2016

Delineating compressional structures through refined geosteering methods

Chad Koury

Follow this and additional works at: <https://researchrepository.wvu.edu/etd>

Recommended Citation

Koury, Chad, "Delineating compressional structures through refined geosteering methods" (2016).
Graduate Theses, Dissertations, and Problem Reports. 6008.
<https://researchrepository.wvu.edu/etd/6008>

This Thesis is protected by copyright and/or related rights. It has been brought to you by the The Research Repository @ WVU with permission from the rights-holder(s). You are free to use this Thesis in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you must obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/ or on the work itself. This Thesis has been accepted for inclusion in WVU Graduate Theses, Dissertations, and Problem Reports collection by an authorized administrator of The Research Repository @ WVU. For more information, please contact researchrepository@mail.wvu.edu.

DELINEATING COMPRESSIONAL STRUCTURES THROUGH REFINED GEOSTEERING METHODS

Chad Koury

Thesis submitted to the Eberly College of Arts and Sciences at West Virginia University in
partial fulfillment of the requirements for the degree of

Master of Science in Geology

Jaime Toro Ph.D., Chair

Thomas Wilson Ph.D.

Taru Holinsworth M.S.

Department of Geology

Morgantown, West Virginia

2016

Keywords: Geosteering; Marcellus Shale; Unconventional Reservoirs;
Horizontal Drilling; Chevron Folding; Fault Propagation Folding; 3-D
Surface Mapping

Copyright 2016, Chad Koury

ABSTRACT

Delineating Compressional Structures Through Refined Geosteering Methods

Chad Koury

Horizontal gas development wells drilled in the Marcellus Formation in Susquehanna County, Pennsylvania encountered tight fold structures, as detected through geosteering. However, compared to fold analogues in outcrop and in laboratory settings, the geosteering interpretations generated from existing methods depicted these sub-surface structures with varying accuracy. To more acutely determine the cross-sectional profile of these geologic structures, I developed a method whereby an algorithm is used to project and extrapolate the existing geosteering data into a valid 2-dimensional cross-section.

Using this new method, I have determined that Devonian strata in the Appalachian Basin has an overlying detachment in the Upper Marcellus Member and an underlying detachment in the Esopus Formation. These detachments are bedding-parallel faults that periodically cut up-section to form fault propagation folds. 3rd and 4th order folds (wavelengths and amplitudes of tens of feet) are disharmonically contained within 1st and 2nd order folds (wavelengths of ½-mile or greater). In each case, conjugate chevron folds dominate the structures observed, indicating that shortening did not exceed 30%, in any case.

3-dimensional formation surface maps were constructed from the projected and extrapolated 2-dimensional cross-sections. These surface maps reveal, in more detail, the structural complexity that is not resolvable through basic seismic imaging. This enhanced view of the subsurface will greatly increase the effectiveness of horizontal drilling programs by being able to construct more accurate directional drilling plans, as well as anticipate changes in geologic structure in order to keep each horizontal wellbore within the optimal zone of production.

ACKNOWLEDGEMENTS

There are many individuals for whom I am endlessly thankful for their support along my unconventional journey of achieving this degree.

I must thank Dr. Jaime Toro and Dr. Thomas Wilson who have supported my efforts to write a paper that is outside of the academic norm.

Mrs. Taru Holinsworth has shown her support of myself and my business throughout my career. She believed in my dream to have an impact on the Oil & Gas Industry, and without her unwavering support, I would not be where I am today.

I must also thank Dan Billman for being a person who has made himself available for any question or concern I have academically or professionally. Additionally, I must thank Rob Glaser for his professional support and, more importantly, for him having initiated the drive in me to undertake this educational expedition.

I need to thank Southwestern Energy, WPX Energy, and Carrizo Oil & Gas for the use of their data.

Mike Stoner at Stoner Engineering has been very helpful during my professional and academic careers. Mike allowing me to use his geosteering program (Stoner Engineering Software) was crucial for my success in this endeavor.

Midland Valley, the developer of the MOVE software suite, was very generous in giving me the use of an academic license for their program; without their generosity, the success of my research would not have been possible.

Additional thanks goes to all of my **Chicos** as well as all of my pugilist pals from Jim's Gym: Jim March, Peter McGinley, and Eric Watkins.

TABLE OF CONTENTS

Introduction	Page 1
Stratigraphy	Page 2
Fold Structure	Page 5
Fault Structure	Page 8
Data Set	Page 9
Software Shortfalls	Page 10
Methods	Page 12
Results	Page 19
Conclusions	Page 27
Acknowledgements	Page 28
References	Page 29

INTRODUCTION

The large-scale development of the Marcellus Formation as a source of hydrocarbons has been facilitated through the application of technologic advancements in horizontal drilling and hydraulic fracturing. The exploration of these resources has allowed for the acquisition of deep well logs, 3D seismic volumes, drilling cores, production data, etc. and has exponentially expanded the knowledge of subsurface geologic characteristics in the Appalachian Basin as a whole.

The subsurface structure of Susquehanna County, Pennsylvania was poorly known prior to the start of the great horizontal drilling and hydraulic fracturing revolution; deep exploration in Northeast Pennsylvania of any kind was almost nonexistent as well. Therefore, the subsurface characteristics of Susquehanna County, PA were not as well-known prior to the development of Devonian shale gas in that area (Gillespie, et. al. 2015).

