ANALYSIS OF POROSITY TRENDS IN THE KEVIN-SUNBURST DOME USING 3D SEISMIC REFLECTION DATA, TOOLE COUNTY, MONTANA

by

Jason A. Stein

A Prepublication Manuscript Submitted to the Faculty of the DEPARTMENT OF GEOSCIENCES

In Partial Fulfillment of the Requirements for the Degree of MASTER OF SCIENCE

In the Graduate College THE UNIVERSITY OF ARIZONA 2008
STATEMENT BY THE AUTHOR

This manuscript, prepared for publication in the American Association of Petroleum Geologists Bulletin, has been submitted in partial fulfillment of requirements for the Master of Science degree at The University of Arizona and is deposited in the Antevs Reading Room to be made available to borrowers, as are copies of regular theses and dissertations.

Brief quotations from this manuscript are allowable without special permission, provided that accurate acknowledgment of the source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the Department of Geosciences when the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

(author's signature) 7/29/08
(date)

APPROVAL BY RESEARCH COMMITTEE

As members of the Research Committee, we recommend that this prepublication manuscript be accepted as fulfilling the research requirement for the degree of Master of Science.

Dr. Roy Johnson 7/29/08
Major Advisor (signature)

Dr. George Zandt 7/29/08
Advisor (signature)

Dr. Clement Chase 29 Jul '08
Advisor (signature)

2
Analysis of Porosity Trends in the Kevin-Sunburst Dome Using 3D Seismic Reflection Data, Toole County, Montana

Jason A. Stein¹, Roy A. Johnson¹, Eric H. Johnson²

¹Department of Geosciences, University of Arizona, Tucson, AZ 85721
²Americana Resources, Billings, MT 59101

Abstract

The Kevin-Sunburst Dome of northern Montana has been an area of established oil and gas production for over 80 years. Exploration by random drilling and subsurface extrapolation of well data have identified eight producing formations, two of which will be the focus of this paper: the Jurassic Sawtooth Formation and the Devonian Nisku Formation. Each contains productive zones of porosity; however, little is known about the lateral extent of porosity. 3-D seismic reflection data in the area provides a relatively detailed image of the subsurface structure, but may not resolve depositional environments or stratigraphic features controlling porosity distribution. More in-depth seismic interpretation allows the correlation of observations from available well logs to attributes in the seismic data in an attempt to characterize specific seismic responses associated with oil- and gas-saturated porosity zones. Identified areas of interest are analyzed via synthetic seismic modeling, attribute extraction, and spectral decomposition to examine relationships between observed anomalies and areas of known production. The result is an improved understanding of the geologic setting, and a clearer perspective on what benefits 3-D seismic data can provide in choosing potentially productive well locations.
Introduction

The Kevin-Sunburst Dome is a prominent structural feature that is part of the larger Sweetgrass Arch of Montana and Alberta (Figure 1). Oil and gas fields found on the dome have been producing for decades; however, little has been done in attempt to characterize the lateral extent of certain porosity zones beyond subsurface well correlation, geologic interpretation, and a few 2D seismic lines. An 39 square mile (~100 km²) 3D seismic reflection survey acquired during 2007 on the northeast portion of the dome has allowed more in depth exploration and interpretation than had previously been done (survey information can be seen in Appendix A). Focusing on zones of porosity within the Jurassic Sawtooth Formation and the Devonian Nisku formation, available well log data was correlated with the 3D seismic. For the first time in this area, attributes potentially associated with the occurrence of hydrocarbons have been modeled, viewed, and mapped throughout the survey area, adding confidence and new insights to previous structural and stratigraphic interpretations. In addition, preliminary spectral decomposition was performed on the intervals of interest in an attempt to view any anomalies or characteristics that were not readily apparent on the full-bandwidth data. The results at the Sawtooth interval are very promising, with attribute maps clearly defining an area of interest supported by well data and stratigraphic interpretations. Results from the Nisku interval produced several interesting observations; however, none could be directly correlated to production, mostly due to the resolution of the seismic data, and the variability and uncertainty of well data.
Geologic Setting

In 1986, Warren Shepard and Betsy Bartow described the geological characteristics of the Sweetgrass Arch and its relation to hydrocarbons (Shepard 1986). They described the Sweetgrass Arch as a late Laramide, north-plunging structural nose immediately east of the Rocky Mountain overthrust belt, which covers a distance of 165 miles (~265 km) through central Montana and Alberta, Canada. It is believed that the east-dipping flank of the arch provided the structural relief that allowed hydrocarbons generated in Mississippian source rocks to migrate westward into the arch from the Williston Basin to the east. A more likely source, however, is that hydrocarbons were thermogenically generated from the Bakken Shale beneath the overthickened sequence of rocks in the thrust belt to the west.

