A seismic attribute study to assess well productivity in the Ninilchik field, Cook Inlet basin, Alaska

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A SEISMIC ATTRIBUTE STUDY TO ASSESS WELL PRODUCTIVITY IN THE
NINILCHIK FIELD, COOK INLET BASIN, ALASKA

A Thesis
Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
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in

The Department of Geology and Geophysics

by
Andrew Sampson
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Abstract

Coal bed methane which has formed in the Tertiary Kenai Group strata has been produced from the Ninilchik field of Cook Inlet, Alaska since 2001. Ninilchik field is located on the eastern margin of the central Cook Inlet along the Kenai Peninsula. Cook Inlet is a forearc basin and is characterized by northeast trending anticlines with upwards of 10,000 feet of Late Oligocene and younger, non-marine sediments. Highly variable well production within the Oligocene to Miocene Tyonek formation of the Kenai Group has been a source of uncertainty.

A series of seismic attributes visualized in Schlumberger's Petrel® software were studied on a 3D seismic volume to investigate potential structural and stratigraphic controls for the observed, variable well production. Geometrical seismic attributes, such as variance/coherence, dip, and azimuth, are the primary attributes used in pattern recognition to investigate the formation properties near well locations. Production data were integrated with the seismic attributes on five distinct well groups targeting sand reservoirs in the Tyonek formation.

A complete seismic attribute evaluation for all well groups is not feasible due to some data quality issues. Overall, structural properties such as folding and faulting are large scale enough to be confidently imaged by seismic attributes. Amplitude or envelope strength mapping to detect fluid changes poses problems in the coal-dominated stratigraphy. No correlation between the source rock thickness and well production quality is evident from log analysis. Variance volumes co-rendered with the ant tracking attribute, a method for enhancing geologic discontinuities, are shown to be useful for highlighting faults in low signal to noise seismic. Bottom-hole locations nearest the anticline fold axis tend to have the highest production histories due to the increased stresses and faulting near the fold crest.
Introduction

The Ninilchik field in Cook Inlet, Alaska is a gas producing basin located approximately 90 miles southwest of Anchorage, Alaska. Cook Inlet has been a producing oil and gas basin since the discovery of the Swanson River field in 1957 (Carter and Adkison, 1972). Biogenic gas produced from the Late Oligocene to Miocene Tyonek and Beluga formations in the Ninilchik field is sourced by the organic rich coal layers (Fisher and Magoon, 1978; Brimberry et al., 2001; Kelly, 1963). Capture of hydrocarbons is accomplished by simple anticline structure with interbedded sandstones, siltstones, and coals providing a series of thin reservoirs, source rock, and seal rock. Anticlines in Cook Inlet are oriented northeast to southwest, parallel to the basin bounding Bruin Bay and Border Ranges faults (Figure 1) (Brimberry et al., 2001).

Figure 1: Tectonic framework of Cook Inlet basin, showing forearc basin geometry (image from Doherty et al., 2002).
Since 2001, twenty five wells have been drilled into the Ninilchik anticline targeting hydrocarbons within the Tertiary formations. High variations in well production, especially between near offset wells, have been observed over the last decade. This study uses seismic attributes to evaluate a 3D seismic volume to determine what structural or stratigraphic controls may be strongly influencing gas production.

The Cook Inlet Tertiary rocks were deposited in a fluvial and alluvial fan environment which has undergone recent tectonic activity responsible for the formation of the anticlines that characterize most of the producing fields (Kirschner and Lyon, 1973; Boss et al., 1976). Methane gas is generated by biogenic degradation of coals within Tertiary formations (Kelly, 1963; Kelly, 1968). Due to the stratigraphic and structural complexity of Cook Inlet, successful wells may be associated with channel sands, reservoir/source pinch-outs, fault compartmentalization and fracture density, subtle structural flexures, or a combination thereof (Swenson, 1997). A preprocessed 3D depth-converted seismic volume and associated wireline logs are evaluated along with publicly available production histories.

Seismic Attributes

Seismic attributes can be used to infer formation physical properties, e.g. porosity, permeability, and changing bed thickness (Taner et al., 1979; Taner, 2001). A seismic attribute can be thought of as a mathematically derived value from seismic data, much in the same way arithmetic mean, minimum and maximum are derived from raw mathematical data. Averages, maximums, and other statistics are calculated because they help our understanding of the data. Likewise, seismic attributes can be more useful to an interpreter than raw seismic data. Many seismic attributes are similar in their qualities and have overlapping applications. Seismic Micro-
Technology (SMT) has categorized seismic attributes into groups according to their computational characteristics: geometric, instantaneous, wavelet, and spectral decomposition (Taner, 2001).

Instantaneous attributes represent instantaneous variations of particular properties on a sample by sample basis. These properties commonly include amplitude, frequency, phase, and their derivatives. Wavelet attributes are a subgroup of instantaneous attributes that are calculated at the peak of the trace envelope. Spectral decomposition is a method of converting seismic data to the frequency domain via a discrete Fourier transform to aid in interpretation of bed thickness and geologic discontinuities (Taner et al., 1979; Taner, 2001).

Geometric attributes relate to the physical properties of the reflected data. These attributes describe the spatial and temporal relationship of all other attributes (Taner, 2001). This category includes attributes such as variance/semblance, dip, azimuth, and curvature. Variance, or its cousin attribute semblance, measures the continuity of the data and is good indicator of bedding similarity and potential faults. Dip, azimuth, and curvature may all relate to depositional patterns and are commonly used for stratigraphic interpretation.

Data Quality and Coal Bed Effects

The Cook Inlet field area is a difficult basin to seismically image due to a variety of subsurface complexities. Recent stress and deformation processes have generated significant faulting through the Plio-Pleistocene sediments. The combination of large faults and potential for upward gas migration results in “gas chimney” noise, a term referring to the general chaotic character within the seismic resulting from energy absorption and distortion caused by accumulation of shallow gas (Figure 2).
Periods of low energy environments occurred frequently throughout the Tertiary and led to numerous coal bed deposits. Compared to the surrounding sandstones and siltstones, coals are significantly less dense (~1.45 g/cc) and have low p-wave velocities (~2500 m/s) (Perz, 2001). Although this makes identifying coals a fairly simple task on density and sonic logs, it creates significant problems for seismic imaging. Coal beds attenuate signal quickly due to the high reflectivity of the coal and the sand/silt interface, and sequences of coal layers may create “ringing” multiples due to energy becoming trapped between coals (Figure 3) (Perz, 2001).

![Figure 2: Inline 232 cross-section parallel to the Ninilchik anticline showing a thick wedge of washed out seismic data. Vertical exaggeration is approximately three times the horizontal scale. Highlighted area is evidence for shallow gas indicated by a shallow, low frequency, high amplitude event.](image)

Given the stratigraphic complexity resulting from the rapidly changing depositional environment and the presence of abundant coal layers, the seismic attribute focus is shifted away...
from the amplitude-dependent attributes (e.g. trace envelope strength, amplitude extractions) and towards geometric attributes (e.g. dip, variance, and azimuth). These attributes are more useful for defining geological discontinuities in a structurally and stratigraphically complex system.

