

Figure 3.12D exhibits changes at the main trace where the fault (1) is finally defined as a single, continuous, vertical fault. Faults 2 and 3 have moved off the trace. The apparent movement to the north of the fault (1) when the main trace is moved towards the east exhibits the linked fault phenomenon in time slice views.

This figure 3.12 gives a good idea about the fault zone definition, and its evolution through the 3D volume.
Figure 3.12 3D volume displayed in a chair style presentation. Each display was described from seismic trace lines and after the consequent time slices. The volumetric seismic attribute displayed is a coherence volume.
Fault Continuity from Seismic Attributes

In figure 3.13 a coherence volume is displayed in a blue-yellow color scale; this color bar helps to identify discontinuous zones in the fault traces. Starting from bottom to top, there are three zones that probably correspond to lithological changes (at south of the volume, there is a zone with poor seismic resolution):

Zone A in the lower section will correspond to brittle layers that can reflect structural features like vertical faults and gently dipping beds.

In zone B, the vertical fault traces disappear and new fault traces can be seen; this is considered the biggest decoupled zone.

In zone C Higher in the section, an intercalated zone is presented due to heterolitic changes and irregular discontinuities in the fault traces. Each red arrow indicates a singular trace fault; and the dashed lines limit the continuous and discontinuous zones.

During fault analysis, these discontinuous zones were tied to ductile formations. At the base of these probably clay rich formations, low angle reverse faults are generated and they are normally difficult to distinguish in volumetric seismic attributes; gentle pop up structures are common. In most of the cases the vertical trace of faults disappears and continues in upper layers with some degree of displacement. It is difficult to affirm if it is the same fault or another one connected vertically. At Mancos Shale Formation, faults decouple in all directions forming small detachment zones. Above the Mancos and higher in the section, vertical faults are also present and some small discontinuities were commonly observed reflecting the intercalations between sandstones and mudstones.
Figure 3.13 3D volume displaying lithological changes and discontinuities in fault traces. The volume attribute is coherence with a blue-yellow color bar.

**Fault Orientation from Seismic Attributes**

The curvature volumetric seismic attribute was adopted as the best attribute to enhance fault/fracture detection and orientation. To confirm the features observed in curvature; the negative curvature time slices were overlapped with interpreted time contour maps. Two overlapped maps were generated and are presented in figure 3.14; Basement at left side and a Shallower level at right.

There is a relatively good match, especially in the major faults interpreted. Negative curvature attribute reflects many more lineaments in several directions that are considered as minor structures. At Basement Level, the major faults interpreted are
represented by the stronger curvature lineaments; short strong features, apparently linked, are arranged en echelon style; other structures bend and die out but in general they follow a common azimuth direction. Some lineaments diverge from main features and others are orthogonal, defining complex networks that in drilling prediction could be crucial to measure.

At the shallower level the lineaments are short, strong, discontinuous, and heterogeneously distributed so it is difficult to establish a fault pattern. The main features are oriented N60°E and more commonly N40-60°W. At shallower levels there are weak features oriented north south that could be artifacts or possible fractures.

To clarify, the features observed in negative curvature time slices shall be described, classified and oriented in the following paragraphs for two levels: Basement at figure 3.15 and Shallower level at 3.16.

![Basement Level](image1)

![Shallow Level](image2)

Figure 3.14 Overlapped negative curvature time slice and time contour maps from basement at the right and top horizon at the left side.
The volumetric curvature attribute reflects a large variety of lineaments in each time slice that need to be carefully analyzed. The curvature time slice at basement level shows four kinds of features (figure 3.15): strong long lineaments, strong short lineaments, east-west lineaments and north south oriented lineaments. A brief description and orientation of each one is given in the following lines.

**Strong Long Lineaments** are those that match reasonably with the time contour maps. They exhibit two preferential orientations: East-West to N80°W described before as a fault zone, and N60°E lineaments located at the upper left corner of the time slice.

**Strong Short Lineaments** are several strong lineaments either connected or disconnected with a general orientation N70-80E and described before as a fault zone.

**East-West Lineaments** are weak lineaments observed and located close to the major faults showing compartmentalized blocks divided by the next group.

**North-South oriented lineaments:** these are weak, short, sometimes deviated differently either east or west. A rose diagram was calculated in this time slice and the results were condensed in figure 3.17 at 3500 ms.
The curvature time slice at Shallow Level exhibits less intense features compared to previous Basement time slice. In figure 3.16 two kinds of features are observed: Strong lineaments and weak ones. Weak features can be divided in straight features and curve ones. A brief description is presented in the following lines.

**Strong Long Lineaments** are irregularly distributed and they represent the major faults interpreted. They exhibit two preferential orientations N60°E, that goes to the middle of the volume and dies out. Some discontinuous fragments oriented N50-70°W prominent in the northern part of the time slice.
Weak Lineaments are observed and located between the major faults showing small blocks with rhombic shapes, which is characteristic of this kind of attributes. The weak features are mainly oriented N50°E and north-south. A rose diagram was calculated in this time slice and the results were condensed in figure 3.17 at 1000 ms.

To establish a fault evolution through the time, a set of curvature time slices was put together and the major azimuth lineaments were measured. Figure 3.17 presents three different columns: First one shows negative curvature (green color scale), where major
lineaments were picked and drawn in the second column (positive curvature), the third one contains the rose diagram for each interval. An analysis of these rose diagrams shows the following characteristics:

At Basement level (3400 ms), four main directions are prevalent W-E; N60°E; N25°E; and N-S. Two of the families N25°E and N-S are represented by weak, short traces that could correspond to fracture zones.

At 2100 ms, the time slice is not showing a clear, well defined lineaments; in contrast short lines are present everywhere and represent four families N75°W; N-S to N25°E; N60°E and W-E lineaments.

At 1500 ms, more disperse azimuth directions are present with fault family lineaments distributed over the 360 degrees. The common directions are W-E; N25-60°E and N-S becomes a common orientation.

At 1000 ms, the same fault families are present W-E, a predominant group oriented N50-80°W and N-S features.

As a conclusion, there is not a significant change in the orientation measured except for shallower levels where N50-80°W direction is consistent.
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</tr>
</tbody>
</table>

Figure 3.17 Time slices at different time depths. The attribute shown is negative curvature; positive curvature with main lineaments marked; and rose diagrams of each interval.
3.5 Dipole Sonic Log Information

The tool measures azimuthal variations indicating anisotropy, which is caused by layering, rock composition, aligned fractures or differential stress. The Dipole Sonic Scanner tool provide P, S, Stoneley and flexural wave slowness measurements at varying radial depths of investigation, and frequency ranges between 300 to 8000 Hz. (Arroyo et al. 2006).

A Sonic Scanner Log was run in the #1 well. In the following lines a summary of the main results presented by the service company (Schlumberger 2006) is compiled.

- All faults and fractures data in the cored interval shows a global strike of 101-281° (N71°W). Most of the structures are dipping 90° with minor 75°, figure 3.18. Fractures are classified as breakouts, partially healed, induced tensile and induced shear.

- Drilling induced fractures strike WNW-ESE (101/281°), figure 3.19. Drilling induced fractures propagates towards the orientation of maximum principle stress (σ_max) and wedge open against the minimum (σ_min). Drilling induced tensile fractures are identical in orientation to future hydraulic stimulation. Breakout strike identifies the orientation of minimum principle stress. Breakout and Drilling Induced fractures should be nearly perpendicular in a single stress field environment with a vertical well Schlumberger (2006).
### ALL FRACTURES

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Figure 3.18 Diagrams representing all fracture data in the cored interval. Global striking 101-281°, most of the structures dips 90° with minor 75°. (Schlumberger 2006 for EOG Resources, Inc. internal report).
Figure 3.19 Drilling induced fractures strikes 101/281° and dips 90°. (Schlumberger 2006 for EOG Resources, Inc. internal report).
Present day stress orientation by stratigraphic levels:

- Sego Formation level 101/281°.
- Sego to Middle Price River Formation 90-110/270-290°.
- Middle Price River to North Horn Formation 90-110/270-290°.

A fracture characterization was obtained from Dipole Sonic Log in the cored interval; Schlumberger (2006) classified them as conductive natural formation fractures from 69 samples found and differentiated two fracture domains, figure 3.20.

- A dominant high angle fracture set striking WNW/ESE with a mean strike of 096°.
- A subordinate NNE-SSW and NNW-SSE striking low-dipping shear fracture set. Most of these fractures are vague and lithologically bound having low height.

Some core intervals were classified from the waveforms of the cross-dipole log by Schlumberger (2006) in their formation microimager (FMI and FMS product) geologic interpretation, as follows:

6100-6400' Stress Induced Anisotropy (at 6120' this anisotropy affected fine grained lithology).

7200-7400' Stress Induced Anisotropy.

8000-8200' Stress Induced Anisotropy (At 8101' intrinsic anisotropy).

8300 8500' Intrinsic Anisotropy.