In its central portion, the Sweetgrass Arch is offset approximately 30 miles (~48 km) to the east by the right-lateral Pendroy fault, causing the closure that is the Kevin-Sunburst Dome (Shepard 1986). The dome covers approximately 1000 square miles (~2590 km²) of north-central Montana, and provides around 850 feet (~259 m) of structural closure (Figure 2). However, it is believed that stratigraphic traps still dominate as the setting for hydrocarbon accumulation (Herbaly 1974). When oil was discovered in the Nisku Formation in the early 1980’s, new interest was sparked in the dome’s reservoir potential (McCaslin 1984).
The youngest formation focused on in this paper is the Jurassic Sawtooth, a shallow marine formation consisting of basal sandstones grading up into shales and calcareous siltstones. In the northeast portion of the Kevin-Sunburst Dome, the sandstones are generally very fine grained and occur as lenses and thin layers in the siltstone (Cobban 1945). In the survey area, the formation varies from around 5 to 60 feet (~1.5 to 18 m) thick based on well logs. The zone of interest is a lower sand unit which ranges from 10 to 20 feet (~3 to 6 m) thick, and can reach porosities of up to 20%. Based on unit thicknesses from available well logs, as well as some known larger structural trends, an initial interpretation predicted the lateral extent of the porosity zone (Figure 3). It was believed that within the extent of the survey, the majority of porosity was controlled by stratigraphy, showing an apparent up-dip pinch-out from northeast to southwest. On the northeast corner of the survey it is believed that porosity may be primarily structurally controlled due to its proximity to significant fault zones.

The Devonian Nisku Formation is a shallowing-upward carbonate/evaporate sequence that grades from open marine wackestones up into supratidal laminated dolomites and anhydrites (Blakeney 1988). In the survey area, the unit ranges from approximately 60 to 75 feet (~18 to 23 m) in thickness based on well logs. The zone of interest is an 8 to 12 foot (2.4 to 3.7 m) thick interval of dolomitized skeletal grainstone with porosity values up to around 18%. This zone is believed to be associated with deposition in shoal conditions, most likely formed in a beach or winnowed island environment (Blakeney 1988). Initial drilling was based primarily on subsurface well
correlation, and led to two main NW-SE drilling trends as seen in Figure 4, which were believed to be these shoal deposits. Little exploration, however, was done beyond these restricted trends, leaving open the possibility for a much wider extent of Nisku porosity than was originally believed.

Methods

Because the intervals of interest are relatively thin (less than 50 ft (15.25 m)), they are predominantly overshadowed by stronger reflections in the full bandwidth data. Therefore, before any major interpretation was done, a 50-60-110-120 Hz bandpass filter was applied to the volume to isolate the higher frequency portion of the data. As seen in Figure 5, a comparison of synthetic correlation before and after the application of the bandpass filter, this is useful in identifying more subtle variations in the seismic character within these intervals.

Synthetic seismograms were created for each of the 15 wells in the survey for which digitized well log data were available (see Appendix B for well locations and names). Wavelets were extracted at each well from the bandpass-filtered volume, and synthetics were correlated to traces from the same volume. For wells in which no digitized density data were available, density logs were calculated from the sonic logs using Gardener’s formula (Sheriff 1995). Figure 7 shows a sample seismic line from the bandpass-filtered data, with overlain synthetics, and some of the key horizons that were selected based on well data.

