TIME-LAPSE CHARACTERIZATION OF THE NIOBRARA
RESERVOIR FROM MULTICOMPONENT SEISMIC
DATA, WATTENBERG FIELD, COLORADO

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geophysics).

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ABSTRACT

The Niobrara Formation has been responsible for the majority of oil production from the Wattenberg Field since its discovery in 1974 (Higley and Cox (2007)). Due to the low porosity and permeability associated with this tight formation, horizontal drilling and hydraulic fracturing has been the standard completion strategy in the field since 2010. The main areas of focus in this thesis include characterizing the natural fracture network within the Niobrara which contributes to permeability, the induced fracture network created through hydraulic stimulation, and the in-situ stress state which influences the hydraulic stimulation.

Fracture characterization of the Niobrara Formation is based on time-lapse multicomponent seismic surveys acquired before and after hydraulic fracturing. Since azimuthal anisotropy and shear-wave splitting (SWS) are exhibited due to the presence of fractures, the SWS phenomenon was studied in poststack and prestack shear volumes. A quick and simple poststack methodology for extracting time-lapse changes in SWS utilizing both traveltime and amplitude variations was demonstrated to provide an estimated volume that relates to the stimulated reservoir volume (SRV). SWS was also studied in terms of the azimuthal variation of the AVO response in the fast and slow prestack shear volumes. Azimuthal traveltime variations in radial and transverse shear volumes were analyzed as an independent methodology to investigate its feasibility for fracture characterization in comparison with the AVO approach. Although they face unique challenges and display varying degrees of sensitivity to azimuthal anisotropy, the two prestack methodologies are in good agreement in terms of final results and interpretations.

Azimuthally varying moveout velocities were studied in the compressional baseline survey through which the residual interval traveltime variations with azimuth were used to identify the orientation and elongation of NMO ellipses. Differential azimuthal traveltimes appear to relate to the current day stress state as verified by production logs and microseismic events.
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LIST OF ABBREVIATIONS

Amplitude Variation with Offset .............................................. AVO
Velocity Variation with Azimuth ............................................. VVAz
Horizontal Transverse Isotropy .............................................. HTI
Vertical Transverse Isotropy ................................................. VTI
Shear-Wave Splitting .............................................................. SWS
Common Offset Common Azimuth ........................................... COCA
Normal Moveout ................................................................. NMO
Common Mid Point/ Common Depth Point ............................... CMP/CDP
Pure Mode Compressional Wave ............................................ PP
Pure Mode Shear Wave .......................................................... SS
Radial Shear Mode ............................................................... SV
Transverse Shear Mode ........................................................ SH
Fast Shear Mode ................................................................. $S_1S_1$
Slow Shear Mode ................................................................. $S_2S_2$
9 Component ................................................................. 9C
Total Organic Content .......................................................... TOC
Formation Micro-Imager ......................................................... FMI
Instantaneous Shut-In Pressure ............................................. ISIP
Stimulated Reservoir Volume ............................................... SRV
Anadarko Petroleum Corporation ......................................... APC
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I would like to thank my advisor, Dr. Tom Davis for his support and guidance during the past two years. I will always be grateful for the incredible opportunity to be part of this department and the research group. The experience has been an absolute privilege.

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I acknowledge my industry colleagues and mentors during the past few years whose collaboration and mentorship played an important role in my success.

Finally, I am thankful to my family who has always supported me from long distances and my friends in Calgary and Colorado who became my second family.
CHAPTER 1
INTRODUCTION

This thesis is part of an integrated research project on Phase XV of the Reservoir Characterization Project. The phase started in mid-2013 and is a joint effort between RCP and Anadarko Petroleum Corporation. The purpose of this phase is to optimize well spacing and completion strategies to improve hydrocarbon recovery from the Niobrara reservoir at Wattenberg Field. Determining the controls on producibility through dynamic and integrated reservoir characterization is a crucial step towards realizing these goals.

This chapter will set the stage with an overview of the Wattenberg Field in general, a review of the geology of the reservoir and the associated petroleum system, a description of the typical reservoir properties in the project area, and a report of the regional tectonics that result in the complex stress field observed in the reservoir. The chapter will then focus on the study area and the seismic and non-seismic data available and utilized in this thesis. Finally the research objectives are discussed.

1.1 Wattenberg Field

Wattenberg Field is located north of Denver, Colorado, covering an extensive basin-centered hydrocarbon accumulation area in the central part of the Denver Basin (Figure 1.1). Discovered in 1974, the field has produced approximately 1.57 TCFG and 76.4 MMBO (through 1999) with over 67% of the total oil and 34% of the total gas production of the field coming from the Niobrara and the underlying Codell Formations (Higley and Cox (2007)). Even after 4 decades into the life of the field, thousands of wells per year are drilled into these formations and the field is believed to have decades of production ahead.
1.2 Niobrara Geology

The Niobrara is an Upper Cretaceous formation deposited in the North American epeiric seaway (Figure 1.2) and consists of alternating chalk and marl facies (Figure 1.3).

With sediment source from the west and east and organic matter from the pelagic sedimentation, the formation exhibits a decrease in depositional energy and an increase in organic matter deeper into the Cretaceous Western Interior Seaway (Longman et al. (1998)). Chalks consisting of higher carbonate percentages represent high sea levels when the sediment input is lowered, and marls with lower carbonate percentages represent higher sediment input during periods of lower sea level (Longman et al. (1998)).

Throughout the Denver Basin, 3 to 4 chalk/marl cycles are identified and are generally referred to as chalk or marl A, B, C, and D from shallowest to the deepest. In the study area, the shallowest chalk has been removed through erosion, placing A marl followed by B chalk as the top of Niobrara Formation. The horizontal wells in the section under study are predominantly drilled into the C chalk.
Figure 1.2: Upper Cretaceous Western Interior Seaway, modified from Blakey (2014)

Figure 1.3: Niobrara type log displaying the alternating chalk and marl benches (after Longman et al. (1998))
1.3 Petroleum System

The Niobrara with type II kerogen and 2-6% TOC is a self sourcing reservoir (Sonnenberg (2014)). It is also an effective seal keeping the hydrocarbons in place due to very low porosity and permeability. Although biogenic accumulation is present in eastern parts of the basin, in the Wattenberg Field the Niobrara is buried into the oil window, resulting in thermogenic accumulation and over-pressuring (Sonnenberg (2014)). The presence of micro-cracks formed during diagenesis and catagenesis contribute greatly to permeability and production of hydrocarbons from this tight formation.

1.4 Reservoir Properties

In Wattenberg, the Niobrara ranges in thickness from 240 to 330 feet (Higley and Cox (2007)) and the production depth ranges between 7300 and 7700 feet within the study area. Some characteristics of a typical well include API gravity of 45 degrees, initial GOR of 5,949 scf/bbl, gas content of 76.2% methane, 40 to 60% water saturation, 10% or less porosity, and less than 0.1mD matrix permeability (Higley and Cox (2007)). Such low porosity and permeability values make natural and induced fractures and faults very important in oil and gas production, and hydraulic stimulation has been a regular completion method allowing for economic production.

The underlying Codell Formation with higher porosity and permeability than the Niobrara is also considered a tight reservoir and relies on hydraulic stimulation for economic production (Dudley (2015)).

1.5 Regional Tectonics

The study area is located near the axis of the Wattenberg paleo-high, an east-west trending paleo-structure leading to the thinning of the upper Niobrara through erosion. Many listric normal faults and horst-graben features are present and are characteristic of extensional structural settings associated with the paleo-high (Birmingham et al. (2005)).
The Laramide Orogeny which started with and continued after the deposition of Niobrara is responsible for the east-west compressive stress and many of the characteristic features such as the right-lateral wrench faulting along multiple fault zones (Higley and Cox (2007)). These east-west wrench fault zones and the Wattenberg paleo-high are shown in Figure 1.4.

Figure 1.4: Tectonic setting near the study area, modified after Higley and Cox (2007)

The redistribution of stress field associated with the wrench faulting creates complicated local stress orientations, causing secondary faults and folds. Figure 1.5 is a modified image from Stone (1969), displaying a primary wrench fault within the tectonic setting of this region along with the secondary faults and fold. To further complicate the problem, some of these faults and fractures are conduits and others are cemented acting as hydrocarbon seals. The study area is away from these major wrench zones; therefore while experiencing complicated stress states, it is not directly subject to the intensive tectonic stress associated
with the wrench zones.

Figure 1.5: Rocky Mountain tectonic setting (modified after Stone (1969))

1.6 The Study Area

The focused study area for this thesis is the Wishbone section approximately 20 miles northeast of Denver, Colorado. In mid-2013, 11 horizontal wells were drilled and hydraulically fractured in this section out of which 7 wells were drilled into the Niobrara (C chalk), and 4 into the underlying Codell Formation (Figure 1.6). Although the Niobrara is the main focus of this thesis, some methodologies extract information from seismic windows containing both formations. Therefore, some sections only discuss the 7 Niobrara wells while others discuss all 11 wells referred to by the names displayed on Figure 1.6.

1.7 Non-Seismic Data

The well data provided by APC and integrated in this research are the following:

- Gamma ray, neutron porosity, resistivity, bulk density and sonic logs
• Formation micro-imager (FMI) logs for 2 horizontal wells (2N and 6N)
• Production spinner logs for 2 horizontal wells (2N and 6N)
• Daily production for all horizontal wells
• Microseismic data for all horizontal wells
• Instantaneous shut-in pressures by stage for all horizontal wells

Figure 1.6: Focused study area - Wishbone section (green outline), the extent of Turkey Shoot survey (red outline), and the vertical and horizontal wells within the survey area

1.8 Seismic Data, Acquisition and Processing

The Reservoir Characterization Project was provided with a 50 square mile merged P-wave 3D seismic survey and a 3C 3D survey over an 11 square mile area both containing the
Wishbone section. A third seismic volume (Turkey Shoot) is a 9C time-lapse survey over a 4 square mile area acquired by RCP and APC such that the Wishbone section contains maximum fold (red outline in Figure 1.6). The baseline survey was acquired before hydraulic stimulation, and the monitor survey was acquired after stimulation and before production. The focus of the analyses covered in this thesis are the pure mode (time-lapse SS and the baseline PP) volumes from the Turkey Shoot survey.

Turkey Shoot acquisition parameters are listed in Table 1.1, and the PP and SS processing sequences are listed in Table 1.2 and Table 1.3, respectively.

<table>
<thead>
<tr>
<th>Table 1.1: Turkey Shoot acquisition parameters</th>
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<tbody>
<tr>
<td>Sample interval:</td>
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<tr>
<td>Source type:</td>
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<tr>
<td>Sweep number:</td>
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<tr>
<td>Sweep length:</td>
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<td>Sweep frequency:</td>
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<td>Receiver type:</td>
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<td>Receiver azimuth:</td>
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<td>Patch size:</td>
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<td>Source point interval:</td>
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<td>Receiver point interval:</td>
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</tbody>
</table>

The processing was performed in time-lapse mode, meaning the baseline was combined and processed with monitor survey in order to increase the repeatability and eliminate the need for further cross-equalization. An analysis of NRMS before and after attempted cross-equalization confirms the high repeatability.