Well log data can be used to generate a large-scale view of subsurface structural features whose wavelengths approach several miles. 2-Dimensional and 3-Dimensional seismic volumes can be used to generate both large-scale and medium-scale views of subsurface structural features whose wavelengths are ½-mile or greater. However, a great challenge faced while drilling horizontal wells in Susquehanna County, PA is the presence of abrupt, steeply dipping, short wavelength structural features whose wavelength and amplitude is on the order of tens of feet. Since Susquehanna County, PA is located no more than 20 miles from major Appalachian fold belts, there are a great deal of large, medium, and small-scale compressional structures that are encountered while drilling a horizontal well (Figure 1).

While well log data and seismic data can be used to anticipate large-scale and medium-scale structural features in order to guide the general placement of a directional drilling plan, small-scale features that are below the resolution of seismic data can prove to be problematic since structures of this scale are only discovered while drilling a horizontal well. Moreover, drilling through these structures can

cause the wellbore to deviate from the Target Zone and, worse yet, into the underlying Onondaga Limestone. Therefore, there is a need to expand upon the existing methodology of mapping and delineating such structures that are encountered while drilling horizontally.

Figure 1: Geologic surface map of the state of Pennsylvania showing the location of the Orogenic Front, the Valley & Ridge Province, Susquehanna County, and the H. Wesley Pease 1 well (Bureau of Topographic and Geologic Survey).

STRATIGRAPHY

The lithostratigraphic units found in NE Pennsylvania are composed of limestones, sandstones, and the gas-bearing shales that are the target of unconventional hydrocarbon exploration and development. Specific to Susquehanna County, PA, the stratigraphy (moving up-section) contains the Silurian Salina Group (Tonoloway Formation, limestone), the Silurian/Devonian Helderberg Group (Keyser Formation, limestone; Coeymans Formation, slightly argillaceous to arenaceous limestone; New Scotland Formation, argillaceous to finely arenaceous limestone; Minisink Formation, limestone; Port Ewen, shale),

the Oriskany Group (Shriver, cherty limestone; Ridgley Formation, sandstone), the Tristates Group (Esopus Formation, argillaceous to finely arenaceous siltstone; Schoharie Formation, calcareous siltstone), the Onondaga Formation (limestone), the Hamilton Group (Marcellus Formation, shale; Hamilton Formation, shale; Tully Formation, limestone), and the Genesee Group (Genesee Formation, shale) (Figure 2) (Berg, et.al., 1983 and Lash & Engelder, 2011).

The H. Wesley Pease 1 exploratory well drilled by Shell Oil down to the Salina Group in 1973 provides an overall view of the stratigraphy of Susquehanna County, PA (Figure 1). As observed from this well, the Upper Silurian Salina Group (consisting of the Tonoloway and Keyser Formations, both being composed of mainly limestone in Susquehanna County, PA) was deposited in a shallow marine environment. Subsequent to the deposition of the Tonoloway Limestone, the Acadian Orogeny augmented the existing salient as well as deepened the existing foreland basin. The heightened orogenic body supplied sediment to fill the deepening foreland basin (Ettensohn, 1992; Ferrill & Thomas, 1988). Into the Devonian, the Helderberg Group, Oriskany Group, Tristates Group, Onondaga Formation, Hamilton Group, and Genesee Groups were deposited.

The contact zone between the top of the Onondaga Formation and the base of the Marcellus Formation has been interpreted as a regional unconformity by some (Potter et. al., 1982; Rickard, 1984, 1989) and as a gradational change by others (Ver Straeten, 2007). However, through the drilling of horizontal wells, it can be shown that this boundary is a gradational contact in Susquehanna County, PA. This gradational change from limestone to black shale has been interpreted as signaling the deepening of the Appalachian foreland basin from the continuation of the Acadian Orogeny. Additionally, it has been widely concluded that the package of Upper Silurian, Lower Devonian, Middle Devonian, and Upper Devonian units from the Salina Group up to the Genesee Group are all components of the same series of transgressive-regressive, eustatic changes (Johnson et. al., 1985; Embry & Johannessen, 1992; Embry, 1993, 1995, 2002). Additionally, it should be noted that when drilling through the carbonaceous inter-

Figure 2: The sequence stratigraphy of the stratigraphic units involved in this paper. General stratigraphy is from Shell Oil Company's H. Wesley Pease 1 well drilled in 1973; gamma ray log is from the I1 gamma ray type log (location seen in Figure 6).

Marcellus members (Cherry Valley, Tully), that their composition is not that of a competent limestone. The actual composition of these units is either marly shale, or argillaceous limestone. Therefore, in this case, the transgressive nature of the depositional environment marking the Cherry Valley Member and Tully Member indicate a moderately shallow marine environment, not an unconformity.

Due to its silica content, matrix of natural fractures, and high Total Organic Content (TOC), the Lower Marcellus Member is an ideal zone for production of natural gas (Lash & Engelder, 2008, 2009). Additionally, since the maximum burial depth in Susquehanna County, PA was one of the greatest in the Appalachian Foreland Basin, the Marcellus Formation super-mature. Therefore, in this area, an over-pressured, dry gas field is present where the main component of gas produced is methane (East, J.A., 2012).

FOLD STRUCTURE

The structural features of Devonian strata vary depending on their location within the Appalachian Basin. These strata in western Pennsylvania follow a very gradual formation dip that approximately matches the incline of the basin. However, further east, towards the salient, orogenesis has led to shortening which has resulted in the development of compressional structures (Figure 1).