8450' the dispersion analysis characterize isotopic homogeneous rocks.
Figure 3.20 Conductive Natural Formation Fractures with two fracture domains: the high angle faults and the low dipping shear fractures (Schlumberger 2006 for EOG Resources, Inc. internal report).
3.6 Core Fracture Characterization

900 feet of core were taken in the well #1; the core was recovered by intervals sampling the main reservoirs in the area: From bottom to top, Sego Formation, Lower Price River, Price River Top, and North Horn Formations. A fracture characterization study was undertaken by the author of this dissertation, in the previously slabbed core, special focus was applied to the sandstone intervals. The well was drilled vertically and the structural setting in the area has the same vertical component so the number of fractures expected was small. During the analysis of the core just six (6) fractures/joints were identified, (figure 3.21).

Figure 3.21 Fracture images from the core taken. A) A joint in sandstone intervals; B) Break Out zones fracture; and C) partially dead oil filling an irregular fracture. Last two fractures are restricted to mudstones rocks.
Those fractures restricted to the sandstones intervals were isolated, straight, vertical in the core, and classified as natural joints of a maximum eight inches in length. Those joints do not present secondary filling minerals, an example is shown in the compound picture of figure 3.21A. Other kinds of fractures were restricted to the mudstone levels.

The Break out zone is composed by small fractures oriented in all directions; each single fracture no longer than 4 inches, generally grouped with maximum length of 8 inches figure 3.21B. They form what is known as break out zones in the well, and their electrical response is particularly well defined. Finally, the other scarce fracture restricted to mudstone layers are composed of small linkage fractures no longer than two inches, with irregular shape, and on total not longer than 6 inches. This fracture was filled by residual oil, figure 3.21C.

At lower stratigraphic levels in the core, there is a very tiny structure, 7 inches long described as a vertical stylolite; this feature gives an idea of lateral compression in the formations.

The orientation of this core is not a good candidate for a fracture characterization study and particular details of fractures were missed.

3.7 Discussion

From conventional seismic picking interpretation, the major structures present in the area were mapped and the fault polygons corroborated with surface attributes like average amplitude and dip-azimuth; the general strike of the main fractures was N70°E, W-E and N50-70°W.

Evaluating the volumetric seismic attributes run, the curvature attribute was the most useful one due to the number of lineaments represented. A visual comparison of fault interpretation and negative curvature gave a good match to the most relevant time slice features.
Azimuth orientation analysis in negative curvature was performed by levels and the results are:

At basement level four main directions are prevalent W-E; N60°E; N25°E; and N-S. Two of the families N25°E and N-S are represented by weak, short traces that could correspond to fracture zones.

At intermediate levels, there are not well defined lineaments; in contrast short lines are present everywhere and represent four families N75°W; N-S to N25°E; N60°E and W-E lineaments.

At shallower levels, the common directions are W-E; N25-60°E, N-S, and a predominant group oriented N50-80°W.

Fault description using the available tools reveals from basement very steep faults that decouple at ductile layers and generate low angle reverse faults.

Higher in the section at intermediate levels vertical faults are common, with low slip and locally discontinuous traces.

At shallower levels, faults form a series of splays dipping vertically. Locally there are common pop up structures with axes parallel to the main structures.

The dipole sonic log information provided two kinds of information: Actual stress direction by levels and fracture analysis. The present day stress azimuth is 101-281°. The fracture analysis shows two main fracture families from 69 samples. The high angle faults striking 110-290° and a low dipping (less than 45°) shear fractures striking 20-200°.
The 900 feet of core do not show enough fractures to achieve their characterization. The few fractures observed in the sandstone levels were classified as joints; in the mudstone layers there are break outs and irregular fractures filled with residual oil.
CHAPTER 4

FRACTURE GENERATION

The main objective of this chapter is to postulate a fracture network that could be generated from the interpreted faults, stress state field and geomechanical information. Initially, the first input (fault network) will be analyzed and some preliminary conclusions discussed. As a second step, the first model for Basement Level was calculated, exploring all possibilities with the software. Finally, the two main reservoirs were analyzed: Price River and Wasatch Formations. This study is considered a good approximation due to the assumptions made during the analyses (the magnitude of the actual state main stress, the cohesive strength and the coefficient of internal friction).

4.1 Input Data (Fault Network, Depth Conversion, Required Information)

All the data used for the input are described and analyzed in the following paragraphs.

Interpreted Fault Network

The input data was the product of the 3D seismic interpretation before volumetric attributes were calculated. The interpreted information comprised eight horizons and sixty interpreted faults distributed throughout the whole stratigraphic column (basement to surface). In map view, all horizons converted to depth were extended to the border of a regular square. This procedure helps the software grid to work in a regular shape during the elastic model generation. Faults were classified by stratigraphic level and colored for visual differentiation; most of the fault planes were edited to define the most homogeneous fault plane. In case of splays, the fault was joined to the master fault by allen line projection. These allen lines are generated by the software in the sense of strike direction. Two general views of the interpreted faults are presented in figure 4.1.
In figure 4.1A, a map view including all faults interpreted is presented. Three dominant colors exhibit the fault domain: Yellow tones represent the shallower faults, greens the faults for intermediate levels and purple to red colors for the basement faults.

At basement level, three different fault orientations can be established: N40-70°W, N70-80°E and W-E. The group of faults oriented N40-70°W is apparently crosscut by a persistent set of faults oriented N70-80°E. On the north side of the view, the faults oriented W-E are limited by two faults striking in opposite directions; At the west limit, the fault trend W-E is cut by a set of faults oriented N40-60°E while at the east side it is cut by faults oriented N40-60°W.

At intermediate levels, some well defined fault orientations are present; N40-70°W apparently interrupted by faults oriented N70-80°E. In the middle of the volume, some W-E fault trends are interpreted, but in general, there is not a well defined fault pattern orientation.

At shallower stratigraphic levels, some of the previous fault orientations are prevalent and oriented N40-70°W, apparently interrupted (in this level) by a diffuse set of faults oriented N70-80°E. A common fault orientation pattern for the shallower levels are N30-60°W.

In the figure 4.1B, a depth model viewed from the east shows the horizons interpreted and the fault sets. The faults are color coded as previously described. The general pattern is that of vertical faults restricted to stratigraphic levels. The most common effect is fault decoupling at ductile layers, and the Basement faults decouple at Mancos Shale. In the upper stratigraphic section, some faults are restricted to Cretaceous rocks and others from the upper most Tertiary section to the surface. Both the decoupled and the fault level restrictions are observable in figure 4.1 emphasized by the horizons.
Figure 4.1 Interpreted horizons and faults used for fracture network generation. Basement level, faults are in purple colors, intermediate in green and shallow faults in yellow. The upper side is a fault map view and the lower side corresponds to a depth view towards the east.
Depth Conversion

Depth Team Express and TDQ software of LandMark were used for time to depth conversion. After the geological interpretation, all horizons and faults were converted from time to depth using constant and instantaneous interval velocities. A general procedure was to determine a constant velocity for the shallower part, surface to H-Marker; the constant velocity used was 10.000 ft/sc. An instantaneous velocity model for the interval between H-Marker and Mesaverde Formation was calculated due to the available check shot information. A velocity function was established by the software and applied in the stratigraphic interval mentioned. The following section from Mesaverde Formation to Basement has no well information. There are no wells drilled in the deeper formations in the area of interest; the source for deeper velocity information was taken from the well Conoco 21-1 FED located 12 miles to the west of the area. The sequence drilled was presented in figure 2.1, and the total depth reached was 20.053 ft in sediments of Mississippian age. A synthetic log created by EOG Resources (2001) was the input velocity data used in the lower part of this velocity model where a constant velocity was determined. The constant velocity used was 15000 ft/sc. The depth converted volume was compared to well markers and there was a good depth match, especially for the surface to upper Cretaceous formations where most of the completion activity has been made.

Software

The software used for fracture interpretation analysis was TrapTester (TT) developed by Badley Geoscience Limited. This structural interpretation tool helps to visualize 3D data volumes and analyze fault statistics as the main data input; one of the modules (FaultED) generates fracture networks from interpreted horizons and faults constrained by geomechanical rock properties.

The module uses the geometry and displacement of the fault surfaces as input to the Elastic Dislocation (ED) equations of Okada (1992). These equations calculate the response of an elastic medium to the fault slip on an array of rectangular fault elements (panels). The output includes the deformation (displacement vectors) of the observation points in the medium and the elastic strain tensor at those points. Using elastic rheology,
this total strain tensor is converted to a stress tensor (strictly a pseudo-stress). The stress tensor is then used in conjunction with a failure envelope to calculate mode of failure and the orientation of fracture planes, at each observation point. FaultED then combines the fault-related strain with a user-defined background (regional) strain to calculate the total geological strain at each observation point. Strain data were not available in the study area. Using elastic rheology, this total strain tensor is converted to a pseudo-stress tensor. The stress tensor is then used in conjunction with a failure envelope to calculate mode of failure and the orientation of fracture planes, at each observation point (Badleys 2005). The magnitude of state of stress was also not available for the study area.

**Required Information**

Interpreted horizons and faults were converted to depth and imported to Trap Tester software.