The SS data consist of baseline and monitor radial (SV) and transverse (SH) volumes as well as ‘fast’ (S₁S₁) and ‘slow’ (S₂S₂) volumes. The S₁S₁ and S₂S₂ volumes are obtained by Alford rotation of the entire survey to N20W, which was determined during processing to be the predominant fast orientation (step 14 of SS processing sequence).
Table 1.2: Turkey Shoot PP processing sequence

<table>
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<tr>
<th>Step</th>
<th>Description</th>
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<tbody>
<tr>
<td>1</td>
<td>Reformat: record length 6 second, sample interval 2ms</td>
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<tr>
<td>2</td>
<td>Geometry assignment: CDP bin size 55 ft × 55 ft</td>
</tr>
<tr>
<td>3</td>
<td>Match baseline and monitor surveys</td>
</tr>
<tr>
<td>4</td>
<td>Amplitude recovery: spherical divergence correction +4 dB/sec gain</td>
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<tr>
<td>5</td>
<td>Trace edit: SVD filter to remove surface generated noise</td>
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<tr>
<td>6</td>
<td>Surface consistent spiking deconvolution with 0.1 percent pre-whitening</td>
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<tr>
<td>7</td>
<td>Refraction statics correction</td>
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<td>8</td>
<td>Surface consistent residual statics</td>
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<td>9</td>
<td>Surface consistent amplitude scaling</td>
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<tr>
<td>10</td>
<td>T-F adaptive noise suppression, offset consistent gain control</td>
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<td>11</td>
<td>Surface consistent residual statics</td>
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<tr>
<td>12</td>
<td>3 term moveout: time variant eta</td>
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<tr>
<td>13</td>
<td>Common offset vector binning: COV regularization, COV F-XY decon</td>
</tr>
<tr>
<td>14</td>
<td>Migration: COV anisotropic time migration</td>
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<tr>
<td>15</td>
<td>Sort to cdp, sum, shift to final datum</td>
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Table 1.3: Turkey Shoot SS processing sequence

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<td>Reformat: record length 6 second, sample interval 2ms</td>
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<tr>
<td>2</td>
<td>Geometry assignment: CDP bin size 55 ft × 55 ft</td>
</tr>
<tr>
<td>3</td>
<td>Alford rotation from field coordinate to radial/transverse</td>
</tr>
<tr>
<td>4</td>
<td>Match baseline and monitor surveys</td>
</tr>
<tr>
<td>5</td>
<td>Amplitude recovery: spherical divergence correction +4 dB/sec gain</td>
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<tr>
<td>6</td>
<td>Trace edit, SVD filter to remove surface generated noise</td>
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<td>7</td>
<td>Surface consistent spiking deconvolution with 0.1 percent pre-whitening</td>
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<td>Surface consistent amplitude scaling</td>
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<td>T-F adaptive noise suppression, offset consistent gain control</td>
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<td>Alford rotation: from radial/transverse to S₁S₁ and S₂S₂</td>
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<td>15</td>
<td>Common offset vector binning: COV regularization, COV F-XY decon</td>
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<td>16</td>
<td>Time migration</td>
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<tr>
<td>17</td>
<td>Sort to cdp, sum, shift to final datum</td>
</tr>
</tbody>
</table>
1.9 Research Objectives

The main objective of this thesis is to perform time-lapse fracture characterization of the Niobrara using pure shear volumes. For this purpose the $S_1S_1$ and $S_2S_2$ volumes were analyzed and signatures of azimuthal anisotropy were extracted on the baseline and monitor surveys. These anisotropy signatures include traveltime and amplitude variations between the $S_1S_1$ and $S_2S_2$ components on stacked volumes and azimuthal variation of AVO gradients on $S_1S_1$ and $S_2S_2$ prestack volumes. The potential of radial and transverse shear volumes to support the interpretation provided by $S_1S_1$ and $S_2S_2$ datasets was also investigated. The FMI logs acquired in 2N and 6N wells are used as calibration data for the fracture characterization results, and microseismic and cumulative production data are used as calibration data for the general stimulated rock volume.

A second research objective is studying the azimuthal variations of moveout velocity in compressional data and investigating the relationship between the extracted symmetry plane and the stress state at the reservoir. Microseismic data, instantaneous shut-in pressures, and production logs which are all influenced by the orientation and magnitude of the stress field are used as calibration data for the PP interval NMO velocity analysis.

Finally, the results from PP and SS volumes were examined in an integrated framework to speculate the influence of the present day stress field on induced fractures, the influence of the natural fractures on the extent and effectiveness of hydraulic stimulation, and finally the influence of natural and induced fractures on production.
Numerous studies have demonstrated the high sensitivity of shear waves to fractures. In the case of Niobrara in particular, it has been shown that fracture induced azimuthal anisotropy can be measured through shear-wave polarization and splitting (Martin and Davis (1987)). More recent studies on unconventional shale plays have shown that time-lapse multicomponent seismic data can detect and monitor changes in azimuthal anisotropy as a result of hydraulic fracturing (Steinhoff (2013)).

This chapter will review a quick and simple analysis for estimating the stimulated reservoir volume utilizing the stacked S\textsubscript{1}S\textsubscript{1} and S\textsubscript{2}S\textsubscript{2} datasets. The chapter will begin by reviewing the methodology, followed by results and the validation of the results by microseismic and initial production data.

2.1 Theory

In the presence of azimuthal anisotropy, shear waves are polarized in two orthogonal fast and slow orientations. These two components travel with different velocities resulting in the phenomenon of shear-wave splitting (SWS). Therefore, in shear surface seismic data, the magnitude and polarization of the components of the recorded shear waves are not only influenced by those of the seismic source but also by such medium properties as the orientation and density of fractures and the differential stress. During shear data processing, the knowledge of the fast orientation allows for separation of the fast and slow components through Alford rotation by computationally rotating the sources and receivers (Hardage et al. (2011)).
2.2 Methodology

As mentioned before, the $S_1S_1$ and $S_2S_2$ volumes are obtained under the assumption of a constant fast orientation ($\text{N20W}$) throughout the survey area. The aim of a detailed fracture characterization is to provide high resolution spatial variability in the splitting coefficient which requires going beyond the simplifying assumption of a single fast orientation. Therefore, the information extracted from the $S_1S_1$ and $S_2S_2$ (both poststack and prestack) are used with caution.

The analysis reviewed in this chapter is based on the investigation of time-lapse changes with respect to both traveltime and amplitude variations between the fast and slow volumes.

The presence of mixed fast and slow modes in $S_1S_1$ and $S_2S_2$ volumes is evident from the fast and slow interval traveltimes. Figure 2.1 displays the Niobrara interval traveltime difference between fast and slow baseline surveys normalized by the fast traveltime. The presence of negative anomalies (in blue) is indicative of mixed mode on a number of samples.

Note the distribution of positive and negative anomalies in Figure 2.1 potentially indicates a spatially varying stress field as controlled by the discontinuity features such as the east-west trending graben.

Since the stacked amplitudes are not the optimal seismic attributes in fracture characterization, and due to the fact that the presence of mixed modes complicates the extraction of time-lapse information further (particularly with respect to the direction of change), the focus of analysis of stacked volumes for estimating an SRV is on time-lapse changes in general. It is expected that the largest time-lapse variations (both positive and negative) would be related to the stimulated reservoir.

2.2.1 Time-lapse Time-Variance

The workflow in obtaining time-lapse time-variance anomalies is as follows:

- Niobrara isochrons were extracted from baseline and monitor $S_1S_1$ and $S_2S_2$ volumes.

The extracted isochron begins 20 ms above the Niobrara horizon and ends at the next
Figure 2.1: Normalized interval traveltime difference between $S_1S_1$ and $S_2S_2$ baseline surveys indicating the presence of mixed fast and slow modes in $S_1S_1$ and $S_2S_2$ volumes. The black lines show interpreted faults according to incoherency along Niobrara top.
most consistent event (highlighted in yellow in Figure 2.2). The extracted isochrons therefore contain both Niobrara and Codell intervals.

- The difference between $S_1S_1$ and $S_2S_2$ isochrons were calculated and normalized by the $S_1S_1$ isochrons to provide percentage variations (Figure 2.1).

- The normalized difference between the fast and slow isochrons in baseline was subtracted from that of the monitor.

\[
TimeVar.ΔT = \left[ \frac{S_2S_2iso - S_1S_1iso}{S_1S_1iso} \times 100 \right]_{\text{Monitor}} - \left[ \frac{S_2S_2iso - S_1S_1iso}{S_1S_1iso} \times 100 \right]_{\text{Baseline}} \tag{2.1}
\]

Figure 2.2: Niobrara Isochron (highlighted in yellow) used for traveltime and amplitude extraction. The isochron begins 20ms above the Niobrara horizon and ends at the next most consistent event. The displayed cross-section is from the $S_1S_1$ baseline survey.
2.2.2 Time-lapse Amplitude-Variance

The workflow in obtaining time-lapse amplitude-variance anomalies is as follows:

- RMS amplitudes over the reservoir window (Figure 2.2) were extracted from baseline and monitor $S_1S_1$ and $S_2S_2$ volumes.
- The difference between $S_1S_1$ and $S_2S_2$ interval RMS amplitudes were calculated and normalized by the $S_1S_1$ interval RMS amplitudes to provide percentage variations.
- The normalized difference between the fast and slow amplitudes in baseline was subtracted from that of the monitor.

$$Amp.\Delta T = \left[\frac{S_2S_2^{amp} - S_1S_1^{amp}}{S_1S_1^{amp}} \times 100\right]_{Monitor} - \left[\frac{S_2S_2^{amp} - S_1S_1^{amp}}{S_1S_1^{amp}} \times 100\right]_{Baseline} \tag{2.2}$$

2.3 Results and Discussions

Time-lapse time-variance and time-lapse amplitude-variance anomalies are highlighted in blue and brown in Figure 2.3 and Figure 2.4, respectively.

The maximum time-lapse time-variance anomalies represent a 10%, and the amplitude-variance anomalies represent a 40% variation post-stimulation. The higher sensitivity of amplitudes to changes compared to traveltimes is expected. The anomalies include both positive and negative and the color scales highlight greater than 5% variation for traveltime and greater than 20% variation for amplitude anomalies. These thresholds were selected in order to bring the anomalies outside the stimulated Wishbone section close to zero, highlighting the time-lapse anomalies above the noise level. Note the section to the west of the Wishbone section has been under production from the Niobrara; therefore the presence of time-lapse anomalies is expected in this area.
Figure 2.3: Time-lapse time-variance anomalies highlighting the areas with maximum time-lapse changes in the difference between the fast and slow interval traveltimes
Figure 2.4: Time-lapse amplitude-variance anomalies highlighting the areas with maximum time-lapse changes in the difference between the fast and slow interval RMS amplitudes.
2.3.1 Validation Data

An overlay of the anomalies from amplitude and time-variance methods allows for creating a composite anomaly map (Figure 2.5). Highlighted in red are qualitative interpretations of time-lapse anomalies within the Wishbone section. These outlines indicate areas of maximum time-lapse change in the splitting coefficient and are therefore related to the stimulated rock volume.