Paleozoic strata in the Appalachian Basin are folded above and below detachments that lie within incompetent units (Gwinn, 1970). The predominant decollement present in the Appalachian Basin is within the Silurian Salina Group which is composed of salt and anhydrite in most parts of the basin (Jamison, 1987). Locally, anticlinal cores see Salina thickness of up to 1000'; this is the result of squeezing of the evaporitic material from under the troughs of synclines into the cores of anticlines (Frey, 1973; Hedlund, 1997). However, in Susquehanna County, PA, the composition of the Salina Group is mainly carbonates and clastics. Therefore, the primary detachment in this area may be in a different unit, such as an over-pressured and/or incompetent shale. These detachments are usually bedding-parallel faults

that periodically cut up section (Jamison, 1987). However, since these strata were at such a great depth under the surface (up to 7km before deformation), folding is, by far, the dominant form of deformation (Anderson, 1974; Kampfer & Leroy, 2009).

Overlying detachments throughout the basin are known to be within the Devonian Upper Marcellus Member and Genesee Formation. Folds resulting from a detachment in the Burkett formation would fall in the range of 1st and 2nd order folds (½-mile+ wavelength). These 1st and 2nd order folds are detectable in vertical well data, seismic data, and geosteering data. The location of the upper and lower detachments of small-scale, 3rd and 4th order folds were found to be the Upper Marcellus and the Lower Esopus Formations, respectively.

Folding in sedimentary rocks is primarily facilitated through bedding-plane slip. A fold will form during a period of compressional stress, nucleating in the foliation of the strata or in a location where the structural integrity of the rock has been compromised (Jamison, 1987). Once a fold has been initiated, a period of amplification and propagation will occur until the necessary parameters for fold growth and propagation diminish (Cobbald, 1976).

The fold forms that are dominant at outcrops in the Valley and Ridge province of Pennsylvania are neither parallel nor similar in shape but rather have narrowly bent hinges and long, planar limbs (Nickelsen, 1963); these folds are known as chevron folds (Twiss & Moores, pp. 379). The evolution of a chevron fold occurs in three phases. 1) unfolded strata, 2) conjugate chevron fold, 3) simple chevron fold (Figure 3). The cross-sectional profile of a chevron fold is rather distinct with limbs maintaining a consistent thickness and hinges taking up very little space allowing for an abrupt change in bed orientation (Figure 4). (Faill, 1973). Chevron folds undergo differential shortening. This implies that a series of folds will diminish and plunge into the planes and hinges of other, adjacent folds, or diminish altogether (Jamison, 1987).

Figure 3: Step by step progression of the formation of chevron folds (Suppe, 1985).

The axis of each chevron fold can have a theoretical line drawn through them to represent an axial plane. An axial plane bisects the hinge of a fold where the bedding bends sharply (Figure 4) (Faill, 1973). Moreover, an axial plane can be defined as a location of rotational deformation within bedding which acts as the axis of rotation for the bed in which it is located (Faill, 1969). Essentially, strain only occurs proximal to where an axial plane intersects bedding.

Figure 4: Schematic examples of a Conjugate Chevron Fold and a Simple Chevron Fold. A Conjugate Chevron Fold is characterized by being composed of three kink bands and an axial plane that bifurcates at the point where the three kink bands converge. A Simple Chevron Fold is characterized by being composed of two kink bands and a single axial plane.

FAULT STRUCTURE

Although folds are most common, there are instances where faulting does occur. When compressional forces persist, but an anticlinal fold reaches its maximum capacity of shortening, a thrust fault will cut up section from the underlying detachment through the forelimb of that fold. (Twiss & Moores, 2007, p. 121). When this fault propagates up from a detachment, a fold is formed above the propagating fault with a steep, to overturned forelimb and a gentle backlimb (Suppe, 1988, p. 342). Given the geometry of the folds present, it is easy to discern that fault propagation folding is the dominant mechanism of faulting. Figure 5 shows an analogue of this folding style tested using the formation thicknesses and detachment depths noted from research carried out in Midland Valley's MOVE software.

DATA SET

The data set used in this research was acquired through horizontal drilling in the development of natural gas resources in Susquehanna County, PA. This dataset is comprised of 18 vertical gamma ray type-logs (locations in red in Figure 6), directional surveys from 93 horizontal wells (black lines in Figure 6a), and Measurement While Drilling (MWD) gamma ray logs from each horizontal well. This data was imported into the geosteering program *Stoner Engineering Software* (SES) and a structural interpretation was generated for the strata through which each wellbore was drilled.

After reviewing the structural interpretation made from each well in the entire data set, one specific area was chosen that best exemplified the nature of folding and faulting seen in this region. Figure 6c shows the Area of Interest (AOI) for this thesis. In the AOI, 13 horizontal wells drilled from 3 pads are lined up adjacent to each other and are positioned such that their structural interpretations can be spliced together to generate very long cross-sections. These long, adjacent cross-sections offer a more detailed view of the subsurface that is beyond the resolution of vertical well data or seismic data.

