DOCUMENTING THE GEOMETRY AND MAGNITUDE OF SHORTENING AT THE ALLEGHENY FRONT: LYCOMING COUNTY, PENNSYLVANIA

by

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The Appalachian Mountain belt extends through the eastern United States and into southeastern Canada, and is expressed as elongated topographic ridges and valleys of folded and thrust faulted sedimentary and crystalline rock. The Appalachian Plateau (AP) in northwest Pennsylvania, and the Appalachian Valley and Ridge in southeastern Pennsylvania have pronounced differences in geologic structure and topographic expression. The AP consists of gentle folds and low relief (but higher elevation) topography, and 10-15 percent layer parallel shortening (LPS) in rocks sampled at the surface. In contrast, the Valley and Ridge province is a blind fold and thrust belt. The duplexing sequence in the Valley and Ridge is bound by a deep decollement surface within shales of the Cambrian Waynesboro Formation, underlying a detachment at the base of the Ordovician Reedsville shale. Twenty-four kilometers of shortening in the Cambrian – Ordovician sequence is expressed as LPS in the AP. Due to the deficiency of geophysical and outcrop data, all the strata in the AP above the Silurian salt detachment has been assumed to be shortening via LPS plus very gentle folding. Increased hydrocarbon exploration has led to the acquisition of new high quality 3-D seismic and well log data which reveal that the strata from Silurian Salina Group through the Devonian Marcellus shale is shortening through a variety of mechanisms including wedge-style thrust faulting and folding. Through kinematically restored and balanced cross sections we show that the magnitude of microscale shortening calculated from the rocks exposed at the surface of the AP is equal to the magnitude of macroscale shortening in the Silurian-lower Devonian units immediately above the salt detachment. Comparing our interpretations with previously published

seismic throughout the AP allows us to extend our model of how shortening in the Salina Group through Marcellus shale is balanced by LPS in the rocks above the Marcellus shale to include the extent of the previously published studies. As the hydrocarbon-rich Marcellus shale is a part of this uniquely deforming Silurian-Devonian package, understanding the geometries of these structures has a potential impact on the quality and quantity of hydrocarbon recovery.

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PREFACE

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1.0 INTRODUCTION

The Appalachian Mountain belt extends through the eastern United States and into southeastern Canada, and is expressed as elongated topographic ridges and valleys of folded and thrust faulted sedimentary and crystalline rock. The deformation that created the mountain chain initiated approximately 480 Ma and comprises three major orogenic episodes that impacted the east coast of present day North America prior to the Late Triassic opening of the Atlantic Ocean (Roger 1949; Hatcher 1989; Faill, 1998). Within Pennsylvania, the Appalachian Mountains present as two distinctly different topographic expressions; the Appalachian Plateau (AP) province in northwest Pennsylvania, and the Valley and Ridge province in southeastern Pennsylvania (Figure 1). The AP is characterized by gentle folds and low relief topography, traditionally thought to be caused by a decollement surface in Silurian Salina evaporates (Prucha, 1968; Wiltschko and Chapple, 1977). In addition to folding, the AP has approximately 10 - 15 percent layer parallel

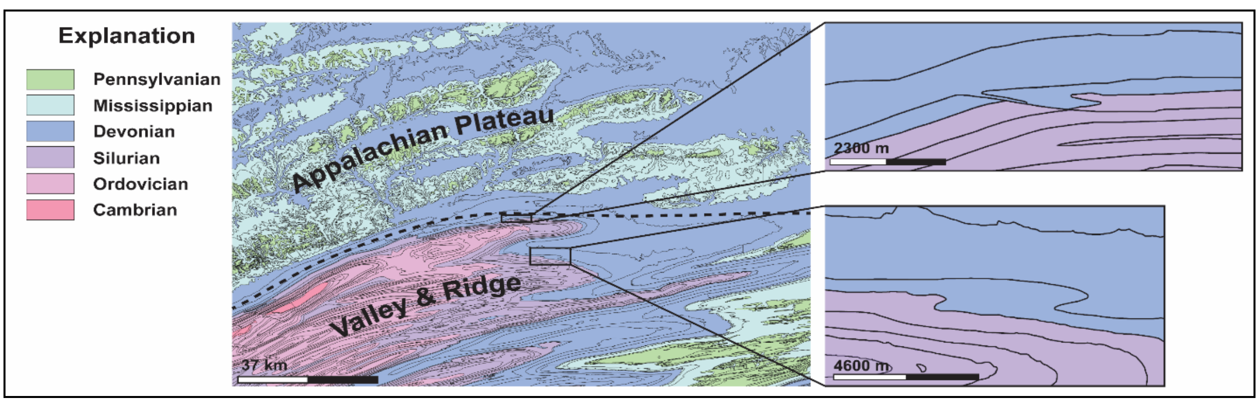


Figure 1: Geologic map of the Valley and Ridge and Appalachian Plateau. The dashed line shows the location of the Allegheny Front. Inset maps reveal unique folding patterns in Late Silurian – Early Devonian units. Map data from Berg et al., 1980; Miles and Whitfield, 2001.