**Rock Properties**

These parameters control the way in which the strain tensor from the elastic dislocation modeling is converted to a stress tensor (via the elastic module), and how failure planes are calculated from the stress tensor (rock strength) (Badleys 2005). The rock properties required are summarized below and some standard values are referenced from the Trap Tester's manual: Poisson's ratio (e.g., limestone 0.2, sandstone 0.25, shale 0.3, and 0.25 for perfectly elastic material); Young's modulus (e.g., limestone 35000-55000 MPa, sandstone 10000-20000 MPa, and shale 5000-70000 MPa), Total Density (2000 Kgr/m³), Cohesive strength (obtained from the interception of the failure envelope on the shear stress axis of the Mohr diagram, in Pa), and Coefficient of internal friction (typically 0.6). All data used in this analysis belongs to EOG Resources and in the next paragraphs the values used will be explained.

In this report three kinds of data were incorporated into the fracture analysis: 1) Measurements derived from logs on three wellbores; 2) Geomechanical analyses (dynamic and static tests) from core samples of one well; and 3) Pump Analysis from one well.
An applicable methodology to handle geomechanical data derived from logs was suggested by EOG Resources (2007). They suggest, that to use log derived data some corrections need to be applied from the Geomechanical lab; a correction factor needs to be obtained from dynamic vs. static analyses. A quick analysis of the data provided by Triaxial Compressive Test under Zero Radial Strain (Static test) reflects very low values with respect to the Ultrasonic Velocities and Dynamic Elastic Parameters; therefore, this information was not considered for the calculations. However, the Ultrasonic Velocities and Dynamic Elastic Parameters data (Dynamic test) exhibits similar values to the average data calculated from the log depth intervals; these data are summarized in table 4.1. For log derived data, the values were statistically manipulated to get the average by depth intervals Table 4.2.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Depth (ft)</th>
<th>Gradient (b/ft)</th>
<th>Pore Pressure (Bars)</th>
<th>Poisson Ratio</th>
<th>Young's Modulus (Pa)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-Marker</td>
<td>2520</td>
<td>0.43</td>
<td>72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wasatch</td>
<td>4300</td>
<td>0.43</td>
<td>148</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mesaverde</td>
<td>6300</td>
<td>0.43</td>
<td>179</td>
<td>0.22</td>
<td>39024.32626</td>
<td>2480</td>
</tr>
<tr>
<td>Price River</td>
<td>7900</td>
<td>Overpressure</td>
<td>302</td>
<td>0.2</td>
<td>42195.91461</td>
<td>2510</td>
</tr>
<tr>
<td>Sego</td>
<td>8350</td>
<td>?</td>
<td>332</td>
<td>0.19</td>
<td>43919.60394</td>
<td>2540</td>
</tr>
<tr>
<td>Mancos Top</td>
<td>11000</td>
<td>?</td>
<td>512</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mancos Base</td>
<td>15000</td>
<td>?</td>
<td>783</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basement</td>
<td>18000</td>
<td>?</td>
<td>987</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The data obtained from logs and referred to depth based curves for Poisson's Ratio, Bulk Density, and Young's Modulus (wells # 1, # 2, and # 3) are summarized in table 4.2 (EOG Resources 2007).
Table 4.2 Average Geomechanical Properties by Depth Intervals

<table>
<thead>
<tr>
<th>Depth (feet)</th>
<th>Poisson's Ratio</th>
<th>Density (RHOB) - kg/m³</th>
<th>Young's Modulus (pa)</th>
<th>Poisson's Ratio</th>
<th>Density (RHOB) - kg/m³</th>
<th>Young's Modulus (pa)</th>
<th>Poisson's Ratio</th>
<th>Density (RHOB) - kg/m³</th>
<th>Young's Modulus (pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000-3000</td>
<td>0.28</td>
<td>0</td>
<td>0.00</td>
<td>0.28</td>
<td>0</td>
<td>0.00</td>
<td>0.26</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>3000-4000</td>
<td>0.48</td>
<td>0</td>
<td>0.00</td>
<td>0.15</td>
<td>0</td>
<td>0.00</td>
<td>0.26</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>4000-5000</td>
<td>0.15</td>
<td>0</td>
<td>0.00</td>
<td>0.23</td>
<td>0</td>
<td>0.00</td>
<td>1.38</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>5000-6000</td>
<td>0.26</td>
<td>0</td>
<td>0.00</td>
<td>0.22</td>
<td>0</td>
<td>0.00</td>
<td>0.27</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>6000-7000</td>
<td>0.22</td>
<td>0</td>
<td>0.00</td>
<td>0.17</td>
<td>0</td>
<td>0.00</td>
<td>0.68</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>7000-8000</td>
<td>0.22</td>
<td>0</td>
<td>0.00</td>
<td>0.14</td>
<td>0</td>
<td>0.00</td>
<td>0.23</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>8000-9000</td>
<td>0.22</td>
<td>0</td>
<td>0.00</td>
<td>0.21</td>
<td>0</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9000-10000</td>
<td>0.21</td>
<td>0</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cohesive Strength and Coefficient of Internal Friction were data not available in the field, so for calculation purposes the software background data were applied: 4 MPa for Cohesive Strength and 0.6 for Coefficient of Internal Friction.

**Strain**

A uniform regional strain should be specified. Regional strain is an optional input for most situations. This option was taken in these calculations because there is not available strain data in the field.

**Stress information**

The state stress field can be defined by inputting values for the three principal compressive stresses: Vertical stress (SV) defined by the average overburden pressure based on depth and rock density data derived by integrating the density logs and average sonic velocity data from check-shot survey data. Maximum Horizontal Stress (SHmax) is constrained by data from borehole breakout, induced fracturing and the world in-situ stress map. And Minimum Horizontal Stress (SHmin) based on leak-off tests and formation integrity tests.

The stress data available were: Vertical stress 1.0 psi/ft, minimum horizontal stress 0.63 and 0.7 psi/ft from injectivity tests. EOG Resources does no have the magnitude of the maximum horizontal stress, so stability and/or slip tendency analyses were not calculated. These analyses reflect the chance of reactivation of the fault-fracture
and hence the greater the chance of transmission of fluids/gas (Trap Tester manual, Badleys 2005).

The orientation of maximum principle stress in the field was obtained from the following wells and presented in table 4.3. The data were provided by EOG Resources (2007). In general, the Maximum Horizontal Stress ranges between N74-84°W, which is slightly different from the actual state stress direction W-E of Bird (2002).

<table>
<thead>
<tr>
<th>WELL</th>
<th>SOURCE</th>
<th>DIRECTION</th>
<th>ORIENTATION</th>
</tr>
</thead>
<tbody>
<tr>
<td># 1</td>
<td>Sonic Scanner</td>
<td>N80°W</td>
<td>100° - 280°</td>
</tr>
<tr>
<td># 2</td>
<td>Sonic Scanner</td>
<td>N82°W</td>
<td>98° - 278°</td>
</tr>
<tr>
<td># 2</td>
<td>FMI</td>
<td>N74°W</td>
<td>106° - 286°</td>
</tr>
<tr>
<td># 2</td>
<td>Sonic Scanner</td>
<td>N84°W</td>
<td>96° - 276°</td>
</tr>
<tr>
<td># 3</td>
<td>Sonic Scanner</td>
<td>N75°W</td>
<td>105° - 285°</td>
</tr>
</tbody>
</table>

In the Sonic Scanner log of well # 1 there are some orientations determinated by levels as shown in table 4.4

<table>
<thead>
<tr>
<th>STRATIGRAPHIC LEVEL</th>
<th>STRUCTURE</th>
<th>ORIENTATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Horn - Price River</td>
<td>Faults</td>
<td>90-110° / 270-290°</td>
</tr>
<tr>
<td>Price River - Sego</td>
<td>Faults</td>
<td>90-110° / 270-290°</td>
</tr>
<tr>
<td>Sego to well depth (8560')</td>
<td>Faults</td>
<td>101°-280°</td>
</tr>
<tr>
<td>Drilling Induced Fractures</td>
<td>Fractures</td>
<td>101°-280°</td>
</tr>
<tr>
<td>Conductive Natural Fractures</td>
<td>Fractures</td>
<td>96°-274°</td>
</tr>
</tbody>
</table>
Pore Pressure

Pore pressure data were required for both the slip tendency and dilation tendency calculations after the state of stress field is established. A crossplot of pressure vs. depth was received and the pressure by depth interval was determined. For depths higher than 6300 ft, EOG Resources applies a formula to calculate the pore pressure. The pore-pressure data collected were presented in table 4.1 (EOG Resources 2007).

\[ P(\text{psi}) = 0.9838 \times \text{Depth (ft)} - 3451 \text{ ft} \ldots \text{(formula provided by EOG Resources)} \]

P(\text{psi}) pore pressure to be calculated

Depth, depth where the pore pressure value is needed

4.2 Fault Structure Analysis

The main input data for fracture prediction in the elastic dislocation method is the interpreted fault network tied to the interpreted horizons. The software Trap Tester includes a useful tool to obtain the basic statistics of the input fault network (fault attributes). In the next section, three fault networks are analyzed in terms of fault orientation, frequency and length-displacement plots.

