Three-Dimensional Multicomponent Imaging
of Reservoir Heterogeneity,
Silo Field, Wyoming

by
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Golden, Colorado

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The Reservoir Characterization Project at Colorado School of Mines acquired a multicomponent three-dimensional seismic survey over Silo field in southeast Wyoming, with the objective of characterizing reservoir heterogeneity. The survey, comprised of five 3-D grids, including compressional, converted and shear wave data, is the first three-dimensional multicomponent survey ever acquired. It was designed to investigate whether anisotropy from shear wave splitting could be used to delineate fractures that control oil production from the Niobrara chalks and lithology changes in the prospective Dakota valley-fills.

Fractures can introduce anisotropy to the reservoir interval. A shear wave entering an anisotropic layer of parallel fractures splits into two waves polarized orthogonally to each other. Near vertical incidence, the polarization direction of the faster split shear wave gives the orientation of the fracture strike, and the delay between the two split shear waves is directly proportional to the fracture density.

The rotation of the shear wave components into their natural coordinates is critical to their analysis. Rotation focuses the shear wave events and gives the natural polar-
ization direction. Recently, concern has arisen that the polarizations of split shear waves may vary with azimuth. In theory, the combination of sedimentary layers and vertical fractures should create an orthorhombic pattern of anisotropy (Crampin, 1988a and 1988b). Since the three-dimensional multicomponent survey included all source-receiver azimuths, the shear wave survey offered a unique opportunity to look for the orthorhombic anisotropy, but no evidence of it was found at Silo field. Instead, the azimuth-dependent rotation analysis found that the process is extremely sensitive to groundroll. Interpretation of the groundroll-free azimuths indicated a fracture orientation of N58W ±8°.

An integrated interpretation of the reservoir heterogeneity was made from the multicomponent seismic survey, cores, and well logs. Dipmeter logs and cores indicate that fracturing is near-vertical and variable in intensity. Well logs substantiate the indication of the shear wave rotation analysis that the orientation of producing fractures in the Niobrara reservoir is N50W to N55W. Large positive anisotropy of 5.2% is associated with the major oil-producing wells in the field. The three-dimensional nature of the survey increased the reliability of the interpretation, because the split shear events were timed several times on
lines running in different directions without a significant change in the pattern of anisotropy.

A structural interpretation of the survey area from the compressional wave survey complemented the interpretation of reservoir fractures from the shear wave survey. The Cretaceous strata dip homoclinal about 45° to the south and west, but several penecontemporaneous listric normal faults cut through the Niobrara Formation at the south end of the survey. They formed over the edge of a salt-solution collapse structure within the Permian and Triassic section. Fractured and dolomitized carbonates involved in drape folding in the Permian are a prospective lead. The Niobrara is draped over the salt-solution structure, consequently fracturing the chalk layers.

Several applications of the multicomponent survey proved disappointing. The reflection coefficients of the split shear waves should be high-resolution detectors of anisotropy along an interface (Thomsen, 1988). However, the shear wave amplitudes did not appear to have a relationship to either fractures or lithology. The amplitudes may have been dominated by noise and fold. The converted wave survey also did not contribute to the interpretation of reservoir heterogeneity, possibly because of processing mistakes. However, the converted wave survey was valuable for its con-
tribution to better shear wave statics and correlation between the compressional and shear wave surveys.

Reflection amplitudes and anisotropy were examined for evidence of lithologic variation in the Dakota Group. The survey is located at the edge of a paleovalley in the J Sand, but logs indicate that the amount of sand is nearly constant, whether it is marine or nonmarine. Compressional wave amplitudes from the deeper Cheyenne horizon bear some resemblance to a valley pattern, but there is no definitive evidence of it from well logs.

The three-dimensional shear wave survey provided a laterally detailed map of the anisotropy associated with fracture patterns in the Niobrara reservoir, and the compressional wave survey gave a precise definition of small-scale structural features within the reservoir. The spatial wavelength of the reservoir heterogeneity caused by fracture patterns is less than the well spacing in the field. Reservoir development could have been more efficient if this seismic survey had been conducted before the field was developed. Combining multicomponent seismic recording with three-dimensional survey techniques gives a detailed picture of reservoir heterogeneity that can enhance the efficiency of reservoir development.
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Japan National Oil Corporation
Marathon Oil Company
Meridian Oil Company
Mobil Research and Development Corporation
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Production Geophysical Services
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Sun Exploration and Production Company
Teledyne Exploration
Tenneco Oil Exploration and Production Company
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INTRODUCTION

Over the last few years, the internal heterogeneity of a petroleum reservoir has been recognized as having a critical influence on its production performance. Structural deformation and facies changes divide the producing horizon into a myriad of compartments. Fracture patterns and lithologic variations create alternating conduits and barriers to fluid flow. A better description of the reservoir is needed for more efficient reservoir development.

Reservoir development has traditionally been the responsibility of geologists and petroleum engineers. Geophysicists were restricted from field management because the resolution of seismic data was considered insufficient for reservoir description. Today, however, geophysicists are developing new tools that are significantly impacting reservoir development. Three-dimensional surveys increase lateral resolution several times over a grid of conventional 2-D seismic lines. Moreover, multicomponent seismic data promise to provide subsurface detection of lithologic and fracture patterns that control fluid flow in the reservoir.

The objective of this study is to combine the benefits of three-dimensional techniques with multicomponent recording to characterize reservoir heterogeneity. The
first three-dimensional multicomponent survey ever acquired was recorded over Silo field in southeastern Wyoming. Silo field, located eighteen miles northeast of Cheyenne, produces oil from natural fractures in the Cretaceous Niobrara Formation (Figure 1). Numerous wells in the field have tested the prospective valley-fill system of the Dakota Group as well. The location is ideal for testing the usefulness of multicomponent seismic data in defining both fracture patterns and lithologic changes.

Compressional and shear wave velocities can be indicators of gross lithology (Winterstein, 1986; Ensley, 1988; McCormack and Tatham, 1988). In addition, shear waves are proving to be sensitive detectors of fractures that are important to fluid conductivity in the reservoir (Martin and Davis, 1987). The presence of fractures introduces anisotropy to the interval, and a shear wave entering the anisotropic layer is split and polarized into two waves travelling at different velocities (Figure 2). These split shear waves provide a measure of the seismic anisotropy. The anisotropy can be used to characterize the orientation and intensity of fractures.

The present investigation using three-dimensional techniques is a continuation of an earlier study carried out by Martin (1987) with a two-dimensional line in the same
Figure 1. Location of three-dimensional multicomponent survey at Silo field, Wyoming.
Figure 2. Shear wave splitting. A shear wave entering an anisotropic layer splits into two waves. The faster S1 wave is polarized parallel to the fractures, and S2 is perpendicular to the fractures.
locality. The two-dimensional three-component line shot in 1985 over Silo field demonstrated that shear wave splitting could be observed in reflection seismic data at the earth's surface. Martin showed that the delays and polarizations of split shear waves are related to the orientation and intensity of fracturing. With the improved resolution of a three-dimensional survey, this study aims at defining the fractures in the productive Niobrara Formation and predicting lithology in the prospective Dakota Group.

The multicomponent survey was interpreted on a Landmark workstation at Golden Geophysical, in Golden, Colorado. It is impossible to reproduce entirely the three-dimensional interpretation in figures in this thesis. The interpretation is available on tape at the Colorado School of Mines Geophysics Department.
PREVIOUS STUDIES

Geophysicists have long treated the earth as an isotropic medium. Exploration seismology has been dominated by compressional wave data, and P-waves are relatively insensitive to small percentages of anisotropy (Crampin, et al., 1984). Over the last decade, new theoretical developments and the ability to record the full waveform have spawned a growing interest in anisotropy. In the last three years, there have been numerous published reports of anisotropy measured with multicomponent seismic data.

Wave propagation in a generally anisotropic solid is so complex that it defied meaningful understanding for many years. Stuart Crampin of the British Geological Survey pioneered the development of anisotropic modeling and spearheaded recognition of the ubiquitous nature of azimuthal anisotropy in the earth (Crampin, 1987). Crampin (1984) reviewed the procedures of modeling wave propagation in anisotropic media and some of the insights that it has provided. Thomsen (1988) elaborated on the aspects of seismic anisotropy that apply directly to exploration problems.

The crucial insight that results from the theoretical investigations is that fractures introduce measurable anisotropy to the earth (Crampin, 1985a). It is the poten-
tial for using split shear waves to image fractures in reservoirs that has spawned a wave of experimentation with multicomponent seismic techniques over the last few years. Shear wave splitting has been observed in vertical seismic profiles (Crampin and Bush, 1986; Johnston, 1986; Becker and Perelberg, 1986). Lynn and Thomsen (1986) recognized the phenomenon in two single-component shear wave seismic lines running perpendicular to each other. Alford (1986) focused split shear waves by coordinate rotation with four components of recorded shear data, with two orientations of sources and two orientations of receivers. Garotta and Marechal (1987) observed splitting on a converted wave seismic line. Martin and Davis (1987) focused split shear waves by rotation on two-component shear wave and converted wave lines. Others have also observed shear wave anisotropy in the earth (Willis, et al., 1986; Lee and Kim, 1987; Justice, et al., 1987; Squires, et al., 1988). Laboratory experiments have substantiated and broadened our understanding of the relationship between anisotropy and fracture patterns (Rai and Hansen, 1986; Tatham, et al., 1987; Ebrom, et al., 1988).
GEOLOGIC SETTING OF SILO FIELD

The three-dimensional multicomponent survey at Silo field was acquired in sections 29, 30, 31, and 32 of Laramie County, Wyoming (Figure 1). It is located at the northern end of the petroleum-rich Denver basin. At Silo field, oil is produced from fractured chalks of the Cretaceous Niobrara Formation.

Structure and Tectonics

The Denver basin is a structurally asymmetric foreland basin. Sediments dip gently on the east flank but plunge steeply off the Front and Laramie Ranges beneath Denver and Cheyenne. Low-amplitude movement of basement arches and sags within the basin controlled regional patterns of sedimentation. The Morrill County High, in proximity to Silo field, is one of several broad, northeast-trending axes of thinning of the Transcontinental Arch (Figure 3; Weimer, 1978; Sonnenberg and Weimer 1981). Regional isopachs indicate that the Morrill County High was active during the Pennsylvanian and Permian and was reactivated in the Cretaceous. The Morgan County Low, trending to the north-
Figure 3. Denver basin structure. The Morrill County high and Morgan County low, identified by regional isopach thins and thicks, are basement structures that were reactivated several times during the Paleozoic and Mesozoic (after Sonnenberg and Weimer, 1981).
northwest, accumulated thick sequences of Mississippian, Pennsylvanian, and Cretaceous strata.

The local influence of reactivated basement faults is subtle but significant. Upthrust basement blocks forced up the sedimentary cover as drape folds and monoclines. Basement faulting below controlled the trends of listric normal faults in the younger sedimentary rocks (Davis, 1985). Fracturing may occur in the hinges of these drape folds and in association with the normal faults (Davis and Gretener, 1988).