shortening (LPS) calculated from distorted fossils and calcite grains in rocks sampled at the surface (Nickelsen, 1996; Engelder and Engelder, 1977; Slaughter, 1982; Geiser, 1974; Sak et al., 2012). In contrast, the Valley and Ridge province is a blind fold and thrust belt, with a deep decollement surface within shales of the Cambrian Waynesboro Formation (Gwinn, 1964, 1970; Rodgers, 1963, 1970; Herman, 1982). Through sequentially restored and balanced cross sections Sak et al. (2012) have shown that the macroscale shortening via faulting in the Cambrian - Ordovician units of the Valley and Ridge balances the 7-12 km wavelength folds in Silurian through Devonian rocks when including 20% LPS. 10 -15 percent LPS in the AP (~ 24 km of shortening total) also must be balanced by equal amount of shortening in the Cambrian - Silurian section requiring 24 km of faulting in the deeper Cambrian - Silurian section of the Valley and Ridge to be fed northward to the gentle folds and microscale shortening in the Silurian and younger rocks in AP (Sak et al., 2012). Due to lack of geophysical and outcrop data, all the strata in the AP above the salt detachment in the Silurian Salina Group has been assumed to be shortening via microscale shortening plus very gentle folding (Sak et al., 2012). The area is now targeted for hydrocarbon exploration resulting in the acquisition of large amounts of high quality seismic data that provide much needed constraints on the subsurface geology. The integration of new seismic data reveal additional macroscale shortening structures in the Silurian – Devonian aged strata above the salt detachment (Scanlin and Engelder, 2003; Donahoe, 2011; Gillespie, 2013; Roberts, 2013; Mount, 2014). The presence of macroscale shortening structures in the Silurian-Devonian age rocks is also revealed by folding geometries in map view which are distinct and different from the deformation expressed elsewhere in the stratigraphic sequence (Figure 1) (Faill, 1979). Distinct and shorter wavelength structures above the Silurian salt detachment but well below the thick siliciclastic deposits that comprise most of the Devonian stratigraphic section that is exposed through the AP, require an additional detachment horizon. The presence of an additional detachment horizon has implications for how shortening is accommodated between the Silurian and lower Devonian rocks at depth and the broad gentle folds and estimates of LPS measured at the surface.

This study utilizes high resolution 3-D seismic and well log data to evaluate the geometry and magnitude of shortening in the central Appalachian mountains of Pennsylvania. Special attention is paid to documenting changes in the shortening style across at the Allegheny Front, marking the transition from the Valley and Ridge to the Appalachian Plateau. We show that the strata in the Appalachian Plateau above the Silurian Salina Group is shortening through a variety of mechanisms and is not limited to microscale shortening. The changes in shortening mechanism are accommodated across newly recognized detachment horizons. Evidence from previous seismic studies and map-view geometries allows us to hypothesize that the Silurian-Devonian units are bound by not only the Silurian salt detachment (the basal decollement) but also an additional Devonian aged detachment (upper decollement) and that the strata between these horizons are shortening via macroscale folds and faults evident in seismic data. Through kinematically restored and balanced cross sections we will show that the magnitude of microscale shortening calculated from the rocks exposed at the surface of the AP is equal to the magnitude of macroscale shortening in the Silurian-Devonian units above the salt detachment. The hydrocarbon-rich Marcellus shale is a part of this uniquely deforming Silurian-Devonian package and understanding the geometries of these structures has a potential impact on the quality and quantity of hydrocarbon recovery.

2.0 GEOLOGIC BACKGROUND

2.1 STRATIGRAPHY AND GEOHISTORY

The stratigraphy of the Appalachian Mountains date back to the opening of the Iapetus Ocean that occurred after the 1.2-0.9 Ga Grenville orogeny (Dalziel, 1997; Tollo et al., 2004). This passive margin setting allowed for the development of a 1,300-8,000 m eastwardly thickening Cambrian to lower Ordovician carbonate shelf sequence (Miller, 1961; Gwinn, 1964; Faill and Wells, 1977; Taylor, 1977; Faill, 1979; Linberg, 1985; Nickelsen, 1988; Faill, 1997; Kauffman, 1999).