![Amplitude Energy](image)

Figure 3: Horizontal (depth) slice at 5400 ft for the top Tyonek coal layer (left). Coal related energy loss shown directly beneath this horizon at 5600 ft (right). The highest attenuation is near the center of the image due to the increased concentration of gas.

Geologic Setting

The Cook Inlet is an intermontane, forearc basin that is approximately 200 miles long and 60 miles wide. The basin is part of the Pacific continental margin which has experienced continuous convergence since the Jurassic (Magoon, 1994; Coney and Jones, 1985). Mesozoic and younger sediments of the Cook Inlet were deposited in a major trough oriented roughly N30°E and are bounded by the igneous and metamorphic rocks of the Alaska Range and Kenai-Chugach Mountains to the northwest and southeast respectively (Kirschner and Lyon, 1973; Kelly, 1963). The basin is bounded to the north by the Castle Mountain fault (Figure 4).
The present basin evolved primarily after the Middle Jurassic when uplift of the volcanic Alaska Range to the northwest led to sediment loading along the western edge of the basin. From the Late Cretaceous through much of the Tertiary, sediment input came from the uplifted Kenai-Chugach Mountains, associated with the accretionary complex, to the east of the basin via alluvial fans. As the basin deepened due to sediment loading from the adjacent mountain ranges, braided streams and channels drained into the basin from the northeast. (Hartman et al. 1972; Kirschner and Lyon, 1973; Hayes et al. 1976; Swenson, 1997; Dallegge and Layer, 2004). Abundant volcanic fragments were supplied to the basin by recent Tertiary uplift of the southern Alaska Range (Hayes et al., 1976; Dallegge and Layer, 2004).

The Tertiary depositional environment of the Cook Inlet can be described best as an anastomosing, braided fluvial system (Kelly, 1963). Nearly 80% of the thick Tertiary sediments belong to the Kenai Group, a system dominated by interbedded conglomerates, sandstones, and coal beds with a significant amount of volcanic and metasedimentary fragments (Fisher and Magoon, 1978; Dallegge and Layer, 2004). The Tertiary sediments are upwards of eight kilometers thick in the northern portion of the Cook Inlet basin and range between two and three kilometers within the Ninilchik field.

Methane gas is generated from the buried coal intervals. The gas either remains trapped in the coal beds or is released into the adjacent, overlying sand bodies. Irregular distribution of fluvial-derived sediments has left a complex system of disjointed reservoirs that is often difficult to correlate between wells in the field (Kelly, 1963). Source and migration of hydrocarbons are controlled by the location of the interbedded coals throughout the formation. Faulting may provide conduits for gas migration as there is significant evidence for shallow gas accumulations typically associated with leaky hydrocarbon systems.
Figure 4: Index map of Cook Inlet area showing major fault zones. Bruin Bay and Kenai Mountain (Border Ranges) fault zones are high angle reverse faults. Tertiary sediments thin towards the southwest near the Augustine-Seldovia Arch (Boss et al., 1976).
Stratigraphy

Tertiary sediments were deposited in two cycles. The depocenter was situated to the northeast of the current Cook Inlet basin in the early cycle and was sourced by a significant area of the interior province of Alaska and Western Canada (Kirschner and Lyon, 1973; Detterman and Hartsock, 1966). Sediment source shifted westward to the adjacent highlands of the Alaska Range during the later cycle, and the depocenter moved to the present day location of the Cook Inlet. The sediments are primarily non-marine, clastic sandstones, conglomerates, and siltstone in an estuarine, fluvial, lacustrine, and alluvial fan environment (Boss et al., 1976; Kirschner and Lyon, 1973; Jones and Detterman, 1966). An Oligocene orogenic episode uplifted and eroded early Tertiary strata and ended with the deposition of the Hemlock formation and the remaining Kenai Group formations. (Fisher and Magoon, 1978; Kirschner and Lyon, 1973).

![Figure 5: Tertiary stratigraphy of the Cook Inlet (modified from Swenson, 1997).](image)
The Kenai Group sits over the West Foreland Formation and has been divided into four formations: the Hemlock conglomerate, Tyonek, Beluga, and Sterling (Figure 5). The Kenai Group rocks are of Oligocene to Pliocene age and consist of conglomerates, coal, siltstone and sandstone. Well data indicate over 20,000 feet of Tertiary sediment north of the city of Kenai, but sediments thin significantly moving southwest towards the Seldovia Arch (Figure 3) (Fisher and Magoon, 1978; Hartman et al., 1972; Kelly, 1963). The lower part of the Kenai Group is a distinct lithologic group referred to as the Hemlock zone. The Hemlock is a poorly sorted sandstone, conglomerate, and carbonaceous shale interbedded with thin streaks of coal seams and lignite streaks (Kelly, 1963). The Hemlock zone is a significant oil reservoir throughout the Cook Inlet, although it has not proven to be a productive interval in Ninilchik field.

The Tyonek formation is a thick sequence of Miocene sandstones, conglomerates, and siltstones and is the most productive reservoir in Ninilchik field. The sandstones were deposited from small tributaries and meandering streams carrying sediment in from the north-northwest. Sand grains may be angular to sub-rounded, very fine to medium-grained, and poor to moderately sorted. Thin siltstone laminations within the sandstones are common and often act as permeability barriers. Effective porosities range from 10-25% and permeability between 3 to 250 millidarcies (mD) for the sand intervals (Brimberry et al., 2001). A defining characteristic of the Tyonek is the occurrence of thick (greater than 10-15 feet) and continuous coal beds typically found at the base of productive sands (Clay and Adkison, 1972).

Conformably overlying the Tyonek is the approximately 2500 feet of sandstones, siltstones, and thin coals of the late Miocene Beluga formation. The lithology of the Beluga is derived from volcanic and metasedimentary rock fragments transported down from the accretionary Kenai-Chugach Mountains to the east of the basin. High quality reservoir sands
with effective porosities between 12-20% and permeability from 5 to 150 mD occur throughout the formation (Brimberry et al., 2001). Coals frequently appear in the section, but are typically very thin (less than 5 feet) and discontinuous. The Beluga is a secondary reservoir target for the Ninilchik field. The base of Beluga is marked at the first thick, continuous coal bed.

The uppermost Plio-Pleistocene Sterling formation contains the thickest packages of sandstones (30-60 feet thick). The sands are partially cemented with kaolinite and smectite clays, but still retain good porosities around 25% (Brimberry et al., 2001). The Sterling formation is overlain by recent glacial till deposits. Near the Ninilchik field, the Sterling outcrops along the western margin of the Kenai Peninsula. It is shallow and relatively thin throughout the section and generally does not contain significant hydrocarbon reservoirs. The Sterling is thicker and deeper to the north-northeast where it becomes a highly sought gas reservoir target (Bruhn et al., 2000).