Movement of basement blocks influenced local sedimentation patterns as well. When eustatic sea level dropped, tectonically low-lying blocks became the focus of erosional incisement, and as it rose again they accumulated valley-fill sediments (Weimer, 1984). Variations in the clay content and porosity of carbonate sediments may have been influenced by basement uplifts (Saiti, 1983).

Solution of Permian salts results in collapse and infill structures in the deep section of the basin. Solution occurred at shallow burial depths as fractures, possibly related to basement fault zones, became conduits for meteoric water flow (Parker, 1967). The timing of solution is marked by the age of subsequent sedimentation that filled in the sinkholes.
Such salt solution and subsidence structures have been recognized in the Powder River and Williston Basins for many years (Parker, 1967), but have only recently been recognized in the Denver basin (Squires, 1986). Doyle (1987) reported evaporites in the Permian section of the northeast Denver basin. The Davis Oil Berry #1 penetrated thirty-five feet of anhydrite just five miles west of Silo field (Doyle, 1987).

Stratigraphy of the Denver Basin

In the vicinity of Silo field, the stratigraphic column is estimated to be about 12,000 ft thick. On top of basement may be Mississippian carbonates, in the Morgan County Low area, although there are no well penetrations to the Mississippian close to Silo field to confirm its presence (Sonnenberg, 1981). On top of a Mississippian karst surface are Pennsylvanian clastic and carbonate sediments, followed by a Permian sequence of carbonates, evaporites, and some sandstone and shale (Figure 4). The Triassic is represented by the Chugwater Formation, overlain by the shales and sand lenses of the Jurassic Morrison Formation (Pearl, 1980).

The Dakota Group and the Mowry Shale make up the Lower Cretaceous (Figure 4). The Dakota Group is comprised of the
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<th>Era</th>
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<td>Mesozoic</td>
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<td>Niobrara Formation</td>
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<td>Cheyenne Ss.</td>
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<td>Mississippian</td>
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Precambrian Basement

Figure 4. Stratigraphy at Silo field (after Pearl, 1980; Sonnenberg, 1981; Weimer, et al., 1986; Doyle, 1987).
Cheyenne Formation, equivalent to the Lytle and Plainview in outcrops, followed by the Skull Creek Shale. The contact between the Skull Creek and the overlying J Sandstone, or Muddy, is in many places a lowstand surface of erosion (Weimer, 1984). The J Sandstone has two origins: in tectonically low areas that were incised during low sea level, it is a valley-fill sequence, and on high blocks that were preserved from erosion it is a delta sequence. It is overlain by the transgressive marine Mowry Shale, which is one of the source rocks in the Denver basin.

The Upper Cretaceous section is over 6,000 ft thick at Silo field. It consists of the Benton Group, made up of the Graneros, Greenhorn, and Carlile Formations, the Niobrara Formation, the Pierre Shale, and the Fox Hills Sandstone. Marine shales and calcareous shales in the Graneros, Greenhorn, Niobrara, and Pierre constitute source rocks for the Denver basin (Sonnenberg, 1981; Rice, 1984; Gautier, et al., 1984). The Niobrara generates oil in the deep part of the Denver basin (Smagala, et al., 1984). At Silo field, the shale member of the Carlile is missing, and only the prospective Codell Sandstone is present (Weimer and Sonnenberg, 1983).

The Niobrara is divided into the Smoky Hill and Fort Hays Members (Figure 4; Berman, et al., 1980). The Fort
Hays is a dense, clean limestone at the base of the formation. The Smoky Hill Member consists of three thin chalks interbedded with calcareous shales. Figure 5 shows the typical log responses of the Niobrara. It is fracture patterns in the lower B and C chalks of the Smoky Hill that stratigraphically trap oil at Silo field (Martin, 1987).

At Silo field, over 5,000 ft of marine Pierre Shale overlie the Niobrara. The Hygiene, Terry, and Rocky Ridge are deltaic and marine shelf sandstone sequences within the Pierre (Porter, 1976; Moredock and Williams, 1976). The Hygiene and Terry Members have been called Shannon and Sussex, respectively, for many years by the petroleum industry, although they are neither lithostratigraphical nor time-stratigraphical equivalents. They are referred to as Shannon and Sussex here as well.

The Pierre is gradationally overlain by the deltaic Fox Hills Sandstone. Casing in the wells is usually set at the base of the Fox Hills, around 2,000 ft.

The major producers in the Denver basin are regressive and valley-fill sands of the Cretaceous Dakota Group. The Cretaceous Niobrara Formation produces shallow, biogenic gas in eastern Colorado and oil at Silo field in Wyoming. A new and active play involves carbonates in the Pennsylvanian and
Figure 5. Niobrara chalks and their log responses. The Smoky Hill Member contains chalk benches A, B, and C, interbedded with calcareous shales.
Permian section of the northeast edge of the basin, near the Wyoming-Nebraska border.

Geology of Silo Field

Silo field produces oil from natural fractures of the Niobrara chalks and the Codell Sandstone. Across the field, the strata dip homoclinal about 1° to the southwest. Economic production is strongly dependent on the intensity of fracturing at each well location (Martin, 1987). Successful wells also depend on proper completion techniques (Iverson, 1988). Since the price of oil plunged in 1986, most of the fifty-plus wells have been shut-in or abandoned. At the present time, the Amoco Goertz B-1 and Exxon Goertz C-2, in 31-T16N-R64W of the 3-D survey area, are the only wells in Silo field that are economic (Iverson, 1988).

Cores have been taken at both the Niobrara and J Sand levels at Silo field. Fracturing in the Niobrara cores ranges from minimal, as in the Golden Buckeye 9-1 in 9-T15N-R64W, to shattered, as in the Combs 1 in 35-T16N-R65W. In the Champlin CPC 41-5, 5-T15N-R64W, the fractures are lined with calcite, confirming their natural origin. Niobrara chalks in outcrop north of Denver are brittle and
splintered as well, suggesting that the chalks at depth may be easily shattered by subtle tectonic movement.

The Dakota has been tested many times in the area, but it is not productive at Silo field. The northwest and southeast parts of the field are part of a thick valley-fill sequence. The center contains a northeast-trending portion of unremoved deltaic sequence (Figure 6). According to regional isopachs, the edge of the paleovalley should be directly under the three-dimensional survey (Cronoble, 1977; Grube, 1984).
Figure 6. Regional isopach of J Sand near Silo field (Grube, 1984). Thick areas of the isopach are valley-fill, whereas thin areas are out of the valley.
ACQUISITION OF THREE-DIMENSIONAL MULTICOMPONENT SURVEY

The acquisition layout for the three-dimensional multicomponent survey was designed by Dr. Tom Davis, Coordinator of the Reservoir Characterization Project, Eugene Asencio, the original student participant, CGG American Services, Inc., and the consortium members (Asencio, 1987). The survey was acquired in December, 1987, by CGG American Services, Inc., during and after a major snowstorm.

The field layout consisted of a 480-channel fixed spread laid out in eight east-west geophone lines (Vuillermoz and Chitwood, 1988). There are eleven north-south lines of vibrator positions, and each shot was recorded into the entire 480-channel receiver grid (Figures 7, 8, and 9). For the converted and shear wave surveys, the 480 channels were divided between 240 geophone groups oriented east-west and 240 geophone groups oriented north-south. Conventional Mertz Model 18 P-wave vibrators were used as compressional and converted wave sources. Mertz Model 13 shear wave vibrators made two passes across the source locations, once oriented east-west and once oriented north-south. The frequency and record length of the vibrator sweeps were adjusted for the expected response of the
Figure 7. Compressional wave survey acquisition layout. Vibrators moved from north to south, with recording into eight lines of sixty geophones.
Figure 8. Converted wave survey acquisition layout. Vibrators moved from north to south, with recording into eight lines of thirty geophones oriented east-west and thirty geophones oriented north-south.
Figure 9. Shear wave survey acquisition layout. Two orientations of shear wave sources occupied opposite corners of the diamond, along north-south lines, recording into eight lines of thirty geophones oriented east-west and thirty geophones oriented north-south.
reflected compressional, converted, and shear waves (see Table 1 for a complete list of parameters). The sampling interval was 4 ms for all three surveys. A total of seven components were recorded: the conventional P-wave component, two converted wave components, and four shear wave components.

Vertical geophone arrays consisted of twelve geophones laid out in an east-west linear array over 165 ft, with 165-foot group spacing. Horizontal geophones arrays consisted of nine geophones laid out in an east-west linear array over 165 ft with 330-foot group spacing. The intention was that the vibrator arrays would provide the north-south dimension of the field filter. With the P-wave source array, including three move-ups in a north-south line over 165 ft, this was successfully accomplished. The field filter responses for the compressional wave and converted wave surveys, including both the source array and the geophone array contributions, are shown in Figure 10.

Two orientations of the shear wave source were recorded into two orientations of the shear wave geophones to acquire a four-component shear wave survey (Figure 11). The east-west orientation is referred to as the x-orientation and the north-south orientation as the y-orientation. The four components are identified as xx, xy, yy and yx, where the first
Table 1. Acquisition parameters (after Vuillermoz and Chitwood, 1988 and Vuillermoz, et al., 1988).

<table>
<thead>
<tr>
<th>Multicomponent Acquisition Parameters</th>
<th>compressional wave survey</th>
<th>converted wave survey</th>
<th>shear wave survey</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>vibrators</strong></td>
<td>Mertz Model 18</td>
<td>Mertz Model 18</td>
<td>Mertz Model 13</td>
</tr>
<tr>
<td><strong>source arrays</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in-line north-south</td>
<td>3</td>
<td>3</td>
<td>3 or 2 in-line</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>and abreast</td>
</tr>
<tr>
<td><strong>VP interval</strong></td>
<td>165'</td>
<td>165'</td>
<td>165';330' for</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>diamond arrays</td>
</tr>
<tr>
<td><strong>sweeps/VP</strong></td>
<td>8</td>
<td>8</td>
<td>8 or 16</td>
</tr>
<tr>
<td><strong>sweep frequency</strong></td>
<td>5-72 Hz</td>
<td>5-54 Hz</td>
<td>5-40 Hz</td>
</tr>
<tr>
<td><strong>pad to pad</strong></td>
<td>165'/55'move-up</td>
<td>165'/55'move-up</td>
<td>165' or</td>
</tr>
<tr>
<td>100'/</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>spacing/move-up</td>
<td>3 times</td>
<td>3 times</td>
<td>no move-up</td>
</tr>
<tr>
<td><strong>sweep length/record length</strong></td>
<td>9/5 s</td>
<td>8/13 s</td>
<td>8/14 s</td>
</tr>
<tr>
<td><strong>sample rate</strong></td>
<td>4 ms</td>
<td>4 ms</td>
<td>4 ms</td>
</tr>
<tr>
<td><strong>filter/notch</strong></td>
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<td>out-62.5/out</td>
<td>out-62.5/out</td>
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<tr>
<td><strong>geophone type</strong></td>
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<td>L28A/8 Hz</td>
<td>L28A/8 Hz</td>
</tr>
<tr>
<td><strong>geophone array</strong></td>
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<td>9 over 165'</td>
<td>9 over 165'</td>
</tr>
<tr>
<td><strong>geophone group spacing</strong></td>
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<td>330'</td>
<td>330'</td>
</tr>
<tr>
<td><strong>channels</strong></td>
<td>480 vertical component</td>
<td>240 east-west +</td>
<td>240 east-west +</td>
</tr>
<tr>
<td></td>
<td></td>
<td>240 north-south</td>
<td>240 north-south</td>
</tr>
<tr>
<td></td>
<td></td>
<td>components</td>
<td>components</td>
</tr>
<tr>
<td><strong>8 geophone lines</strong></td>
<td>990' apart</td>
<td>990' apart</td>
<td>990' apart</td>
</tr>
<tr>
<td><strong>11 VP lines</strong></td>
<td>330' to 1320'</td>
<td>330' to 1320'</td>
<td>330' to 1320'</td>
</tr>
</tbody>
</table>
Figure 10. Compressional wave and converted wave field filters. The attenuation of groundroll is azimuth-dependent because the source and geophone arrays are linear.
Figure 11. Four components acquired in shear wave survey. The east-west orientation is designated as x, and the north-south orientation as y. A shear wave from the x-source splits into an S1-wave and an S2-wave in the anisotropic earth. The two waves are recorded as two components each by the x-geophone and y-geophone, making the xx and xy traces, respectively. In like manner, the y-source traces are yy and yx.
letter designates the source and the second letter the receiver. The shear wave vibrators moved across the survey from north to south, to record the xx and xy traces, and from west to east, to record the yy and yx traces.