Figure 5: A simplified, analogue model of a fault propagation fold conducted in Midland Valley's MOVE v.2015.1

SOFTWARE SHORTFALLS

The H5 1H horizontal well (Figure 6b) will be used to demonstrate the problems faced while Geosteering in this region, as well as the techniques developed to overcome these problems. Figure 9 shows an image of SES depicting the geosteering interpretation of the 'Target Zone.' The Target Zone is the zone in which it is most desirable to place the horizontal wellbore. The selection of the Target Zone is such that the initiation of hydraulic fractures into the formation and the propagation of these fractures will be most effective during injection of hydraulic fracturing fluid. In the case of many operators in Susquehanna County, PA, the 'Target Zone' is a 15'-20' thick zone of the Lower Marcellus Member that lies above a zone that is used as a safety or 'buffer zone' between the Target Zone and the underlying Onondaga Limestone.

Figure 6a: Locations of vertical gamma ray type logs (RED) and horizontal wellbores (Black). Image generated using SES v 5.20

Figure 6b: Horizontal wells drilled from the H5 pad

Figure 6c: Horizontal wells drilled from the T1, T2, and H1 pads

Geosteering programs work by first associating an MWD gamma ray log with the trajectory of a wellbore (Figure 7 & Figure 8). The user will stretch or squeeze the MWD gamma ray log so that it correlates to a gamma ray type log from a nearby vertical well, thus calculating the depth and dip of the strata through which the wellbore drilled. Geosteering programs are excellent at determining a wellbore's location in section and the formation dip of the strata through which a wellbore drilled (Figure 9). However, all data acquired while drilling a vertical or horizontal well is a direct measurement of the rock in which a wellbore is drilled and, therefore, this data is a 1-dimensional measurement. As a result, the nature of the overlying, underlying, and adjacent structure is left up to interpretation.

SES can generate reasonably accurate cross-sections when formation dips do not exceed a few degrees. However, in instances when formation dips make frequent and rapid changes of 20° or greater over distances of less than 100', SES and many other geosteering packages are unable to illustrate a realistic cross-section from the data measured at the horizontal wellbore. One primary shortfall of these geosteering programs is their inability to determine the amplitude of a fold, the vertical profile/shape of a fold, and a fold's depth of overlying and underlying detachment. This is because these geosteering

programs extrapolate interpreted structures as *similar folds* (using vertical axial planes) rather than *parallel folds* (constant orthogonal thickness) or *kink/chevron folds* (using axial planes that are bisectors of adjacent dip measurements).

As shown in Figure 9 (geosteering interpretation) and Figure 10 (cross-section generated from the geosteering interpretation in Figure 9), SES will erroneously exaggerate formation thicknesses as formation dip increases. Also, large changes in formation dip are incorrectly portrayed as faults. A major contributor to SES's incorrect depictions of geologic structure, as seen in Figure 10, is the fact that this program assumes vertical axial planes at each change in formation dip, rather than an axial plane bisecting the hinge of a fold. This leads to the depiction of structure not necessarily adhering to geologic principles.

METHOD

The primary purpose of this research is to develop a method to generate an accurate cross-section using only the data measured at each horizontal wellbore.

Applying the concept of kink-band folding allows us to depict geologically reasonable structures from the 1-dimensional horizontal well data. The X, Y, & Z coordinates (using UTM coordinates) of the wellbore where it encounters a change in formation dip, and thus an axial plane, is entered into a spreadsheet along with the dip of the formation before and after the axial plane. Assuming that each change in formation dip is the location of an axial plane, the vertical extent of a fold or a series of folds can be calculated. The angle of the axial plane is calculated as the angle perpendicular to the mean of both adjacent formation dips. This '*bisector angle*' is recorded, as well as the well bore's stratigraphic distance from a particular formation top at each axial plane (generally, the Onondaga top was used). From here, each fold can then be projected accurately to a desired formation top using the equations in Figure 11. The new X, Y, & Z coordinates now accurately depict a specific formation top based on the trajectory of the horizontal wellbore (equations in Figure 11).

Figure 7: Illustration of how differing drilling inclinations will generate gamma signatures of similar signature, but differing length.

Figure 8: Comparison of both MWD gamma ray logs from Figure 7 showing how drilling through a formation at a shallower inclination will generate a gamma ray log that is more “stretched-out.”

Figure 9: Stoner Engineering Software geosteering program showing the amalgamation of **MWD Surveys** and **MWD Gamma** correlated to an offset type log to generate a cross-section of the strata through which the H5 1H horizontal wellbore drilled. Image generated using SES v5.20.

Figure 10: Incorrect extrapolation of geologic structure observed while drilling the H5 1H horizontal well due to assumed vertical axial planes. This image is a zoomed-in section of Figure 9 from 8,700' MD to 10,200' MD. Image generated using SES v5.20.

$$\begin{aligned}
 X &= X_0 + \left\{ [\sin(\text{VSAZI})] \left[\cos\left(90 - \frac{\text{Dip1} - \text{Dip2}}{2}\right) (\text{TopDist}) \right] \right\} \\
 Y &= Y_0 + \left\{ [\cos(\text{VSAZI})] \left[\cos\left(90 - \frac{\text{Dip1} - \text{Dip2}}{2}\right) (\text{TopDist}) \right] \right\} \\
 Z &= Z_0 + [\text{TopDist} + (\text{KB} - \text{TVD})]
 \end{aligned}$$

X_0 = Original X Value
 Y_0 = Original Y Value
 Z_0 = Original Z Value

$X, Y, \text{ \& } Z$ coordinates are in UTM feet;
 KB elevation is in SubSeaTVD (feet above/below sea level)

VSAZI = Approximate Azimuth of the Wellbore

Dip1 = Formation Dip on Heel-Side of Axial Plane

Dip2 = Formation Dip on Toe-Side of Axial Plane

TopDist = Wellbore's Stratigraphic Depth to Specific Top

KB = Kelly Bushing Elevation

TVD = Total Vertical Depth of Wellbore

Figure 11: Equations I developed to project to the nearest formation top.