**Structure**

Figures 6 and 7 describe the structural setting for the region. The Bruin Bay fault to the northwest, the Border Ranges fault to the southeast, and the Castle Mountain fault to the north outline the basin province (Kirschner and Lyon, 1973; Magoon, 1994). The structure is dominated by the ongoing subduction of the Pacific plate with the North American continent and the associated microplate collision of the Yakutat block (Figure 6). Tertiary sediments have been deformed along fault propagated folds that have formed series of asymmetrical, doubly-plunging anticlines throughout the basin (Kirschner and Lyon, 1973; Boss et al., 1976). The anticline at Ninilchik field fits with this trend, striking northeast and straddling the present day shoreline. The Ninilchik anticline displays steeply dipping beds along both the northwest and southeast
flanks. West-northwest striking normal faults segregate the Ninilchik anticline into distinct areas with independent hydrocarbon systems.

Trapping of biogenic methane gas is accomplished primarily through structural closures, which have formed recently from deformation processes active from the Late Miocene to the present day (Haeussler, 2000). Although most trapping is structurally controlled, there is a high level of stratigraphic variability influencing the system. The sand and silt deposits are distributed irregularly and can be difficult to track on electric logs. Furthermore, clay content, e.g. kaolinite and smectite, can act as permeability inhibitors within the reservoirs. The effect of faulting on migration of gas is difficult to assess due to the overall poor seismic imaging of the area. Shallow gas accumulations, however, are thought to be indicators of upward migration and will be explored more thoroughly in the seismic attribute analysis.
Figure 6: Tectonic map showing relative plate motions and subduction trench zone. The microplate collision by the Yakutat block is thought to be responsible for the dextral component of movement along the major bounding faults in Cook Inlet. (modified from Haeussler, 2000).
Figure 7: Regional tectonic map showing Plio-Pleistocene anticlines along with major basin-bounding faults (image from Bruhn, 2006).
Data and Methods

Data for this study include wireline logs from wells within the 3D seismic survey. Digital log data were accessed through the Alaska Oil & Gas Conservation Commission website (doa.alaska.gov). Sixteen wells had publicly available production data downloaded from the DrillingInfo website (www.drillinginfo.com). All wells with surface coordinate data and well deviation path files were loaded into Schlumberger's Petrel® 2010 software. Most wells drilled within the last ten years in Ninilchik belong to one of five pads positioned onshore. These pads are the Falls Creek, Grassim Oskoloff, Ninilchik State, Susan Dionne, and Paxton wells (Figure 8). Bottom hole locations for wells belonging to a pad can be offset by a mile or more, utilizing S-shaped patterns to gain further reach along the anticline.

Not all imported digital logs contained the same suite of wireline data. Refer to Appendix B for details on available logs for wells used in this study. Corrected gamma ray (GR) logs were available for most wells. Gamma ray is a useful proxy for identifying lithology and correlating logs. Deep resistivity, density, and sonic logs were also used where available to aid in picking tops and correlation between wells.

A 128 square mile 3D seismic survey was provided with a processing report by CGGVeritas detailing the steps taken to merge a newly acquired 2007 survey with an adjacent 2003 survey (Figure 9). Because two acquisition methods were utilized (onshore and offshore), a phase cross-correlation comparison was performed. No phase rotation was identified between the two surveys, thus no phase correction was taken. Both PSDM (pre-stack depth migration) and PSTM (pre-stack time migration) surveys were available. Mis-ties between wells and seismic averaged 0.55% after the depth conversion.
Figure 8: Base map of Ninilchik field. Map includes both 2003 and 2007 surveys. Rectangle outline represents seismic survey boundaries. Red outline indicates unit outline for the Ninilchik anticline. Surface location of well pads shown for all sixteen wells used in study.
A new processing method, 5D interpolation, was developed by CGGVeritas to address the acquisition problems. 5D interpolation uses inline, crossline, offset, azimuth, and frequency data to interpolate signal in gaps where receivers were unable to be positioned due to terrain issues. After 5D interpolation, the seismic volume includes 1120 crosslines and 365 inlines with an adjusted bin size of 82.5x110 feet and a nominal fold of 28. A processing length of 5000 ms was selected. Receiver lines were orientated northwest to southeast while source lines were oriented perpendicular to receivers. An anisotropic velocity model was built based on the RMS interval velocities calculated from the PSTM volume by CGGVeritas and a depth converted volume was created (Figure 10).

Figure 9: Outline of 3D seismic surveys used to merge Ninilchik field data (from CGGVeritas report, 2009). Purple lines indicate offshore (air gun) and receiver lines. Yellow/green lines indicate onshore, dynamite-source lines. Difficult terrain, indicated by gaps and discontinuities near the shoreline interface presented acquisition problems.
Figure 10: Final anisotropic depth velocity model. Interval velocities ($V_{\text{int}}$) shown in feet/second. The observed low velocity zone between 6000 and 12,000 feet is likely associated with the abundant presence of coal and gas in Tyonek reservoir (image from North Ninilchik 3D, Cook Inlet, Alaska Report by CGGVeritas, 2009).

Tops were picked for three surfaces based primarily on gamma ray, resistivity, density, and seismic character. The surfaces picked are the top of the Beluga (TkB), the top of the Tyonek (T1A), and a middle Tyonek coal bed (T3A). Figure 11 shows an example of surface picks based on the Clam Gulch well gamma ray and resistivity log superimposed over a seismic section. A synthetic seismogram for the vertical Corea Creek #1 well was applied to tie picks with the PSDM seismic volume (Figure 12). The synthetic tie performs reasonably well for correlating formation tops, but intra-formational coals tend to attenuate signal deeper in the section, particularly below the top of the Tyonek horizon.
Figure 11: Clam Gulch #1 well with gamma ray (left) and resistivity (right) tracks shown with horizon picks on inline 263 cross-section. Black marks on gamma ray indicate reasonably thick coal layers. Coals in the Beluga formation tend to be too thin and discontinuous to be resolved accurately. Top and mid-Tyonek surfaces were picked where strong reflectors, most commonly associated with coal intervals, could be confidently tracked.
Figure 12: Comparison of seismic data with synthetic trace shown with the Tyonek section of well logs from Corea Creek #1. High amplitudes tend to be attenuated throughout the section due to the presence of coal indicated by spikes on the density and sonic logs. See Figure 7 for well location.
Horizon picks for the three surfaces were selected on every twenty crosslines and every fifth inline where data quality was adequate to confidently follow reflectors. Horizons were generated using a minimum curvature algorithm using horizon picks in Petrel® 2010. The intended use of the interpreted surfaces was to create attribute horizon slices, or attribute volumes that closely follow the interpreted surface layer. Misinterpretations will result in a horizon slice that does not accurately describe a true, geologic surface and may lead to erroneous attribute interpretations. Due to the considerable amount of interpolation between gaps in the data, horizon slices were abandoned in favor of flat, depth slices with the intention to remove a potentially large source of user interpretation error. Depth slices must be used with caution, however, as they do not represent true, geologic surfaces in highly structured areas. A discussion of how depth slices can be used in attribute interpretations is presented in the next section.