Fault orientation analysis was conducted by rose diagrams at different stratigraphic levels: Basement for pre-Cretaceous age (figure 4.2), Mesaverde Formation Cretaceous age (figure 4.3), and H-Marker Formation for Tertiary age (figure 4.4). All the diagrams exhibit the average orientation; orientation by the group of faults; then there is a comparison to the orientation of maximum horizontal stress obtained from well analysis (Table 4.3) or by levels from table 4.4; a comparison between curvature analyses and the orientation of the horizontal stress from world wide stress map. Finally a fault orientation analysis was performed including some regional features from published data.
Basement Level (Fault Orientation)

Figure 4.2 Rose diagram showing fault orientation at Basement Level.

Mesaverde Formation (Fault Orientation)

Figure 4.3 Rose diagram showing the mean strike fault orientation plot at Mesaverde Formation.

Mesaverde Formation shows a general fault orientation $87^\circ-267^\circ$ (N$87^\circ$E).

Main orientation by group of faults $60^\circ-240^\circ$ and $90^\circ-270^\circ$.

General Well orientation $98^\circ-278^\circ$ (table 4.3). Difference $11^\circ$ counterclockwise.

Well CWU 854-33 orientation at this level $90^\circ-270^\circ$ (table 4.4). Difference $3^\circ$ clockwise.

Curvature orientation analysis $285^\circ$, $025^\circ-100^\circ$.

World wide maximum horizontal stress direction $105^\circ-285^\circ$. 
Figure 4.4 Rose diagram showing fault orientation at H-Marker Formation.

Each stratigraphic level reveals a different orientation tendency due to the development of new faults or different fault contains.

**Fault Orientation Analysis**

The first approach of a fault rotation analyses can be postulated from the interpreted faults and the regional structural setting. In figure 4.5, all interpreted faults are shown in a map view display. Additionally, some very well known lineaments (considered as regional features) were included from the literature; Uncompahgre terminations from Stone (1977), Duchesne Graben and Gilsonite Dikes from (Fouch et al. 1992); indicating their preferential orientation and approximate location for interpretation and correlation purposes.

Figure 4.5 Fault Orientation Analysis from interpreted faults and regional features. Numbers 1 and 1’ are showing genetically related faults rotated approximately 10° counterclockwise. Other numbers are showing some degree of correlation with regional structures.
The description of figure 4.5 starts with the interpreted faults inside the area marked by the dotted line (some numbers were added to represent groups of faults but they do not refer to any sequence order). Number 1 (in purple) shows a group of faults from Basement level oriented N70-80°E; number 1’ (in green) represents the equivalent group of faults at the shallower level, oriented approximately N60-70°E. The basement faults decouple at Mancos level, and perhaps, this same set of faults evolved in the upper levels with a rotation angle of 10-15° towards the south (the red arrow in the figure indicates the sense of the postulated movement). These two groups of faults, according to the interpretation, are genetically interrelated and they are the only group of faults that exhibit this rotation phenomenon in the area of study.

Another group of faults; number 2 (in purple) shows an E-W trend at the Basement Level; they decoupled at Mancos Level, but did not propagate towards the shallower levels.

Group number 3 represents a group of faults oriented N40-50°W; these faults were interpreted in the whole stratigraphic sequence and their orientation is similar to the postulated Uncompahgre Uplift trend proposed by Stone (1977). These deeper postulated Uncompahgre Uplift trends were added to the figure 4.5 in black dashed lines conserving the original orientations. These features are approximately parallel to the interpreted faults (group of faults 3) and they are offset by the fault set represented by numbers 1 and 1’. This group of faults decoupled at Mancos Level are also present in the shallower levels with the same orientation, slightly displaced towards the northeast; a common evolution could not be established.

Group of faults number 4 affects the shallowest most stratigraphic section with faults oriented N50-80°W and subparallel to the regional Gilsonite Dikes represented by blue dashed lines. This group of faults is not associated with any deeper structure.

Finally, group of faults number 5 is represents some faults restricted to the shallower levels and oriented W-E. These faults terminations are not well developed in
the area, but the faults interpreted are approximately parallel to the Duchesne Graben faults shown in brown color.

These interrelationships show the area of Coyote Wash as a very complex structural area with a complicated evolution through the geological time.

The following two analyses: Frequency plot and the Length-Displacement plot were included because they revealed long faults with small throws. This relationship shows very low rock deformations (low strains and low stresses), and consequently very few fractures would be generated.

**Frequency Plot**

This statistical method used to predict fractures below seismic resolution, shows the fault throws plotted versus fault-fracture cumulative number in a log/log scale; this is done to predict fractures below the seismic resolution limit (figure 4.6).

The frequency plot generated for Coyote Wash 3D shows approximately the same pattern for faults at Basement in purple, Mesaverde in green and H-Marker in yellow colors. However, the straight line segment of each curve equivalent to the power law of fractal distribution after the seismic resolution limit shows an out of range number (logarithmic scale) of predicted fractures below the limit of seismic resolution. This plot is reflecting some abnormal fault interrelationships because the projection of the straight line is revealing thousands or hundred thousands of predicted fractures, as pointed by the arrow in figure 4.6. Two considerations could be true: 1) The study area is affected by long faults with small slips that are not generating deformation (strain); therefore they generate very few fractures; or 2) the study area is affected by many small faults with small slips that are generating few isolated fractures. After modeling the software is generating few localized fractures corroborating that the fracture prediction below seismic resolution is exaggerated.
Figure 4.6 Frequency plot analysis of faults from Basement, Mesaverde and H-Marker formations.
Length - Displacement plots

These plots (figure 4.7) are useful for determining population scaling relationships and checking fault interpretations. Populations of faults can be analyzed on cumulative frequency plots to predict the number of faults-fractures expected in set class intervals below a given size resolution. During the fault interpretation most of the faults picked exhibited 2 to 5 km of length and occasionally more. These long faults are showing very homogeneous throws ranging between 0.6 and maximum 10 m. This relationship displacement – length of a fault shown is not the expected one according to the Power Law Relationship.

\[ D = cL^n \]

where \( D \) is the displacement, \( c \) is related to material properties, and \( n \) ranges between 1.0 and 2.0.

One application of this relationship is to validate fault correlation by plotting the values obtained. In this case, the fault pattern interpreted in Uinta Basin is below the range of the global Displacement – Length Plot. The average values plot approximately where the blue star is, and in some cases there is displacement below seismic resolution. One conclusion could be that this current plot does not apply for the Coyote Wash faults. Another conclusion would be that the faults in Coyote Wash 3D survey were over-correlated.

Faults are potentially over-correlated when the point of correlation in the plot is located below the regression line (when \( c = 0.03 \) or less). If the faults were over-correlated the new interpretation has to include small fault segments, and faults overlaps. The anomalous relationships between the lengths of faults (2 to 5 km) versus the small throws (0.6 and 10 m) generate small deformations (strain) along the faults reflected in the number of fractures generated in the following analyses. And finally, a pattern of large fault lengths and small throws is common when the fault pattern was inherited from pre-existing faults (the fault pattern is highly influence by Basement faults).
Figure 4.7 Power Law Relationship for the Coyote Wash Area; Interpreted faults.

To clarify the concept of over-correlated faults (small faults interpreted as a single long fault), the composite figure 4.8 was created to illustrate this phenomenon. The arrow shows the starting point of the interpreted fault. In the upper view, the fault interpretation made reveals a single long fault; while in the lower view, the negative curvature attribute presents small features in an en echelon geometry. The dotted double arrow shows common points in each view. On the other hand, in this type of geological environment, each negative curvature time slice will exhibit a different set of features. Fractures at different levels have a similar orientation, but different fault tips, fault linkage and the
number of secondary features will either increase or disappear in response to the stratigraphic level rheology (brittle or ductile layers). These local changes make the fault evolution and the interpretation a very difficult issue.

Figure 4.8 Interpreted faults at Basement Level versus Negative Curvature Attribute showing the echelon distribution of small fault segments.

4.3 Fracture Generation

Eight horizons and approximately sixty (60) faults were loaded into Traptester as point set data. Initially, the point set data for faults needs to be synchronized or retessellated in order to calculate fault attributes (this is to construct surfaces defined by triangles); then, all the information should be synchronized to compute consistent models. This synchronization procedure consists of horizon-fault interrelation by triangle generation through all surfaces matching the row data including the fault polygons.
4.3.1 Methodology - Software

Fault surface edition and synchronization would be done before any calculation. Polygons should be created at the intersection of the mapped horizons and the fault surfaces. After a horizon-fault intersection polygon is completed, the horizon surfaces must be synchronized with their raw data and polygons: creating trimesh surfaces. Modeling the intersections between horizon and faults is a fundamental step in building faulted framework models. Two intersection lines are derived for each horizon fault intersection: Up thrown (or footwall) polygon and downthrown (or hanging wall) polygon. The aim of the horizon fault intersection modeling is to create fault polygons that best represent the intersection of the horizon raw data with the fault surface. Some rock parameters need definition for modeling purposes.