This projected formation surface is further extrapolated to form a complete cross-section. This process can be completed by hand, or with the assistance of software programs such as Midland Valley's *MOVE* software. Three assumptions are made while generating these cross-sections:

1. Folds are kink folds
2. Axial planes bisect each fold
3. Stratigraphic thickness is known, and is conserved

Using given stratigraphic thicknesses, *MOVE* uses chevron/kink fold modelling to extrapolate the projected formation top into a 2-dimensional cross-section. The user can manually refine and guide the software's operations, using additional constraints such as overlying detachments, underlying detachments, fault geometries, etc.

The result of this process demonstrated on the H5 1H horizontal well is shown in Figure 12. In this case, the horizontal well data was used to calculate the geometry of the Onondaga formation. The geologic structure was then extrapolated up-section and down-section using *MOVE* to generate an accurate cross-section. Conjugate chevron folds dominate because the magnitude of shortening is too low to form simple chevron folds. Moreover, these conjugate chevron folds are components of a disharmonic folding system. Overlying axial plane convergence occurs in the Upper Marcellus Member and underlying axial plane convergence occurs in the Esopus Formation (Figure 12). This convergence indicates zones of detachment. The development of the cross-section from the H5 1H horizontal wellbore from Figure 9 to Figure 10 to Figure 12 shows the evolution of this projection & extrapolation process through application of the equations in Figure 11, as well as use of Midland Valley's *MOVE* software.

Figure 13 shows an overlay of the projected and extrapolated cross-section constructed in *MOVE* superimposed over the cross-section generated by SES. In areas where formation dip is flat, both cross-sections converge and resemble each other relatively well. However, areas where the formation dip

increases and the wellbore is a significant distance from the Onondaga top (the Onondaga Formation top was used as the projected surface in this case), it can be clearly seen how SES's use of vertical axial planes generates an erroneous cross-section. Moreover, SES's depiction of formation tops become increasingly more inaccurate the further up-section and down-section they lie from the wellbore.

Finally, folds contained in groupings of adjacent 2-dimensional cross-sections are delineated to construct 3-dimensional surfaces. This practice is especially helpful when drilling multiple adjacent horizontal wells. Being able to predict upcoming structural features while drilling a horizontal well increases the ability to place the wellbore in a desired zone without having to make constant directional changes, reducing wellbore tortuosity, and thus reducing drilling and completion costs.

Figure 12: Cross section of the H5 1H horizontal well using Midland Valley's MOVE software. Image created using MOVE v.2015.1

Figure 13: SES's cross-section (depicted by color coded formations) versus MOVE's extrapolated cross-section (depicted by black lines as formation tops and red lines as axial planes/kink band boundaries). Images generated using SES v.5.20 and MOVE v.2015.1.

It should be noted that one potential pitfall exists when drilling through a conjugate chevron fold. Drilling through a conjugate chevron fold will yield different geometric results depending on the level in section through which the wellbore is drilled (Figure 14). In the case of *Wellbore A* in Figure 14, the geometry encountered leads to the interpretation of a conjugate chevron fold, while *Wellbore B* in Figure 14 would lead to the interpretation of a simple chevron fold. Again, having multiple adjacent horizontal wells will increase available data points that can be used to refine previously interpreted cross-sections. Additionally, instances of conjugate chevron folds misdiagnosed as simple chevron folds can be spotted when the extrapolation of a simple chevron fold (like the one found by *Wellbore B* in Figure 14) will generate a cross-section that is geologically unlikely. In this instance, additional adjustments are made to ensure sound geologic principles are maintained while constructing each cross-section.

Figure 14: The location of a wellbore in section will dictate the Geosteering interpretation of the geologic structure. Wellbore A would yield data that implies a conjugate chevron fold while Wellbore B would yield data that implies a simple chevron fold.

RESULTS

Figure 15 shows how structures were delineated across individual cross-sections to create a formation surface. Starting with the extrapolated Onondaga Formation tops along each horizontal wellbore, additional surface lines were drawn connecting structures that can be confidently correlated from cross-section to cross-section. Green lines were drawn on the hinges of positive structures, red lines were drawn on the hinges of negative structures, and black lines were drawn on the limbs of folds to guide the computer interpretation of the structures into a 3D surface using a *minimum curvature* calculation. Due to the sparse nature of the data, these folds were delineated using straight lines, while, in fact, these fold structures likely curve due to differential shortening. Therefore, it is assumed that these fold structures have strikes ranging from East-West to 15° above and below West and East, respectively.

Figure 16 shows a rose diagram of the strike of all of the lines in Figure 15. The two sets of strike trends don't necessarily imply that there are two individual sets. Rather, the folds present are curved and the best representation of their delineation in Figure 15 is done via straight lines.

Figure 15: Delineation of folds across adjacent wellbores guided the generation of an Onondaga Formation surface map in MOVE. **GREEN** lines signify anticlinal fold hinges, **RED** lines signify synclinal fold hinges, and **BLACK** lines were placed to supplement and guide the mapping software. Images generated using MOVE v.2015.1.