In order to model the seismic response associated with the zones of porosity, wells were chosen for each interval that clearly showed good
development of the porosity zones from porosity logs. Unfortunately, in each case, the porosity zone occurred at the very bottom of the well logs, so to better synthetically image the porosity zone, portions of sonic and density data from the underlying formations were copied from deeper wells and added to the logs of interest. Once this was completed, the thickness of an individual porosity zone was systematically modified to represent the full range of porosity scenarios observed in wells throughout the survey area. These modified well logs were used to create new synthetic seismograms for each scenario, and were compared to one another to observe predicted seismic responses associated with varying thicknesses of porous and non-porous zones. Once particular characteristics were determined, attributes such as amplitude and isochron data were extracted over the range of the survey in an attempt to identify the lateral extent of the porosity zones.

In addition, preliminary spectral decomposition was performed on each interval in an attempt to support or elaborate upon the attribute anomalies. For the Sawtooth formation, a 30 ms volume centered on the area of interest was isolated in both the full-bandwidth and bandpass-filtered volumes, and exported as separate subvolumes for analysis. The same was done for the Nisku formation, except that the extracted subvolume spanned a 40 ms window. These subvolumes were then imported into ProMax3D© for spectral analysis. First, a Hanning taper was applied to the edges of each trace to smooth the data and suppress ringing (Sheriff 1995). Next, because each trace consisted of so few samples (30 and 40 ms with 2 ms sample interval), each volume was extended
to 300 ms by adding zero values to create a total of 151 samples for analysis. The Fourier Transform of each trace was then calculated, and displayed as a new “vertical trace” now in terms of frequency instead of time. Also included in each vertical trace was the phase data, added onto the bottom of the trace after the Nyquist frequency of 250 Hz. These frequency volumes were then exported from ProMax3D© and imported back into the interpretation software where they could be viewed as frequency slices, or phase slices, showing the contribution of a single frequency or phase value at a time in map view. Had better software been available, this process would have been repeated for a variety of time windows around the areas of interest in an attempt to isolate the contributions from those zones. However, since the survey was fairly large (~250,000 traces), the processing time in ProMax3D was significant, and this was the only analysis done.

Results

*Jurassic Sawtooth Formation*

For the Sawtooth seismic modeling, the well located at SWNW Sec. 13, T35N-R1E was selected because of available digitized sonic and density logs, as well as the presence of a well-developed porosity zone. At this particular location the total thickness of the Sawtooth sandstone is 33 ft (~10 m), the bottom 18 ft (~5.5 m) of which have porosity values from 15 to 20% (Figure 7). As would be expected, the original well logs show that the porosity zone exhibits an increase in travel-time (or decrease in velocity), and a decrease in density, which would
give it a negative impedance contrast from the overlying non-porous sand, and the underlying Mississippian Madison Formation. From this point on the notation used to describe the Sawtooth formation will be “total sand thickness/porosity zone thickness”, i.e. “33'/18’”. Keeping a consistent 15 ft of “tight”, or non-porous sand at the top of the unit, the thickness of the high porosity zone was systematically changed in the well logs to reflect the following scenarios: 0'/0’, 15'/0', 25'/10’, 45'/30’, and 55'/40’. These values provided a suitable representation of the Sawtooth formation within the survey area. Synthetic seismograms were created for each scenario with the modified well logs, and arranged in order of increasing porosity thickness as seen in Figure 8. Although in the original synthetic the Sawtooth formation does not appear to be distinguishable from the surrounding reflections, as the thickness of the porosity zone is changed, some interesting observations can be made. Due to the negative impedance contrast, the contributions from the porosity zone can be observed in the character of the overlying trough in the seismic data. As the thickness of the porosity zone increases, two things can be noted: first, the amplitude of the overlying trough decreases, and second, the time duration, or the wavelength between the bounding peaks increases. These characteristics are important, because both of these attributes can be extracted from the 3D data and viewed over the extent of the survey. The trough amplitude was simply extracted from a horizon picked on the trough, and can be seen in Figure 9. For the time difference between peaks, a horizon was picked for each peak, and an isochron was created between them, as can be seen in Figure 10. A similar
anomaly should be noted on each amplitude map, the NW/SE trending “bright spot” in the northwest portion of the survey. When compared to the original stratigraphic interpretation based on wells, this anomaly corresponds very closely to the predicted area of porosity in the northwest portion of that map. In the predicted porosity zone immediately to the southeast, similar anomalies are observed, however are not as well defined. Unfortunately, the porosity zones believed to be structurally controlled in the eastern area of the prediction map are either outside of the survey boundaries, or right on the edge, and therefore cannot be clearly observed.