Figure 2.5: Composite time-lapse anomalies (red outlines) obtained by qualitative interpretation of both time-variance and amplitude-variance anomalies from the analysis of $S_1S_1$ and $S_2S_2$ volumes. Microseismic events colored by stage are displayed with small dots, and 90-day cumulative oil production values are displayed with green dashed circles for Niobrara (top) and Codell (bottom) wells. The best and worst producer show a cumulative production difference of approximately 18%.
Microseismic events on all 11 horizontal wells are displayed on Figure 2.5 for a comparison with the composite anomalies (red outlines). The green circles at the bottom of the figure represent the 90-day cumulative oil production from each horizontal well. The circle size is proportional to the production value with 18% difference between the maximum and minimum values. The general increase in the number of microseismic events from east to west correlates with the size and number of time-lapse anomalies as well as the 90-day production in the Niobrara wells. Note the order of both stimulation and flow-back in the horizontal legs goes from east to west with the easternmost well beginning production first. The higher permeability values in the Codell Formation explain some of the larger IPs in Codell wells on the east side as the order of flow-back leads to the higher tendency of fluid to flow towards east if allowed by higher permeability.

2.3.2 Discussion

In the presence of fluid-infill (such as in the Niobrara), the crack aspect ratio is an important factor influencing the effective elasticity of the medium (Shafiro and Kachanov (1997)). For example, large aspect ratios describing open fractures correspond to ‘soft’ rock with low effective compliance. As the wave propagation reacts to the effective rock compliance, the open fractures are expected to have a larger influence on the seismic attributes describing the cracks than the closed fractures. According to the formation image logs within the Wishbone section, the majority of fractures within the reservoir are open (Dudley (2015)). Therefore the anisotropy signatures discussed in poststack analysis of this chapter and prestack analyses of the future chapters are presumed to reflect the open in-situ fractures in baseline and the propped fractures in time-lapse studies.

It is important to note the limitations in applying the poststack analysis discussed in this chapter. Since the identified anomalies represent the time-lapse change between the difference between the fast and slow attributes, stimulated areas with multiple sets of induced fractures are not expected to highlight significant anomalies. Additionally, in the case of samples with mixed modes, the interval traveltimes tend to be representative of the fast
component which may not display a significant time-lapse variation, especially when the predominant fracture orientation remains consistent. Therefore, while the number and size of the anomalies on a larger regional scale can be representative of the effectiveness of hydraulic stimulation, each anomaly or lack thereof does not definitively determine the presence and the effectiveness of stimulation.

With a correct separation of fast and slow components through residual Alford rotation, the SRV can be estimated with higher accuracy and information can be extracted on the directionality of the induced fractures.

The amplitude methods are generally much more sensitive to the presence of anisotropy (resulting in higher vertical resolution), compared to the traveltime methods. The difference between the time-lapse anomalies in these two methods can therefore be party attributed to resolution variations. Note however that in the methodologies discussed in this chapter, both approaches reveal average time-lapse effects in the entire reservoir.

The percentage variations and the thresholds for highlighting the time and amplitude-variance anomalies are based on a visual comparison of the stimulated area and the areas with no expected time-lapse change. Modeling would be required to identify the expected time-lapse variation in each attribute to accurately estimate a threshold that captures the estimated SRV. This analysis was repeated for multiple isochrons at different depths above the reservoir and showed a decrease in time-lapse percentage change with a decrease in depth of analysis window. As the overburden (far enough from the reservoir) is unaltered by the hydraulic stimulation, this suggests that the anomalies identified reflect the effect of hydraulic stimulation rather than random noise caused by repeatability issues.
CHAPTER 3
TIME-LAPSE FRACTURE CHARACTERIZATION FROM PRESTACK FAST AND
SLOW SHEAR DATA

This chapter summarizes the analysis of prestack fast and slow shear data for character-
ing the in-situ fracture network in terms of fracture orientation and magnitude as well as
the time-lapse response. The chapter begins by reviewing the theory and AVO modeling in
the symmetry planes of a two-layered orthorhombic model to identify the prestack attributes
most sensitive to fractures and to provide justification for the methodology discussed later.
The methodology section covers the step by step workflow and the corresponding observa-
tions. The chapter concludes with further discussions and interpretations as well as future
recommendations for analysis of prestack $S_1S_1$ and $S_2S_2$ datasets.

3.1 Theory and AVO Modeling

Synthetic modeling of the Niobrara top is a crucial first step in identifying the expected
reflectivity response and the influence of azimuthal anisotropy on amplitudes.

The simplest realistic model representing a typical fractured shale reservoir is an or-
thorhombic model containing a single set of vertical fractures in a VTI background (Fig-
ure 3.1).

The presence of azimuthal anisotropy can be highlighted effectively using common-offset-
common-azimuth (COCA) displays (Gray (2007)). In an example of a COCA display from
Turkey Shoot SH survey, the traces corresponding to a CMP within the full-fold part of the
survey are organized with offset and azimuth (Figure 3.2). The offsets increase from left to
right and every stripe (yellow and white) corresponds to azimuthal variations between $0^\circ$ and
$180^\circ$. The VVAz sinusoidal behavior indicates the presence of azimuthal anisotropy which
begins just above the Niobrara within the overlying Pierre Shale (red arrow in Figure 3.2).
Therefore, the model used for predicting the AVO behavior consists of two orthorhombic
layers with the same orientation of the vertical symmetry planes above and below the interface. For this model, the reflection coefficients along the symmetry planes can be directly adapted from the corresponding VTI equations (Tsvankin and Grechka (2011)).

It has been established that if the intrinsic matrix anisotropy, as well as the fracture induced anisotropy are weak, the effective anisotropy parameters can be obtained by algebraically adding the anisotropy parameters of the background medium and those of the HTI medium resulting from the fractures in an imaginary isotropic background (Bakulin et al. (2000)).

\[
\epsilon_\parallel = \epsilon_{\text{background}} \tag{3.1}
\]

\[
\delta_\parallel = \delta_{\text{background}} \tag{3.2}
\]

\[
\gamma_\parallel = \gamma_{\text{background}} + \frac{(\Delta_V - \Delta_H)}{2} \tag{3.3}
\]

\[
\epsilon_\perp = \epsilon_{\text{background}} - 2g(1 - g)\Delta_N \tag{3.4}
\]

\[
\delta_\perp = \delta_{\text{background}} - 2g[(1 - 2g)\Delta_N + \Delta_V] \tag{3.5}
\]
Figure 3.2: Example of a COCA display from SH volume. Sinusoidal VVAz behavior starting just above the Niobrara horizon (red arrow) is indicative of azimuthal anisotropy.
\[ \gamma_{\perp} = \gamma_{\text{background}} - \frac{\Delta H}{2} \quad (3.6) \]

Equations 3.1 to 3.3 (after Bakulin et al. (2000)) represent the anisotropy parameters in the symmetry plane parallel to fractures and Equations 3.4 to 3.6 represent those in the symmetry plane orthogonal to fractures. \( g \) is the square of the ratio of shear to compressional wave velocity \( \left( \left( \frac{\beta}{\alpha} \right)^2 \right) \), \( \Delta V \) and \( \Delta H \) are the tangential fracture weaknesses related to the crack density, and \( \Delta N \) is the normal weakness related to both crack density and the fluid content of the fractures.

\[
R_{\parallel \text{fast}} = -\frac{1}{2} \frac{\Delta Z^s}{Z^s} + \left\{ \frac{7}{2} \frac{\Delta \beta}{\beta} + \frac{2}{\rho} \frac{\Delta \rho}{\rho} + \frac{1}{2} \frac{\Delta \sigma_{\parallel}}{\sigma_{\parallel}} \right\} \sin^2 j \\
- \frac{1}{2} \frac{\Delta \beta}{\beta} \sin^2 j \tan^2 j
\quad (3.7)
\]

\[
R_{\perp \text{fast}} = -\frac{1}{2} \frac{\Delta Z^s}{Z^s} + \frac{1}{2} \left( \frac{\Delta \beta}{\beta} + \Delta \gamma_{\perp} \right) \tan^2 j
\quad (3.8)
\]

Equations 3.7 and 3.8 express the shear-wave reflection coefficients for waves polarized parallel to fractures (fast) and propagating in the two symmetry planes of the orthorhombic model (after Rüger (2001)). \( R_{\parallel \text{fast}} \) is the reflectivity of the shear wave traveling parallel to fracture strike, \( R_{\perp \text{fast}} \) is the reflectivity of the shear wave traveling orthogonal to fracture strike, \( Z^s \) is the shear wave impedance for the vertically incident fast shear wave, \( \beta \) is the vertical shear wave velocity, \( \rho \) is the medium density, \( j \) is the incident angle, and \( \Delta \sigma_{\parallel} \) and \( \Delta \gamma_{\perp} \) are the changes of Thomsen’s anisotropy parameters across the interface for the corresponding propagation azimuth.

Figure 3.3 displays in red the AVO response for estimated/presumed medium properties for these shear waves. The two symmetry plane orientations are represented by the solid red line (fracture parallel) and the dotted red line (fracture perpendicular).

\[
R_{\parallel \text{slow}} = -\frac{1}{2} \frac{\Delta Z^s}{Z^s} + \frac{1}{2} \left( \frac{\Delta \beta}{\beta} + \Delta \gamma_{\parallel} \right) \tan^2 j
\quad (3.9)
\]
\[ R_{\text{slow}} = -\frac{1}{2} \frac{\Delta Z^s}{Z^s} + \left\{ \frac{7}{2} \frac{\Delta \beta}{\beta} + 2 \frac{\Delta \rho}{\rho} + \frac{1}{2} \Delta \sigma_\perp \right\} \sin^2 j \]
\[ -\frac{1}{2} \frac{\Delta \beta}{\beta} \sin^2 j \tan^2 j \] (3.10)

Similarly, equations 3.9 and 3.10 express the reflectivity of shear waves polarized orthogonal to fractures (slow S-wave) and plotted in blue in Figure 3.3. The two symmetry plane orientations are represented by the solid blue line (fracture parallel) and the dotted blue line (fracture perpendicular). In each case, the AVO curve with the steep gradient is associated with the reflectivity of the pure SV mode.

Figure 3.3: Shear-shear AVO response of Niobrara top modeled in MATLAB. The AVO curves corresponding to the fast and slow modes are shown in red and blue, respectively. The solid and dotted lines correspond to propagation parallel and orthogonal to fractures, respectively. The pair of curves with steep gradients represent the reflectivity response of the radial (SV) mode.
3.1.1 Model parameters

The estimated compressional and shear wave velocities and densities are given based on the well logs, and the anisotropy parameters for the overlying Pierre shale are given based on the parameter estimation performed by Tamimi (2014) using a VSP dataset in the Wattenberg Field. In the modeling of Figure 3.3, the Niobrara δ parameter is kept constant across the interface and ε is increased by 25%.

The influence of changing the anisotropy parameters on the separation between the SV and SH mode reflection coefficients was studied at the maximum incident angle of 30° (Figure 3.4, Figure 3.5, and Figure 3.6). The parameters for the overlying Pierre shale are varied within the range suggested by Tamimi (2014) and for the Niobrara are varied within the range of possible values for each corresponding parameter.