Coherence/Variance

The application for coherence and variance attributes can range from aiding in interpretation of structural deformation history, such as faults and folds, to depositional environment and stratigraphy, such as channels and bedding characteristics (Chopra et al., 2007). For attributes that define stratigraphic features to work well, zones of interest (ZOI’s) should be well defined in the seismic interpretation. Due to a lack of data of locations for producing sand intervals and the poor seismic resolution in the deep Tyonek section, discrete zones of interest could not be well defined. Therefore, the focus was shifted towards geometric seismic attributes which are useful for interpreting faults, fractures, subtle folds and changes in bedding dip.

Attributes in this category include dip and azimuth, coherence/variance and ant tracking (Chopra et al., 2007). Coherence is the measure of spatial similarity between traces (Taner, 2001;
Chopra et al., 2007). On a processed volume, the seismic section is the response of the input seismic wavelet generated from the source with the subsurface geology. That response, which differs depending on acoustic impedance contrasts affected by lithology and rock-fluid physical properties, is observed through changes in amplitude, phase and frequency. Coherence essentially measures the magnitude of those changes, both laterally and vertically.

In Petrel® software, coherence is accomplished through an alternative attribute, variance. Although both variance and coherence measure the similarity between waveforms, variance is mathematically expressed as one minus the coherence value. For example, if all traces are equal, the coherence semblance value, \( c_s \), is 1.0, and the variance, \( c_v \), is 0.0 (Chopra et al., 2007).

When calculating variance, dip and azimuth values must be defined for each trace. This can be done manually by flattening on an interpreted surface or through a separate calculation by estimating dip and azimuth in a semblance scan. The latter method corrects for bedding dip and attempts to remove its effects from the variance output. To avoid as much interpretation error as possible, the variance attribute was calculated by allowing the software to perform a semblance scan. A comparison was made in Figure 13 to demonstrate the difference between variance calculated with and without a semblance scan. The flanks of the anticline with the most dip show higher variance indicated by the gray and black shades representing a strong indication of seismic variance. The bottom image in Figure 13 shows considerably less variance along the more steeply dipping flanks, indicating a successful removal of noise due to structural dip. By using a semblance scanned variance attribute, flat depth slices theoretically should not be influenced by bedding dip which might otherwise introduce noise when interpreting faults or other structural features.
Figure 13: Comparison of two variance attribute maps at 6550 ft TVD. Shown without dip guidance (above) and with dip guidance (below). Darker colors are high variance, and lighter colors are low variance. Blue arrows indicate areas where dipping beds were misinterpreted as low coherence events in the top image and removed in the bottom image.
Local Structural Azimuth

Azimuth maps are used to extract information about bedding dip direction. Although using pre-stack depth migrated volumes provide a more geologically sound interpretation for reflector dip magnitude, there is inherent error caused by the background velocity model (Chopra et al., 2007). Nevertheless, it is an improvement over the estimation for reflector dip and azimuth based on a time migrated volume. The azimuth attribute maps are excellent for interpretation of subtle folds or other flexures in seismic waveform related to changes in the subsurface geology. Dip can be defined as two components, dip magnitude and dip direction. When discussing dip and azimuth in seismology, dip can be defined as the first aforementioned component, the dip magnitude, \( \theta \). Azimuth is therefore defined as the second component, the maximum dip direction, perpendicular to reflector strike. The azimuth attribute, therefore, reflects changes in the dip direction (Chopra et al., 2007). The focus for this study will be on the application of the local azimuth attribute to define the subtle flexure of the Ninilchik anticline. Due to the noisy character of the data, the azimuth attribute is smoothed which reduces the sensitivity to noise but also reduces the resolution of the resulting maps.

Envelope Strength

Amplitude mapping, also known as envelope strength, is one of the most common and well known applications of seismic attribute analysis due to the direct correlation between changes in amplitude with changes in geology. Changes in the amplitude strength in the lateral direction can be related to tuning effects, a phenomenon where closely spaced events cause constructive or destructive interference of the waveform and become difficult to distinguish as separate events. Amplitude variations may also reflect changes in lithology and pore fluid
content (Chopra et al., 2007). The envelope strength attribute measures the absolute value of the energy signature of a waveform independent of phase and polarity. Bright spots, a term used to describe anomalously high amplitude zones in seismic, typically are interpreted as a gas indicator in clastic, Tertiary basins. Bright spots in the Cook Inlet basin, however, can normally be associated with the presence of a coal bed of substantial thickness which typically mark the base of potential sandstone reservoirs.
Results and Discussion

Horizon Interpretations

Three horizons were interpreted based on well tops and seismic picks. These horizons include the top of the Beluga, the top of the Tyonek, and a middle Tyonek coal. Figure 11 shows the seismic character associated with each surface. The Beluga formation is identified in the seismic by its low amplitude reflectors. Coal beds are too thin and discontinuous to provide strong, bright reflectors. The top Beluga is picked just beneath the last, bright reflector in the Sterling formation, although the transition between the Beluga and Sterling formations is often highly gradational and difficult to identify. The top of the Tyonek is marked by the appearance of the first, thick coal horizon, associated with a bright, continuous reflector beneath the Beluga. The middle Tyonek coal surface is picked along another coal bed event that can be confidently tracked and is recognized as the approximate top of the reservoir sand intervals.

Figure 14 displays the structure contour maps for the three interpreted surfaces. Three distinct capture areas are identified. Areas 1 and 2 are separated by a normal fault striking primarily east-west with a maximum vertical displacement of roughly 1000 feet. Constraining the location of this fault is discussed in detail in the attribute section. Areas 2 and 3 are separated by a spill point creating two distinct, structural closures. The Falls Creek wells are the only set of wells belonging to the first area. The Grassim Oskolkoff and Ninilchik State wells belong to area 2, and the Susan Dionne and Paxton wells to area 3 (Figure 14). Well groups are evaluated under the consideration that each area represents an independent hydrocarbon system. Although not shown in the structure contour maps in Figure 12, numerous faults are present in the subsurface, often difficult to identify due to noisy data in the vicinity of the wells. Fault locations and geometries are explored more fully on a case by case evaluation for each set of wells.
Figure 14: Surface interpretations for top of the Beluga (above), top of the Tyonek (bottom-left) and middle of the Tyonek (bottom-right) using minimum curvature algorithm. Surface locations for each set of wells shown in the top of the Tyonek structure map. All well groups belong to one of three, distinct areas.
Falls Creek Wells

The Falls Creek wells were drilled on the northeastern fault block of the Ninilchik anticline within area 1 (Figure 14). The original Falls Creek #1 well was drilled in 1960 to test for oil in Hemlock formation, but producible amounts were not discovered. The first well to come online in the past decade was the Falls Creek #1 re-drill, or 1-RD, in early 2003. The Falls Creek #3 well was completed shortly afterwards and began producing from the Tyonek sands a month after Falls Creek #1-RD well. Falls Creek #4 well was drilled into the shallower Beluga formation to test the sands as a potential secondary reservoir. Falls Creek #1-RD and #3 wells targeted gas-bearing sands in the lower Tyonek formation along the crest of the anticline. The lower Tyonek section of Falls Creek #1-RD well is slightly updip from Falls Creek #3 well (Figure 15). Figure 16 shows the production histories for the two Tyonek Falls Creek wells, #1-RD and #3.