The demise of the passive margin occurred at approximately 480 Ma as North America attempted to subduct under an island arc (Rowley and Kidd, 1981), initiating the Taconic orogeny. During this period intense faulting, uplift, and erosion occurred, shedding sediment into the adjacent foreland basin. The westward migrating basin preserved a package of lower Ordovician to Silurian age rocks, approximately 1,800-3,300 m thick, thickening eastward (Figure 2) (Miller, 1961; Faill and Wells, 1977; Taylor, 1977; Faill, 1979; Lehmann et al., 1995). The Acadian orogeny, (~375-300 Ma), brought a series of exotic terranes that accreted to the eastern margin of Laurentia, and facilitated the development and westward propagation of a new foreland basin system (Faill, 1997). As a result, a thick (2,300-2,500 m) interbedded deltaic package of upper Devonian to lower Carboniferous age was deposited into the upper Devonian basin and defined

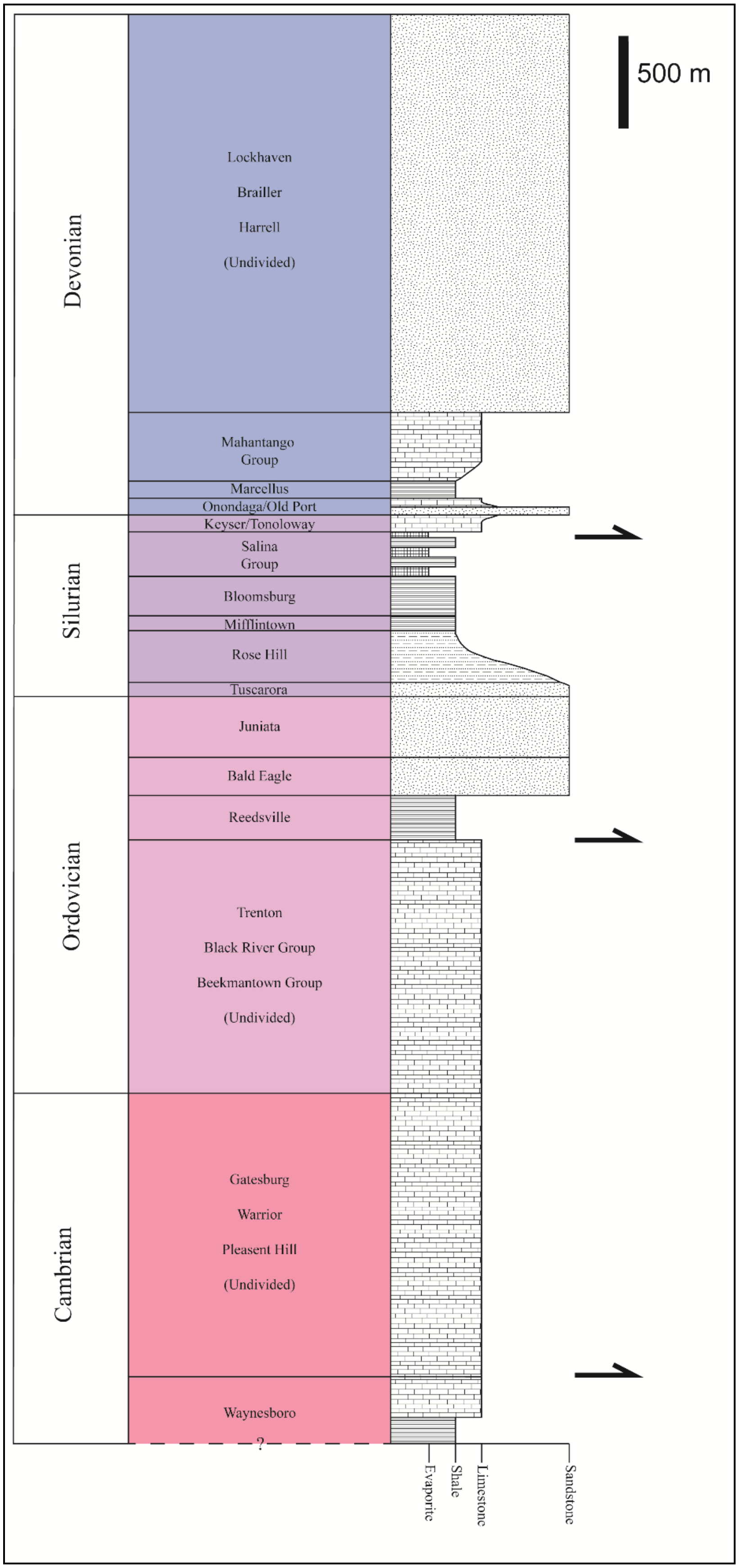

500 m
Devonian
Silurian
Ordovician
Cambrian
Lockhaven
Brailler
Harrell
(Undivided)
Mahantango
Group
Marcellus
Onondaga/Old Port
Keyser/Tonoloway
Salina
Group
Bloomsburg
Mifflintown
Rose Hill
Tuscarora
Juniata
Bald Eagle
Reedsville
Trenton
Black River Group
Beekmantown Group
(Undivided)
Gatesburg
Warrior
Pleasent Hill
(Undivided)
Waynesboro
?
Evaporite
Shale
Limestone
Sandstone

Figure 2 (previous page): Stratigraphic column for the central Appalachian Mountains. Complied from Miller, 1961; Gwinn, 1964; Faill and Wells, 1977; Taylor, 1977; Faill, 1979; Linberg, 1985; Nickelsen, 1988; Kauffman, 1999; and well data provided by Inflection Energy, LLC.

as the Catskill deltaic complex (Walker and Harms, 1971). These rocks display eastward shoaling (to shallower-water and nonmarine facies), and thickening (Miller, 1961; Faill and Wells, 1977; Taylor, 1977; Faill, 1979).

The collision of Gondwana and Laurentia marks the Alleghanian orogeny, which occurred approximately 325 Ma. The Alleghanian orogeny is the last major compressive tectonism to affect the Appalachian orogen, creating the long arcuate folds of the Valley and Ridge, which typify this fold and thrust belt in Pennsylvania (Faill, 1998). These first order anticlines and synclines plunge both SW and NE in central Pennsylvania, meeting in a hinge zone defined as the