To test the validity of these observations, and ensure that the observed anomalies are due to changes in thickness of the porosity zone and not just overall thickness of the unit, more synthetic models were created varying the thickness of the overlying tight Sawtooth sand. Synthetics were made for scenarios of 0'/0', 15'/0', 33'/0', 33'10', 45'/18', and 55'/18', and can be seen side by side in Figure 11. Some very favorable observations can be made here: first, although the amplitude of the trough decreases with increasing unit thickness, it does not decrease to the same extent it did when the modeled sand was porous. Second, and most importantly, the time difference between the peaks bounding the trough changes very little.

Incorporating these new observations, a composite attribute map was created using the data from the two previous attribute maps, weighted roughly 70% to the isochron, and 30% to the trough amplitude. This was done in a very simplistic manner. The dominant range of numerical values in the isochron data
is between 0.01 and 0.02 seconds, representing a difference of 0.01. The dominant range of amplitude values in the data is between 0 and -3.5, representing a difference of 3.5. First, the isochron values were multiplied by 350 to put these different types of values in the same range. Next, the new isochron values were multiplied by 7, the amplitude values multiplied by 3, and the two added together:

\[ \text{New Attribute} = (350 \times \text{Isochron}) \times 7 + \text{Amplitude} \times 3 \]

This works well because amplitude values are negative (trough), and ideally a low amplitude value is desired to represent a thick porous zone. Areas of high negative amplitude, presumably little porosity, will subtract more from the total of the new attribute than areas of low amplitude. The resulting map can be seen in Figure 12, and highlights a now fairly well-defined zone in the northwest portion of the survey that is believed to represent the lateral extent of the porosity zone. The predicted up-dip pinch-out of porosity appears as a well defined line paralleling the structural contours. The down-dip side shows a more irregular character, with the most intriguing feature being a northeast trending linear anomaly that follows along a subtle structural nose. The predicted zone immediately to the southeast now has slightly better definition, but is still not as clear. The observed patterns are well supported by available well data shown in Figure 3. Not only do the larger occurrences of porosity correlate well, but also a somewhat erratic pattern of porosity occurrence throughout sections 21 and 22 of T35N-R1E is shown to be consistent with the observed anomalies.
Several interesting observations can be made regarding the anomaly’s relationship to the structure of the Sawtooth unit. The extent of the anomaly appears to be contained within the confines of the subtle northeast trending structural nose in the northern portion of the survey (Figure 12). The anomaly abruptly stops on its southwest side where the structural contours begin to parallel one another, where the nose is no longer prevalent. Also, the anomaly is particularly well defined along the axis of the nose, relative to the immediately surrounding areas. With such a relationship to the unit’s structure, it is reasonable to interpret that the distribution of this portion of the porosity zone is not simply stratigraphically controlled, as was initially interpreted. There also appears to be a significant structural influence, possibly the result of fractures, formed during the flexure that produced the nose, enhancing the porosity.

In an attempt to support these findings, spectral decomposition was performed on a 30 ms window centered on the area of interest, with intriguing results. Patterns of attenuation (decreased strength of reflection) at frequencies between 60 and 80 Hz are observed in the same areas that the amplitude and isochron anomalies predict porosity, as seen in Figure 13. The same primary area is well defined in the northwest portion of the survey, and there is also a prominent linear feature following the northeast trending structural nose. The reasons for the observed frequency response are not entirely clear; however, Rapoport et al. (2004) have suggested in several papers that seismic attenuation can be a direct indicator of hydrocarbons. Their method involves measuring the vertical gradient of the power spectrum from vertical seismic profiles (VSP). After
correcting for thin-layered media using synthetic models generated from sonic logs, they are able to produce curves representing velocity dispersion and attenuation increase, which in the cases presented were directly linked to discovered producing intervals. Although this method cannot be recreated in this instance due to lack of VSPs, it is promising to note significant attenuation in the areas where oil and gas saturated porosity zones are predicted to be.