Abundant coal beds provide the source of methane gas produced from the sands in the Tyonek and Beluga formation (Claypool and Magoon, 1980). The Tyonek formation is characterized by thick and continuous coals which have significantly lower density and acoustic velocities than the surrounding sandstones and siltstones. These properties give coal a strong acoustic impedance contrast to the interbedded sands and silts. Tracking coals can be accomplished by identifying high amplitude reflectors on normal seismic sections. Figure 18 shows the envelope strength volume cube from 6000 to 8000 ft with low amplitude events removed, leaving only high amplitude events. Hotter colors are higher amplitudes and cooler colors are lower amplitudes. Three separate coal horizons are identified. Based on the thickness of the coal beds (10-20 feet) observed in the electric logs, the diminishing of high amplitude events towards the wellbores is likely due to thin-bed tuning effects combined with normal wave
attenuation. It is apparent from the numerous density, resistivity, and sonic "spikes" on the logs that more coal intervals occur throughout this section (Figure 17).

![Figure 15: Structure contour map of area 1 Falls Creek wells. Surface shown is the interpreted mid-Tyonek horizon. Falls Creek #1-RD and #3 are Tyonek production wells drilled to the same interval.](image)

Despite the limitations to identifying coal on the seismic presented here, envelope strength volumes can be a valuable first order estimation to the presence of coal, and subsequently the presence of potential source rock material. As sand bodies are irregularly distributed throughout the section, detecting source rock volume may be an alternative to estimating potential volumes of hydrocarbons.
Figure 16: Production history for Falls Creek Tyonek wells. Unit MCF is equivalent to one thousand cubic feet of gas. Falls Creek 1-RD is the up-dip well in this location.
Figure 17: Log correlation of coals for the Falls Creek Tyonek wells. Wells are spaced approximately 3000 ft apart. Coals are used to correlate due to their characteristic log signature and tendency to be laterally continuous in the Tyonek formation.
Figure 18: Distinct, high amplitude events, labeled "A", "B", and "C", in the lower Tyonek formation. See Figure 17 for correlation to electric logs. A perspective from the west was chosen to highlight the distinct layers identified using this method. Vertical extent from 6000 to 8000 ft TVD.

In Figure 19, a seismic section and corresponding variance depth slice at 5500 ft shows the advantage of using the variance attribute to identify faults, independent of their strike. A seismic section displaying normal amplitudes at the 5500 ft depth slice shows the changing magnitude of bedding dip towards the major reverse fault to the northwest and and the edges of the highly chaotic seismic around the Falls Creek wells. The location and presence of geologic discontinuities are not apparent on the seismic section. The variance depth slice highlights several linear features that appear to be faulted related and aligned sub-parallel to the main reverse fault zone. The faults do not appear to extend, however, through the wellbore locations.
Figure 19: Depth slice at 5500 ft TVD of the seismic section at Falls Creek (above) and corresponding variance depth slice (below). Arrows indicate distinct, linear features associated with faults clearly identified by the variance attribute section.
An ant tracking attribute cube was created using the dip-guided variance volume. Ant tracking was originally developed to help reduce noise in a variance plot by connecting adjacent low coherence events in the shortest distance possible. In a practical sense, ant tracking is conventionally used on a variance volume to enhance linear incoherencies such as faults and remove horizontal noise associated with stratigraphy (Chopra et al., 2007).

Figure 20 shows a map view of the Falls Creek wells with high variance features isolated after an ant tracking attribute was applied. The white arrows indicate the major reverse fault zone that bounds the anticline to the northwest. The red arrows highlight the pair of linear features that are sub-parallel to the main reverse fault and can be observed on a depth slice of the variance section as seen in Figure 19. Because this pair of linear features extends continuously from 5500 to 6500 ft, they are interpreted as a set of faults.

Some difficulty occurs when determining the lateral extent of the pair of faults near the Falls Creek wells. While there is little evidence to support that fault compartmentalization is a valid explanation for the difference in production seen between Falls Creek #1-RD and Falls Creek #3 wells, it is interpreted that the increase in production on the Falls Creek #1-RD is due in part to enhanced permeability caused by the faulting associated with tensional and stress forces acting on the crest of the main fold. Based on the variance model, production history of the wells, and amplitude analysis, it is interpreted that the wells’ reservoirs are laterally connected, and that a contributor to the Falls Creek #1-RD’s higher overall production is the updip position of the bottom hole location. Production history in Figure 16 shows a slight increase in Falls Creek #1-RD around month 25 when Falls Creek #3 was declining rapidly. This suggests some degree of reservoir connectivity between the two Tyonek wells.
Figure 20: Ant tracking co-rendered with variance attribute cube displaying continuous, low coherency seismic (above). Depth slice at 6000 ft TVD showing all ant tracking results (below). White arrows indicate major reverse fault bounding anticline. Red arrows indicate presence of smaller, normal faults sub-parallel to the major reverse fault.
Grassim Oskolkoff Wells

The Grassim Oskolkoff (GO) wells were drilled into the central fault block of the Ninilchik anticline (Figure 22). Seven wells were drilled from the Grassim Oskolkoff pad from 2003 to 2007. Figure 21 shows the overall production results from four of the Tyonek wells for which production history was available. Grassim Oskolkoff #1 well is the superior producing well, although the source of the sharp rise in production around month forty is unknown. The objective of the Grassim Oskolkoff wells was to develop the gas sands in the Tyonek pool over an apparent faulted three way closure. Analysis of these wells through attribute characterization is difficult due to the poor seismic quality in the vicinity of the wells. Noisy data is likely due to a combination of acquisition challenges near the shoreline compounded with faulting and associated shallow gas pockets.

Figure 21: Production history for Grassim Oskolkoff wells.
Figure 22: The middle of the Tyonek structure contour map for area 2 with Grassim Oskolkoff and Ninilchik State wells. Note that target sands range in depth from 5000-7000 ft TVD based on limited perforation data from GO #2 well.