Trim distance

This parameter controls how much horizon data immediately adjacent to the fault will be excluded from the intersection modeling.

Patch Zone

This parameter controls how much data are included in the modeling. The zone of data occurs outside the area defined by the trim distance. Increasing the patch width will include more data in the modeling.

Prediction of Small Scale Faulting and Fracturing

Prediction of small scale faulting and fracturing is based on elastic dislocation modeling. The basic components of the module are: Scenarios (the collection of parameters which control the boundary element code), observation grids (the observation points at which the boundary element code makes calculations), paneled faults (the fault data used by the boundary element code), and the generation of the elastic model.

To generate an elastic model (calculate response of an elastic medium as defined by the observation grid to the fault slip on the fault panels) the following methodology was applied. At each observation point on the grid, the Okada (1992) equations combine
the effect of fault slip on every panel in the model, to provide a 3D displacement vector. These displacement (deformation) vectors of the observation points in the medium are then used to define the Deformation Surface. The aim of a forward model is to create a deformation surface to match the seismically defined horizon geometry. At each observation point, the Okada equations combine the effect of fault slip on every panel in the model to provide a strain tensor. The Elastic Dislocation derived strains are then added to the regional (background) strain that produced the fault slip. The resultant strain tensors calculated at each observation point are then converted to stress tensors using an elastic rheology. These are 'pseudo-stress' tensors because the model does not include any stress relaxation as fault slip was accumulated. However, the stresses can be scaled to represent arbitrary increments of strain as the fault structures grew. The results of the modeling can be displayed in two ways deformation surfaces and vector attributes describing the displacement, stress/strain orientations and fracture planes displayed at grid points on the deformation surface (Badleys 2005).

4.3.2 Fracture Modeling - Basement Level

In order to define the procedures and calibrate the results from the software a first model was generated at Basement Level; the required parameters are described one by one, and then summarized in table 4.5. This example shows the methodology applied for the next two levels: Price River and Wasatch formations.

**Definition of Required Parameters**
- Modeling Direction set as forward in time for normal faulting.
- Control for Elastic Space defined as half-space set as default software setting.
- Fault Blanking Width determines the width on either side of a fault panel that will be blank of observation nodes.
- Rock properties were defined in section 4.1.
- Slip Options. The throw/displacement is the input to the modeling on a pure dip-slip movement; for displacement magnitude the average direction of dip of the entire fault was defined.
- Scale slip magnitude. The scaling factor for displacement in model usually set 1.0 to
match the power law relationship plot, but in some of these calculations the scale of slip magnitude was incremented to 10 for modeling effects; in order to create additional fractures.

- Fault Paneling parameters. These parameters control how each fault is discretized into panels. The minimum panel dimension controls paneling around the fault tip-line.
  - Minimum Horizontal Dimension along-strike.
  - Maximum Horizontal Dimension along-strike.
  - Minimum Vertical Dimension down-dip in the projection.
  - Maximum Vertical Dimension down-dip in the projection.
- Projection Mode is the projection type for generating panels and Strike Projection was the software recommendation.
- Observation Grid defines the deformation surface in terms of grid points and orientation, normally corresponds to a horizon of interest.

The modeled scenario shows the following possibilities: A deformation surface map with areas of subsidence or uplift respect to the observation grid, horizon attributes, vector attributes tied to the observational grid, and the fractures generated.

The first model was created for the Basement Level, and compared with the results of curvature attribute analysis.

**Fracture Modeling - Basement Level**

This analysis corresponds to the horizon termed Basement and the associated faults. This model was calculated in order to establish which parameters in the software were more sensitive. Figure 4.9 exhibits the faults interpreted and the curvature time slice without interpretation. Table 4.5 summarizes the parameters used for the fracture generation analysis.
Figure 4.9 A. Fault polygons interpreted at Basement Level. B. Negative Curvature time slice at Basement Level.
Table 4.5 Fracture Generation - Basement Level -

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<td>Width</td>
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</tbody>
</table>

All the attributes calculated are tied to the previously defined observation grid. This grid was set at the same depth of the studied horizon and covers all the interpreted area.

The first attribute calculated is the deformation surface map with areas of subsidence or uplift respect to the observation grid. The map shown in figure 4.10 exhibits two areas: one solid yellow color where the uplift above observation grid
occurred; and a grid pattern colored with yellow colors or areas of subsidence. Areas left white around the faults correspond to the trim and patch zones previously defined. This map correlates with the regional dip of the basin and show the southern part of the area uplifted with respect to the northern one. Locally, the upthrows and downthrows blocks of each fault are emphasized.

Figure 4.10 Deformation surface map generated at Basement Level.
The importance of this deformation surface map is to compare it with the horizon and check the degree of compatibility. In this case, the deformation surface map is corroborating the dip of the interpreted horizon and the interpreted fault blocks; therefore the advance model attributes can be calculated.

The following pre-defined Deformation Surface Attributes are available in the software (Badleys 2005): X, Y and Z displacements; volume change as a percentage (volume increase is +ve, loss is -ve); K-shape, the ratio of the major and intermediate axes of the strain ellipsoid; Max Coulomb shear stress (MCSS) is the intercept, on the shear stress axis, of a tangent to the Mohr stress circle having the same slope as the Coulomb failure envelope. Shear failure is expected when MCSS exceeds the cohesive strength of the rock C. Larger values of MCSS are expected to correlate with higher fracture densities; Mean Stress mean shear stress i.e. \((\sigma_1 + \sigma_3)/2\); Differential stress i.e. \(\sigma_1 - \sigma_3\); Sigma-1: maximum principle stress values; Sigma-2 intermediate principle stress values; Sigma-3 minimum shear stress values; Depth calculated depth of the deformation surface; Maximum curvature; and Gaussian curvature. Due to the low attribute definition in the horizons studied, most of the attributes were not included in this report.

**Principal Stress values**

For each of the principal stress axes, the results are stored as either positive (compression green color) or negative (tension red color): \(\sigma_1\): Maximum principal stress, \(\sigma_2\): Intermediate principal stress and \(\sigma_3\): Minimum principal stress.

The two principal pseudostresses \(\sigma_1\) and \(\sigma_3\) were generated, plotted and colored as mentioned in the last paragraph (figure 4.11) for the Basement Level. From elastic dislocation method the compression areas are shown in green and the tension ones in red. Areas of influence of fault panels are showing uniform stress directions. All the stresses presented were generated by the fault panels and these directions are not tied to a regional stress direction.
The elastic dislocation method generates fault panels that create a stress field independently for each panel. When two panels interact with each other their stresses generate compression or tension depending on the kind of interrelationship. When a fault bends the movement is exaggerated, as is the stress field. This condition is shown in figure 4.12. The software generates orthogonal planes to the obtained stress directions in order to predict the failure planes, on fractures.
Figure 4.12 Pseudo-stress directions from fault panels.

**Principal Planes of Stress**

Positive stress (compression) and negative stress (tension). S1: Principal plane - plane perpendicular to $\sigma_1$ (maximum principal stress), S2: Principal plane - plane perpendicular to $\sigma_2$ (intermediate principal stress), and S3: Principal plane - plane perpendicular to $\sigma_3$ (minimum principal stress). The compression – tension case in the same fault is presented in the figure 4.13 from the Basement Level.

**Predicted Failure Planes**

Conjugate shear planes (from $\sigma_1$ and $\sigma_2$) are displayed normally as discs in the relevant orientation at the observation points where the selected failure criterion is exceeded. The normal shear planes for conjugate normal faults were applied here and they are planes of failure produced at $30^\circ$ from the maximum stress ($\sigma_1$).
Figure 4.13 Positive stress in green (compression) and negative stress in red (tension). S1: Principal plane - plane perpendicular to σ1 (maximum principal stress), and S3: Principal plane - plane perpendicular to σ3 (minimum principal stress). The failure planes (possible fractures) are represented by the purple colors.

There are more options to generate fracture planes in the software:

- Normal Shear Planes - conjugate normal faults.
- Reverse Shear Planes - conjugate reverse faults.
- Dextral Strike-slip planes - dextral plane in strike-slip conjugate pair.
- Sinistral Strike-slip planes - sinistral plane in strike-slip conjugate pair.
- Tensile Failure planes - tensile fracture plane.

In the example shown below for the basement level figure 4.14, the predicted failure planes from normal shear planes (green discs) were generated near to the main faults with orientations subparallel to the fault strike and locally divergent from the fault plane.
Figure 4.14 Predicted failure planes are mostly normal shear planes (green discs) for Basement Level.

From these planes the fractures will be generated. In figure 4.15 the generated planes are presented in three dimensions at Basement Level.
Figure 4.15 Fracture planes generated at Basement Level.

Extracting the major orientation lineaments from the generated fractures, the principle orientations were measured and displayed in figure 4.16.

The principle fracture orientations for Basement Level can be grouped in N40-85°E and N45-75°W, with minor W-E and N-S.
Figure 4.16 Major orientation lineaments from the fractures generated at Basement Level.