The plan for the shear survey source arrays was to have three vibrators over 165 ft with no move-up, with 165-foot spacing between vibrator points. For each orientation of the source, three vibrators would occupy opposite points of a diamond pattern in the field (Figure 12a). Then the VP interval would be reduced to 330 ft by vertical summation of the traces from the two source orientations so that both sources would have the same effective ground location. The east and west points of the diamond, 165 ft apart, were occupied by the three-vibrator north-south or y-source array, with vibrators abreast and facing east. Then the vertical stack of the traces from the diamond made a 165-foot square array of six points. Likewise, the north and south points of the diamond, 165 ft apart, were occupied by the three-vibrator east-west or x-source array, with vibrators abreast and facing south. Then the vertical stack of the traces from the diamond again made an aerial array of six points in a 165-foot square. The field filters for these configurations, including both the source array and the geophone array contributions, are shown in Figure 13.
Figure 12. Shear wave vibrator arrays. Arrows indicate polarization of source. 

a) Planned arrays of three vibrators abreast occupying opposite corners of the diamond pattern. 
b) Often only two vibrators had access, which changed the array. 
c) In the most difficult snow conditions, sometimes the y-source vibrators were in-line instead of abreast.
Figure 13. Field filter responses for x- and y-sources with three vibrators abreast (Figure 12a). The attenuation of groundroll is azimuth-dependent because the source and geophone arrays are linear.
Snow conditions significantly influenced the acquisition procedures. Two to three feet of snow were dumped on the survey area during the acquisition, and deep drifts and severe cold inhibited the functioning of the shear wave vibrators. The observer's report indicates that there were high winds throughout most of the recording (Snyder, et al., 1987). Fortunately, the geophones had been laid out before the snow, so that the shear wave geophones were insulated from wind noise.

Frequently during the shear wave survey, only two vibrators were operable or had access because of the deep snow (Figure 12b). The power loss due to the absence of one vibrator was overcompensated by increasing the number of sweeps per vibrator from eight for three vibrators to sixteen for two vibrators.

The loss of a vibrator also affected the source arrays. When there only two vibrators, they were apparently positioned about 100 ft apart, according to a photograph taken by Tom Davis in the field. This changes the cut on the field filters (Figure 14). Moreover, the observer's report indicates that sometimes the y-source vibrators were in-line instead of abreast because of the snow conditions (Figure 12c; Snyder, 1987). An in-line configuration for the vibrators facing east created an in-line east-west array,
Figure 14. Field filters for x- and y-sources with two vibrators abreast (Figure 12b). The attenuation of groundroll is azimuth-dependent because the source and geophone arrays are linear.
with no field cut on groundroll in the north-south direction (Figure 15).

Figure 16 is a portion of a typical raw shot record for the shear wave survey. Groundroll is difficult to suppress in shear wave recording because its bandwidth and velocity are nearly the same as for shear waves (Edelmann and Helbig, 1987). The shear wave records show the linear moveout and high amplitude of groundroll.
Figure 15. Field filter for y-source with vibrators in-line (Figure 12c). There is no attenuation of ground-roll in the north-south azimuth because both the sources and geophones are in east-west arrays.
Figure 16. Shear wave shot records. Many of the records show severe groundroll contamination (GR).
COMPRESSIONAL WAVE PROCESSING

The compressional wave data was processed for the consortium by CGG American Services, Inc., in Denver, Colorado. Using 82.5 by 82.5 ft common midpoint (CMP) bins, there are 93 east-west lines with 110 CMP's per line. Processing steps are summarized in Table 2. Line numbers are 50 to 142, and CMP numbers are 46 to 155 (Figure 17).

After an amplitude balance of the field records, a divergence correction and a "Q-filter" were applied. The Q-filter was set to \( t/Q = 15 \), where the gain is \( e^{-\pi ft/Q} \). Spiking deconvolution before stack with a 120 ms operator was applied over two gates, 0.2 to 1.6 s and 1.5 to 2.4 s, and spectral whitening of 5-80 Hz was applied. After stack, the final bandpass filter was 8/16-60/70 Hz (Vuillermoz and Chitwood, 1988).

Three-dimensional refraction statics were computed for the vibrator stations of the P-wave survey, and geophone statics were obtained by Kriging from source statics. Near surface compressional velocity ranges from 2350 to 4000 ft/s, and replacement velocity ranges from 6750 to 6950 ft/s (Vuillermoz and Chitwood, 1988).

Two passes of velocity analysis and residual statics were applied to the data. The first pass of velocity analy-
Table 2. Compressional wave processing (after Vuillermoz and Chitwood, 1988 and Vuillermoz, et al., 1988).

<table>
<thead>
<tr>
<th>Compressional Wave Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>demultiplex</strong></td>
</tr>
<tr>
<td><strong>elevation statics</strong></td>
</tr>
<tr>
<td>datum: 5800'  datum velocity: 6000 ft/s</td>
</tr>
<tr>
<td><strong>amplitude balance</strong></td>
</tr>
<tr>
<td>normalized by maximum shot record amplitude</td>
</tr>
<tr>
<td><strong>amplitude decay recovery</strong></td>
</tr>
<tr>
<td>amplitudes x (4t/100)(^{1.7})</td>
</tr>
<tr>
<td><strong>attenuation compensation</strong></td>
</tr>
<tr>
<td>Q-filter: t/Q=15 ms</td>
</tr>
<tr>
<td><strong>spiking deconvolution</strong></td>
</tr>
<tr>
<td>120 ms operator length</td>
</tr>
<tr>
<td>windows: 0.2-1.6 s and 1.5-2.4 s</td>
</tr>
<tr>
<td>2% white noise</td>
</tr>
<tr>
<td><strong>spectral whitening</strong></td>
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<tr>
<td>5-80 Hz</td>
</tr>
<tr>
<td><strong>3-D refraction statics</strong></td>
</tr>
<tr>
<td>weathering velocities:</td>
</tr>
<tr>
<td>2350-4000 ft/s</td>
</tr>
<tr>
<td>replacement velocities:</td>
</tr>
<tr>
<td>6750-6950 ft/s</td>
</tr>
<tr>
<td><strong>CMP sort</strong></td>
</tr>
<tr>
<td>bin size: 82.5' x 82.5'</td>
</tr>
<tr>
<td>fold: 1-77, ave. 24</td>
</tr>
<tr>
<td><strong>velocity analysis</strong></td>
</tr>
<tr>
<td>spectra for lines 58, 70, 94, 118, and 142 and crosslines 76, 106, and 136</td>
</tr>
<tr>
<td><strong>residual statics</strong></td>
</tr>
<tr>
<td>window: 1.2-2.4 s</td>
</tr>
<tr>
<td><strong>velocity analysis</strong></td>
</tr>
<tr>
<td>constant velocity stacks for lines and crosslines: 6000 to 12,500 ft/s</td>
</tr>
<tr>
<td><strong>regional equalization</strong></td>
</tr>
<tr>
<td><strong>final stack</strong></td>
</tr>
<tr>
<td>preserved amplitude</td>
</tr>
<tr>
<td><strong>bandpass filter</strong></td>
</tr>
<tr>
<td>8/16-60/70 Hz</td>
</tr>
<tr>
<td><strong>3-D migration</strong></td>
</tr>
<tr>
<td>45° finite difference stacking velocities</td>
</tr>
</tbody>
</table>
Figure 17. CMP basemap for multicomponent survey with well locations. All wells reached total depth in the Niobrara or Codell except for the Amoco State of Wyoming Y-1, which reach the Skull Creek of the Dakota. Line and trace numbers are the same for both the compressional and shear wave surveys, except that shear wave line numbers are even only and trace numbers are odd only. Converted wave line and trace numbers are adjusted to agree with the compressional and shear wave line and trace numbers in this thesis.
sis was made with velocity spectra, and the final velocity analysis was done with constant velocity stacks both in-line and crossline. The final stack was made with both preserved amplitude and equalized amplitude. Fold increases toward the middle of the survey to a maximum of 77. Mean fold is 24 (Vuillermoz and Chitwood, 1988). The survey was migrated with three-dimensional 45° finite difference migration, using moveout velocities (Vuillermoz, et al., 1988).
SHEAR WAVE PROCESSING

The shear wave survey was processed by CGG American Services, Inc., in Denver, Colorado, and Houston, Texas. Using 165-foot square CMP bins, the survey contains 42 east-west lines with 55 CMP's per line. Line numbers and CMP numbers correspond to the compressional survey numbering system. The line numbers are even numbers, from line 60 at the north edge to line 142 at the south edge, and the CMP numbers are odd numbers, from 47 to 155 west to east (Figure 17). The average fold is 24, with a range from 1 to 60. The processing is summarized in Table 3.

Pre-Rotation Processing

After the field traces were demultiplexed into the four components for each trace, the amplitudes were normalized by vibrator point, based on the largest amplitude for each shot record (Vuillermoz, et al., 1988). Elevation statics were applied, and the VP interval was increased from 165 ft to 330 ft by a vertical stack of the diamond pattern of shots, as discussed earlier. The vertical stack consisted of an NMO correction before summation, followed by its removal after summation.
Table 3. Shear wave processing (after Vuillermoz, et al., 1988).