The depth slice in Figure 23 was based on the known perforated zones in the Grassim Oskolkoff #2 well. Information for perforated zones was available only for this well, which was used to constrain the range of attribute investigation from 5000 to 7000 ft TVD. Poor seismic in the vicinity of the well did not allow interpretation of reservoir horizons to be made based off of known perforated zones. Observations based on the variance slice, even after accounting for dipping beds, proved to be difficult given the seismic noise around the Grassim Oskolkoff wells. A fault is suggested to exist between the Grassim Oskolkoff wells and the Falls Creek wells due to considerable stratigraphic vertical offset between them. Ant tracking on the variance slice was found to be particularly useful for identification of the possible location for this fault (Figure 23).
Figure 23: Variance depth slice (above) and ant tracking attribute output (below) at 6950 ft TVD for Grassim Oskolkoff wells. The low coherency zone does not mimic the shoreline trend in this area. Strong, northeast-southwest trending linear features are related to major reverse fault zone in lower image. Arrows indicate presence of fainter features within the chaotic section interpreted as normal fault segments.
The variance map in the top image from Figure 23 does not identify any significant fault related events but does provide the edges of the poor seismic area and the major reverse fault system bounding the anticline. The bottom image in Figure 23 displays two fault interpreted features labeled "A" and "B". The map was made by running the ant tracking algorithm on the variance dip-guided volume. Fault "A" is interpreted as a normal fault with the downthrown side to the north. Fault "B" is interpreted as a synthetic fault to "A". These faults are only evident from a depth range between 6500 to 7500 feet. Above and below these depths the continuity in the ant tracking attribute is lost. It is interesting to note that the primary fault "A" is oriented roughly east-west which corresponds well with the trend of the chaotic seismic in the top image. One explanation for this trend is the potential for fracture density to increase in the vicinity of a large fault. Although fractures are not generally resolvable seismically, they can alter the acoustic energy propagation enough to create a zone of low signal to noise which often makes interpretation near complex fault systems difficult. Furthermore, it could be a potential conduit for gas migration contributing to the noise content in the seismic.

Based on the timing of completion and steady decline in initial production of the Grassim Oskolkoff wells, reservoir connectivity and pressure depletion appear to be driving factors. The data suggest the short offset wells are producing from sands that have some reservoir connectivity. Grassim Oskolkoff #1 well is located in an up-dip location from the subsequent wells and is nearest the identified fault "A" which may be providing enhanced permeability through higher density of fractured coals. This interpretation suggests that the placement of the #1 well is nearest the furthest extent of lateral, up-dip migration on the structure. Other conventional attribute applications such as amplitude strength, dip and azimuth were not evaluated due to low signal to noise and overall low confidence in stratigraphic interpretation.
Ninilchik State Wells

Located about two miles southwest of the Grassim Oskolkoff well pad, the Ninilchik State wells were drilled between 2005 and 2007. The goal was to develop the gas sands in the Tyonek formation along the flanks of the structural high adjacent to the Grassim Oskolkoff wells (Figure 22). Production data for Ninilchik State #1 and #3 wells are shown in Figure 24.

![Ninilchik State wells - Production History](image)

**Figure 24:** Production history for Ninilchik State wells. No production history information was available for Ninilchik State #2 well.

The bottom-hole locations for the Ninilchik State (NS) wells are on the edge of the very poor seismic section that encompassed the Grassim Oskolkoff wells. In Figure 25, a gas chimney expression is observed bounding the northern-most Ninilchik State #3 well. Gas chimneys are identified by a low frequency, high amplitude signature over a structural high, typically followed
by a low amplitude washout zone beneath. The attenuation associated with the shallow gas normally diminishes with depth.

Recognition of a gas chimney has two important implications. For one, hydrocarbons have been generated, and secondly, the system is leaky or not completely sealed. Whether this has significant implications for hydrocarbon volumes depends on the timing of hydrocarbon generation versus the timing of the fault system that opened up pathways to the surface.

Figure 25: Identification of a gas chimney near Ninilchik State wells. Chimneys are characterized by high amplitude energy near the surface, followed by a low amplitude washout below. Arrows indicate the presence of vertical gas pathways to the surface. Ninilchik State wells #1 (green), #2 (red), and #3 (yellow) shown. Viewed from the west.

A noteworthy difference of the Ninilchik State wells from the previous well groups discussed is the down-dip location of the highest producing well, Ninilchik State #1, relative to
its peer well, Ninilchik State #3 (Figure 22). No production data were available for the Ninilchik State #2 well. Figure 25 shows the relative borehole locations for each of the three Ninilchik state wells. There is evidence for gas migration indicated by the pair of narrow, vertical chaotic zones. Furthermore, a variance depth slice at 5000 ft (mid-Tyonek) supports the presence of a laterally extensive variance noise connected to the vertical pathways (Figure 26).

Figure 26: Migration pathways based on structure and apparent gas chimney events. Seismic shown with crossline 850 and variance depth slice at 5000 ft. Two gas chimney zones are identified and labeled as "A" and "B". Ninilchik State #1 (green), #2 (red), and #3 (yellow) shown.

Ninilchik State #1 well's higher production is likely associated with its position relative to the observed migration pathways. Gas generated along the eastern flank of the anticline travels up-dip and enters the first pathway "A". Barring this, hydrocarbons would continue migrating up towards pathway "B" through the sands intersecting the Ninilchik State #1 well. The position of
the Ninilchik State #3 well along the western flank is outside the ideal zone where maximum stresses occur to generate faults and fracture pathways. The Ninilchik State #1 well's favorable location between the two vertical migration pathways best explains its production advantage over its structurally up-dip peer well.

Overall, area 2, which includes the Grassim Oskolkoff and Ninilchik State wells, is a challenging area to evaluate using seismic attributes due to a combination of factors leading to high noise and attenuation in the seismic. Nevertheless, both sets of wells have a clear, superior producing well. In both cases, the #1 well (earliest well to begin production) has production results that average higher than their offset wells. One explanation is that the reservoirs are at least partially connected, causing later wells to produce from lower volumes and formation pressures. Production decline curves, however, do not seem to support strongly connected systems. For example, the Ninilchik State #1 well, which began production in 2007, showed higher initial production than the much earlier Grassim Oskolkoff #3 well in late 2005. This evidence suggests that the sand reservoirs are somewhat irregular and other explanations must be sought.

While the latter explanation seems reasonable, it has also been shown that each #1 well was positioned near a low coherent feature of some linear quality, an indication of a fault or migration pathway. Wells more distal to these events or positioned down-dip to the western side of the anticline consistently perform lower (e.g. Grassim Oskolkoff #6 and Ninilchik State #3). Given the lateral heterogeneity of the Tertiary sequence, changes in reservoir properties, such as porosity and permeability, could be significant over short distances. It therefore becomes critical for a vertical well to be positioned favorably near a pathway for gas as the lateral migration of hydrocarbons may be severely hindered.
Susan Dionne and Paxton Wells

The Susan Dionne wells were drilled into the southernmost four-way structural closure in area 3 on the Ninilchik anticline. Production curves can be seen on Figure 27 for the Susan Dionne wells. Completed between 2002 and 2007, the Susan Dionne wells were among the most consistent and successful wells in the entire field. Paxton wells were drilled into the same structure but slightly down-dip to the southwest. The Paxton wells include the most recently drilled wells in Ninilchik field. Production data for Paxton #1 and #2 wells are seen in Figure 29.