To confirm this fracture orientation, a visual comparison with the lineaments obtained from negative curvature was made. The Basement Level time slice was interpreted from negative curvature where most of the lineaments were enhanced by lines (figure 4.17). The red circle included in the figure is pointing out some wavy features not interpreted in this study.
Figure 4.17 Negative curvature at Basement Level. Most of the lineaments were enhanced by small lines to obtain the orientations of the features.

An additional figure 4.18 was generated from the lineaments drawn in curvature time slice and overlapped by the fracture orientation analysis obtained in figure 4.14. The super-imposed lineaments exhibit some degree of correlation, especially where the green circles are located.
Figure 4.18 Comparison between lineaments from Negative Curvature (in black) and strike of the fractures generated by normal shear planes (in red) at Basement Level. Green circles show some similarities in strike orientations.

**Sensitive Parameters**

The scale slip magnitude is the factor that controls fracture generation in terms of abundance. If this factor is incremented, more fractures would be generated and the sense of the orientation is preserved. It is practically a visual effect. Combining normal shear planes, reverse shear planes, sinistral strike-slip planes, and tensile failure planes, more fractures were generated and the results constrained by fault orientation.
4.3.3 Fracture Modeling for Reservoirs

In order to reach the goals of this research, two different set of fractures will be model in this section and they correspond to the most important reservoirs in this gas field: Price River from Mesaverde Formation and Wasatch Formation.

4.3.3.1 Price River Formation

These analyses were performed in the horizon termed Price River Formation and the faults associated with it. Figure 4.19 A exhibits the faults interpreted, and 4.19 B the negative curvature time slice without interpretation for visual comparison. The Price River Formation level is affected by three sets of faults: The older set of faults originated at the Basement level and oriented N70°-80°E. The second set of faults probably comes from the shallower levels and oriented N40°-60°W at the south pat of the volume; the last group of faults is oriented N50°-80°W parallel to the Gilsonite Dikes and restricted to the upper most stratigraphic section (Mesaverde to Surface).

Table 4.6 summarizes the parameters used for the fracture generation analysis.
Figure 4.19 A exhibits the faults interpreted at Price River Formation, and B the negative curvature time slice without interpretation for visual comparison.
Table 4.6 Fracture Generation - Price River Formation -

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</table>

* This factor was exaggerated in order to get some additional fracture orientations.

After defining the scenario for fracture modeling in the Price River Formation, the first deformation surface map exhibits two areas: an area of uplift at the south of the fault and a subsidence area at the northern part; as shown in figure 4.20. This quick analysis helps to decide if the following vector attributes will be consistent with the interpretation.
Figure 4.20 Deformation surface map generated at Price River Formation with areas of subsidence (grid colored with yellow colors) and uplift (solid yellow color).

The map observed matches the horizon information and the further analysis will be undertaken.

Two principal stresses S1 (the maximum stress) and S3 (the minimum stress) were generated and displayed on figure 4.21, for the Price River Formation. All arrows colored green represent compressional stresses, when they are red are indicating tensile stress. All stresses axes generated obey the fault panels and they were not tied to regional
stresses. From the stresses generated the failure planes were generated in the elastic dislocation method, as shown in figure 4.22.

Figure 4.21 Maximum and Minimum stresses for the Price River Formation (the accuracy stress directions are closest to the faulted areas). Green colors show compression stress and red ones tension stress.

Areas adjacent to the fault structures present the maximum stress; the axes are oriented in all directions from the major structures especially where the faults bend and according to the fault panel interactions. Between the faults, the maximum stress
generated varies drastically. The borders off the area reveal some constant directions not considered to be important. In figure 4.22 the orthogonal failure planes from normal shear failure were generated. A common factor is the scarce fracture planes generated.

Figure 4.22 Predicted failure planes from normal shear planes (pink discs) at Price River Formation. Some of the fault planes are hidden in order to clarify the points where fractures were generated.
The software generates very few failure planes from normal shear planes (S1 maximum stress and S3 minimum stress), located near the principal fault and especially where the fault bend. For visualization purposes some of the fault planes were hidden and some faults polygons preserved. The orientation of this scarce future fracture planes were measured and plotted in figure 4.23.

Figure 4.23 Major orientation lineaments from the fractures generated at Price River Formation.
Extracting the major orientation lineaments from the generated fractures at Price River, the principle orientations obtained are plotted in the rose diagram and oriented N25-45°E and N30-65°W, with minor W-E.

A visual comparison with the lineaments obtained from negative curvature was accomplished in the Price River Formation horizon slice. Most of the lineaments were enhanced by lines (figure 4.24) obtaining a complex network of fracture orientations. The red circles included in the figure are pointing out some strong, wavy features not interpreted in this study.

An additional figure 4.25 was generated from the lineaments drawn in curvature time slice and overlapped by the fracture orientation analysis obtained in figure 4.23 from failure planes. The overimposed lineaments exhibit some degree of correlation pointed out by the green circles.

This kind of visual comparison reveals some similarities that statistically will be considered as tendencies of occurrence. The software uses the elastic dislocation method to predict the failure planes and most likely fracture planes generated. There is always a set of planes by grid observation point, but all grid points are not generating fractures. The way a set of fractures is generated can be seen in figure 4.26 for the interval of interest.
Figure 4.24 Negative curvature at Price River Formation. Most of the lineaments were enhanced by small lines to obtain the orientation of the features.
Figure 4.25 Comparison between lineaments from Negative Curvature (in black) and the fractures generated by normal shear planes (in red) at price River Formation. Green circles show some similarities in strike orientations.
Figure 4.26 Fracture planes generated at Price River Formation.

The green subhorizontal line is the polygon generated over which the displacement of the fault would be measured. Any fracture generated would be tied to this depth and horizon-fault interrelationship.
4.3.3.2 **Wasatch Formation**

Another reservoir of interest in the field is at Tertiary level in the Wasatch Formation. The faults present are more common for shallower levels and can be divided in N40°-60°W at the south of the volume; and locally interrupted by a deeper fault set oriented N60°-70°E. At northern part of the volume, the presence of W-E faults parallel to the Duchesne Graben Structure and the N40°-70°W oriented in the same direction of Gilsonite Dikes is a common characteristic. There are some N-S lineaments in the negative curvature difficult to correlate with a fault /fracture structure, figure 4.27.

The negative curvature time slice at Wasatch Formation reveals two zones: The northern one with short lineaments in all directions with a common N-S orientation feature. At the southern part the attribute become less defined and some common wavy features oriented N-S that apparently are not real.

The parameters applied in Wasatch Formation calculations are summarized in table 4.7 and they were provided by EOG Resources (2007).
Figure 4.27 A Fault polygons interpreted at Wasatch Formation. B Negative Curvature time slice at Wasatch Formation.
Table 4.7 Fracture Generation - Wasatch Formation

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* This factor was exaggerated in order to get some additional fracture orientations.

At the Wasatch Formation, the deformation surface map shown in figure 4.28 is complex and exhibits various uplifted areas as well as regions of subsidence; around the major faults. In this map there is not a pattern easy to interpret. The map matches the horizon interpreted so the further calculations will be undertaken.
Two principal stresses $\sigma_1$ (the maximum stress) and $\sigma_3$ (the minimum stress) were generated and displayed on figure 4.29, for the Wasatch Formation. All arrows colored green represent compressional stresses, when they are red, they indicate tensile stress. All stress axes generated obey fault panels and they were not tied to regional stresses. From the stresses generated the failure planes were generated by the elastic dislocation method.
Figure 4.29 Maximum stress on green and minimum stress on red for the Wasatch Formation (the accuracy stress directions are closest to the faulted areas).

An analysis of this stress map at Wasatch Formation is exhibiting areas of compression in the south of the block; an areas of tension at the north part of the area of influence between the subparallel oriented faults to the Gilsonite Dikes. The compression areas are generally scarce failure planes while the tension areas are generating more common failure planes at irregular distribution according to the observation grid (figure 4.30).
Figure 4.30 Predicted failure planes oriented in different direction from normal shear planes (green discs) at Wasatch Formation.

From those failure planes, fractures are generated and disposed close to the fault paneled blocks. These fractures are presented in figure 4.31.
Figure 4.31 Fracture planes generated at Wasatch Formation.
The same procedure was implemented here, extracting the major orientation lineaments from the generated fractures and plotted them in a separate figure 4.32.

The principle fracture orientations for Wasatch Formation can be grouped in W-E, N5-65°W, N5-35°E, and scarce N-S and they were plotted on the rose diagram.
The negative curvature time slice for the Wasatch Formation was interpreted highlighting the features, figure 4.33. The red circles included in the figure are pointing out some wavy features not interpreted in this study.

Figure 4.33 Negative curvature at Wasatch Formation. Most of the lineaments were enhanced by small lines to obtain the orientations of the features.
The comparison figure 4.34 was generated from the lineaments drawn in curvature time slice and overlapped by the fracture orientation analysis obtained in figure 4.32. The super-imposed lineaments exhibit some degree of correlation, especially where the green circles are.