*Devonian Nisku Formation*

Modeling the Nisku proved to be slightly more difficult, as very few wells had digitized logs penetrating deep enough to represent the formation. The well which was used was located at NWWN Sec. 22, T35N-R1E, which has a 14 foot (~4.25 m) thick zone within the Nisku with porosity values from 6-10% (Figure 14). The modeled logs were simple, decreasing the thickness of the porosity zone to zero, and increasing its thickness to 24 feet (~7.3 m), all the range necessary to represent the observed thickness values within the survey area. The resulting synthetic models, which can be seen in Figure 15, were disappointing, not only because they show no significant variations due to changes in porosity, but also because the synthetic from the unaltered well logs does not match the seismic data very well. The data shows a strong peak over a very weak peak; however, this is not represented by the synthetic data. The primary cause for this discrepancy is believed to be the lack of a complete digitized density log in this well. As previously described, the density log was calculated from the sonic log using Gardener’s formula. Perhaps there are
unique density variations within the unit which have significant influence on reflectivity that are not accurately represented by the calculated log. To test this, a small available portion of a paper density log (~300 ft of data centered on Nisku porosity) was digitized and incorporated into the calculated density log and synthetic seismogram. However, the results were again disappointing, with the changes causing little improvement to the synthetic (Figure 15).

With no clear direction to follow from synthetic modeling, a search was begun to identify any anomalous characteristics in the seismic data that might be associated with the occurrence of Nisku porosity. To begin, a horizon was picked in the data on a strong peak located just above the Nisku Formation. The volume was then flattened on this horizon, and viewed in map view as a “horizon slice”. When slicing down through the data from the flattened horizon, it becomes possible to view the Nisku Formation approximately as it was deposited, which becomes potentially beneficial when looking for particular depositional features such as those that might control Nisku porosity. The most intriguing observation comes on a slice 11 ms below the flattened peak (Figure 16), which is approximately the level at which the porosity zone is indicated by well logs. Here a positive-amplitude anomaly appears to correlate with the trend in which producing wells were drilled. If this anomaly is indeed associated with the occurrence of the porosity zone, it is believed to be a positive reflection from the base of the porous zone, where density and velocity both increase back into the solid Nisku. When re-examining the vertical seismic data, it is apparent that the observed positive-amplitude trend is associated with a low-amplitude,
discontinuous peak just below the peak on which the volume was flattened. This
discontinuous peak was picked as a horizon, and can be seen in map view in
Figure 17 (can be seen in cross-section in Figures 6 and 18), where it is
interesting to note that though the peak is relatively uniformly distributed over the
entire survey, its areas of highest amplitude are roughly correlated to the well
trends. It is also interesting to note the east-northeast-trending zone through the
middle of the survey in which the peak is not present at all, especially since this
zone passes through both trends of interest. This is a distinct zone of attenuation
associated with a stratigraphic pinch-out occurring in the overlying Devonian
Potlach Carbonate Formation, which is shown in Figure 18. As a result of this
attenuation, the peak of interest is either not present, or is “smeared” into the
overlying peak so that it is no longer distinguishable, even in the bandpass-
filtered data. While this is all an interesting visual correlation between the
discontinuous peak and productive well trends, with the failure of synthetic
modeling, and the lack of higher resolution data, it can not be said for sure
whether or not this anomaly is actually associated with the occurrence of
porosity.

Another interesting observation occurs approximately 40 ms below the
Nisku zone in the seismic data. A band of otherwise strong reflections shows a
significant decrease in amplitude (Figure 18) in areas below wells with productive
porosity zones. To view the extent of this effect, a window of approximately 110
ms centered on the strong reflections was analyzed, from the horizon just above
the Nisku on which the data was previously flattened, down to a deeper horizon
in the Cambrian section called CAM1. Since the reflections both above and below the band of strong reflections showed relatively uniform low amplitudes, the average absolute amplitude within the window was extracted to identify areas where the low amplitudes were vertically continuous through the band. This amplitude attribute, which can be seen in Figure 19, also shows a very strong correlation to the existing trend of producing wells, though in a slightly different configuration than the previous anomaly. Without additional data, however, it is difficult to constrain the actual cause of this anomaly. One possibility is that this anomaly is caused by attenuation due to the presence of hydrocarbons, as suggested by Rapoport et al. (2004); if so, however, it would have to be explained how higher amplitudes return below the attenuated area in the Cambrian section. The data has had Automatic Gain Control (AGC) applied, which would tend to smooth amplitude variations, but does not easily explain the abrupt lateral and vertical amplitude variations within the window. One factor that could contribute to the amplitude effect is the relatively stronger contributions at deeper levels from greater-offset traces that could be bypassing the attenuated zones. This effect could be tested by analysis of variable-offset gathers to look at the nature of amplitude-versus-offset (AVO) patterns, but pre-stack gathers were not available for this study.