Juniata culmination. Rifting during the opening of the Iapetus created a reentrant geometry, which guided the shape of the Pennsylvania salient (Thomas 1977, 2006; Beardsley and Cable, 1983; Ong et al. 2007). These folds are underlain by southeast dipping thrust faults, the majority of which are blind, dying out in middle Devonian siliciclastics (Faill, 1998). The material shed from the Alleghanian Mountains was deposited on the AP and is upper Carboniferous to lower Permian in age (Faill, 1998). The erosional remnants of this depositional system are estimated to be 300-500 m thick, and thickening eastward, however the original thickness of the foreland basin is unknown because these sediments are only partially preserved on the AP, and as isolated fragments in the cores of synclines in the Valley and Ridge. This final compressive stage comes to a close at approximately 235 Ma, followed by the breakup of Pangea approximately 200 Ma, and the opening of the Atlantic (Faill, 1998).

2.2 STRUCTURAL PROVINCES

2.2.1 Valley and Ridge

The Valley and Ridge province in southern Pennsylvania is a classic example of a blind fold and thrust belt. On the surface, this area is characterized by an approximately 110 km wide swath of elongated valleys and ridges trending northeast/southwest (Faill, 1997; Berg et al., 1980; Miles and Whitfield, 2001). The thin skinned deformation style has produced various structures, including duplexes, low angle reverse faults, and tight folding. The folds in the Valley and Ridge show high amplitudes and short wavelengths (Harrison et al., 2004), and are generally thought to be forced folds, controlled by fault-bend folding in subsurface layers (Gwinn, 1964; Shumaker et al., 1985; Wilson and Shumaker, 1992). The dips of fold limbs in this province are variable, ranging from 10-15° to near vertical (Sak et al., 2012). Previous work has quantified fold wavelengths to be 7-12 km (Sak et al., 2012), with approximately 100 km long fold axes (Berg et al., 1980; Miles and Whitfield, 2001). The mechanics of folding are observed to be flexural slip and flexural flow folding (Herman, 1984; Sak et al., 2014). Flexural slip mechanisms have affected the geometry of the anticlines causing thickening of the hinge, however, the limbs remain a consistent thickness (Herman, 1984).