Figure 4.34 Comparison between lineaments from Negative Curvature (in black) and strike of the fractures generated by normal shear planes (in red) at Wasatch Formation. Green circles show some similarities in strike orientations.
Feature orientations from negative curvature and fracture generated from elastic dislocation method are similar in some points of the volume, showing a statistically tendency of occurrence.

In order to visualize the exercise performed, a compound figure 4.35 was included to show the two major reservoirs: Price River Formation at the bottom and Wasatch Formation at the top with their fractures generated, respectively.

Figure 4.35 Fractures generated at Price River Formation and Wasatch Formation in the same fault plane.
4.4 Discussion

The Fracture generation model uses an elastic deformation equation, where the main parameters are fault dip and strike. The interpreted faults are initially divided by blocks (panels). The software estimates block interrelationships to generate strain, stress and failure planes. Additional information is included into the analysis: the geomechanical rock conditions, pore pressure and the actual state of stress.

In this dissertation the fractures generated are oriented as follow, according to the stratigraphic level:
- Basement Level N40-85°E, N45-75°W, with minor W-E and N-S.
- Price River N25-65°E, N40-75°W, with minor W-E.
- Wasatch Formation W-E, N25-70°W, N40-65°E and scarce N-S.

Fracture characteristics such as dimensions, density and fracture continuity were not generated. This background information should be acquired from other sources such as outcrops, wells and production testing. In order to accomplish this fracture description a reference paper of a fracture study in the Altamont field within Uinta Basin from Narr and Currie (1982) was consulted and summarized here. Figure 4.36 contains three parts: a) rose diagrams from the measured fractures in the basin; b) a general Uinta Basin Map and c) the Uinta Basin map with fractures from core descriptions.

The rose diagram, figure 4.36(a) represents the azimuth of the fractures measured in the well Gulf 1 Verl Johnson. The main fracture orientation is N20-30°W, with fewer fractures oriented 20-40°/200-220° and 150°-330°. The Uinta Basin map figure 4.36 (b) shows some fracture orientations (x) that represent measured joints emphasizing their azimuth. In the lower part of the figure 4.36 (c), a summary of the fractures described in the well Gulf 1 Verl Johnson was included in order to compare these results with the fractures described in the well CWI 854-33.
In the well from the Altamont field, there are at least three fracture orientations N20-85°E, N5-20°W and N-S. The dip of the fractures ranges between 65° and vertical fractures. The length of the fractures varies between 5 and 38 cm. Fractures are normally unfilled, and occasionally filled with calcite mineral. The fractures described are presented in depth (meters) and they correspond to Flag Staff Member of the Green River Formation.

Fractures in well CWU 854-33 are scarce and technically speaking they are joints restricted to sandstone levels. The joints are vertical with respect to the core, with lengths ranging between 12 and 24 cm, normally unfilled and they are located in the Price River Formation of Mesaverde Group.

As a conclusion the fractures presented here are similar to the cored well in Coyote Wash 3D survey; joints are vertical, restricted to the sandstone levels and lengths vary between 6 to 8 inches.

One of the initial purposes of this research was to determine the applicability of a wrench assemblage diagram from model published by Harding (1974a, in Lowell 1987 p.52) to the Coyote Wash area. A similar diagram adapted to left-lateral couple was drawn in order to illustrate the generated structures, figure 4. 37. During the fault interpretation and analysis, there was not sufficient evidence of left lateral movement in the 3D volume. However in a regional sense, authors like Tikoff and Maxson (2001) presented the interpretation of sinistral strike-slip motion occurring on east-west structures, particularly in the northern Rocky Mountains of the United States. Paylor and Yin (1993) documented approximately four kilometers of left-lateral slip along the South Owl Creek fault system, along the south side of the Owl Creek Mountains. Farther west, along the same fault system, 10 km of sinistral offset was inferred by Sundell (1990).
Figure 4.36 (A) Rose diagram of the joints observed in well Gulf 1 Verl Johnson. (B) location map of the joints in Uinta Basin. (C) Summary of the fractures described in the well Gulf 1 Verl Johnson (Narv and Currie 1982).
These sinistral faults are consistent with physical models of Laramide uplifts that involve both folding and sinistral faulting (Sales 1968). Locally, Stone (1977) published evidence of sinistral offsets of fold axes in Uinta Basin (map presented in figure 2.16 of this dissertation).

The results of this research indicate that the wrench assemblage diagram for the left-lateral movement can not be used to predict the kind of structures, mapped orientations or presence of fault-fractures in the study area.

Figure 4.37 Wrench Assemblage diagram from the Left-lateral Couple, adapted from Harding 1974a, in Lowell 1987 p.52.
CHAPTER 5

RESERVOIR CONSIDERATIONS

This chapter assesses the practical benefit of using a predictive fracture generation model for enhanced recovery; the comparison was made in the Price River Formation, one of the reservoirs of interest.

5.1 Tight Gas Sand Resource Play Definition

A tight gas sand reservoir by definition is a reservoir with permeabilities less than 0.1 millidarcies (Law et. al., 2002). Within the reservoir, hydrocarbons are distributed throughout a large area rather than being concentrated into a discrete field. Continuous type accumulations occur in many lithologies, but are most common in sandstones, fractured shales and coalbed methane gas accumulation. Normally, these accumulations do not have well-defined hydrocarbon water contacts and commonly are abnormally pressured. In a tight reservoir, the natural gas cannot flow as quickly to the well or in sufficient volumes to be economical. In addition, the area that a well drains in a tight reservoir is much smaller than the drainage area for a conventional reservoir. However, tight gas reservoirs of various ages and types produce where structural deformation creates extensive natural fracture systems, and they are mechanically stimulated by hydraulic fracturing. Fractured, tight and unconventional reservoirs can occur in tectonic settings dominated by extensional, compressional or wrench faulting and folding.

Cumella (2006) published a cross section illustrating gas migration model for the Mesaverde Formation in Piceance Basin. This model can be applied to the Uinta Basin where most of the gas produced is generated from coals or natural fractures related to overpressuring (small arrows) that allowed gas to migrate upward. The gas also migrates through the major fault fracture system to the sandstone bodies in Price River and Wasatch Formations (figure 5.1).
The Price River and Wasatch Formations in the Uinta Basin are coeval deposits with Mesaverde Group and Wasatch in Piceance Basin. The mechanism of production in the study area is similar as that one described by Cumella (2006).

Well production is dominated by the presence of faults and fractures according to the diagrams shown by Nelson (2001) in figure 5.2: Graph 1 represents the number of wells with the same cumulative production in a certain period of time in a particular stratigraphic interval. A cumulative production curve with only matrix contribution shows a bell shape; Graph 2 shows a production curve with more number of wells with common cumulative production history; the tail of the production curve exhibits some
picks of production increasing the cumulative production, and Nelson 2001 assumes this cumulative production curve from fracture contribution; Graph 3 exhibits the same curve of production of graph 2 highlighting the production peaks with less cumulative production. The hydrocarbon contribution is assumed through fractures with some matrix influence. Graph 4 is another combine cumulative production curve, where both mechanisms of production are contributing: fractures with more matrix influence.

Figure 5.2 Well production curves, Nelson (2001).

5.2 EUR Maps Definition

Using as a reference the USGS publication (2002) an expected ultimate recovery map (EUR map) is an estimate of the expected ultimate recovery of oil or gas from a producing well during certain period of time. For USGS assessment purposes, the production data for individual wells are analyzed for rate of production during some
specified lifespan of a well. In general, for wells with oil or gas production data, the data are plotted with respect to time, and a hyperbolic or exponential decline curve is fit to the data. The intersection of the decline curve with the X-axis terminates the forecast span of the well, and the EUR is the sum of hydrocarbons that is forecasted to have the potential to be produced up to the economical production point. The EUR map produced for the Price River Formation with wells that have more than one year of production was correlated to the positive curvature by Kidney (2007, personal communication), figure 5.3.

Figure 5.3 EUR map on top of the positive curvature for Price River Formation (Kidney 2007, personal communication).
In figure 5.3, the EUR bubbles shown were color coded: purple bubbles represent less production, green and yellow bubbles with intermediate and red bubbles for the higher productions. This first correlation shows highest production wells located in the intense fault/fracture zone revealed by the seismic attribute.