In another attempt to identify relevant seismic anomalies, the same process of spectral decomposition was performed on a 40 ms window centered on the zone of interest. No trend is clear at the lower frequencies; however, around 50-55 Hz it appears as though there may be a trend of attenuation
showing up associated with the well trend in the western portion of the survey (Figure 20). Unfortunately, it is impossible to tell if this trend develops more definitively at higher frequencies, because at 65 Hz, attenuation from the pinch-out in the overlying Potlach Formation begins to dominate, and completely washes out any other features in the areas of interest (Figure 21). This effect only grows stronger as frequency increases through the remaining range up to 120 Hz, so little about the Nisku porosity zone can be derived from this analysis.

Conclusions

Many successful wells have been drilled on the Kevin-Sunburst Dome since oil was first discovered there in 1922, guided primarily by subsurface well correlation; however, availability and analysis of 3D seismic reflection data is proving useful in identifying seismic characteristics associated with two particular producing zones of porosity, the Jurassic Sawtooth Formation, and the Devonian Nisku Formation, and constraining the lateral extent of these zones. By correlating available digitized well data to the seismic data, synthetic seismic modeling was able, in the case of the Sawtooth formation, to predict distinct anomalies associated with the occurrence of porosity zones within the formation. The result is a well-defined prospect map that clearly identifies areas within the survey that show these particular characteristics, potentially identifying the aerial extent of the productive porosity zone. It also shows the interpreted porosity zone’s interaction with the local structure of the unit, which suggests that the distribution of Sawtooth porosity is not controlled solely by stratigraphy as was
initially interpreted, but also exhibits a significant influence from structure. Spectral decomposition supports the location of the anomalies, showing a distinct zone of attenuation at certain frequencies coincident with the other anomalies. While the exact cause of this spectral anomaly is unknown, some studies (Rapoport 2004) have suggested that such attenuation may be directly linked to the accumulation of hydrocarbons.

Results for the Nisku formation were not as promising, mostly due to lack of sonic and density data and the relatively small thickness of the interval of interest. Synthetic seismic modeling, which was successful for the Sawtooth Formation, showed no distinct seismic variations related to differing thicknesses of the porosity zone. There were, however, several anomalies that were found to visually coincide with subsurface well correlation interpretations as well as productive drilling trends. While these anomalies cannot, with any justifiable confidence, be directly associated to the occurrence of Nisku porosity, they do provide interesting direction for future work should additional data become available. Spectral decomposition did not provide support to any of the observations, due to a significant amount of attenuation caused by a stratigraphic pinch-out in the overlying unit.

These results clearly show the nature of the details that 3D seismic reflection data can provide in hydrocarbon exploration and interpretation. While subsurface well correlation can give a general idea of productive trends, 3D seismic data has been shown to specifically identify and constrain these trends far better than well data alone ever could. It is believed that these results will
also apply on a much broader scale; not only over the rest of the Kevin-Sunburst Dome, but perhaps for other areas in the Sweetgrass Arch. For the Sawtooth Formation, these same seismic attributes could be identified and explored wherever seismic data is available, and again put much better constraints on existing trends and/or prospective well locations. More work needs to be done before the same can be said for the Nisku Formation; however, the availability of more data would provide further opportunities to analyze specific seismic anomalies associated with porosity that could be used for exploration over the rest of the Kevin-Sunburst Dome and Sweetgrass Arch. Valuable data for achieving this goal would be higher frequency/resolution seismic data, more digital well logs penetrating the formation, and shear sonic logs and pre-stack gathers for amplitude-versus-offset (AVO) analysis (Castagna 1997).