Figure 17 shows a 3D side-view of the Onondaga surface generated from the interpretation of the folds in adjacent wellbores (shown in gray-scale to accentuate the presence of folds). Figure 18 shows a 3D side-view of the Ridgeley Formation surface which underlies the Onondaga by approximately 500'. As discussed previously, the over-pressured, weaker, gas-bearing shales were deformed between overlying and underlying detachments. The underlying basal surface has been interpreted as the Ridgeley with the Esopus being the detachment zone and the Onondaga being the 'slab' (primary competent unit). The structural trend of both of these formation surfaces reinforces the argument that the weaker units surrounding and including the Onondaga formation were folded disharmonically within larger scale folds.

Figure 16: Rose diagram of the strike of the surface lines from Figure 15. Due to the limited data points I am connecting, the two individual sets of fold strikes seen above actually implies a range of fold strikes, rather than two exclusive sets.

Figure 17: 3-Dimensional view of the Onondaga Formation surface in a 3:1 vertical:horizontal exaggeration, looking east. (Image generated using MOVE v.2015.1).

Since larger-scale structures are detectable in seismic data, wellbore placement is planned to avoid potentially problematic areas as to keep the wellbore in the Target Zone without having to generate excessive doglegs. This effort to reduce wellbore tortuosity can be seen in the wells drilled off of the T2 pad (Figure 6c). Each of these wells were landed near the center of a syncline and drilled up-dip and away from the center of the syncline. However, using the projection and extrapolation methods developed in this research, the structure of the trough of this syncline area is decipherable since both the northwestward and southeastward drilled wells were landed adjacent to each other.

The primary area of interest for this thesis shows an excellent example of disharmonic folding within large 1st order/2nd order folds, whose wavelength is ½ mile or greater. Also shown are examples of asymmetric folds that indicate the presence of fault propagation folds (Figure 20).

Folds can be delineated in each of these adjacent cross-sections showing the lateral extent of folds of various orders. Figure 19 shows the cross-sections developed through my methods of projection and extrapolation of horizontal well data in the primary AOI. While drilling these horizontal wells, the wellbore would generally stay within or near the Lower Marcellus, Target Top, Target Base, and Onondaga. Because of this, the interpretation of these tops has the greatest amount of certainty. Therefore, only these formation tops are shown in Figure 19.

Figure 19: Cross-sections of the horizontal wellbores drilled from the T1 and T2 pads (Figure 6c); cross-sections are exaggerated on a 3:1 scale. Red dashed lines connect the structures of folds **2**, **3**, **a**, and **b** along each Onondaga surface. Image generated using MOVE v.2015.1

As stated, the 1st and 2nd order folds in Figure 19 are likely detectable in a seismic volume, albeit, not as precisely as those shown in Figure 19, while the higher order, disharmonic folds are below seismic resolution. A large box syncline 2,000' to 3,000' wide is detected in each of the cross-sections in Figure 19. This large negative structure contains tight groupings of higher order folds that have been individually recognized across the adjacent wellbores. Conversely, the large positive structure to the northwest of the negative structure also houses higher order folds. Folds **a**, **b**, **c**, **d**, & **e** (positive structures that are housed in the large syncline) as well as folds **1**, **2**, & **3** (asymmetric folds housed in the large anticline that are likely

forelimbs of an underlying thrust fault) are all components of a succession of disharmonic folds which formed through the loss of space during the larger-scale folding that houses them.

Figure 20: Enlarged view of the cross-sections from the T1 2H and T2 4H horizontal wellbores; cross-sections are exaggerated on a 3:1 scale. Image generated using MOVE v.2015.1

The folds interpreted along each horizontal wellbore were viewed in sequence in 3-dimensions (similarly to Figure 17) in order to determine their relationship to each other across adjacent wellbores. Moving from East to West, Fold **a** undergoes differential shortening by dissipating into the limb of the larger-order fold, adjacent. Moving from West to East, Fold **d** and Fold **e** also undergo differential shortening when they dissipate into the opposite limb of the larger-order fold into which Fold **a** dissipated. Folds **b** and **c** span the entire distance of the AOI.

Folds **1**, **2**, & **3** do an excellent job of demonstrating the primary folding mechanism in Appalachian Basin Devonian aged strata, which is bedding plane slip. As mentioned in prior pages, bedding plane slip leads to bedding parallel faulting which will periodically cut up-section to form fault propagation folds. Specifically, the geometry of Folds **1**, **2**, & **3** were interpreted in SES to match the nature of fault propagation folding (analogue seen in Figure 5). Therefore, the extrapolation method used herein was guided with the principals and geometry of fault propagation folding in mind. A forelimb anticline overtop

of an underlying fault can be seen in the geometry of Folds **1** and **2** in the T2 4H cross-section and plainly as a fault in the T1 2H cross-section. Fold **3** shows the cross-sectional geometry of a fault propagation forelimb in each of the 5 adjacent cross-sections with the example observed in the T2 1H cross-section also showing the kink band that constitutes the backlimb of the structure.

There are several instances where folds of a specific geometry are observed in the geosteering interpretation that would indicate that there is an underlying thrust fault driving deformation. Fold **2** in the T2 4H cross-section is an example of an asymmetric forelimb with a formation dip that is essentially vertical. Figure 21 shows the geosteering interpretation of this fold in the T2 4H horizontal well. Prior to encountering the steep, downward formation dip, the wellbore entered the top of the Onondaga Limestone. It is clear to assume that the wellbore travelled through the forelimb, very near the fault, but without encountering the fault. Figure 21 also shows the geosteering interpretation of the T1 2H horizontal well which shows the same near-vertical formation dip, but in this case, with a fault beyond the steep formation dip that has propagated into the Lower Marcellus.