Figure 3.4: The influence of varying ε parameter on the modeled AVO response. Subscripts 1 and 2 represent the ε parameter of the overlying Pierre shale and the Niobrara, respectively. The rest of model parameters are those indicated in Figure 3.3. The separation between the SV and SH reflection coefficients at 30° incident angle is positive for the majority of ε combinations.
Figure 3.5: The influence of varying $\delta$ parameter on the modeled AVO response. Subscripts 1 and 2 represent the $\delta$ parameter of the overlying Pierre shale and the Niobrara, respectively. The rest of model parameters are those indicated in Figure 3.3. The separation between the SV and SH reflection coefficients at 30$^\circ$ incident angle is positive for the majority of $\delta$ combinations.

Figure 3.6: The influence of varying $\gamma$ parameter on the modeled AVO response. Subscripts 1 and 2 represent the $\gamma$ parameter of the overlying Pierre shale and the Niobrara, respectively. The rest of model parameters are those indicated in Figure 3.3. The separation between the SV and SH reflection coefficients at 30$^\circ$ incident angle is positive for all $\gamma$ combinations.
The plots of Figure 3.4 to Figure 3.6 suggest that except for the unlikely scenarios of extremely large $\epsilon_1$ combined with extremely small $\epsilon_2$ or small or negative $\delta_1$ ($\delta_1<0.2$) combined with $\delta_2>0.3$, the separation between the SV and SH AVO curve (at 30° incident angle) remains positive. Therefore, in this particular model for a wide range of reasonable anisotropy parameters, the azimuthal variation of the AVO gradient can be considered a reliable measure of fracture orientation. Specifically, in the case of fast S-wave (red curves in Figure 3.3), the steepest gradient is associated with a propagation orientation parallel to fractures, and in the case of slow S-wave (blue curves), the steepest gradient is associated with the propagation orientation orthogonal to fractures.

The tangential and normal weaknesses ($\Delta_V$, $\Delta_H$, and $\Delta_H$) range between zero (no fractures) and one (extreme fracturing) and the selected values for modeling are arbitrary within this range. The influence of varying these parameters is insignificant and limited to the separation between the AVO gradients of the two SV curves (maximum separation of approximately 12%). Therefore, as far as the symmetry plane orientations are concerned, all possible values of these three parameters result in consistent azimuthal AVO responses.

### 3.2 Methodology and Results

The workflow used for analysis of $S_1S_1$ and $S_2S_2$ prestack volumes is as follows:

- Map the Niobrara top, ensuring it represents the correct polarity event through shear-shear well-ties (Section 3.2.1).
- Create 6 bi-directional azimuthal sectors of 50° azimuth ranges (overlapping by 10° to improve signal-to-noise ratio).
- Improve event alignment and signal-to-noise ratio through gather conditioning (Section 3.2.2).
- Perform a 2-term AVO analysis on each sector and identify the AVO gradient at every CMP.
• Fit cos (2θ) functions to AVO gradients (where θ is the azimuth) and identify the azimuth of the steepest gradient on S₁S₁ (reflectivity given in equations 3.7 and 3.8) and S₂S₂ (reflectivity given in equations 3.9 and 3.10) volumes

• Create a composite symmetry plane orientation map by combining the results from S₁S₁ and S₂S₂ and eliminate data points that do not fit the model discussed in Section 3.1 (i.e. a predominant set of vertical fractures).

3.2.1 Shear Well Ties

The vertical wells within the Turkey Shoot survey only contain compressional sonic logs. Synthetic shear sonic logs were predicted for these wells using a neural network with 3 training wells, one test well, and 4 well logs: gamma ray, resistivity, neutron porosity and bulk density. The output from the neutral network showed 94% precision for the test well (Matthew Bray, personal communication).

Figure 3.7 and Figure 3.8 display simple zero-offset shear-shear well ties to the S₁S₁ volume for wells V-B and V-D, respectively. The wavelet used for creating the synthetic is extracted from a 2000 ms window containing the Niobrara interval. The seismograms in blue are the synthetic seismograms and those in red are 5 identical traces extracted at the corresponding well location. The cross-correlation of the synthetic and seismic traces are displayed on the right. The acceptable zero-lag correlation coefficients of 61% and 78% for wells V-B and V-D respectively indicate the accuracy of the well-ties and the confidence in the trough event marked by the blue horizon representing the Niobrara top.

\[
R_{iso}^{pp}(j) = \frac{1}{2} \frac{\Delta Z^p}{Z_p} + \frac{1}{2} \left( \frac{\Delta V_p}{V_p} - \left( \frac{2 \bar{V}_s}{V_p} \right)^2 \frac{\Delta G}{G} \right) \sin^2 j + \frac{1}{2} \frac{\Delta V_p}{V_p} \sin^2 j \tan^2 j \tag{3.11}
\]

\[
R_{iso}^{sh}(j) = -\frac{1}{2} \frac{\Delta Z^s}{Z_s} + \frac{1}{2} \frac{\Delta V_s}{V_s} \sin^2 j + \frac{1}{2} \frac{\Delta V_s}{V_s} \sin^2 j \tan^2 j \tag{3.12}
\]

\[
R_{iso}^{sv}(j) = -\frac{1}{2} \frac{\Delta Z^s}{Z_s} + \left( \frac{7}{2} \frac{\Delta V_s}{V_s} + \frac{2 \Delta \rho}{\rho} \right) \sin^2 j - \frac{1}{2} \frac{\Delta V_s}{V_s} \sin^2 j \tan^2 j \tag{3.13}
\]
In order to generate a shear synthetic using the algorithms designed for compressional synthetics, the shear sonic logs are represented as compressional sonic logs and the wavelet phase is rotated by 180° (note in equations 3.11 to 3.13 (after Rüger (2001)), the opposite polarity of shear and compressional events from the zero-offset term in the Shuey and Thomsen’s representation of reflection coefficients).

In equations 3.11 to 3.13 which represent the reflectivity for a simple isotropic medium, the subscripts represent the wave mode, $j$ is the angle of incidence, $Z$ is the impedance (product of velocity ($V$) and density ($\rho$)), and $G$ is the shear modulus.

Figure 3.7: Shear synthetic seismogram and well tie for V-B - The blue seismogram is the synthetic seismogram created from the shear sonic and density log, and the red seismogram is the extracted seismic trace at the well location. The statistical wavelet used for generating the synthetic seismogram is extracted from a 2000ms window and rotated by 180°. The cross-correlation of the two seismograms shows a 61% zero-lag correlation coefficient.
Figure 3.8: Shear synthetic seismogram and well tie for V-D - The blue seismogram is the synthetic seismogram created from the shear sonic and density log, and the red seismogram is the extracted seismic trace at the well location. The statistical wavelet used for generating the synthetic seismogram is extracted from a 2000ms window and rotated by 180°. The cross-correlation of the two seismograms shows a 78% zero-lag correlation coefficient.
3.2.2 Gather Conditioning

Modeling the SV wave reflectivity at Niobrara top suggests that the critical angle associated with the S to P conversion at the Niobrara top occurs around 27° angle of incidence significantly influencing the pure shear wave reflectivity. As indicated in Section 1.8, the gathers in shear volumes were muted beyond 27° incidence angle (step 13 of processing sequence). Rolling super-gathers were created to improve the signal-to-noise ratio by averaging the adjacent traces and trim statics were performed to improve the alignment of the events within each sector. The parameters used for these processes were a rolling window of 3 by 3 traces for the super-gather and a 2000 ms window centered on Niobrara top for trim statics with a 5 ms maximum allowed time shift. Finally, converting the offset gathers to angle gathers using the shear velocity volumes further improved the signal-to-noise ratio by interpolating the traces, allowing additional data points for performing the AVO analysis.

3.2.3 AVO Analysis and Gradient Curve Fitting

After gather conditioning, 2-term AVO analyses were performed on all sectors extracting the AVO gradients providing 6 data points for every CMP. Using MATLAB scripts, the AVO gradients were fit to \( \cos(2\theta) \) functions from which the azimuth of the steepest gradient was calculated. The curve fitting approach used here and in Chapters 4 and 5 is based on the methodology proposed by Lynn (2014). Following the definition in the same publication, the difference between the minimum and maximum gradients divided by the RMS error in fit of \( \cos(2\theta) \) was calculated as the measure of reliability, and the difference between the minimum and maximum AVO gradients normalized by the minimum AVO gradients were calculated as a representation of anisotropy magnitude.

Figure 3.9 and Figure 3.10 display the orientation of steep gradient from \( S_1S_1 \) (blue color scale) and from \( S_2S_2 \) (orange color scale) in the baseline and monitor surveys, respectively. The icon color intensity represents the magnitude of anisotropy and only the icons with reliability of 3 or larger are displayed. The background grey scale shows the dot product of
the azimuths of the two sets of icons with darkest colors indicating the areas of orthogonal fast and slow orientations.

As discussed in Section 3.1, when the Alford rotation correctly separates the fast and slow components, the steep gradient in $S_1$ is aligned with the fracture orientation while the steep gradient in $S_2$ is orthogonal to the fracture orientation. These areas are generally highlighted in dark grey displaying nearly orthogonal fast and slow orientations and are predominantly associated with $S_1$ icons aligned in NW (presumed fast orientation in processing). A few examples of these areas are indicated by the red arrows. The rare case of interchanged $S_1$ and $S_2$ is recognized by small dot product and interchanged azimuths of steep gradient in $S_1$ and $S_2$ (blue arrow in Figure 3.10). Conversely, the samples with similar azimuths of steep gradients in $S_1$ and $S_2$ (white background) correspond to areas encountering an even distribution of fast and slow energy in $S_1$ and $S_2$ volumes. In these cases, the red and blue curves in Figure 3.3 no longer represent the unique polarizations and the orthogonal orientation of steep gradients begin to converge. This group of CMPs generally corresponds to fracture orientations in the NE (i.e. approximately 45° from the presumed fast and slow orientations), and comprises a significant portion of the dataset. Examples of these areas are indicated by the black arrows. Finally, the group of CMPs with non-parallel or non-orthogonal $S_1$ and $S_2$ orientations do not fit the assumption of a predominant fracture orientation.

3.2.4 Composite $S_1/S_2$ Fracture Maps

Since the relative orientations of steep gradients in $S_1$ and $S_2$ volumes indicate the presence of a preferred fracture orientation, the two maps ($S_1$ and $S_2$ steep gradient azimuths) are combined into a single composite map allowing for separation of sample points that fit the model from those that do not. The composite predominant fractures in baseline (green) and monitor (red) are displayed in Figure 3.11.