<table>
<thead>
<tr>
<th>Shear Wave Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>prerotation processing:</td>
</tr>
<tr>
<td>demultiplex elevation statics</td>
</tr>
<tr>
<td>amplitude balance</td>
</tr>
<tr>
<td>vertical stack of shot records</td>
</tr>
<tr>
<td>amplitude decay recovery</td>
</tr>
<tr>
<td>velocity analysis</td>
</tr>
<tr>
<td>residual statics</td>
</tr>
</tbody>
</table>

| rotation analysis: |
| common geophone sort | data without deconvolution |
| sort by azimuth | ten 18' "pie slices" of azimuth |
| geophone azimuth stack | single velocity function |
| rotation test | five 18' increments of counter-clockwise 4-component rotation |
| vertical stack of rotated azimuths | 6 geophones summed |
| statistical minimization of energy | 4 components |
| rotation into natural coordinates | single 58° angle |

| post-rotation processing: |
| deconvolution | separate operators on xx'(S2) and yy'(S1) |
| velocity analysis | operator length 250 ms 70 ms gap |
| constant velocity stacks of S2 | lines 70, 82, 94, 106, 118, 130, and 142 |
| residual statics | spectra of 8 S1-supergathers |
| final velocity analysis | time-shifted S1-velocities on S2 |
| NMO-corrected S1- and S2-supergathers | |
| final stack | bin size: 165' x 165' |
| fold:1-60, 24 ave. | |
| amplitude gain | AGC 1000 ms sliding window |
Initially, elevation and residual statics for the shear wave survey were computed independently, apart from the compressional and converted wave surveys (Figure 18). However, this set of statics was abandoned when the converted wave survey was purchased by the consortium. Source statics for the shear wave survey were obtained by Kriging from the receiver statics from the converted wave survey, which took source statics from the compressional wave survey. The shear wave source and receiver statics derived from the other surveys are superior to the independently calculated statics (Figure 19).

In the pre-rotation processing, any process that might distort the wavelet shape or relative amplitude between the four components was carefully avoided. The amplitude adjustment was one factor for all four components. Residual statics were calculated on deconvolved data, but deconvolution and moveout (FK) filtering were avoided in the rotation analysis and rotation, because these processes might change the relative amplitudes between the four components.

Rotation Analysis

A three-dimensional rotation algorithm was implemented in the rotation analysis of the four-component shear wave
Figure 18. Shear wave data with independently calculated statics.
Figure 19. Converted wave receiver statics applied to shear wave data.
survey at Silo field. The purpose was to examine the data for a dependence of the polarization direction on source-receiver azimuth. However, the azimuth-dependent rotation analysis revealed that groundroll can seriously corrupt rotation analysis. The problem of groundroll was overcome by careful interpretation and elimination of those azimuths influenced by groundroll from the rotation analysis of the survey.

The rationale behind the three-dimensional rotation analysis of the shear wave survey was that azimuthal anisotropy might be more complicated than what was previously conceived. The familiar azimuthal anisotropy is extensive dilatancy anisotropy (EDA), which results from a vertical system of parallel microcracks (Figure 20; Crampin, 1987). On a larger scale, these cracks are tectonic fractures that are of interest in reservoir analysis. In contrast, horizontal layering in a sedimentary basin is characterized by azimuthal isotropy, produced by periodic thin layering (PTL). At the SEG/AGU Conference on Seismic Anisotropy in 1988, Stuart Crampin of the British Geological Survey showed on theoretical grounds that horizontal layering and vertical fractures can combine to produce a complicated pattern known as orthorhombic anisotropy (Crampin, 1988a).
Figure 20. Causes of seismic anisotropy (after Crampin, 1987 and 1988b).
The patterns of shear wave anisotropy can be described by equal area projections of the shear wave polarizations (Booth, et al., 1986). Figure 21 illustrates how to read the projections. Imagine a very small hemisphere just below the receiver. Any ray arriving at that receiver must cut through the lower hemisphere at a point. The point is projected vertically upward to the circle in the horizontal plane, where the radial direction records the incidence angle and the circumferential direction represents the source-receiver azimuth. The outside circle represents 90° of incidence for a ray travelling horizontally. The inner circle is the outer limit of the shear wave window, at about 35°, inside which the shear wave arrivals are free of mode conversions at the free surface (Evans, 1984).

Figure 22 illustrates the polarization patterns of shear waves for the cases of EDA and orthorhombic anisotropy (Crampin, 1988b). The hachures represent the polarization direction of the first-arriving shear wave. In the case of EDA anisotropy, the first-arriving shear wave is always polarized parallel to the fracture orientation, within the shear wave window. With orthorhombic anisotropy, however, polarization of the first-arriving shear wave may change by 90° even near zero offset (Crampin, 1988a). A seismic line running in a direction perpendicular to the major axis of
Figure 21. Equal area projection of lower hemisphere. On the plane projection, the radial direction indicates the incidence angle, and the circumferential direction represents the source-receiver azimuth.
Figure 22. Equal area projections of EDA and orthorhombic anisotropy. The fractures are oriented north-west. Hachures are the polarization directions of the first-arriving shear wave (after Crampin, 1988a and 1988b).
anisotropy, or oblique to it, would encounter one of two difficulties: either the shear wave line would lose coherency because rapidly changing polarizations near the shear wave singularity (indicated by the dot on the lower hemisphere projection) were being stacked, or the rotation analysis would indicate a polarization direction that would be an incorrect interpretation of fracture orientation (Figure 23).

At Silo field, the shear wave survey includes all source-receiver azimuths, since each shot was recorded into all eight lines of geophones (Figure 9). For the three-dimensional rotation analysis, the offset was limited to the shear wave window, where the arriving shear waves are free from interference from mode conversions at the free surface. Then by dividing the survey into ten "pie slices" of source-receiver azimuth, parallel and subparallel polarizations were isolated, except for the azimuth containing the shear wave singularity (Figure 24). The four shear wave components were stacked by common geophone and by azimuth, since within the azimuths polarizations were not being mixed. Rotation analysis was performed on each of the geophone-azimuth stacks (Figure 25).

Initially the geophone-azimuth stacks were rotated by five 18° increments. Figures 26 and 27 show the rotated in-
Figure 23. Pitfall of orthorhombic anisotropy. a) A shear wave seismic line shot parallel to the fracture orientation resolves the fracture pattern. b) A line shot perpendicular or oblique to the fracture orientation will either lose coherency or give an incorrect answer for the fracture pattern, because of mixed polarization directions.
Figure 24. "Pie slices" of source-receiver azimuth stacked to look for orthorhombic anisotropy. Each pie slice isolated parallel or subparallel polarizations, except for the one containing the singularity, indicated by the dot.
Figure 25. Five rotations per azimuth. Each pie slice of azimuth was examined for its natural polarization direction, first by five displayed rotations in 18° increments, and then by Gurch's statistical analysis (1989).
Figure 26. Five rotations of geophone-azimuth stack, xx-component, east-west azimuth. Thirty traces are one geophone line.
Figure 27. Five rotations of geophone-azimuth stack, yy-component, east-west azimuth. Thirty traces are one geophone line.
line components for azimuth 1, an east-west azimuth, of geophone line 6. Figures 28 and 29 show the rotated in-line components for azimuth 5, a north-south azimuth, of geophone line 6. It became apparent from the geophone-azimuth stacks that the high-amplitude, incoherent energy is not unrotated shear waves but groundroll (Figure 30). Notice how the groundroll increases from the east-west azimuths to the north-south azimuths, so that in the north-south azimuths the rotated Shannon (3.1-3.5 s) and Niobrara (3.6-4.0 s) reflectors are not even discernible. Because the survey was shot with in-line arrays of geophones, the azimuth-dependence of the groundroll should be expected.

An estimate of the average fold in each azimuth of the eight geophone lines indicated that this difference in signal/noise is not the result of a variation in fold (Figure 31). Fold does range from 11 to 24, but the pattern of fold variation does not follow the pattern of noise level variation.

Frequency filtering was considered to suppress the groundroll, but harmonic analysis on geophone line 6 indicated that it would also damage the reflections (Figure 32). Instead, the groundroll was suppressed by a straight stack of six adjacent geophone-azimuth traces, so that the
Figure 28. Five rotations of geophone-azimuth stack, xx-component, north-south azimuth. Thirty traces are one geophone line.
Figure 29. Five rotations of geophone-azimuth stack, yy-component, north-south azimuth. Thirty traces are one geophone line.
<table>
<thead>
<tr>
<th>Azimuth 1 (N72E-N90E)</th>
<th>Azimuth 2 (N54E-N72E)</th>
<th>Azimuth 3 (N36E-N54E)</th>
<th>Azimuth 4 (N18E-N36E)</th>
<th>Azimuth 5 (N0E-N18E)</th>
</tr>
</thead>
</table>

Figure 30. Azimuth-dependence of groundroll. Groundroll increases from the east-west azimuths (azimuth 1 and 2) to the north-south azimuths (4 and 5).
Figure 31. Estimated average fold of azimuth stacks by geophone line.
Figure 32. Frequency filter test. In no frequency band do the shear wave events emerge from the groundroll.
geophone line was reduced to five traces (Figure 33). The summed azimuth stacks enhanced the Shannon and Niobrara reflectors and additional reflectors above and below them, although some groundroll is still present.

Interpretation of the rotation angle for the Silo field data was made with careful examination of the groundroll content in each azimuth. Because of the severity of the problem, analysis was performed on the strongest shear wave reflection, which has been referred to here as the Shannon. The reflection is not the top of the Shannon, but it results from a calcareous shale within the Shannon Member of the Pierre. The rotation of the Niobrara reflector was evaluated and compared to the Shannon. The displays of 18' increments of rotation lacked resolution, and so the results of a statistical analysis implemented by Mike Gurch were used hand-in-hand with the rotated traces in making the interpretation (Gurch, 1989). In the statistical analysis, the rotation angle that maximizes the energy ratio of the in-line components to the crossline components was determined to an precision of 1'.

The S1 polarization directions from the rotation analysis were plotted within each azimuth for geophone line 4 (Figure 34). The azimuths that are contaminated with groundroll are marked with "GR". Figures 35 and 36 are
summed azimuth stacks
geophone line 6
azimuth 1

Figure 33. Summed geophone-azimuth stacks, in-line components, 18° increments of rotation.
Figure 34. S1 polarization directions plotted by azimuth from statistical rotation analysis. Azimuths contaminated with groundroll (GR) were eliminated from the interpretation.
Figure 35. Rotation analysis on Shannon reflector.
Figure 36. Rotation analysis on Niobrara reflector.
plots of S1 polarizations for all eight geophone lines, for the Shannon and the Niobrara, respectively. The overall S1 direction is N58W, and the S2 direction is N32E. Figures 37 through 46 are displays of the rotated four-component traces for ten azimuths of geophone line 4, windowing the Shannon and Niobrara reflectors.

The first observation from the rotation analysis is that orthorhombic anisotropy is not present in the Silo field area. Since azimuth 9 is the sector containing the principal axis of anisotropy, in the N58W direction, azimuth 4 would be the sector that would contain the minor axis (Figure 34). Although the calculated rotation angle for azimuth 4 is distorted by a groundroll on one trace, the S1 event is still evident on the rotated yy-component, indicating an S1 polarization to the northwest. This result was substantiated by all the other geophone lines.

Azimuths 5 and 6 are examples of how the rotation angle can be corrupted by the presence of groundroll (Figures 41 and 42). The calculated angles are 73° and 36°, respectively, and examination of the rotated traces leads to the conclusion that the statistical algorithm has keyed in on the groundroll amplitude.