Another important geometric exercise is determining the percentage of shortening at which these folds 'lock-up' causing the bedding parallel faults in the Esopus Formation to cut up-section. The presence of the forelimb observed in the T2 4H horizontal wellbore indicates that the folds in this area had reached their maximum amount of shortening and were then subjected to faulting.

Shortening was calculated from ends Fold **2** to Fold **3** in Figure 19. Folds **2** and **3** were encountered in all 5 horizontal wellbores in the northern part of the AOI. The Onondaga formation surface was used to calculate the amount of shortening; amounts in Figure 22. The average shortening of these folds is approximately 10%. The entire series of folds that is encompassed within the large anticline in the northern part of the AOI can be qualitatively compared to the 10% shortening example seen in Figure 3.

Figure 21: SES geosteering interpretation of the Target Zone of the T1 2H and the T2 4H horizontal wells showing the asymmetric, steeply dipping nature of a fold that is very likely the forelimb that overlies a thrust fault (image generated using SES v5.20).

Wellbores of Cross-Section	Fold 2 to Fold 3 Shortening	Fold b to Fold c Shortening	Fold 2 to Fold c Shortening	Cumulative Low-Order Shortening
T1 4H – T1 5H	6.2%	1.7%	3.03%	2.5%
T1 1H – T1 6H	9.9%	5.0%	2.51%	2.4%
T1 2H – T1 3H	10.9%	6.0%	5.01%	6.1%
T2 4H – T2 3H	13.3%	4.1%	5.48%	4.8%
T2 1H – T2 2H	8.3%	11.3%	5.30%	4.1%

Figure 22: The percentage of shortening experienced from fold 2 to fold 3 in each of the horizontal wellbores.

Folds b and c that are housed within the syncline of the cross-sections of Figure 19 also had their shortening calculated. The syncline itself appears to undergo the most shortening in the T2 1H horizontal wellbore and decreases towards the T1 4H horizontal wellbore.

Overall, the cumulative inner-anticlinal and inner-synclinal shortening experienced increases moving from the east to west in the AOI. This trend of shortening observed in the 3rd and 4th order folds

is consistent with the overall trend in shortening observed in the larger, low-order folds that house these disharmonic folds.

CONCLUSIONS

The development of a method for projecting 1-dimensional data and further extrapolating it to make a 2-dimensional cross-section is a step towards understanding the development of folds at depth to improve future drilling. The extrapolation of these cross-sections up-section and down-section give a more detailed view of the vertical extent of these folds. Delineating structures across multiple projected & extrapolated 2-dimensional cross-sections enhances overall spatial knowledge of the subsurface structure to a finer detail than seismic imaging and accelerates the learning curve of drilling subsequent wells.

The primary mechanism of strain observed in the Lower Marcellus Formation of Susquehanna County, PA is folding; the geometry of which is conjugate chevron folding. 3rd and 4th order folds form above and below detachments in the Esopus Formation and Upper Marcellus Member, respectively, and are disharmonic within larger 1st and 2nd order folds. However, there are several instances where 3rd and 4th order folds exist disharmonically in otherwise docile structural areas void of 1st and 2nd order folds.

On occasion, existing anticlinal chevron folds will reach a maximum amount of shortening of approximately $\pm 10\%$ at a formation dip of approximately 45° . At this point, the underlying detachment in the Esopus Formation will cut up-section, through the Schoharie Formation, Onondaga Formation, Lower Marcellus Member, Cherry Valley Member, and converge with the overlying detachment in the Upper Marcellus Member. These thrust faults propagate up-section, deforming the overlying strata, asymmetrically, towards the forelimb.

The wavelength and amplitude of these disharmonic, 3rd and 4th order folds are on the scale of tens of feet, and therefore, these folds are not detectable in 3D seismic data. These folds extend along

their strike a considerable distance with respect to their short amplitudes and narrow wavelengths. In the case of the primary AOI, several of these 3rd and 4th order folds extended across the entire width of the adjacent cross-sections. For example, fold **b** in Figure 19 extended from the T1 5H horizontal wellbore to the T2 2H horizontal wellbore, a total of 5,338'. While at the same time, adjacent to these laterally extensive folds, there are folds that converge with other folds or dissipate altogether through differential shortening. An example of this fold dissipation is fold **e** which was encountered in the T2 2H horizontal wellbore, the T2 3H horizontal wellbore, and the T1 3H horizontal wellbore, but not present in the T1 6H horizontal wellbore or the T1 5H horizontal wellbore.

This research was conducted to improve the structural interpretation of geosteering data. Current low commodity prices make it imperative to improve drilling efficiency. Having a more accurate view of the subsurface will increase wellbore exposure to payzones and increase the production potential of wells drilled in this region and beyond.