The CMP locations fall into one of the following categories according to which the composite symmetry plane orientation and magnitude are calculated:
Figure 3.9: Symmetry plane orientations identified from $S_1S_1$ and $S_2S_2$ baseline surveys. The icon orientations represent the azimuth of steepest AVO gradients in $S_1S_1$ (blue) and $S_2S_2$ (orange), and the icon color intensity shows the normalized difference between the largest and the smallest AVO gradients. Only the icons with reliability values of 3 or larger are displayed. The background grey color shows the dot product of the two sets of icons. Grey areas (orthogonal symmetry planes from fast and slow volumes) generally indicate correct separation of fast and slow energy.
Figure 3.10: Symmetry plane orientations identified from $S_1S_1$ and $S_2S_2$ monitor surveys. The icon orientations represent the azimuth of steepest AVO gradients in $S_1S_1$ (blue) and $S_2S_2$ (orange), and the icon color intensity shows the normalized difference between the largest and the smallest AVO gradients. Only the icons with reliability values of 3 or larger are displayed. The background grey color shows the dot product of the two sets of icons. Grey areas (orthogonal symmetry planes from fast and slow volumes) generally indicate correct separation of fast and slow energy.
Figure 3.11: Composite symmetry plane orientation in baseline (green) and monitor (red) surveys obtained by combining the results from $S_1S_1$ and $S_2S_2$ volumes. The icon color intensity is related to the fracture density in the presence of a single fracture set.
1. CMPs with a 0.4 or smaller dot product and an $S_1 S_1$ steep gradient azimuth within the same quadrant of the presumed N20W, for which the azimuth and magnitude of composite symmetry plane are those of $S_1 S_1$ steep gradient

2. CMPs with a 0.4 or smaller dot product and an $S_1 S_1$ steep gradient azimuth outside the quadrant of the presumed N20W, for which the azimuth and magnitude of composite symmetry plane are those of $S_2 S_2$ steep gradient

3. CMPs with a 0.9 or larger dot product and an average azimuth of $S_1 S_1$ and $S_2 S_2$ between $0^\circ$ and $50^\circ$ or $90^\circ$ and $140^\circ$, for which the orientation and magnitude of composite symmetry plane are the average azimuth and magnitude of $S_1 S_1$ and $S_2 S_2$ steep gradients

4. The CMPs that do not fit in any of the above categories and are removed from the composite map

This approach is an attempt to extract the maximum information possible from the fast and slow shear volumes without significantly compromising the accuracy of interpreted preferred fracture orientations. The fractures in the third category are considered to be those approximately $45^\circ$ to the presumed fast and slow orientations resulting in an even distribution of fast and slow energy in $S_1 S_1$ and $S_2 S_2$ volumes. It is important to realize that these areas are subject to higher uncertainty, potentially misrepresented by $90^\circ$. The data points in the fourth category are eliminated due to unpredictable orientation and magnitude, however they can represent areas with potentially lower anisotropic symmetry. For example, the presence of multiple fracture sets with different azimuths and comparable fracture densities can translate to a lack of a detectable preferred fracture orientation.

3.2.5 Validation Data - FMI Logs

Formation image logs were obtained for two horizontal legs (2N and 6N) before hydraulic stimulation and therefore should reflect the natural fractures as identified by the baseline
survey (Figure 3.12). The predominant fracture orientations and intensities from \( S_1S_1/S_2S_2 \) baseline analysis are displayed in green scale and FMI interpretations (Dudley (2015)) are displayed in dark purple along the horizontal legs.

The red circles highlight the intervals where the azimuth of the symmetry plane identified from shear data and the interpreted fractures from FMI logs agree (or agree with one of the fracture sets in the case of multiple fractures) and the blue circles highlight those intervals where the two do not agree. The black arrows indicate highly fractured intervals with multiple fracture orientations interpreted from FMI and no preferred fracture orientation captured from the shear data analysis. Note the symmetry plane orientations of nearly north-south in the two southern mismatch intervals in well 2N. Considering the limited ability of the image logs to see fractures oriented along the well bore, and therefore ignoring the mismatch in these two intervals as well as the highly faulted zones along the grabens, 67% (6 out of 9 intervals) match can be observed. Note the predicted azimuth in some of the mismatch intervals (pointed by blue arrows) fall into the third category discussed in the previous section and are approximately 90° different from the FMI fractures.

It is important to note that while the two methodologies are expected to yield similar information, a number of factors can result in dissimilar interpretations.

The shear-data analysis is based on the Niobrara top while the image logs are obtained from the well bores (generally targeting the C chalk which lies approximately 50 ms from the Niobrara top). With a wavelet dominant frequency of 15 Hz, the C chalk likely influences the amplitude response leading to the fracture characterization in question; however the identified fracture orientations can potentially reflect different azimuths associated with fractures in shallower units.

There are significant differences between the two methodologies with respect to data resolution and scales. Seismic data capture the effective predominant fracture orientation and intensity which can be the cumulative effect of many present fracture sets. In addition, due to the band-limited nature of the seismic data, the reflectivity of the Niobrara top
Figure 3.12: Composite symmetry plane orientations from $S_1S_1/S_2S_2$ baseline surveys and calibration with image logs - The purple icons represent fracture interpretations from formation image logs by Dudley (2015), and green icons represent the composite symmetry plane icons introduced in Figure 3.11. The circles highlight the areas of match (red) and mismatch (blue) from the two datasets.
represents a large interval, potentially hundreds of feet of rock column. On the other hand, the FMI log which essentially provides an image of the well bore contains much higher resolution on much smaller samples of the reservoir immediately adjacent to the well bore. Therefore, while indicative of fractures at the well bore, the FMI interpretations may not be representative of the reservoir interval as a whole. Finally, due to incorrect Alford rotation in some areas, some symmetry plane orientations are potentially misrepresented.

### 3.3 Discussions and Recommendations

As observed in the previous section, only a fraction of CMPs display a N20W predominant fracture orientation, with many sample points indicating the presence of mixed components in $S_1$ and $S_2$ volumes. Therefore, the ideal approach for fracture analysis using these shear volumes would be to perform a residual Alford rotation on every CMP to fully separate the fast and slow components. Using the available volumes, however, one can effectively identify the predominant fracture orientation aligning with the presumed orientation, those orthogonal to the presumed orientation, and estimate the areas of mixed mode.

What is clear from the baseline survey is the presence of a complex in-situ fracture network rather than a single preferred fracture orientation throughout the survey area. Presence of fracture icon gaps in large areas of the survey potentially suggests multiple fracture sets, the evidence of which is captured in FMI logs. Areas with preferred fracture orientations are also present although they seem to be localized.

The ‘magnitude of anisotropy’ as displayed by the icon color intensity is essentially only meaningful in the presence of a single fracture set in which case this magnitude is related to the fracture density. In this dataset, the presence of a complex fracture network restricts the interpretation of fracture density from this attribute.

The time-lapse map in Figure 3.11 suggests induced fracture orientations that largely agree with the natural fractures. As will be discussed in Chapter 5, the orientation of induced fractures is influenced by the orientation of present day maximum stress although it is very sensitive to the existing planes of weakness.
CHAPTER 4
TIME-LAPSE FRACTURE CHARACTERIZATION FROM PRESTACK RADIAL AND TRANSVERSE SHEAR DATA

The conventional approach in working with shear data is to analyze the fast and slow volumes obtained through mathematically separating the two components (Chapter 3). Due to the interpretation uncertainties associated with the regional Alford rotation, the applicability of radial and transverse volumes as an alternative approach was investigated. This chapter will focus on examining whether fracture information can be extracted from the radial and transverse volumes in this particular dataset. The chapter will begin by explaining the theory, followed by methodology and results, and concludes with a comparison of results with those obtained from S_1S_1/S_2S_2 analysis.

4.1 Theory

The radial and transverse components are explicitly defined by the source-receiver pairs. They represent the components of energy recorded in the plane and orthogonal to the plane containing the source-receiver line in radial and transverse components, respectively.

Consider a model with a single set of vertical fractures in which shear waves encounter shear-wave splitting (Figure 4.1). In this scenario, the recorded signal along the fracture strike is strictly fast mode in radial volume and slow mode in transverse volume. The recorded signal orthogonal to fracture strike is strictly slow mode in radial volume and fast mode in transverse volume. In directions oblique to fractures, shear-wave splitting results in the presence of both modes.

Assuming a VTI background for this single fracture set, the AVO modeling discussed in Section 3.1 would apply for this scenario. While separating the fast and slow components allows the use of amplitude response due to an azimuthal variation of AVO gradient, this is not the case in the SV and SH volumes. For example, in Figure 3.3, the two similar AVO
curves with steep gradients correspond to SV mode and no significant amplitude variation is expected between the two symmetry directions. Therefore, rather than studying the amplitude responses, the traveltime variations with azimuth are studied.

The idea of SWS conveyed in Figure 4.1 is demonstrated in Figure 4.2 by fast and slow shear wave arrivals in the case of radial (SV) signal for a fractured test sample (after Sondergeld and Rai (1992)). The figure represents the end view of the test sample with source placed at the center and polarized at angle $\Phi$ with respect to the fracture azimuths. The receiver placed on the opposite side of the sample is rotated $360^\circ$ at increments of $10^\circ$ measuring the various polarizations of the arriving shear wave.

The nature of signal transition from the isotropy plane to symmetry axis plane (Figure 4.2) is dependent upon the source waveform and the time lag between the fast and slow arrivals. The time lag is influenced by the fracture density and the thickness of the fractured medium. If azimuthal anisotropy is weak enough and the dominant frequency of the signal is low enough such that the two arrivals interfere and merge into a single arrival, a smooth
arrival time transition from fast to slow azimuth would exhibit a sinusoidal VVAz behavior in radial and transverse volumes. Since the polarizations of fast and slow shear waves are interchanged in radial and transverse volumes, in an anisotropic medium with a predominant fracture orientation, the radial and transverse traveltimes would be perfectly out-of-phase (Figure 4.3). The degree to which the traveltimes fit these sinusoidal functions and display this out-of-phase behavior is representative of the degree to which a predominant fracture orientation model is applicable.

4.2 Methodology and Results

The workflow used for analysis of radial (SV) and transverse (SH) volumes is as follows:

- Create 6 bi-directional azimuthal sectors of 30° azimuth ranges
- Improve event alignment and the signal-to-noise ratio through gather conditioning (Section 4.2.1)
Stack all traces within each sector, map the top and base of Niobrara, and extract isochrons for each sector

Ensure the assumptions about the source waveform and the maximum time lag are valid for expecting the out-of-phase sinusoidal behavior of Figure 4.3 (Section 4.2.2).

Fit the isochrons to cos(2θ) functions (where θ is the azimuth) and identify the symmetry plane azimuth from SV and SH volumes.

Create composite symmetry plane azimuth maps by combining the results from SV and SH volumes eliminating the data points that do not fit the preferred fracture orientation model (out-of-phase sin functions).

4.2.1 Gather Conditioning

Gather conditioning steps applied to SV and SH volumes were similar to those applied to $S_1S_1$ and $S_2S_2$ volumes (mute, super-gather and trim statics). The applied mute limits the maximum incident angle to 27° as discussed in Section 3.2.2. An inner trace mute to
6° was also applied in order to maximize the identified azimuthal velocity variations most reflected by far offsets. Super-gather applied a 5 by 5 trace rolling window, and trim statics were applied to a 2000 ms window centered on the Niobrara top with 8ms maximum allowed time shift.

4.2.2 Estimation of Maximum Time-Lag

After stacking the azimuthal sectors over all incident angles, the Niobrara isochron was extracted containing all Niobrara benches as well as the Codell interval. The maximum recorded time lag between the fast and slow arrivals was estimated from the maximum azimuthal variation of isochrons to be approximately 50% of the average isochron itself. The comparison of Niobrara isochrons in different azimuthal sectors indicates much smaller time lags between the fast and slow arrivals on average (Figure 4.4). In Figure 4.4 the Niobrara top and base horizons are colored by the corresponding azimuthal sectors shown in the lower left corner. Given the target dominant frequency of approximately 15 Hz (a period of 66 ms), and the average target isochron of less then 130 ms, the mixed mode azimuths are not expected to display separate arrivals but rather a smooth transition from the fracture strike to fracture perpendicular direction. Therefore, the out-of-phase sinusoidal behavior illustrated in Figure 4.3 can be expected for this particular dataset and zone of interest.