Acknowledgments

This research was funded jointly by Americana Exploration and Target Energy E&P. Seismic Micro Technology’s (SMT) Kingdom software version 8.1 was used for interpretation. Promax3D was used for processing. Kiriaki Xiluri at the University of Arizona provided excellent technical support.
References Cited


Figure 1: Location map of the Sweetgrass Arch area, north-central Montana. From Shepard and Bartow, 1986.
Figure 2: Diagrammatic cross section of the Kevin-Sunburst Dome showing major depositional units as well as general structural relief. Red and green areas represent gas and oil respectively.
Figure 3: Jurassic Sawtooth structure, porosity, and gas accumulation based on well data. $42'/24'P$ = Sawtooth thickness / Feet of porosity. Dashed blue line represents approximate outline of 3D seismic reflection survey. Thick green line represents proposed updip pinchout of Sawtooth porosity. Dashed dark red lines represent approximate location of several faults. Pink areas represent interpreted zones of hydrocarbon accumulation. Contours on Sawtooth, C.I. = 25 ft.
Figure 4: Map of wells drilled deep enough to penetrate Nisku formation within and just outside of the survey area. Black ovals represent drilling trends based on subsurface well correlation which can be seen in cross-sections A-A' and B-B'. Porosity distribution appears to be continuous parallel to the trend, and discontinuous perpendicular to it (Cross-sections from Blakeny and Eby, 1988).
Figure 5: Comparison of synthetic seismogram correlation from the well at NWSW Sec 26, T35N-R1E before and after the application of 50-60-110-120 Hz bandpass filter.
Figure 6: Bandpass filtered seismic line showing two synthetic well ties, as well as four key horizons which were picked based on those ties. Jsa: Trough most closely associated with the Sawtooth interval. Mm: Mississippian Madison formation underlying the Sawtooth formation. Dn: Strong peak which occurs close to the Nisku formation. Dn-PZ: Low amplitude, discontinuous peak believed to be potentially associated with the occurrence of Nisku porosity.
Figure 7: Porosity log over the Sawtooth interval for the well that synthetic models were based on, showing the zone of increased porosity in the bottom 18 feet of the section.
<table>
<thead>
<tr>
<th>Total Thickness</th>
<th>Porosity Thickness</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>0'/0'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15'/0'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25'/10'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33'/18'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45'/30'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55'/40'</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 8:** Comparison of modeled synthetic seismograms showing varying thicknesses of the porosity zone. Arranged by increasing porosity from left to right. Notation indicates total thickness of Sawtooth section / thickness of porous Sawtooth sand.
Figure 9: Amplitude map of the seismic trough most closely associated with the Sawtooth interval (Jsa).
Figure 10: Isochron map showing the time difference between the seismic peaks bounding Jsa.
Figure 11: Comparison of modeled synthetic seismograms showing varying thicknesses of the non-porous Sawtooth zone. Arranged by increasing thickness from left to right. Notation indicates total thickness of Sawtooth section / thickness of porous Sawtooth sand.
Figure 12: "New attribute" prospect map for the Sawtooth formation combing isochron data weighted to 70% and amplitude data weighted to 30%. C.I. = 10 ms.
Figure 13: Spectral decomposition of the Sawtooth interval shown at 75 Hz. Note the zone of decreased amplitudes in the region believed to have hydrocarbons.
Figure 14: Porosity log over the Nisku interval for the well that synthetic models were based on, showing the zone of increased porosity in the middle 10 feet of the section.
Real Porosity

<table>
<thead>
<tr>
<th>Decreased Porosity</th>
<th>Real Porosity</th>
<th>Increased Porosity</th>
<th>Data</th>
<th>With Corrected Density Log</th>
</tr>
</thead>
</table>