REFERENCES

- Anderson, T.B., 1974, The relationship between kink-bands and shear fractures in the experimental deformation of slate: *Journal of the Geological Society, London*, Volume 130, Page 367-382
- Berg, T.M., McInerney, M.K., Way, J.H., MacLachlan, D.B., 1983 Stratigraphic Correlation Chart of Pennsylvania: Commonwealth of Pennsylvania Department of Environmental Resources
- Geologic surface map of the state of Pennsylvania, Bureau of Topographic and Geologic Survey, Third Edition, 1990; Fourth printing, slightly revised, 2007
- Cobbold, P.R., 1976, Fold shapes as functions of progressive strain: *Philosophical Transactions of the Royal Society of London B*, volume 283, pages 129-138
- East, J.A., et. al., 2012 Thermal maturity map of Devonian Shale in the Illinois, Michigan, and Appalachian Basins of North America, US Geological Survey, Scientific Investigations MAP 3214, 2012
- Embry, A., 1993, Transgressive-regressive (T-R) sequence analysis of the Jurassic succession of the Sverdrup Basin, Canadian Arctic Archipelago: *Canadian Journal of Earth Science*, Volume 30, Pages 301-320
- Embry, A., 1995, Sequence boundaries and sequence hierarchies: Problems and proposals: *Norwegian Petroleum Society Special Publication 5*, Pages 1-11
- Embry, A., 2002, Transgressive-regressive (T-R) sequence stratigraphy: *Gulf Coast SEPM Conference Proceedings*, Houston, TX, Pages 151-172
- Embry, A. and Johannessen, E., 1992, T-R sequence stratigraphy, facies analysis and reservoir distribution in the upper most Triassic-Lower Jurassic succession, western Sverdrup Basin, Arctic Canada: *Norwegian Petroleum Society Special Publication 2*, Pages 121-146
- Ettensohn, F.R., 1992, Controls on the origin of the Devonian-Mississippian oil and gas shales, east central United States: *Fuel*, Volume 71, Pages 1487-1492
- Faill, R.T., 1969 Kink band structures in the Valley and Ridge Province, Central Pennsylvania: *Geological Society of American Bulletin*, volume 80, pages 2539-2550
- Faill, R.T., 1973 Kink-band folding, Valley and Ridge Province, Pennsylvania: *Geological Society of America Bulletin*, volume 84, pages 1289-1314
- Ferrill, B.A. & Thomas, W.A., 1988, Acadian dextral transpression and syn-orogenic sedimentary successions in the Appalachians: *Geology*, Volume 16, Pages 604-608
- Frey, M.G. 1973, Influence of salina salt on structure in New York-Pennsylvania part of Appalachian Plateau: *Bulletin of American Association of Petroleum Geologists*, volume 57, pages 1027-1037

- Gillespie, P., et al, 2015 Hierarchical kink band development in the Appalachian Plateau decollement sheet: American Association of Petroleum Geologists Bulletin, volume 99, pages 51-76
- Gwinn, V.E., 1970 Kinematic patterns and estimates of lateral shortening, Valley & Ridge and Great Valley provinces, central Appalachians, South Central Pennsylvania: Studies of Appalachian Geology: Central and Southern: New York, John Wiley and Sons, pages 127-146
- Hedlund, C.A., 1997 Geometry, kinematics, and mechanics of decollement folding: published doctoral dissertation Colorado State University
- Jamison, W.R., 1987 Geometric Analysis of fold development in overthrust terranes: Journal of Structural Geology, volume 9, pages 207-219
- Johnson, J.G., et.al., 1985, Devonian eustatic fluctuations in Euramerica: Geological Society of America Bulletin, Volume 96, Pages 567-587
- Kampfer, G., & Leroy, Y.M., 2009, Imperfection and burial-depth sensitivity of the initiation and development of kink folds in laminated rocks: Journal of Mechanics and Physics of Solids, Volume 57, Pages 1314-1339
- Lash, G. & Engelder, T., 2008, Marcellus Shale Play's Vast Resources Potential Creating Sitr in Appalachia: The American Oil & Gas Reporter
- Lash, G. & Engelder, T., 2009, Joint sets that enhance production from Middle and Upper Devonian gas shales of the Appalachian Basin: AAPG Bulletin, Volume 93, Number 7, Pages 857-889
- Lash, G. & Engelder, T., 2011, Thickness trends and sequence stratigraphy of the Middle Devonian Marcellus Formation, Appalachian Basin: Implications for Acadian foreland basin evolution: AAPG Bulletin, Volume 95, Number 1, Pages 61-103
- Nickelsen, R.P, 1963, Fold patterns and continuous deformation mechanisms of the central Pennsylvania folded Appalachians: Cabro-Ordovician Stratigraphy Cnetral Appalachians of Pennsylvania
- Potter, P.E., et.al., 1982 Appalachian gas bearing Devonian shales: Statements and disucssions: Oil and Gas Journal, Volume 80 (January, 25) Pages 290-318
- Rickard, L.V., 1984, Correlation of the subsurface Lower and Middle Devonian of the Lake Erie region: Geological Society of America Bulletin, Volume 95, Pages 814-828
- Twiss, R.J. and Moores, E.M., 2007, Structural Geology Text Book: Published by W.H. Freeman & Company, New York, Page 121, Pages 379-382, Page 388
- Suppe, John, 1985, Principles of Structural Geology Text Book: Published by Prentice-Hall, INC., Englewood Cliffs, New Jersey, Page 342
- Ver Straeten, C.A. & Brett, C.E., 2006, Pragian to Eifelian strata (middle Lower to lower Middle Devonian), northern Appalachian Basin: Stratigraphic nomenclatural changes: Northeastern Geology and Environmental Sciences, Volume 28, Pages 80-95