4.2.3 Isochron Curve Fitting

In Figure 4.5, the CMP locations which display the sinusoidal behavior discussed in Section 4.1 are marked in blue (SV) and black (SH) in baseline and monitor surveys. These data points have reliability values of 3 or larger. Clearly most of these data points lie along the faults due to the high sensitivity to inconsistencies in horizon mapping in azimuthal sectors. Since few data points are observed in the north side of the graben, and in order to avoid gridding artifacts originated from the data points along the faults, a relatively unfaulted area was selected (highlighted in red) to perform the analysis on SV and SH volumes.
Figure 4.4: Comparison of Niobrara isochrons in different azimuthal sectors - The displayed seismic cross-section corresponds to the 150° to 180° sector of the SH volume.

Figure 4.6 displays with blue icons the fast orientation as identified by the SV volume and in orange icons the fast orientation as identified by the SH volume. The color intensities represent the magnitude of velocity anisotropy measured as the normalized difference between the maximum and minimum isochrons, and the size of the icons represent the reliability defined as the difference between the isochrons divided by the RMS error in fit of \( \cos (2\theta) \) curve (after Lynn (2014)). The icons plotted are the gridded data points with reliability of larger than 4. The larger reliability cut-off used in this analysis compared to the analysis of \( S_1S_1/S_2S_2 \) (reliability=3) is due to the higher uncertainty introduced as a result of gridding. In the SV/SH analysis the data points are gridded due to their sparsity (Figure 4.5), whereas in the \( S_1S_1/S_2S_2 \) analysis every data point represents an independent CMP. The background grey scale represents the dot product of the two sets of icons with darker areas representing the smallest dot products or those with the largest orientation disagreement. The white background potentially highlights the areas with a preferred fracture orientation resulting in
Figure 4.5: Output data points displaying the sinusoidal behavior in SV (blue) and SH (black) volumes in baseline (left) and monitor (right) - Red outline highlights the focus area for performing the SV/SH analysis (away from highly structured zones).
the out-of-phase VVAz behavior of Figure 4.3. Once again, the purple icons are the fracture azimuths according to image logs. Figure 4.7 displays the preferred fracture set icons in the monitor survey.

Figure 4.6: Symmetry plane orientations identified from SV and SH baseline surveys: The blue and orange icon orientations represent the azimuth of predominant fracture orientation from SV and SH volumes, respectively. The icon color intensity represents the normalized difference between the maximum and minimum isochrons, and the icon size represents the reliability. Only icons with reliability values of 4 or larger are displayed. The background grey color shows the dot product of the two sets of icons with bright colors representing the areas following the VVAz behavior described in Figure 4.3.

Areas with icon gaps and those with small dot products can be interpreted as areas that do not fit the model described in Figure 4.1, i.e. either with no detectable SWS or having multiple fracture sets in multiple azimuths such that no preferred fracture orientation is identified.
Figure 4.7: Symmetry plane orientations identified from SV and SH monitor surveys: The blue and orange icon orientations represent the azimuth of predominant fracture orientation from SV and SH volumes, respectively. The icon color intensity represents the normalized difference between the maximum and minimum isochrons, and the icon size represents the reliability. Only icons with reliability values of 4 or larger are displayed. The background grey color shows the dot product of the two sets of icons with bright colors representing the areas following the VVAz behavior described in Figure 4.3.
4.2.4 Composite SV/SH Maps

Composite symmetry plane orientation maps combining the SV and SH results are shown in Figure 4.8 in baseline (green) and monitor (red). These maps filter out the data points with dot product of smaller than 0.9 and ideally only represent the CMP locations which match uni-directional azimuthal anisotropy with the out-of-phase VVAz behavior described in Figure 4.3. This figure suggests an induced fracture orientation of NW-SE and E-W in this area. The background grey scale represents the dot product of the baseline and monitor icon azimuths with extensive large values potentially indicating the tendency of induced fractures to reopen natural fractures. The correlation with orientation of fractures from FMI is lower than captured by the $S_1S_1/S_2S_2$ analysis which can be attributed to its lower accuracy as a result of fewer data points and gridding.

Figure 4.8: Composite symmetry plane orientation in baseline (green) and monitor (red) surveys obtained by combining the results from SV and SH volumes - The background color displays the dot product of the two sets of icons.
4.3 Interpretation and correlation with $S_1S_1/S_2S_2$ Results

A comparison of the composite predominant fracture icons obtained from $S_1S_1/S_2S_2$ and SV/SH analysis in the baseline surveys shows a significant agreement (Figure 4.9). The composite predominant fractures in $S_1S_1/S_2S_2$ and SV/SH analysis are displayed in navy-blue and magenta respectively. As indicated by the histogram, 83% of the data points from these two different approaches are within 45° azimuth range. The correlation of azimuths obtained from these two methodologies is lower in the monitor potentially due to far fewer common location data points. The correlation from the baseline survey is substantial particularly considering the fact that the methodologies are not only based on different seismic volumes (radial and transverse versus ‘fast’ and ‘slow’) but also are based on different seismic attributes (traveltimes versus amplitudes).

The SV/SH analysis indicates that the majority of the area does not obey the out-of-phase sinusoidal behavior expected from a predominant fracture set. Although this can also be influenced by the lower sensitivity (to azimuthal anisotropy) of traveltimes compared to amplitudes, the presence of a complex fracture network agrees with the results obtained in the previous chapter as manifested by the sparsity of the fracture icons. The methodology reviewed in this chapter relies heavily on interpolation of data points and should be used with caution to avoid gridding artifacts.
Figure 4.9: Comparison of symmetry plane orientations from SV/SH and $S_1S_1/S_2S_2$ methods in baseline survey. Composite symmetry plane icons from $S_1S_1/S_2S_2$ gradient curve fitting and SV/SH isochron curve fitting are shown in navy-blue and magenta, respectively. The background shows the dot product of the orientation of the two sets of icons. The histogram of dot products indicates that 83% of icons are oriented within the same quadrant.
CHAPTER 5
AZIMUTHAL TRAVELTIME ANALYSIS OF BASELINE PP DATA

An understanding of the current day stress orientation can provide explanations for some of the observations specifically on the time-lapse effects discussed in previous chapters. While shear waves are sensitive to fractures and small scale micro-cracks, certain attributes from compressional waves can provide information about the stress field. Previous studies have shown that P-wave azimuthal interval velocities can help constrain the local stress orientations and magnitudes (Lynn et al. (2014)). In this chapter, the PP azimuthal interval traveltimes at mid-to-far offsets were used to identify the symmetry plane orientation and the relative magnitudes of velocity anisotropy.

The chapter will begin by discussing the theory followed by methodology and results. Instantaneous shut-in pressures, microseismic data, and production logs are all used as calibration data in examining the relationship between the characterized anisotropic symmetry and the in-situ stress state.

5.1 Theory

In the presence of azimuthal anisotropy, the NMO velocity which is responsible for the hyperbolic moveout in the near and mid offsets varies azimuthally tracing an elliptical shape in the horizontal plane (Tsvankin (2012)). In an orthorhombic media, the axes of the NMO ellipse align with the vertical symmetry planes (Grechka and Tsvankin (1998)). Since the prestack time migration did not correct for the azimuthal velocity variations, azimuthally varying residual moveout is expected to be preserved in these volumes. In this chapter, sinusoidal functions were fit to these residual azimuthal traveltimes as a proxy to fitting NMO ellipses for identification of symmetry plane orientations.
5.2 Methodology

The workflow used for analysis of far offset PP azimuthal traveltimes is as follows:

- Create 6 bi-directional azimuthal sectors of 30° azimuth ranges
- Improve event alignment and signal-to-noise ratio through gather conditioning
- Create limited offset stacks containing incident angles between 30° and 40°
- Extract Niobrara isochrons on each limited offset and azimuth sector
- Fit the isochrons to cos (2\(\theta\)) functions (where \(\theta\) is the azimuth) and identify the azimuth of minimum isochron (maximum interval NMO velocity)
- Find a measure of minimum interval moveout velocity by normalizing the maximum azimuthal interval traveltimes by the traveltimes extracted from the stacked volume

It has been shown that for moderate structural complexity and offset ranges less than or equal to the reflector depth, the moveout can be described by NMO velocity defined in the zero-spread limit (Tsvankin (2012) and Tsvankin and Thomsen (1994)). The incident angle range of 30° to 40° which includes the offset-to-depth ratio of unity, was selected in order to capture the largest azimuthal variation of moveout with minimal influence of non-hyperbolic moveout.

5.3 Results and Calibration Data

This section will discuss the meaning and significance of the PP azimuthal traveltime results through the comparison with validation data, specifically instantaneous shut-in pressures, microseismic, and production logs.

5.3.1 Instantaneous Shut-In Pressures

The instantaneous shut-in pressure value represents the final injection pressure after the fluid injection has been stopped and is considered a proxy for the magnitude of minimum
horizontal stress. A small minimum horizontal stress allows the rock to break ‘easier’, with a smaller breakdown pressure. Therefore, the varying ISIP values along the well bore reflect the local minimum stress which is in turn related to the local minimum interval velocities. ISIP values were identified from the pressure records provided for all 11 horizontal wells.

The normalized maximum azimuthal interval traveltimes are displayed by the background colors in Figure 5.1 and are expected to relate to the localized minimum horizontal stress. The squares plotted along the well bores represent the instantaneous shut-in pressures with square sizes proportional to the ISIP values. The normalized traveltimes were cross-plotted against the ISIP values for all horizontal wells with the exception of well 9N that had a different completion method and shows consistently lower ISIPs (Figure 5.2). The cross-plot on the right corresponds to the 3 easternmost wells and the one on the left corresponds to the remaining 7 wells. In the 3 easternmost wells where the hydraulic fracturing targets the relatively fresh rock, the largest ISIP values correspond to the smallest normalized slow traveltimes or the largest minimum interval velocities. This matches the expected negative general trend (dashed yellow curve) which follows from the speculation that the magnitude of minimum interval velocities represent the magnitude of minimum horizontal stress. Smaller ISIP values also generally correspond to the presence of differential traveltimes (data points highlighted by red).

Keeping in mind that hydraulic fracturing started from the east moving towards west, the breakdown of this potential correlation from east to west can be attributed to an alteration of the stress field as a result of the stimulation from east. There is however a clear lack of trend in the plot to the left as well as in the case of intermediate ISIP values on the plot to the right. As will be discussed further later, the moveout velocities can react to many influencing factors and do not constrain the stress field definitively.

5.3.2 Microseismic data

The stimulation propagation is often identified through acquiring and processing of microseismic data. According to previous studies, the propagation orientation of microseismic
Figure 5.1: Normalized maximum azimuthal traveltimes overlain by ISIPs - Size of the squares is proportional to the ISIP values for each stage.
Figure 5.2: Cross-plots of ISIP values and the normalized azimuthal PP far offset traveltimes for the 3 easternmost wells (right) and the rest of the wells (left) excluding well 9N with a different completion method. Largest ISIP values correspond to largest azimuthal interval moveout velocities (smallest azimuthal interval traveltimes) resulting in a potential general trend in the eastern wells targeting the relatively fresh rock.