Figure 15: Synthetic seismograms showing varying modeled scenarios of Nisku porosity. Note that not even the synthetic using real porosity values ties to the data very well. The synthetic on the right was created after digitizing a small available portion of the paper density log, and incorporating it into the calculated density log. Note that the synthetic still does not tie to the data very well.
Figure 16: Horizon slice 11 ms below a flattened Dn horizon (strong peak just above the Nisku formation).
Figure 17: Dn-PZ horizon, a low amplitude, discontinuous peak just below Dn potentially associated with Nisku porosity.
Figure 18: Seismic line showing the stratigraphic pinchout in the Potlach Formation just above the Nisku Formation, which is the cause of significant attenuation at the Nisku level. Also shows the band of strong reflections just below the Nisku Formation that show a significant decrease in amplitude coincident with productive drilling trends. Dpt: Devonian Potlach Formation – strong peak indicated by arrow. CAM1: Strong Cambrian reflection below the Nisku Formation that was used in the average absolute amplitude calculation.
Figure 19: Average absolute amplitude calculated beneath the Nisku formation, from Dn to CAM1. Note distinctive zones of decreased amplitude associated with drilling trends.
Figure 20: Spectral decomposition of the Nisku interval shown at 55 Hz. Note the thin trend of low amplitudes beginning to form beneath the western drilling trend.
Figure 21: Spectral decomposition of the Nisku interval shown at 85 Hz. Note the significant band of attenuation associated with the overlying Pollach pinchout, which interferes with any potential analysis on the Nisku interval.
Appendix A: Information on the Seismic Reflection Data

- 82.5 ft bin spacing
- 495 ft receiver line interval
- 825 ft source line interval
- Source: 2 vibrators x 4 sweeps
- 10 to 120 Hz sweeps with 3db boost of high frequencies
- 2 ms sample rate
- 3 sec record length
- ~36.75 mi^2 of data

Appendix A: General information on the 3D seismic reflection survey, and map view of the source and receiver line layout. Survey was shot in two halves, east and west, then “zippered” together, resulting in a full spectrum of raypath coverage.
Appendix B: Township and Range map showing the outline of the 3D seismic reflection survey. Shows all wells drilled in the area, and which ones have available digitized data.
<table>
<thead>
<tr>
<th>Well Name</th>
<th>UWI</th>
<th>Location</th>
<th>Depth Digitized</th>
<th>Sonic</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-34-1 State #1</td>
<td>2510123020</td>
<td>SWSW Sec 16, T34N-R1E</td>
<td>3330</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>State Carden #1</td>
<td>2510121498</td>
<td>SENW Sec 16, T34N-R1E</td>
<td>3300</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Pruitt #1</td>
<td>2510107726</td>
<td>SWSW Sec 21, T34N-R1E</td>
<td>1780</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Butkay #12-13</td>
<td>2510124079</td>
<td>NWSW Sec 13, T35N-R1E</td>
<td>2166</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>B&amp;B Ranch #21-14</td>
<td>2510123010</td>
<td>NENW Sec 14, T35N-R1E</td>
<td>3450</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Grinde #41-17</td>
<td>2510123011</td>
<td>NENE Sec 17, T35N-R1E</td>
<td>3450</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Selina Ireland #1</td>
<td>2510121499</td>
<td>SENW Sec 19, T35N-R1E</td>
<td>3330</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>#33-21 Tordale</td>
<td>2510122848</td>
<td>NWSE Sec 21, T35N-R1E</td>
<td>4410</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>#42-21 Tordale</td>
<td>2510122755</td>
<td>SENE Sec 21, T35N-R1E</td>
<td>3460</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>#31-21 Tordale</td>
<td>2510122987</td>
<td>NWNE Sec 21, T35N-R1E</td>
<td>3470</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Turner #13-22</td>
<td>2510122965</td>
<td>NWSW Sec 22, T35N-R1E</td>
<td>3450</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>#11-22 B&amp;B Ranch</td>
<td>2510122862</td>
<td>NWWN Sec 22, T35N-R1E</td>
<td>3430</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Turner #24-22</td>
<td>2510123016</td>
<td>SESW Sec 22, T35N-R1E</td>
<td>3450</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Turner #12-26</td>
<td>2510124085</td>
<td>NWSW Sec 26, T35N-R1E</td>
<td>2139</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>State #24-36</td>
<td>2510107714</td>
<td>SESW Sec 36, T35N-R1E</td>
<td>1830</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

Appendix B: Instructions on how to read well names/locations, as well as a list of the wells which were used in this study due to the availability of digitized logs.