![Figure 27: Production history for Susan Dionne wells.](image)

The structure of the Ninilchik anticline in the southern area of the field undergoes a slight directional shift. The fold crest broadens into a wide "plateau" with shallower bedding dips as opposed to the more steeply dipping, narrow fold seen in previous sections of the field. Figure 28
shows a crossline segment intersecting the anticline near the Susan Dionne wells demonstrating this change. Compared to the previous areas observed to the northeast, the width at the crest of the anticline is nearly twice as wide.

Figure 28: Crossline 997 showing broad shape of the anticline near Susan Dionne wells. Viewed from the southwest.

The broad capture zone may explain some of the high production results from the Susan Dionne wells. The azimuth attribute was used to examine this characteristic further. Local structural azimuth is an attribute that assigns an azimuth, or dip direction, value to each trace, independent of dip magnitude. Chopra and Marfurt (2007) provide a detailed definition for the dip and azimuth calculation methods. Due to significant amount of poor seismic, a higher weighted average attribute (greater smoothing) was applied to mitigate the effects of the noisy seismic data and create a more coherent image. Some resolution is lost in the smoothing process.
The advantage to using this attribute is it allows the interpreter to see subtle structural or dip changes in the seismic that are otherwise less apparent. Figure 29 shows a depth slice at 7000 ft near the Susan Dionne wells. Note the shift abruptly towards the south near the top of the image.

Figure 29: Local structural azimuth attribute depth slice at 7000 ft TVD. Susan Dionne #2 (orange), #3 (red), #4 (purple), and #5 (blue) wells shown. Solid, black lines indicate the trend of the anticline axis.

A secondary fold also becomes apparent in the vicinity of the Susan Dionne #2 well which appears to be parallel with the original axis of the anticline. If we consider that the transition from the warmer to cooler colors occurs at the crest of the anticline, it becomes evident that the majority of the Susan Dionne wells were placed in line with the original, or more northerly, fold axis. The Susan Dionne #5 well was positioned adjacent to the shifted fold axis. Although all the Susan Dionne wells show production results considerably higher than other wells in the field, the Susan Dionne #5 produced at the highest, consistent rates, despite being
one of the later wells to come online. Previous well groups examined have shown a trend where earlier wells produce at higher rates than subsequent, offset wells.

Strong amplitude events below the surface similarly identified above previous well locations provide evidence for gas accumulation above the target zone. Figure 30 demonstrates the abrupt seismic character change on a northeast-southwest inline shown with the Susan Dionne #2, #3, #4 and Paxton #1 wells. Two zones indicated by the black lines outline the washed-out seismic sections. Evaluation of the amplitude attribute is therefore severely limited due to loss of energy in the wells' vicinities.

Figure 30: Inline 266 shown with Susan Dionne wells #2, #3, and #4 along with Paxton #1. Boundaries for two gas-related washout zones are indicated by two sets of black lines.
The Paxton well #1 spudded in 2004 to test and develop known gas sands in the Tyonek formation. After its initial production in 2005, another Paxton well was not drilled until 2008. Production results from Paxton #1 were significantly less than the initial production seen in the 2008 Paxton #2 well (Figure 31). Similar to the adjacent Susan Dionne wells, the more favorable well is drilled later than the initial well. The bottom-hole location of Paxton #2 is approximately 3000 feet offset to the southeast from the Paxton #1 and slightly up-dip. Paxton #2 is positioned in line with the crest of the fold, similar to the Susan Dionne #5 bottom hole location. Because both the Paxton #2 and Susan Dionne #5 wells are highly successful wells that penetrate the formation along a fold axis further to the southeast, it is suggested that these two wells are producing from a higher permeability zone (Figure 32).

![Paxton wells - Production History](image)

**Figure 31: Production history for Paxton wells.** The Paxton #2 well constitutes one of the most recent wells drilled in the Ninilchik field with available production results.
Figure 32: Local structural azimuth attribute at a depth slice of 7000 ft TVD for Paxton and Susan Dionne #5 wells. White dots indicate bottom hole locations. Colors represent direction of dip at the depth displayed. Dark line indicates approximate location of fold axis based on the smoothed azimuth attribute.

The variance and ant tracking attribute are used in the same manner as the Grassim Oskolkoff wells. The majority of the low coherence observed in the top image of Figure 33 is related to the shallow gas and its associated poor seismic quality. A linear, low coherent event is identified oriented approximately east-west. This feature is likely associated with a narrow gas migration pathway due to a normal fault segment bisecting the anticline. The corresponding depth slice with the ant tracking attribute further suggests the presence of a low coherent event aligned nearly perpendicular to the major reverse fault zone to the northwest.
Figure 33: Depth slice at 6200 ft TVD of variance (above) and ant tracking cube on the variance attribute volume (below) over Susan Dionne and Paxton wells. Green arrows indicate linear feature that shows some offset in the chaotic zone. Red arrows indicate lateral displacement along this feature. Paxton #1 (light purple) and Paxton #2 (green) shown with Susan Dionne #2 (orange), #3 (red), #4 (purple), and #5 (dark blue).
Based on correlation of prominent coal beds using density and gamma ray logs, the Tyonek formation is offset 100 to 150 ft down-dip to the Paxton #1 well from the Susan Dionne #4 well. Considering the horizontal distance between these two bottom-hole locations is approximately 3000 ft, it is not unreasonable that bedding dip, as opposed to a fault, is responsible for the offset between these wells. However, cleaner seismic in the shallower portions of the data above these wells shows minor faulting in the bedding (<40 ft displacement). Estimating displacement for the fault seen in Figure 33 is difficult in both the seismic and well log correlation, though it can be inferred from the variance and ant tracking images that some displacement is evident from the sinistral shift component, indicated by the red arrows in Figure 33, which bisects the chaotic zone.

The Susan Dionne and Paxton wells are some of the most successful in Ninilchik field. The seismic attribute work suggests that this structure-related trap is more complex than it appears initially. A broad, undulating anticline fold contrasts with the narrower, singular fold observed elsewhere in the field. Evidence for shallow gas accumulation is apparent as the structural peak is strongly chaotic in character compared to the peripherals of the anticline. Two wells drilled near the more southeasterly fold axis display the highest and most sustained production. The overall success of every well in this zone, however, suggests potential for development in this area, especially along the eastern flank of the structure.
Conclusions

Ninilchik field is part of a prolific basin with abundant shallow gas resources sourced from regionally extensive series of coal layers. Shallow gas coupled with the complex structure and coal bed acoustic properties degrades the seismic data quality in some areas. Seismic attributes such as dip, variance, and azimuth, which fall in the geometric attribute family, broadly define the seismic character better than direct, instantaneous measurements, such as frequency, amplitude and phase, which are more sensitive to noise.