...events is controlled by the orientation of maximum horizontal stress, and the distribution of the events is controlled by the horizontal stress ratio (Wikel (2011)). Specifically, a high horizontal stress ratio results in linear growth of events along the maximum stress direction whereas a low horizontal stress ratio results in complex event patterns.

In Figure 5.3, the orientation of maximum interval velocity (minimum azimuthal travelttime) is displayed by needle icons and colored by the magnitude of the difference between the minimum and maximum traveltimes (normalized by minimum traveltimes). Microseismic events are colored by stage for well 3N, with events corresponding to other wells removed for the purpose of visualization.

The orientation of microseismic events within each stage largely agree with the symmetry plane aligned with the maximum interval moveout velocity. The length of the microseismic cloud appears to be a function of the relative orientation of the symmetry plane and the well. Smaller clouds correspond to intervals where the symmetry plane orientation is aligned...
Figure 5.3: Symmetry plane orientation from PP azimuthal traveltime analysis and orientation of microseismic events. The green icons indicate the orientation of semimajor axis of P-wave NMO ellipses, and the icon color intensity represents the normalized difference between the minimum and maximum azimuthal travel times. The square icons represent the ISIP values with icon size proportional to the ISIP value at each stage. The distribution of microseismic events (colored by stage) and the orientation and shape of microseismic cloud (black outlines) are predicted through the identification of symmetry planes from PP azimuthal traveltime analysis.
with the well orientation. A relationship between the orientations of NMO ellipse and the maximum stress can be speculated explaining the orientation of microseismic events. The higher tendency for forming N70W oriented microseismic clouds is apparent from this as well as all other horizontal legs.

The lack of differential azimuthal traveltimes in certain areas is reflected by the absence of symmetry plane icons. Among other influencing factors, this can be due to a transition between two various stress fields, multiple stress orientations acting on the same area or simply the absence of a significant differential stress. These areas of no differential azimuthal velocity are outlined in black around the well 9N along with the microseismic events and coincide with no or very few microseismic events (Figure 5.4). It is speculated that due to the influence of stress state on interval moveout velocities, microseismic events avoid the areas which require higher break-down pressures and instead concentrate on areas where a differential stress allows opening of fractures in the minimum horizontal stress orientation. Stages 21 and 22, indicated by the red arrow and which coincide with one of the differential velocity gaps, required the largest ISIP values within this well to initiate breaking of the rock.

The distribution of symmetry plane icons suggests a complex NMO ellipse orientation throughout the survey area. While the predominant elongation of the NMO ellipse seems to be approximately N60W, there are isolated blocks within the section with other orientations. These blocks of differing orientation appear to be separated by boundaries of no symmetry plane icons.

It is important to note that while related, the orientation and shape of the NMO ellipse does not constrain the orientation and intensity of the current day stress field. The NMO ellipse reflects the influence of many factors such as spatial variations of lithology, porosity and fluid saturation in the overburden, and the paleo-stress state influencing the in-situ fracture network. Therefore, while the differential velocities contain information about the current day stress field they can not solely constrain the stress state without a more extensive
knowledge of the geologic model.

5.3.3 Production logs

Cumulative production data was provided by APC for all 11 horizontal wells. The difference between the cumulative production of the best and worst producer is approximately 37% and 18% for gas and oil respectively. Spinner logs were provided for 2 horizontal legs (2N and 6N) for the purpose of identifying the oil and gas producing intervals and quantifying the production profile. Since the study area is small (one section), the reservoir properties of interest change rapidly along the well bore, and both best and worst reservoir properties are shared between multiple horizontal legs. Therefore, rather than the cumulative production data, the spinner logs on the two horizontal legs were used when studying the impact of reservoir properties on production. Figure 5.5 displays the oil and gas production rates along the 2N and 6N wells with green and red circles, respectively. The size of the circle is proportional to the production rate in each interval. The contours represent incoherency extracted from the Codell horizon. The background color is the normalized maximum azimuthal traveltimes introduced in Figure 5.1.

The intervals of highest production coincide with contours of highest incoherency representing potentially higher permeability zones created by faults and structures in adjacent zones (red arrows in Figure 5.5).

Normalized maximum azimuthal traveltimes were cross-plotted against the incremental oil and gas production excluding the high incoherency intervals and the graben zones (Figure 5.6). The general trend indicates a relationship between production and the differential azimuthal interval moveout velocities which potentially relates to the tendency of fractures to remain open and contribute to production. Note the horizontal wells have encountered multiple Niobrara benches with different lithologies. Varying brittleness among different lithologies can explain some of the scattering of data points, and separating the lithologies is expected to improve the correlations.
Figure 5.4: Differential azimuthal NMO velocities predicting the effectiveness of hydraulic stimulation. The green icons indicate the orientation of semimajor axis of P-wave NMO ellipses, and the icon color intensity represents the normalized difference between the minimum and maximum azimuthal traveltimes. Microseismic events (colored by stage) appear to avoid the gaps in symmetry plane icons (black outlines). The square icons represent the ISIP values with icon size proportional to the ISIP value at each stage. The red arrow points to stages 21 and 22 with high ISIP values which coincide with absence of symmetry plane icons.
Figure 5.5: Normalized maximum azimuthal PP traveltimes overlain by contours of incoherency along the Codell horizon and oil (green circles) and gas (red circles) production rates by stage - The highest producing intervals (red arrows) correspond to high incoherency along the Codell horizon.
Figure 5.6: Cross-plot of production rate and normalized maximum azimuthal PP traveltimes
-Both oil and gas production is generally higher in areas with smaller interval NMO velocities.
CHAPTER 6
SHEAR AND COMPRESSIONAL DATA INTEGRATION

This chapter will review a comparison between the results from time-lapse fast and slow shear data amplitude analysis and compressional data traveltime analysis in the baseline. The chapter will continue by discussing the validation data in particular FMI, ISIPs, microseismic, and production data as related to these two results.

6.1 Azimuthal Anisotropy Signatures in Shear versus Compressional data

A qualitative comparison of the anisotropy signatures from shear and compressional baseline data indicates both consistencies and differences (Figure 6.1). The green icons indicate the composite predominant fracture orientation obtained from the $S_1S_1/S_2S_2$ analysis (Chapter 3), and the brown icons indicate the azimuth of fast interval velocity from compressional data. The icon color intensity indicates the magnitude of anisotropy in each case. The purple needles along the well bores indicate fracture orientation from FMI logs (Dudley (2015)). The differences between the orientations of symmetry planes obtained from shear and compressional data can be attributed to varying sensitivity of different wave modes to different rock properties. For example, shear waves are expected to show higher sensitivity to natural fractures due to SWS, and compressional waves (which are influenced by both rigidity and incompressibility) are expected to show higher sensitivity to stress. Note the stress field and natural fractures are not always expected to align due to possible changes in stress orientation over time. The red circles highlight the intervals where the shear data has provided an accurate prediction of predominant natural fracture orientation which differs from the fast orientation captured by the PP traveltime analysis.
Figure 6.1: Comparison of azimuthal anisotropy signatures in baseline shear (green) and compressional (brown) data - The icon orientations represent the symmetry plane orientation identified from the corresponding method. The red circles highlight the intervals where the $S_1S_1/S_2S_2$ amplitude analysis has provided a more accurate prediction of natural fractures compared to the PP traveltime analysis as calibrated by FMI logs (purple icons by Dudley (2015)).
6.2 Natural versus induced fractures

As discussed in Chapter 3, the Alford rotation towards a single presumed fast orientation results in only a fraction of dataset providing reliable information about predominant fracture orientation. A portion of the dataset provides that information with higher uncertainty, while another portion of the dataset was eliminated due to substantial uncertainty and/or undetectable symmetry plane orientations. While pure shear data have significant potential in extracting information in fractured reservoirs, the high spatial variability in fast orientation in this study area is detrimental to the value that these data can offer. Effectively separating the fast and slow components through Alford rotation for small survey portions will allow the use of the full potential that S-wave data has to offer.

Despite the eliminated data points and the high degree of uncertainty on a subset of data, interpretations can be speculated from shear time-lapse composite maps and PP baseline interval velocity maps with respect to rock’s response to hydraulic fracturing and the importance of natural fractures and the present day stress field.

Figure 6.2 displays on the same map the composite predominant fracture orientation maps created and discussed in Chapter 3 and the symmetry plane orientation created and discussed in Chapter 5. Three categories of data points are highlighted by different colored outlines separating areas of different time-lapse responses.

Blue outlines indicate the areas displaying preferred fracture orientations both in the baseline and monitor surveys. With only a few exceptions, the preferred fracture orientation identified post-stimulation generally agrees with those pre-stimulation. This is true for both agreeing and disagreeing fast orientation captured by the PP data and confirms the tendency of new fractures to form along the existing planes of weakness. Note multiple fracture orientations can exist both in-situ and after fracturing, but the cumulative response captured by shear seismic data points to the original set of fractures remaining to be the predominant fracture orientation.
Figure 6.2: Various time-lapse responses according to shear and compressional symmetry plane orientations. Symmetry plane orientations identified from the baseline and monitor fast and slow shear surveys, and baseline compressional survey are displayed in green, red, and brown icons, respectively. Different colored outlines highlight areas with different time-lapse responses in terms of changes in the predominant fracture orientations.
Green outlines highlight the areas that originally displayed a preferred fracture orientation and hydraulic fracturing eliminated the predominant fracture orientation likely as a result of forming new fracture sets. The drilling and completion factors in this area create a tendency for fractures to form in an E-W orientation and will do so readily when the stress orientation is nearly orthogonal to the well orientation. Some fractures in this category are oriented close to N-S aligning with the orientation of horizontal legs. This agrees with the hypothesis that formation of new fractures has increased the fracture complexity and has eliminated a detectable fracture orientation post-stimulation.

Red outlines highlight the areas that originally did not identify a preferred fracture orientation, but after hydraulic stimulation a detectable predominant fracture orientation was created. Qualitatively examining these areas suggests that with some exceptions, in the absence of a preferred fracture orientation, the fast orientations from PP and SS data agree. Exceptions to this statement can be attributed to more complex stress fields (for example, the highly faulted zone at the toe end of 3N well) as well as higher azimuthal heterogeneity in the overburden. The mismatch in some areas can also be explained by the 90° uncertainty in two conjugate orientations centered at 25° and 115° azimuths.

A comparison of Figure 6.2 and Figure 2.5 does not show a clear match between the time-lapse anomalies. Note the outlines in Figure 6.2 simply highlight the different time-lapse responses as related to the presence of a predominant fracture orientation and are not expected to represent the stimulated rock volume.

6.3 Validation Data

In this section, the validation data will be integrated with seismic data to examine the obtained predictions.

6.3.1 Instantaneous Shut-in Pressures

The instantaneous shut-in pressures were discussed in Section 5.3.1 when they were found to correlate weakly with the minimum PP moveout velocity in un-stimulated rock (Figure 5.2
right plot). Specifically, the smaller the minimum interval velocity, the easier the fractures open, and the smaller the ISIP values would be. In addition to these observation, it is expected that the naturally fractured intervals would be stimulated easier with lower fluid pressure required. A number of intervals fit this hypothesis where preferred fracture icons coincide with smaller ISIP values even in the presence of relatively high maximum traveltime values (yellow circles in Figure 6.3). The maximum azimuthal PP traveltimes are displayed with colors in the background, and natural fracture icons from the shear analysis are displayed in green. Note that incoherency contours also highlight the areas of potentially high fracture density towards the base of the reservoir although they would not be captured by the amplitude analysis of the Niobrara top. Figure 6.4 shows the plot from Figure 5.2 but only for the 1N well (with stimulation initiating in fresh rock). After removing these naturally fractured intervals, there will be a higher correlation between ISIPs and the maximum traveltime values (red data points and plots in Figure 6.4).