Azimuths 1, 2, 3, 8, and 9 were averaged to determine a rotation angle on geophone line 4, because they are the az-
Figure 37. Four-component rotation, azimuth 1. High event amplitude on one of the displays of 18° increments of rotation gave an approximate rotation angle, except where groundroll was present.
summed azimuth stack
geophone line 4
azimuth 2

3.0
s

4.0
18° 36° 54° 72° 90°

XX

Kp

Kn

4.0
18° 36° 54° 72° 90°

xy

yy

18° 36° 54° 72° 90°

yx

3.0
s

Figure 38. Four-component rotation, azimuth 2.
Figure 39. Four-component rotation, azimuth 3.
summed azimuth stack
geophone line 4
azimuth 4

18° 36° 54° 72° 90°

xx

yy

Figure 40. Four-component rotation, azimuth 4.
Figure 41. Four-component rotation, azimuth 5. Note the disruption of the rotated event by groundroll, xx-component 18° and 36°, yy-component 72° and 90°.
Figure 42. Four-component rotation, azimuth 6. Note the groundroll content.
summed azimuth stack
geophone line 4
azimuth 7

Figure 43. Four-component rotation, azimuth 7. Note the groundroll content.
summed azimuth stack
geophone line 4
azimuth 8

Figure 44. Four-component rotation, azimuth 8.
Figure 45. Four-component rotation, azimuth 9.
Figure 46. Four-component rotation, azimuth 10. Note the groundroll-free rotation of both the Shannon and Niobrara reflectors.
imuths that are free of groundroll in the Shannon window from 3.1 to 3.5 s (Figure 34). Clean azimuths are more difficult to find in the Niobrara interval, 3.6 to 4.0 s. Azimuths 8 and 10 are free of groundroll, and they indicate a rotation angle that parallels the Shannon rotation angle.

Rotation angles for all the other geophone lines were determined in the same interpretive manner. The statistically calculated rotation angles between groundroll-free azimuths in the same geophone line vary by about 10° to 15°. Because the anisotropy at Silo field is not the orthorhombic but the EDA pattern of anisotropy, the true polarization direction must be the same in all azimuths. This suggests that the noise level inherent in the data is ±8°. The rotation angles vary between geophone lines from 54° to 62°. Since the variation of the rotation angle between geophone lines is at the noise level of the analysis, a single rotation angle of 58° counterclockwise was used for the entire survey. A ±8° error in rotation angle would produce only a 2% error in rotated amplitudes.

Since the EDA pattern of azimuthal anisotropy was determined, the rotation was applied without regard to source-receiver azimuth. Figures 47 and 48 compare the unrotated and rotated shear wave data. The 58° counterclockwise rotation was successful in focusing the split shear waves.
Figure 47. Unrotated in-line components of shear wave data.
Figure 48. Final stack of shear wave data, rotated 58°. Events have been sharpened by rotation.
About 80 ms of shear wave splitting can be seen on the rotated data, whereas the unrotated data shows no splitting. The yy' component, oriented N58W, is the S1 component; the xx' component, oriented N32E, is the S2 component.

**Stability of Four-Component Rotation Analysis**

The objective of the rotation analysis is twofold: to find a rotation angle that will focus the split shear waves and to obtain a polarization direction that is related to the fracture orientation in the subsurface. The rotation analysis as performed will most certainly do the first, but questions have arisen about whether the rotation angle can be distorted from the natural polarization direction by factors in the acquisition of the data. These could be variations in the source strengths, the geophone coupling, the array responses, and the shear wave vibrator radiation pattern.

Whether unequal source strengths might create an apparent rotation angle that does not correspond to the fracture orientation was of particular concern at Silo field because of the snow conditions during acquisition. During the acquisition, when one of the three vibrators was disabled, the other two overcompensated for the loss with additional
sweeps, so that one source might in fact be three-fourths as strong as the other.

Figure 49 shows the apparent rotation angle that would be calculated from windowing both split shear waves if either the y-source were weaker or the x-source were weaker. Along the outside axes the sources are equal in strength and the correct rotation angle is indicated. For one source half as strong as the other, the error is only 1.5° at a true polarization direction of 30°. Large errors in rotation angle only occur when the sources differ in strength by an order of magnitude, or when only one of the split shear waves is windowed. Therefore, the unequal source strengths at Silo field could not cause an error larger than the noise level of the data. Unequal geophone coupling has exactly the same effect (Figure 49). However, at Silo field, the geophones were frozen into the ground, and it is unlikely that they are a problem.

A similar calculation was made for the case of changing reflection coefficients between the S1 and S2 events. The four-component rotation is insensitive to any change in reflection coefficient.

Vibrator radiation patterns were examined as a possible culprit for error. The worst case of amplitude difference because of the shear wave vibrator radiation pattern, either
Figure 49. Error analysis for unequal source strengths and unequal geophone coupling. Outer axes are weights x:y:1:1, which give the true polarization direction.
with incidence angle or with azimuth, would be a factor of a half (Robertson and Corrigan, 1983). From the previous source strength calculation, it is clear that a weight of 0.5 does not produce a serious error. The vibrator radiation patterns do suggest that the rotation angle could vary with source-receiver azimuth, but only up to about two degrees.

Another concern in the rotation analysis was that the difference in source array patterns between the x- and y-sources could bias the outcome of the rotation analysis. The field filters for the various array patterns are shown in Figures 13 to 15. Reflected shear waves are only affected by the filter response to wavenumbers between zero and 0.0025 ft\(^{-1}\). This is the range of apparent wavenumbers for a reflected shear wave with an 80 ms cycle, travelling at the near surface velocity of 2500 ft/s, and arriving with an incidence angle between 0° and 30°.

In the process of stacking by geophone and azimuth for the rotation analysis, the variations of the field filters with two or three vibrators, in-line or abreast, were averaged in different combinations. In order to test what the errors might be, the difference between the x-source and the y-source field filter, with the several variations, was plotted. Figures 50 through 52 show the field filter dif-
Figure 50. Field filter differences between x-source arrays and y-source arrays. Incidence angles for 12.5 Hz shear waves travelling at 2500 ft/s.
Figure 51. Field filter differences between x-source arrays and y-source arrays.
Figure 52. Field filter differences between x-source arrays and y-source arrays.
ference, x-source filter minus y-source filter, for the wavenumbers corresponding to shear waves incident from 0° to 30°. For the planned three-vibrator arrays, the maximum difference is ±5 dB for the north-south and east-west source-receiver azimuths. It is almost zero for the pie slices at 45°, corresponding to azimuths 3 and 8. For the two-vibrator x- and y-source arrays, the maximum difference is ±8 dB for the north-south and east-west azimuths. Again, near 45°, there is no difference. From the previous analysis of weighted sources, it is clear that this difference could distort the rotation analysis only by about two degrees in a few of the pie slices of azimuth.

The field filter difference increases to ±10 dB for the comparison of the two-vibrator array to the three-vibrator array. This difference includes the overcompensation in power by the two-vibrator array, from eight sweeps to sixteen sweeps. The error still varies by azimuth, and it is a maximum of 4° for a true rotation angle of 30° or 60°.

It is apparent that the stability of the four-component rotation algorithm, when both split shear events are windowed, reduces the error that would be introduced by variations in array patterns or vibrator strength. Low signal/noise contributes more uncertainty than other variables in the acquisition system.
Post-Rotation Processing

After rotation of the shear wave survey into its natural coordinates, a conventional processing flow was implemented to complete the processing. The cross-components, $xy'$ and $yx'$, were dropped at this stage from the processing since they consist of pure noise. Post-rotation processing of the in-line components, $xx'$ and $yy'$, included deconvolution, two passes of velocity analyses, and 3-D automatic statics.

Since groundroll was such a problem in the rotation analysis, it was necessary to attempt to suppress it before the final stack. The geophone azimuth stacks were as high as 24-fold, but the stack was insufficient to suppress the noise. Unfortunately, the reflected shear waves are very close to the groundroll in frequency and wavenumber. FK filtering was tested, but it was unsuccessful in improving the signal/noise (Figure 53).

Predictive deconvolution with a 70 ms gap was used to remove the groundroll from the rotated shear components. Separate operators were designed for each component, since the gap preserves the relative amplitude between the components. There was one operator per shot record for each geophone line.
Figure 53. FK filter test on shear wave supergather. The filter did not effectively remove the groundroll.
The post-rotation velocity analysis of the shear wave survey required careful attention. It is common knowledge that a change in moveout velocity can move the onset time of an event up or down on the stacked section. Since delay times between the split shear components are significant to the interpretation of anisotropy and fracture intensity, it is extremely important to make sure that the velocities correctly flatten the shear wave events.

Thomsen (1988) indicated that the moveout velocities of split shear waves vary with the azimuth with respect to the fracture direction (Figure 54). Parallel to the fractures, the S1 and S2 events move out without interference, but perpendicular to the fractures their moveout curves cross each other. From the 2-D Silo field line, a maximum of 3% velocity anisotropy might be expected for this area (Martin, 1987). Moveout of the Shannon and Niobrara reflectors at the large t₀ of shear waves is not sensitive to this amount of velocity change, so an azimuth-dependent velocity analysis was not necessary. However, since time splitting of the split shear waves may be up to 100 ms, separate velocity functions were warranted for the S1 and S2 components.

An intermediate velocity analysis after rotation was performed using constant velocity stacks of the S2 compo-
Figure 54. Shear wave moveout hyperboloids in a fractured medium. S1 and S2 events move out with their respective vertical velocities parallel to the fractures, but the S1 event moves out with the S2 vertical velocity and the S2 event with the S1 vertical velocity perpendicular to the fractures.
ponent. S2 velocities were adjusted 80 ms upward in time for the S1 component to account for the earlier event times. Then 3-D residual statics were calculated for the S1 component and applied to both components.

The final velocity analysis employed both velocity spectra and moveout-corrected CMP gathers. Because of the low signal/noise of the shear wave data, supergathers were created at eight positions within the 3-D grid. The supergathers pulled together traces from many CMP locations and stacked traces at similar offset into 82.5-foot offset bins. Traces were combined from all directions in the survey, since an azimuth-dependent analysis was not needed. Each supergather is approximately 70-fold.

Velocity spectra were run on the S1 component, and the supergathers were corrected with these velocities (Figure 55). The S1 events were effectively flattened (Figure 56). Then the S1 velocities were applied to the S2 supergathers, but some of the S2 events were not quite flat. Comparison of the t₀ of the S1 and S2 events showed that the S1 velocities should be shifted downward for the deep S2 events below 2.6 s. The time-shifted S1 velocities successfully flattened the S2 events (Figure 56).

The rotated final stacks show a dramatic signal/noise improvement over the unrotated shear wave data (Figures 47
Figure 55. S1 velocity spectra on supergathers.
Figure 56. NMO-corrected S1 and S2 supergathers.
and 48). The strong Shannon event is crisp and focused at 3.2 and 3.3 s. The Niobrara event was barely visible on the unrotated data. The refined velocity analysis and statics after rotation have sharpened its image on the S1 and S2 components, at 3.68 and 3.75 s, respectively.
CONVERTED WAVE PROCESSING

The converted wave data were processed at Compagnie Generale de Geophysique in Massy, France, by Robert Garotta. The survey contains 43 east-west lines with 53 CMP's per line. The CMP bin size was enlarged compared to the compressional wave survey to 165-foot square. The fold is a little higher than the P-wave survey because of the larger bin size. It is between 30 and 60 for most of the survey (Garotta and Granger, 1988a).