Early wells drilled in the structurally up-dip position are shown to have the highest production rates in most circumstances. This is supported by the Falls Creek and Grassim Oskolkoff wells where the variance attribute shows no evidence of fault compartmentalization or presence of channelized features that might otherwise explain production rate variations. Proximity to major faults and their association with fractures and enhanced permeability may be responsible for the success of the Grassim Oskolkoff #1 well. Similarly, the best producers from the Susan Dionne and Paxton well groups are adjacent to an identified fault evident from an ant tracking and variance co-rendered attribute volume.

Envelope strength/amplitude mapping is useful for a first order approximation for the presence of coals. However, conventional "bright spot" mapping is not applicable to this environment as high reflectivity from abundant coals is the main source of strong amplitudes and not necessarily related to hydrocarbon accumulation. Furthermore, attenuation and distortion of energy detracts from the quality of the signal in the deeper sections and reduces confidence in accurate interpretations of horizons.

Wells positioned closest to the crest of the anticline consistently outperform wells structurally down-dip. A broadening and eventual shift of the crest orientation as the anticline
progresses southward is well defined by the local structural azimuth attribute. Susan Dionne well #5 and Paxton #2 have bottom hole positions in line with the shifted fold axis and show the highest production relative to their peer wells. Furthermore, the ant tracking attribute volumes suggest wells nearer the faults associated with tensional stresses along the main fold axis have higher, sustainable production of methane gas.

Favorable opportunities for future development wells exist for the Ninilchik field, particularly in the southern portion where the broad extension and of the anticline should provide a broader capture zone. Reprocessing the seismic data would be a low cost method to assist future well planning in the Ninilchik field. A detailed fault interpretation could be accomplished from an improved seismic imagining process and would be an invaluable tool for more fully understanding migration, reservoir connectivity, and other well controls.
References

Ayres, M.G., 1959, Regional geology of the Cook Inlet area, Alaska: unpub. rept.


Appendix A: Glossary of Terms

**analytical trace:** A complex trace composed of the real trace and its imaginary component.

**anisotropy:** A property of a material in which there is a predictable variation based on the direction in which it is measured.

**bin:** A subdivision of a seismic survey, used to describe the size of an area to which all traces belonging to that subdivision are assigned.

**bright spot:** A zone in seismic data that has an anomalously strong amplitude. For gas plays in a Tertiary siliciclastic basin, bright spots typically have strong negative amplitude.

**coal bed methane:** A term referring to the formation of methane gas, the principal component of natural gas, from the micro-organisms associated with organic coal layers.

**coherence:** A measure of seismic waveform similarity.

**complex-trace attributes:** Time/frequency attributes obtained from the complex or analytical seismic trace.

**crossline:** The axis perpendicular to the inline direction of shooting.

**depth slice:** Extraction of values from a seismic or attribute volume corresponding to a constant depth value, $z$.

**deviated well:** A wellbore that is not vertical. The term can describe any number of non-vertical well shapes, including S-shaped and L-shaped well paths.

**dip azimuth:** The direction of the maximum dip vector.

**dip magnitude:** The magnitude of the dip vector, typically defined as $\theta$.

**envelope:** The magnitude of the complex or analytical trace. Synonymous with reflection strength.

**flexure:** A term that defines a simple lateral change in dip magnitude and/or dip azimuth.

**fold (seismic acquisition):** Used to refer to the number of traces sharing the same midpoint (in 2D acquisition), or the number of traces sharing the same bin (in 3D acquisition).

**gas chimney:** A region of gas escaping and migrating upward from a hydrocarbon accumulation. Gas chimneys appear as low-amplitude, chaotic zones on conventionally imaged seismic data.

**geometric attributes:** Multitrace attributes the measure changes in reflector shape or morphology. Examples include coherence, dip/azimuth, energy gradients, and curvature.
**horizon slice:** Extraction of values from a seismic or attribute volume corresponding to an interpreted horizon.

**inline:** The axis parallel to the direction of shooting. The inline may also be selected arbitrarily and used mainly as a means of referencing the data grid.

**instantaneous attributes:** Time-frequency attributes based on the real and quadrature (or imaginary) components of the complex trace at each instant in time.

**P-wave:** An elastic body wave or sound wave in which particles oscillate in the direction the wave propagates. Synonymous with compressional or acoustic waves.

**pattern recognition:** Analysis of data to discover the combinations of different measurements or features that are distinctive of specific patterns.

**phase (geophysics):** A description of the motion of, or means of comparison of, periodic waves using wave shape, frequency, symmetry, and amplitude.

**quadrature component:** The Hilbert transform of the original (real component) seismic trace. Also called the imaginary component of the analytical trace.

**ricker wavelet:** A zero-phase wavelet commonly convolved with a reflectivity trace to generate a synthetic seismogram.

**spectral decomposition:** Decomposition of a temporal window of data into its Fourier magnitude and phase components.

**stratal slice:** A means of displaying seismic data along a surface that is proportionally equal between an upper- and lower-interpreted surface, mimicking surfaces that display a fixed geologic time.

**synthetic:** A one-dimensional model of acoustic energy traveling through layers of the Earth.

**time slice:** Extraction of values from a seismic or attribute volume corresponding to a constant time value, \( t \).

**tuning effect (thin-bed event):** An event occurring from the constructive or destructive interference of waves from closely spaced reflections. At a spacing below one-quarter wavelength, reflections undergo constructive interference and become difficult to distinguish as separate events.

**variance:** A statistical measure of data or attribute variability about the mean or average. The variance cube is a coherence attribute which is mathematically equivalent to 1D semblance.

**wavelet attribute:** Time-frequency attributes corresponding to the instantaneous attribute at the peak of the envelope in which each sample falls.
**Appendix B: Wells Used in Study**

<table>
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<th>TVD (ft)</th>
<th>Logs Available*</th>
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* SP = Spontaneous Potential  
  GR = Gamma Ray  
  ResD = Resistivity (deep induction log)  
  Sonic = Compressional (p-wave) velocity  
  RhoB = Bulk Density
Vita

Andrew Sampson was born in Jackson, Mississippi, in 1983. He attended high school at St. Andrew's Episcopal School in Ridgeland, Mississippi. After graduating in 2001, he remained in Jackson and enrolled at Millsaps College where he graduated with a Bachelor of Science in geology and a minor in mathematics and physics in 2005. After briefly considering a career in medicine, Andrew instead chose to pursue a master’s degree in geology at Louisiana State University in Baton Rouge beginning in 2008. He spent the summer of 2010 working as a Teaching Assistant for the LSU Field Camp program in Colorado Springs, Colorado, where he gained a greater appreciation for field work and geology. During the summer of 2011, Andrew interned with Marathon Oil in Houston and was offered a full time position as a geophysicist in Oklahoma City working with the Woodford Shale Gas Asset team. Andrew plans to begin his career with Marathon Oil beginning in the early part of 2012.