5.3 Fault-Fracture Impact on a Tight Gas Sand Resource Play

The Greater Natural Buttes Field was described by Cuzella and Stancel (2006) and some characteristics are summarized below:

<table>
<thead>
<tr>
<th>Trapping mechanism</th>
<th>Continuous gas accumulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Discontinuous lenticular sandstone reservoir</td>
</tr>
<tr>
<td></td>
<td>No discrete water contact</td>
</tr>
<tr>
<td>Producing Formations</td>
<td>Wasatch (gross thickness 1000-3600 ft)</td>
</tr>
<tr>
<td></td>
<td>Mesaverde (gross thickness 3800-5600 ft)</td>
</tr>
<tr>
<td>Reservoir Lithology</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Source Beds</td>
<td>Mesaverde organic mudstones and coals</td>
</tr>
<tr>
<td>Gas Characteristics</td>
<td>BTU (average) 1100</td>
</tr>
<tr>
<td></td>
<td>WGR (average) 100 bbl/mcfg</td>
</tr>
<tr>
<td></td>
<td>Specific Gravity 063 g/cc</td>
</tr>
<tr>
<td></td>
<td>Associated water 20000 ppm</td>
</tr>
<tr>
<td></td>
<td>Current production 1.16 TCFG</td>
</tr>
</tbody>
</table>

**PRICE RIVER FORMATION**

Characteristics of the Price River Reservoir, Cuzella and Stancel (2006):

- Porosity 11 %
- Permeability 0.01 md
- Water saturation 0.43 %
- Reservoir Pressure 0.43 to 0.52 psi/ft
- Type of drive Solution Gas Drive
Depositional Environment

The Price River reservoir are discontinuous lenticular sandstone bodies with limited areal extend, and with no distinct hydrocarbon water contact.

Figure 5.4 represents a production curve from the same number of wells with the same Gross Gas EUR production from wells in the Price River Formation with at least one year of production history. The initial cumulative production is assumed from matrix contribution and the sporadic peaks of production from fractures. Due to the different operational works performed on each well (hydraulic fracturing) and the different sand bodies in the reservoir, there is difficult to establish a production correlation. The EUR bubbles give a better idea of the production distribution and contribution because the highest production is assumed from fractures. (Kidney 2007, personal communication).

Figure 5.4 Production histogram and EUR bubbles for Price River Formation from figure 5.3 (Kidney 2007, personal communication).
A comparison of the production histogram presented in figure 5.4 for Price River Formation exhibits a similar production curve with those proposed by Nelson (2001), in graphs 3 and 4 of figure 5.2. Figure 5.5 shows this comparison of production diagrams form matrix and fracture contribution.

![Diagram of Price River Wells, IP Date > 1 Year](image)

**Price River Wells, IP Date > 1 Year**

- **Matrix**
- **Fractures**

**Well Count**

**Gross Gas EUR (MMCF)**

- **Wells Located In Fault / Fracture Zone**

Figure 5.5 Comparison of production curves and mechanism of production from figures 5.2 and 5.4 (Kidney 2007, personal communication).

**Correlation of Fault-Fracture Analysis and EUR Maps**

The EUR map available for the Price River reservoir was presented in figure 5.3, according to Kidney (2007). Figure 5.6 is showing EUR bubbles location posted in a negative curvature for the Price River Formation; in order to show the influence of rectilinear features observed in the attribute. (There are not significant differences between positive curvature and negative curvature at the level of Price River Formation according to this study). The rose diagram of the rectilinear features from negative curvature exhibits a higher presence of features oriented almost N-S.
Figure 5.6 EUR bubbles for Price River Formation displays over negative curvature attribute. Red bubbles represent high production; orange and yellow bubbles intermediate and green bubbles less production.

The fractures generated by elastic dislocation method are limited by the major faults interpreted. The fractures mainly strike N40°-65°W and N25°E at Price River Formation level, figure 5.7. This figure represents the negative curvature features by
black lines and super-imposed the generated fractures in red lines; additionally, EUR bubbles for Price River reservoir were included, for better visual correlation.

Figure 5.7 EUR bubbles for Price River Formation display over highlighted negative curvature features (black lines) and generated fractures (red lines).
The higher production wells (red bubbles) are located over negative curvature lineaments oriented mainly W-E and N10°W in an intense faulted zone. The intermediate production wells (green and dark yellow bubbles) are close to the curvature features oriented N10-20°E, N50°E and less N20-30°W. The lower productive wells (yellow dots) are dispersed in the area and there is not a correlation tendency. The generated fractures (red lines) are not related to the actual productive wells.
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study was undertaken from the geological point of view using seismic information, volumetric seismic attributes, geomechanical data, and fracture generation by an elastic deformation method. Based on the analysis presented in the previous chapters, the following conclusions are drawn from the study.

1. Faults in the area are dominantly sub-vertical normal faults, locally decoupled at ductile layers with particular behavior for each stratigraphic level. The interpreted faults include large faults (3 to 5 km long) with small throws (0.60 to 10 m). Locally, there are common fold structures with the axes parallel to the major structures.

Fault description by levels:
- Basement Level: Sub-vertical normal faults that decouple at ductile layers and locally generate low angle reverse faults. Main orientations are W-E; N60°E; N25°E; and N-S.
- Intermediate Level: Sub-vertical faults, with small throws and locally discontinuous fault traces; oriented N75°W; N-S to N25°E; N60°E and W-E.
- Shallow Levels: Sub-vertical faults with a series of sub-vertical splays, mainly oriented W-E; N25-60°E and N-S, with a predominant group oriented N50-80°W.

2. There is counter-clockwise rotation of 10 to 15° evidenced by faults coming from the Basement level oriented N70-80°E that extend to the shallower stratigraphic levels with slightly different orientation N60-70°E. These two groups of faults, according to the interpretation, are genetically interrelated and they are the only group of faults that exhibit this rotation phenomenon in the area of study.
3. The fracture characterization from the core represents two groups dominated by the lithologic conditions:

**Sandstone intervals.** Fractures are isolated, straight, vertical in the core, and classified as joints with maximum 24 cm long (restricted to the Price River Formation).

**Mudstone intervals** (two kinds of fractures). A group of small fractures oriented in all directions (no longer than 8 cm each) with low angles (30-45°), generally grouped with a maximum length of 24 cm; that constitutes the break out zones. And finally, small fractures (6 cm long) linkage together with irregular shapes (total length 18 cm), and filled by residual oil. The Dipole Sonic Log established: a dominant high angle fracture set striking WNW/ESE with a mean strike of 096.

4. The mechanism of production in the Uinta Basin is mainly through matrix with locally enhanced production from natural fault – fractures. The EUR bubbles (Price River) can be correlated to the lineaments shown in curvature analysis and as an example, the highest production wells are located over lineaments oriented mainly W-E and some N10°W.

5. Curvature attributes, positive and negative curvature, were the best attributes in terms of structural definition. Curvature reveals strong features linked together and many small, weak features with a tendency in orientation that could represent fractures. The curvature analyses shows different orientation patterns related to the stratigraphic levels.

6. A general horizontal maximum state of stress direction for the study area is 101-281°. The maximum stress orientation by stratigraphic levels was obtained from Dipole Log information (from deepest to shallow):
   - Sego Formation level 101/281°.
   - Sego to Middle Price River Formation range between 90-110/270-290°.
   - Middle Price River to North Horn Formation range between 90-110/270-290°.
Fracture Generation for the main reservoirs

The Price River Formation level is affected by three sets of faults: The older set of faults originated at Basement and oriented N70°-80°E. The second set of faults probably affecting the shallower levels and oriented N40°-60°W at the south part of the volume; and the last group of faults oriented N50°-80°W parallel to the Gilsonite Dikes and also restricted to the upper most stratigraphic section (Mesaverde to Surface). The generated fractures are oriented N25-45°E and N30-65°W, with minor W-E.

The Wasatch Formation reveals two sets of faults: The northern one with short lineaments in all directions with a common N-S orientation feature. In the southern part the attribute become less defined and some common wavy features oriented N-S that apparently are not real. The principle fracture orientations for Wasatch Formation can be grouped in W-E, N5-65°W, N5-35°E, and scarce N-S.
Questions:

In chapter 1, the following questions were poised regarding fracture analysis

1. Are shallow faults (section from surface to Price River Formation) associated with Gilsonite Dikes?
   Yes, there are discontinuous features (curvature attribute) in the whole stratigraphic sequence that are oriented parallel to the Gilsonite Dikes and they confirm the pattern and interrelationship of this fault group. At Wasatch Formation level the generated stress axes show tension stress aligned to the Gilsonite dike orientations.

2. Are deep basement faults associated or dissociated with shallow faulting?
   Deep Basement faults are associated with shallow faulting in the southern part of the volume, faults oriented N70-80°E and N50-70°W. They are dissociated with shallow faulting at the north part of the volume, Gilsonite dike orientations and W-E faults that are restricted to the Mesaverde to surface Formations.

3. Is there a decoupled zone at Mancos Shale Formation level?
   Yes, Mancos Shale Formation can be considered a decouple zone in the area, however this is not the only one observed. This study reveals several intercalated ductile layers that acts as decouple zones. Faults-fractures are better defined in brittle layers while in ductile ones the fault-fracture traces are vanished and secondary structures could be generated.

4. Are linked faults associated with deep basement faults?
   Not necessarily. The linkage phenomenon was observed in both basement faults and shallower ones. However the stronger features shown linked faults are restricted to the basement levels (curvature).
6.2 Recommendations

The following recommendations are specific for future fault-fracture studies.

1. The magnitude of the principal stresses will help to generate dilation diagrams, where the faults and fractures could be plotted. After plotting, the analysis will define which set of fault/fractures enhance productivity and which group do not.

2. Fracture characteristics as dimensions, density and fracture continuity were not generated. This background information should be acquired from other sources such as outcrops, wells and production testing.
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