Garotta created a numbering system that was independent from that used for the compressional wave and shear wave surveys (Garotta and Granger, 1988a). In this report, I have renumbered the survey to correspond to shear wave line numbers 52 to 138 (even numbers) and CMP numbers 51 to 155 (odd numbers) (Figure 17).

Garotta summarized his processing sequence for the Reservoir Characterization Project's sponsors (Garotta and Granger, 1988a). Table 4 of converted wave processing parameters was adapted from that report. The salient differences between the converted wave processing sequence and the P-wave and S-wave processing sequences are the two-component rotation and the asymmetrical stack.
Table 4. Converted wave processing (after Garotta and Granger, 1988).

<table>
<thead>
<tr>
<th>Converted Wave Processing</th>
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<tbody>
<tr>
<td>prerotation processing:</td>
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<td>demultiplex</td>
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<tr>
<td>amplitude decay recovery</td>
</tr>
<tr>
<td>rotation analysis:</td>
</tr>
<tr>
<td>rotation into radial-transverse coordinates</td>
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<tr>
<td>elevation statics</td>
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<tr>
<td></td>
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<tr>
<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>velocity analysis</td>
</tr>
<tr>
<td>common geophone stack</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>flattening of S1 and S2 components</td>
</tr>
<tr>
<td>energy ratio analysis</td>
</tr>
<tr>
<td>post-rotation processing:</td>
</tr>
<tr>
<td>common reflection point sort</td>
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<tr>
<td></td>
</tr>
<tr>
<td>bandpass filter</td>
</tr>
<tr>
<td>bichannel dynamic equalization</td>
</tr>
<tr>
<td>elevation and residual statics</td>
</tr>
<tr>
<td>velocity analysis</td>
</tr>
<tr>
<td>rotation into natural coordinates</td>
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<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>CRP stack</td>
</tr>
</tbody>
</table>


Garotta's rotation analysis was distinct from that used for the shear wave survey (Garotta and Granger, 1988b). The algorithm rotated the unstacked traces into radial and transverse components with respect to the source-receiver azimuth. The traces were then stacked into 18° sectors of azimuth in common-geophone mode. Rotation analysis is based on the energy ratio between the radial and transverse components. Since the P-wave impinging on the reflector is a polarized source, only the S1-wave propagates in the direction the fractures. Likewise, in the direction perpendicular to the fractures, only the S2-wave propagates. In those particular directions, the transverse component vanishes. Therefore, the energy ratio peak of the radial to the transverse component from each sector can be used to determine the natural coordinate directions.

Garotta found the average S1 direction to be N44W and the average S2 direction to be N49E (Garotta and Granger, 1988a). The rotation angle was refined to 3° increments over the survey area, and the converted wave survey was rotated counterclockwise by a variable angle between 108° and 153° (Figure 57). The rotation angle varied rapidly over the survey area.

The two-component rotation algorithm for converted waves is mathematically different from the four-component
Figure 57. Variable rotation angle applied to converted wave survey (Garotta and Granger, 1988).
rotation used on the shear wave data (Garotta and Granger, 1988b; Thomsen, 1988). Since the two converted shear modes have the same P-wave source, the rotation analysis could only be distorted by unequal coupling of the geophones (Figure 58). The rotation is just as stable as the four-component rotation, but when an error occurs it is in the opposite direction. Again, since the geophones were frozen into the ground, it is unlikely that there is any distortion due to geophone coupling. Since the azimuth sort windowed the S1 and S2 events in separate analyses, any change in reflection coefficients between the two would have no effect.

The stack of the converted waves is much more difficult than for pure compressional or shear wave data. The $v_p/v_s$ ratio must be assumed, and then the CMP binning is calculated based on the asymmetric raypath (Helbig, 1988). It is impossible with a conventional stack to focus all the horizons at the same time, since the reflection point location for a source-receiver pair varies with both its depth. The converted wave survey was processed with a focus at about 2.4 s, about 300 ms above the Niobrara level.
Figure 58. Effect of unequal geophone coupling in two-component converted wave rotation analysis. Outer axes are weights x:y::1:1, which give the true polarization direction.
STRUCTURAL INTERPRETATION

The structural interpretation of the survey area was made from the interpretation of the compressional wave data. Eight wells penetrated the Niobrara, and one reached the Dakota (Figure 17). The strata locally dip homoclinaly to the southwest and west. Penecontemporaneous normal faults in the Cretaceous section occur at the edge of a deeper Mesozoic salt-solution collapse feature. Precambrian basement faults probably are responsible for the localization of the subsequent structures.

Seismic and well log sections that correspond approximately to the strike and dip of the Upper Cretaceous sediments, through eight of the wells, are shown for the survey (Figure 59). Figures 60 and 61 are compressional wave strike and dip seismic sections. The structural log sections of the Niobrara correspond to the seismic lines (Figures 62 and 63). The Cretaceous reflectors were tied to synthetic seismograms for six wells in the survey area. The State of Wyoming Y-1, located just at the eastern edge of the survey, is the only one that penetrates the Dakota (Figure 64).
Figure 59. Key to strike and dip sections through the survey.
Figure 60. Compressional wave strike section. Tops of formations are labeled. Note listric normal faults in the Niobrara.
Figure 61. Compressional wave dip section.
Figure 62. Niobrara structural strike section.
Figure 63. Niobrara structural dip section. The Niobrara dip steepens to the southwest, over the area of Permian salt dissolution.
Figure 64. Synthetic tie from Amoco State of Wyoming Y-1 to P-wave line 136. Synthetic filter is 11/15-45/65 Hz, zero phase.
The deepest reflector that can be traced is probably the top of the Mississippian section. Sonnenberg's regional isopach (1981) indicates that it is less than a hundred feet thick, if it is present at all, and so the structure at Mississippian level is representative of the basement. The Mississippian dips about 1/2° to the northwest, at a depth of 12,000 feet (Figure 65). The basement block is inclined to the northwest off the north flank of the Morrill County High. Amplitude variation along the Mississippian reflector may be related to karst development (Figure 66).

Salt-Solution Collapse Structure

The Pennsylvanian, Permian, Triassic, and Jurassic reflectors of the survey were tied to a synthetic seismogram from the Davis Oil Berry #1, about seven miles to the west of the survey in S13-T16N-R66W (Figure 67). Doyle (1987) recorded about thirty-five feet of anhydrite in the Wolfcamp in this well. Formation tops for the deep horizons were taken from an Sonnenberg's unpublished cross-section containing the Berry #1 well that accompanies his thesis (Sonnenberg, 1981). Figure 68 is an arbitrary line through the three-dimensional survey showing a salt-solution collapse and fill structure in the Permian and Mesozoic sec-
Figure 65. Mississippian structure map. Dip is 1/2° to the northwest.
Figure 67. Synthetic from Davis Berry #1, off-survey tie to line 94. Synthetic filter is 11/15-45/65 Hz, zero phase. 15 ms was edited out of the Triassic.
Figure 66. Mississippian amplitudes from P-wave survey. All amplitudes are positive. Blue is weaker amplitude.
Figure 68. Seismic line showing salt-solution structure. Location of line is shown in Figure 69.
tion. The Wolfcamp reflector is truncated where Permian salt has been removed.

The solution feature, in the far southwest corner of the survey, is characterized by two lobes of collapse, which can be seen on an isopach of the lower Permian section (Figure 69). Solution began after five to six hundred feet of Permian and Triassic sediments had been deposited on top of the salt (Figure 70). About 350 feet of Permian salt was removed. Solution may have been localized by underlying fractures or permeable lithofacies.

Figure 71 is a structure map of the top of the draped Triassic, at a depth of 9300 to 9600 feet. Salt movement occurred first in the smaller lobe at the west end of the survey during early Jurassic time, indicated by a local area of thickening that corresponds to underlying salt dissolution (Figure 72). Salt dissolution then moved to the lobe in the southwest corner later in the Jurassic (Figure 72). Figure 74 shows that both areas had about a hundred feet of infill during the Jurassic. Salt movement continued into the Cretaceous, which is indicated by an area of isopach thickening in the Benton and Niobrara intervals (Figure 75). In the far southwest corner of the survey, a small area of thickening in the Shannon and Lower Pierre interval is the last evidence of salt movement (Figure 76).
Figure 69. Deep Permian isopach showing thinning due to salt solution.
Figure 70. Isopach of Permian and Triassic sediments involved in drape into sinkhole. Erosion or fracturing may have caused thinning (<500 ft).
Figure 71. Structure on top of Triassic drape into sinkhole.
Figure 72. Isopach of Permian through lower Jurassic, showing first stage of infill.
Figure 73. Isopach of Jurassic Morrison, showing second area of infill.
Figure 74. Isopach of Permian through Morrison, showing both salt solution areas active in the early Mesozoic.
Figure 75. Isopach of Benton and Niobrara, showing structural thinning by the normal faults and sedimentary thickening into salt-collapse area just west of the faults.
Figure 76. Shannon and Lower Pierre isopach, showing sedimentary thickening by growth of the normal faults and also by infilling of salt-collapse area just west of the faults.
Cretaceous Structure

A pair of small listric normal faults form a trap door structure in the Niobrara Formation, and another smaller fault dips to the north off their flank (Figure 77). Faults cut down into the Benton Group, and growth continued until the end of Shannon deposition. The isopach of the Niobrara Formation and Benton Group shows thinning of the section between the antithetic faults, and the Shannon isopach shows thickening within the trap door structure (Figures 75 and 76). The Sussex and Rocky Ridge isopachs indicate that movement ceased during the time they were deposited (Figures 78 and 79).

The Niobrara and Dakota locally dip about 1° to the south-southwest into the salt-solution structure (Figures 77 and 80). The strata within the Pierre dip homoclinaly to the southwest and west, with no evidence of structural disturbance above the Shannon. Note the dip of the Mississippian reflector on the seismic line that shows the strike of the Cretaceous section (Figure 60). The dip of the Cretaceous sediments differs 90° from the Paleozoic strata. Dips were influenced by the salt collapse feature.
Figure 77. Niobrara structure map, showing drape and faulting in response to salt-solution in the deeper section.
Figure 78. Sussex isopach, showing thickness variations at the level of seismic resolution and no response to either the listric normal faults or the salt-solution.
Figure 79. Rocky Ridge isopach, showing thickness variations at the level of seismic resolution and no response to either the listric normal faults or the salt-solution.
Dakota Structure

Figure 80. Dakota structure map, showing drape in response to salt-solution in the deeper section.
INTEGRATED INTERPRETATION

An integrated interpretation of the reservoir heterogeneity at Silo field was based on cores, well logs, production history, and the multicomponent seismic survey. Cores were available at Colorado School of Mines, the U.S.G.S. Core Library, and Amoco's core warehouse. Dipmeter logs and full waveform sonics were available for most of the wells in the survey area, and Bill Iverson of the University of Wyoming supplied production information. Interpretation of the multicomponent survey was made on a Landmark™ workstation at Golden Geophysical.