Note a clear calibration of this hypothesis is not possible since fracture density has not been estimated in these analyses. The absence of symmetry plane icons does not indicate the absence of fractures; in fact it may represent highly fractured areas with multiple fracture orientations.

6.3.2 Production Logs

In Section 5.3.3 the high producing zones were shown to relate to two controlling factors: 1) high permeability zones mapped as high incoherency along the underlying Codell horizon, and 2) large minimum azimuthal PP traveltimes which relate to small minimum horizontal stress.

In order to investigate the influence of natural and induced fractures on production these two factors need to be isolated from the analysis. For this purpose, multiple isolated intervals outside of high incoherency intervals and with similar slow azimuthal velocities have been studied. These intervals correspond to normalized azimuthal maximum traveltimes between 1 and 1.015 (Figure 6.5) and between 1.015 and 1.03 (Figure 6.6).
Figure 6.3: The influence of natural fractures on instantaneous shut-in pressures -ISIP values are displayed in squares with sizes proportional to values. Background colors represent the normalized maximum azimuthal traveltimes, the contours indicate high incoherency extracted along the Codell horizon, and green needles represent the composite symmetry plane icons introduced in Figure 3.11. The yellow circles highlight the intervals where the presence of symmetry plane icons (or high incoherency along Codell) coincides with small ISIP values despite relatively large interval moveout velocities.
Figure 6.4: Cross-plot of production rate and normalized maximum azimuthal PP traveltimes for well 1N (removing the intervals with symmetry plane icons improves the correlation).

In both figures, higher production is associated with absence of fracture icons. As discussed in Chapter 3, the identification of a preferred fracture orientation is dependent upon the relative orientations of fast and slow steep gradients which ideally occur in the presence of a single fracture set. Therefore, one possible interpretation for the lack of fracture icons could be the presence of multiple fracture sets with equal development of fracture density such that no predominant fracture orientation is detectable. A more complex fracture network translates to higher permeability and higher production from the interval.

### 6.3.3 Microseismic Data

As discussed previously, the extent and orientation of microseismic events are greatly influenced by the present day stress orientation which was shown to align with the symmetry plane orientation captured from the PP azimuthal traveltimes (Section 5.3.2). The natural fracture network is expected to have an influence on the outcome of hydraulic stimulation. Examples of this effect are observed by examining the microseismic event density as related
Figure 6.5: The control of symmetry plane icons on production (in ‘fast’ stages) - Zoomed-in panels display stages with consistent minimum interval NMO velocity (background color) between 1 and 1.015 normalized traveltimes. Spinner production logs are displayed for oil (green circles) and gas (red circles) with circle sizes proportional to production from each stage. The needles represent the baseline (green) and monitor (red) symmetry plane icons introduced in Figure 3.11. High producing intervals are associated with the lack of symmetry plane icons.
Figure 6.6: The control of symmetry plane icons on production (in ‘slow’ stages) - Zoomed-in panels display stages with consistent minimum interval NMO velocity (background color) between 1.015 and 1.03 normalized traveltimes. Spinner production logs are displayed for oil (green circles) and gas (red circles) with circles sizes proportional to production from each stage. The needles represent the baseline (green) and monitor (red) symmetry plane icons introduced in Figure 3.11. High producing intervals are associated with the lack of symmetry plane icons.
to the shear and compressional results (Figure 6.7); however they do not represent a clear calibration.

The symmetry plane orientations as identified by the $S_1S_1/S_2S_2$ analysis and the compressional traveltime analysis are displayed in green and brown icons, respectively. The icon color intensity represents the magnitude of anisotropy. Size of the circles along the horizontal legs is proportional to the number of microseismic events recorded as a result of stimulation on that stage. The range of these numbers varies approximately between 5 and 150 events and the red circles highlight the stages with 95 or more events. Each of these high event density stages is shown in a zoomed-in panel displaying the microseismic events corresponding to the stage in question (red dots). Due to a high tendency of stimulation energy to open existing planes of weakness, there are many examples with much higher microseismic events along the faults and incoherency zones extracted from the Niobrara top. For this reason and for the purpose of investigating the influence of smaller scale natural fracture networks on stimulation outcome, high event density stages along the grabens (the three blue outline) are excluded from the discussion in this section. Panel ‘G’ also displays a high event density stage that seems to be influenced by the orientation of the faults towards the west and south west.

An analysis of the panels indicates the influence of a predominant natural fracture orientation in increasing the number of microseismic events. Most of the cases are associated with similar azimuth of symmetry plane orientation as identified by the shear and compressional data suggesting that two potentially independent factors (fractures and stress) facilitate the formation of induced fractures in preferred locations.

As mentioned before, the fracture characterization results obtained in this thesis do not conclusively constrain the presence and the density of fractures but rather provide information about the presence of a preferred fracture orientation with varying uncertainty levels. Therefore, when the property of interest is the fracture network density, such as most analyses in this chapter, a clear calibration can not be expected.
Figure 6.7: The control of symmetry plane icons on microseismic event density. The size of the circles along the well bores is proportional to the number of microseismic events recorded as a result of stimulation at that stage. Red circles correspond to the stages with 95 events or more, and are displayed in zoomed-in panels. Background icons represent symmetry plane orientation in SS (green) and PP (brown) baseline surveys. Red dots highlight the microseismic events of the stage of interest, and blue circles represent high density microseismic stages along the grabens. The presence of symmetry plane icons is associated with high microseismic event density, particularly in the areas of matching symmetry planes from SS and PP analysis.
CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

The time-lapse poststack traveltime and amplitude analysis of fast and slow shear volumes prove effective in distinguishing the areas with varying degrees of stimulation effectiveness. The size and number of time-lapse anomalies were shown to relate to the stimulated reservoir volume in the Wishbone section as verified by microseismic and 90-day cumulative production data. The SRV estimation from seismic is important in identifying the un-fractured areas which make potential candidates for future re-completion.

The prestack amplitude analysis of fast and slow shear volumes verifies the effectiveness of this technology to provide high resolution fracture characterization when the fast and slow components are correctly separated through Alford rotation. This is due to distinct AVO responses in SV and SH components and azimuthal variations of fast and slow amplitudes as they transition from SV to SH with changing propagation azimuth. Formation image logs provide a high resolution localized measure of fracturing which can be used as calibration data in seismic interpretation. The azimuths of the preferred fracture orientation obtained through prestack amplitude analysis of $S_1S_1$ and $S_2S_2$ volumes show a 67% agreement with the fracture azimuths interpreted from FMI logs (Figure 3.12).

The traveltime analysis of shear volumes is a relatively lower resolution tool for fracture characterization than amplitude analysis and has conventionally been used on fast and slow shear volumes. The radial and transverse analysis presented in this thesis suggests the potential of these datasets to provide similar interpretations to those provided by fast and slow volumes. This traveltime analysis is possible only in the case of validity of certain assumptions such as a maximum time lag threshold between the fast and slow arrivals. Furthermore, the heavy reliance on gridding makes this analysis an experimental evidence for its lower reliability compared to the analysis of fast and slow volumes. As demonstrated
in Chapter 4, azimuthal anisotropy within the zone of interest needs to be strong in order to be identified using azimuthal traveltime-variance.

Azimuthal PP traveltime analysis proved successful in identifying the symmetry plane orientation and was shown to be related to the stress state as calibrated by ISIPs, microseismic, and production data. The comparison of results from prestack PP traveltime and prestack SS amplitude analysis suggests that the SS analysis provides a higher accuracy prediction of the orientation of natural fracture.

The rock’s response to hydraulic fracturing in terms of the orientation and size of the stimulated rock volume and the required fluid pressure to initiate fracturing is a function of magnitude and orientation of the current day stress field, the well bore orientation relative to this orientation, and the presence of natural fractures. The induced fractures are known to be influenced by the existing planes of weakness and the present day stress field, the evidence of which is observed in this study. Yet, the relative importance of these factors has not been conclusively calibrated.

This research has shown the presence of multiple controlling factors on production. Highly fractured zones highlighted through incoherency on the underlying formations are expected to represent high permeability areas with higher production. The absence of a preferred fracture orientation in some areas is believed to be indicative of higher fracture complexity contributing to higher production. Finally, the higher tendency of these natural fractures to remain open as measured by the smaller size of minimum horizontal stress is shown to be related to higher production.

7.1 Recommendations and Future Work

Performing a residual Alford rotation for the purpose of separating the fast and slow energy in shear volumes is imperative. This would highly decrease the uncertainty associated with some of the fracture azimuths and would provide a more definitive interpretation of natural and induced fracture complexity and the size of SRV from prestack data. A second monitor survey will be acquired in winter 2016 and processed in time-lapse mode providing
the means to estimate the produced volume. The estimated stimulated and produced volumes will serve as tools in targeting future re-fracturing areas for development optimization.

When feasible, the amplitude and traveltime methodologies particularly in time-lapse analyses are recommended to contain the reservoir interval as a whole rather than the reservoir top.

The analysis of azimuthal variation of NMO velocity which attempts to minimize the influence of non-hyperbolic moveout by using the incident angles between $30^\circ$ and $40^\circ$, can improve by correcting for the azimuthal variation of non-hyperbolic moveout.

The azimuthal sectoring followed by curve fitting approaches utilized in this thesis encounter potentially significant uncertainty associated with the limited number of data points. For example, it has been shown that azimuthal velocity analyses via non-sectoring methods yield significantly more accurate interval velocity volumes compared to those using azimuthal sectoring methods (Lynn (2007)). When possible, the preferable method of fitting NMO ellipses using all offsets and azimuths rather than applying the sectoring method is recommended.

Most of the analyses discussed in this thesis presume a 2-dimensional view of the horizontal wells. As mentioned in Chapter 5, the horizontal wells have encountered multiple facies with varying lithologies. These lithology variations should be taken into account in each analysis, for example in studying the ISIPs, image logs, and production logs as related to the extracted seismic attributes. Finally, the microseismic events are only studied in horizontal views without taking into account the vertical distribution. Although low vertical resolution is expected due to the survey array, the microseismic events discussed in this thesis range in depth within an approximately 1000 feet window.

PP amplitude analysis for the purpose of fracture characterization was conducted by Matthew White. The mismatch between the results is attributed to the regional Alford rotation and the varying tendency of different wave modes to respond to fracture versus pressure changes. Future shear wave analysis with the residual Alford rotation is recom
mended to continue integration with compressional mode datasets.

Most conventional fracture characterization methods (including those covered in this thesis) assume the presence of a single fracture orientation. Previous studies have shown the feasibility of characterizing multiple fracture sets by jointly inverting the compressional and shear NMO ellipses for fracture densities, fracture azimuths and fluid factors (Vasconcelos and Grechka (2007)). Given the complex nature of the fracture network recognized in the study area, utilizing similar approaches are recommended in order to extract more accurate information with respect to fracture orientation and density as well as the fluid-infill.
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