A multicomponent vertical seismic profile in the Amoco State of Wyoming Y-2 processed by O'Rourke (1986) was critical to making the seismic ties between the different components. The vertical (400-foot offset) shear and converted wave VSP's were used to tie the shear and converted wave surveys in the Cretaceous section. Unlike synthetic ties, the vertical seismic profile ties are absolute in time, taking datum differences and statics into consideration. The shear wave VSP indicates that the Niobrara reflection occurs at 3.77 seconds on the S2 component (Figure 81). The converted wave VSP puts the Niobrara at 2.73 seconds on the S1 component. Landmark is a trademark of Landmark Graphics Corporation.
Figure 81. Shear wave VSP tie from Amoco State of Wyoming Y-2 to line 102.
component (Figure 82). The strongest reflector on the converted and shear wave surveys is a calcareous shale within the Shannon or Lower Pierre at 6600 feet depth in the VSP well. It is designated the Shannon for the shear and converted wave surveys, but it is not the top of the Shannon that was timed on the compressional wave survey.

The deeper Dakota and Mississippian reflectors were located by character ties among the component surveys. The seismic character of the converted wave survey is a valuable link between the compressional and shear wave surveys. Once the reflector was fixed in time on the converted wave trace, its shear wave interval time was known and it could be located with certainty on the shear wave trace.

The top of the Niobrara and the Fort Hays are easy to follow from the compressional wave survey to the converted wave survey to the shear wave survey. However, the top of the Dakota Group, or the J Sand, is not a continuous reflector in the shear wave survey. It is the Cheyenne Formation of the Dakota Group that can be correlated as a peak on the shear wave survey. The Mississippian was also identified by making this kind of tie between the surveys. It is the deepest reflector, immediately above the basement.
Figure 82. Converted wave VSP tie from Amoco State of Wyoming Y-2 to line 102.
Fractures in the Niobrara

An economic indicator of fractures in the Niobrara at Silo field is the production history of the wells. Unfortunately, the productivity of an individual well depends on the completion technique that was used as well as the fracture intensity (Iverson, 1989). Iverson (1988) summarized the status of the wells near the 3-D survey (Table 5). The Goertz B-1 and Goertz C-2 are the best producers at Silo field. The State of Wyoming Y-2 was abandoned after an experimental completion, although it made a good show of oil (Iverson, 1988 and 1989). The Epler 2 is still producing, but the other wells have been abandoned.

The Goertz B-1 well was cored in the C chalk and Fort Hays interval of the Niobrara. Petroleum Information reported that the core was very fractured from 8214 to 8274 feet. Figure 83 shows the full waveform sonics from the Goertz B-1 and Goertz C-2 wells. The interval that was noted to be very fractured in core has an attenuated full waveform response in the chalk horizons. The Goertz C-2 has the same signature in the equivalent zone and the B chalk interval as well. The State of Wyoming Y-2 and the Goertz D-1 have nearly as much fracturing in the B interval, judging from full waveform sonics. The Parker 2 has a cyberlook
Table 5. Production statistics (Iverson, 1988) and shear wave splitting.

<table>
<thead>
<tr>
<th>Production and Shear Wave Splitting</th>
<th>IPP (B/D)</th>
<th>cumulative oil (MB)</th>
<th>Kn shear wave delay (ms)</th>
<th>Kn anisotropy (%)</th>
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<td>Producing wells:</td>
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<tr>
<td>Amoco Goertz B-1</td>
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<td>200</td>
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<tr>
<td>Exxon Goertz C-2</td>
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<tr>
<td>Exxon Goertz D-1</td>
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<td>12</td>
<td>3.6</td>
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<td>2</td>
<td>-4</td>
<td>-0.4</td>
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<tr>
<td>Amoco State of</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>22</td>
<td>2</td>
<td>12</td>
<td>3.2</td>
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<tr>
<td>Amoco State of</td>
<td></td>
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<tr>
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<td>lost hole</td>
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<td>26</td>
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<tr>
<td>Parker 2</td>
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<td>14</td>
<td>-12</td>
<td>-3.6</td>
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Figure 83. Full waveform sonic logs, showing attenuated amplitudes in response to fractures in the chalks. Bar on Goertz B-1 is cored interval.
log (full waveform sonic run in casing) that indicates minimal fracturing.

Dipmeter logs to determine fracture orientation were run in five of the nine wells in the survey area. Figures 84 and 85 are portions of the logs in the Goertz D-1 and Goertz C-2 wells. Low resistivity on pads 1 and 3 in the Goertz D-1 indicate a fracture orientation between N30W and N65W in the B chalk interval. Pads 1 and 3 in the Goertz C-2 well again see fractures between N40W and N70W. The Parker 1 dipmeter reads N35W to N70W, with a clear reading of N55W over ten feet in the B chalk. The dipmeter log for the Goertz E-1 is unusable because of tool problems. Iversen (1989) reported N40W for the CPC 41-5, 700 feet south of the survey, and N20W with minimal fracturing for the Parker 2 in the far northeast corner of the survey area. Except for the Parker 2, all the well information points to an average fracture orientation of N50W to N55W.

The three-dimensional shear wave survey provides a laterally detailed picture of the intensity of fracturing in the Niobrara. The anisotropy of an interval may be measured as the delay between the components, normalized by the shorter interval time:

\[
\frac{\Delta t_{S2} - \Delta t_{S1}}{\Delta t_{S1}}
\]
Figure 84. Schlumberger dipmeter log for Exxon Goertz D-1. Low resistivity on pads 1 and 3 indicates that both pads sense the fractures on opposite sides of the borehole. Azimuth of pad 1 gives the fracture direction. Low resistivity consistent over fifteen feet suggests near-vertical fractures.
Figure 85. Gearhart dipmeter log for Exxon Goertz C-2. Low resistivity on pad 1 from 8174' to 8188' and on pads 1 and 3 from 8168' to 8172' indicates fractures. Azimuth of pad 1 gives the fracture direction. Low resistivity consistent over twenty feet suggests near-vertical fractures.
where $\Delta t_{S2}$ is the interval time of the S2 component and $\Delta t_{S1}$ is the interval time of the S1 component (Martin, 1987). The shear wave anisotropy is proportional to the crack density $\epsilon$:

$$\epsilon = N_v \langle a^3 \rangle,$$

where $N_v$ is the number of cracks per unit volume and $\langle a^3 \rangle$ is the mean cubed radius of the cracks (Lynn and Thomsen, 1986). The component with the overall faster velocity is referred to as the S1 component in this equation. In certain cases, the S2 component for the survey may be the S1 component for the interval, so that the equation gives a negative anisotropy.

Figures 86 through 89 are the split shear wave seismic sections through the wells, corresponding to the previous compressional sections along the same lines. The anisotropy of the Niobrara interval, between the reflectors from the top of the Niobrara and the Dakota Cheyenne, ranges from -7% to +8%, calculated from delays up to 28 milliseconds (Figure 90). The 5.2% anisotropy at the Goertz C-2 and the Goertz B-1 wells can be directly related to their productivity from natural fractures oriented to the northwest (Table 5). The 5.2% anisotropy observed at these producing wells is almost twice as large as the maximum 2.7% found by Martin (1987) from the two-dimensional line adjacent to the three-dimen-
Figure 86. S1 seismic strike section.
Figure 87. S2 seismic strike section. Note that the events are later than the same events on the S1 section.
Figure 88. S1 seismic dip section.
Figure 89. S2 seismic dip section.
Figure 90. Niobrara anisotropy, calculated from the interval delay between the S1 and S2 components.
sional survey. The Goertz B-1 and Goertz C-2 wells are bet-
ter producers than those on Martin's line with 2.7% anisotropy.

The anisotropy at the State of Wyoming Y-2 well is also 5.2%. This is the hole that was lost in an experimental completion, and it looks like it would have been a good producer. The Goertz D-1 well falls at the edge of an area of positive anisotropy. The Parker 1 well is slightly positive also.

The Goertz E-1 and Epler 2 wells show minimal splitting, although they are at the edge of areas of strong positive anisotropy. The Parker 2 is strongly negative in anisotropy, which might be interpreted as indicating fractures to the northeast. However, it has minimal fracturing, and the negative anisotropy may be the result of stress-in-
duced microcracks.

The dominant fracture direction at the Niobrara level is N50W to N55W. The dipmeter logs indicate this, and the 58' rotation of the shear wave data agrees with the well in-
formation. The dominantly positive anisotropy indicates that the faster split shear wave is polarized to the north-
west, which indicates that the fracture strike is in that direction. Merin and Moore (1986) reported lineaments from Landsat imagery at Silo field oriented N65E and N58W.
The structural trend of the area of intense fracturing, indicated by maximum anisotropy, is northwest and northeast. The 3-D survey area is on trend with the northwest fractures detected by Martin and Davis (1987). The most intense fracturing occurs in the vicinity of the salt-solution structure and the listric normal faults.

The spatial wavelength of the reservoir heterogeneity resulting from variations in fracture intensity is just a few hundred feet (Figure 90). The strongest areas of positive anisotropy in the Niobrara interval, indicating the most intense fracturing, were missed by every one of the nine wells drilled in the survey area. If this survey had been available at the time of field development, the Goertz B-1, Goertz C-2, Goertz D-1, and State of Wyoming Y-2 wells could have been better located or deviated to tap the high-permeability areas of greater fracture density.

Reliability of Fracture Interpretation

The three-dimensional survey has the advantage of increasing the confidence in the measurement of the delays on the noisy shear wave data. The reflectors can be timed on crosslines and arbitrary lines as well as in the in-line direction. The southwest corner of the survey, covering
Goertz C-2 well, is particularly noisy, but the interpretation was reworked several times in various line directions without a dramatic change in the outcome of the delays.

Because the shear wave survey was sampled at 4 milliseconds, the percentage error in measuring the small interval delay between the two components could be large. However, error should not be measured on a single trace, considered apart from the surrounding traces. In reality, the measurement is not being made on a single trace, but it is based on the interpretation of the 3-D grid of traces. Comparing the timing of the split shear wave events on a trace with two traces on either side significantly reduces the error, because in three dimensions there are twenty-four traces within two trace spacings.

The anisotropy in the Niobrara can be compared to the anisotropy of the two intervals above the Niobrara. The Rocky Ridge interval, from the top of the Rocky Ridge to the Shannon reflector is almost uniformly positive in anisotropy, with values ranging from -3% to +5% (Figure 91). It is assumed to be stress-induced anisotropy, with a maximum stress direction to the northwest. The Shannon interval, from the trough of the Shannon reflector to the top of the Niobrara, is variable in anisotropy, from -5% to +8%
Figure 91. Rocky Ridge anisotropy. The anisotropy is almost constant across the survey.
(Figure 92). At first it alarmingly resembles the negative of the Niobrara anisotropy, implicating that the pattern of variable anisotropy in the Niobrara and Shannon could be the result of timing errors. A test for that possibility is to make a total delay map from the Dakota to the Shannon (Figure 93). If the anisotropy were constant and the anisotropy measurement were in error, the total delay would be constant. Instead, the interval from the Shannon to the Dakota is characterized by a variable amount of splitting.

Limitations of Multicomponent Interpretation

Shear wave reflection amplitudes should be a high-resolution detector of fracture orientation and intensity (Thomsen, 1988). The compressional wave amplitudes of the Niobrara and Fort Hays are insensitive to the fracture-induced anisotropy (Figure 94). Amplitudes of the Niobrara and Fort Hays on both shear wave components were examined (Figures 95 and 96). The amplitudes seem to follow the pattern of the fold, increasing toward the center of the survey for both reflectors. The amplitudes to the west are a little weaker, which seems to be related to the increasing noise level in that direction. The ratio of S1/S2 for the Niobrara ranges from about 0.6 to 6, but the pattern does
Figure 92. Shannon anisotropy.
Figure 93. Total delay from Dakota to Shannon. The anisotropy is variable over the survey, suggesting that Niobrara anisotropy measurements are not the result of timing errors on the Niobrara reflector.
Figure 94. P-wave amplitudes for Niobrara top and Fort Hays. All amplitudes are positive. Blue is weaker amplitude.
Figure 95. Shear wave amplitudes from Niobrara top.
Figure 96. Shear wave amplitudes from Fort Hays. Note the similarity between the Fort Hays amplitude pattern and the Niobrara top amplitude pattern.
not follow that of the delays or appear to be associated with areas of better or worse production. The split shear wave delays are a more reliable indicator of fracturing, because the amplitudes seem to be overwhelmed by fold and noise.

The delays between the split shear waves of the converted wave survey were also unsuccessful in resolving the reservoir heterogeneity. Figures 97 through 100 are seismic sections through the wells, and Figure 101 is a map of the anisotropy derived from the converted wave surveys. The trend to steadily increase from +6% in the west to +27% in the east looks like a processing artifact and does not resemble any geologic feature of the area. The lateral resolution of the converted wave data may have been destroyed because it could only focus one reflector in stacking, in this case the Shannon reflector 300 ms above the Niobrara, or because the rotation did not correctly focus the split shear waves.

The three-degree increments of variable rotation angle on the converted wave survey are probably at the noise level of the data, and do not give valid fracture information. The S/N of the converted wave data is not much better than that of the shear wave data, despite the fact that its fold is double the shear wave fold. Some of the noise in the
Figure 97. Converted wave S1 strike seismic section.
Figure 98. Converted wave S2 strike seismic section.
Figure 99. Converted wave S1 dip seismic section.
Figure 100. Converted wave S2 dip seismic section.
Figure 101. Niobrara anisotropy from converted wave survey. The anisotropy increases steadily from west to east, suggesting that it is a processing artifact.
converted wave data is obviously groundroll, and it has been demonstrated in the shear wave rotation analysis how sensitive the rotation analysis is to groundroll. The determination of the natural polarization directions by rotation analysis was probably distorted by groundroll. The rotation was made on a shallow window that encompassed noise between reflectors, instead of focusing on a clean reflector.

**Lithology in the Dakota**

A secondary objective of the multicomponent survey was to investigate the possibility of improving lithology detection in the Dakota. Compressional wave amplitudes have been used to detect Dakota valley-fills previously (Weimer, et al., 1988). Since the survey was located at the edge of a mapped valley in the J Sand, it seemed a likely location for such an application (Grube, 1984).

There are three cores of the J Sand in proximity to the survey area. The Davis Sandberg 1-A in 5-T16N-R64W cored almost a hundred feet of valley fill, overlain by fifteen feet of marine sand (Figure 102). In contrast, the Champlin 300 Amoco A-1, just three miles away in 23-T16N-R64W, encountered marine sediments at the same level of the
Figure 102. Dakota wells near Silo field. Cross section C-C' of J Sand valley-fill and D-D', of variable sand content in the Cheyenne.
J interval. The core taken closest to the survey area is from the Champlin 300 Amoco B-1 in 5-T15N-R64W. The J Sand consists of a much thinner valley-fill than the Sandberg 1-A, capped by the same fractured marine sand. Figure 103 is a stratigraphic cross-section of the Dakota, showing the incisement of the lowstand surface of erosion and the transgressive marine sand overlying the valley fill sequence.

Note that the J Sand contains about 40 to 45 feet of sand, whether it is marine or nonmarine (Figure 103). In this case the edge of the paleovalley is not characterized by a sharp lithology change. The amplitude of the J Sand is relatively constant across the survey (Figure 104).

There are no holes through the Cheyenne interval of the Dakota Group in the survey area itself. However, there are two Cheyenne wells within a few hundred feet of the south edge of the survey. These penetrations show a possible three-fold variation in Cheyenne sand content (Figure 105). The Cheyenne sand in the Blevins 1 in 1-T15N-R65W is only about thirty feet thick, but in the Champlin 300 Amoco B-1 it may be seventy-five feet thick. In light of this, the Cheyenne and not the J Sand interval is the target for testing the sensitivity of multicomponent data to lithology variations.
Figure 103. Stratigraphic cross-section of J Sand, showing the edge of the paleovalley. Cross-section location in Figure 102.
Figure 104. P-wave Dakota J Sand amplitude. All amplitudes are positive. Blue is weaker amplitude.
Figure 105. Stratigraphic cross-section of Cheyenne, with variable sand content and possible valley. Location of section in Figure 102.
The curvilinear pattern of the compressional wave amplitudes of the Cheyenne reflector could be interpreted as a paleovalley or facies change, and the anisotropy of the Dakota interval, from the top of the Cheyenne to the Mississippian, could also be interpreted as valley-fill (Figures 106 and 107). However, there are no deep penetrations in the area to confirm the interpretation. The anisotropy ranges from -7% to +5%. The Mississippian reflector was very difficult to time on the shear wave survey, and the anisotropy is subject to error for that reason. It is, of course, a very large interval of anisotropy encompassing much more than the thin Cheyenne interval. Reflection coefficients would have much higher resolution, but the shear wave amplitudes do not show any distinct geologic pattern, because they are probably distorted by noise and fold, like the Niobrara shear wave amplitudes (Figure 108).
Figure 106. P-wave amplitude of Cheyenne reflector. All amplitudes are positive. Blue is weaker amplitude.
Figure 107. Anisotropy from Cheyenne to Mississippian.
Figure 108. Shear wave amplitudes from the Cheyenne.
FUTURE WORK

The future of multicomponent seismic data will depend on better acquisition and processing technology, because its potential to define reservoir heterogeneity has been confirmed. Geophone and source arrays need to be designed to suppress groundroll in shear wave surveys. This is particularly challenging to do economically with three-dimensional surveys. Noise-reduction techniques that do not destroy resolution should be developed and tested. Shear wave amplitudes and amplitude ratios may be high-resolution detectors of anisotropy when the noise is suppressed.

The orthorhombic pattern of anisotropy, which results from the combination of vertical fractures and horizontal layering, may still be a pitfall in other areas outside Silo field. The azimuth-dependent rotation analysis could be refined to examine various ranges of source-receiver offset. Dipping fractures would be reflected in polarizations that are both offset- and azimuth-dependent.

The difference in the rotation angles and in the split shear wave delays defined by the shear wave survey and the converted wave survey is a concern that needs to be investigated. Is there an inherent difference between the behavior of converted and shear waves? Is there a difference intro-
duced by the processing or the rotation algorithms? The converted wave survey could be reprocessed to look for these answers.

Negative anisotropy, implying an azimuth of anisotropy perpendicular to the overall trend, is not well understood. Negative anisotropy occurred at the location of the Parker 2 well, which shows minimal fracturing, and so northeast-oriented fractures are not a plausible cause in this case. Is it caused by the orientation of stress? Is it possible for stress, and hence stress-induced anisotropy, to change rapidly in direction in the subsurface? Perhaps not all the causes of anisotropy are understood.

The three-dimensional multicomponent survey technique should be extended to areas with geologic structure. The third phase of the Reservoir Characterization Project under Tom Davis is now doing that. Split shear waves have been successful in defining fracture patterns, which in turn are controlled by structure.

Multicomponent data may contain valuable information about lithology. Velocity ratios have been used as gross detectors of lithology, but shear wave anisotropy may give more information. Further investigation needs to be carried out in a location with adequate well control and strong lithologic variation.
CONCLUSIONS

Azimuthal anisotropy determined from split shear waves was used to map the fracture orientation and intensity in the producing chalks of the Niobrara Formation at Silo field. Areas of large positive anisotropy correlate to intense fracturing indicated by the dipmeter well logs and full waveform sonic logs. Production is more difficult to correlate to the anisotropy, because the production depends on the completion techniques and on interference between the wells.

The reservoir heterogeneity has a spatial wavelength that is shorter than the typical development well spacing. Although the measurement of fracture density is qualitative, the map of Niobrara anisotropy indicating the fracture pattern in the reservoir would have been valuable at the time of field development. The reliability of the interpretation is greatly enhanced because of the survey is three-dimensional.

The orientation of fractures in the survey area of Silo field is dominantly N50W to N55W. The rotation analysis of the shear wave survey, yielding an S1 direction of N58W, and the dipmeter well logs concur in this measurement for the Niobrara Formation. The survey area is on trend with the
northwest-oriented fractures mapped by Martin and Davis (1987). The development of fractures was probably the result of the structural drape of the overlying sediments over the edges of the salt-solution sinkhole.

A secondary objective in this study was to investigate lithology changes in the prospective Dakota Group. However, the J Sand penetrations nearest the survey indicate that there are no large variations in sand content even at the edge of its paleovalley. There may be a variation in sand content in the Cheyenne, but there is little well control to define it. The multicomponent survey could not provide a definitive answer to this problem. A valley-fill system in the Cheyenne could be a prospective lead.

The three-dimensional compressional wave survey clearly resolved a salt-solution collapse structure in the Paleozoic and deep Mesozoic section. Permian salts began to dissolve in the Jurassic, and movement continued until the time of Shannon deposition in the Cretaceous. Fractured or dolomitized carbonates involved in the drape structure are a prospective lead, provided that there are a deep source and an adequate seal. Syndepositional listric normal faults formed in the Benton Group, the Niobrara Formation, and the Lower Pierre and Shannon intervals at the edge of the salt-collapse structure.
Additional insights in shear wave processing were gained from this study. The sensitivity of rotation analysis to the presence of groundroll was unexpected. The azimuth-sorted rotation analysis enabled the interpreter to distinguish between unrotated shear waves and groundroll, and eliminate groundroll-contaminated azimuths from the rotation analysis. The noise level of the rotation analysis is about ±8°. A single rotation angle of 58° was used for the entire survey. The orthorhombic pattern of anisotropy is not present in the survey area at Silo field.

Careful flattening of the shear wave moveout curves insured accurate timing of the stacked events, which is critical to the anisotropy measurement. There was not enough moveout difference between the S1 and S2 events to require separate velocity analysis, but the time shift between the two velocity curves did affect the moveout correction.

The converted wave survey was valuable for its contribution of improved statics to the shear wave processing. It was also helpful in correlating deep seismic events from the compressional wave survey to the shear wave survey. The converted wave survey failed in mapping the fracture heterogeneity, probably because the rotation did not correctly focus the split shear wave events.
REFERENCES


Garotta, R.J., and P.Y. Granger, 1988a, Silo Field II - Wyoming 3C x 3D project, processing report of converted waves: Compagnie Generale de Geophysique, Massy, France.