2.2.2 Appalachian Plateau

The Appalachian Plateau is characterized by gentle folding and relatively low relief (~ 30 – 460 m) topography. The folds generally trend northeast southwest, which is parallel to the fold trends within the Valley and Ridge. The dips of these gentle folds range from horizontal to <10°

(Wedel, 1932; Sak et al., 2012). Geologic mapping reveals fold wavelengths of 14 – 20 km, with ~ 60 km long fold axes (Berg et al., 1980; Miles and Whitfield, 2001). Unlike the Valley and Ridge province that has a deep shale decollement within Cambrian Waynesboro Formation, the AP has a shallow upper Silurian evaporite decollement (Gwinn, 1964; Prucha, 1968; Frey, 1973; Wiltschko and Chapple, 1977; Davis and Engelder, 1985; Beardsley et al., 1999; Shumaker, 2002). The differences in decollement geometry contributes to observed differences in surface and subsurface geology, between the Valley and Ridge and AP provinces (Rodgers, 1963; Prucha, 1968; Wiltschko and Chapple, 1977; Davis and Engelder, 1985). Anticlines through the AP have been structurally thickened by the migration of mechanically weak salt while the salt layer under the adjacent synclines is thin or absent (Davis and Engelder, 1985; Wiltschko and Chapple, 1977; Harrison et al., 2004; Mount, 2014). The evaporate layer serves as a decollement from which faults original and propagate into the younger units (Mount, 2014).

2.3 LAYER PARALLEL SHORTENING (LPS)

Low temperature microscale shortening changes the grain shape of an original spherical grain, such as an ooid, into an ellipsoid through the process of mineral dissolution (Rutter, 1976). In two dimensions, the axial ratio between the long and short axes of the ellipse yields a measure of the strain (Figure 3). In a regional context, when the short axis is parallel to bedding and perpendicular to fold axes, this style of shortening is called layer parallel shortening (LPS). Early work in the Appalachian Plateau revealed the presence of approximately 10% LPS in distorted fossils (Nickelsen, 1966; Slaughter, 1982). The discovery of pressure solution cleavage planes with roughly 0.5 mm of material removed indicated that shortening amounts in the AP could

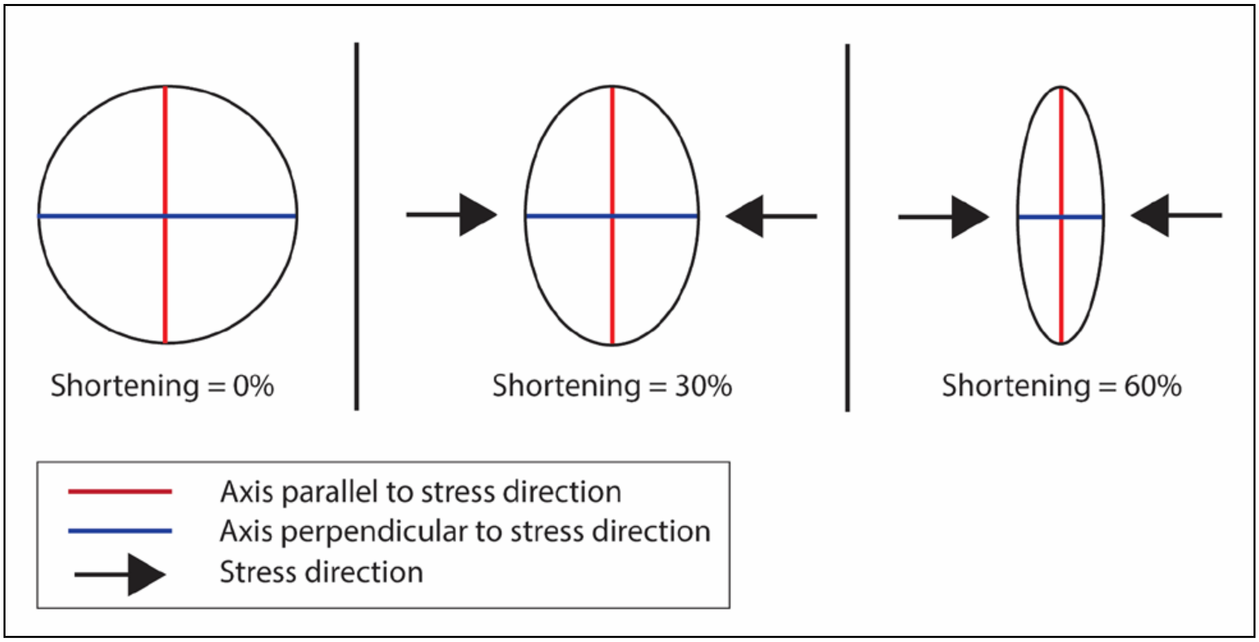


Figure 3: Diagram illustrating a theoretical spherical grain shortening through layer parallel shortening. This style of compressive shortening will shorten the axis of the grain which is parallel to the direction of stress.

be ≤15% (Geiser, 1974; Engelder and Engelder, 1977). Measurements of grain scale strain in quartzite rocks and distorted fossils across the Valley and Ridge province indicate higher LPS values. New and compiled data across the Valley and Ridge and AP in the region of the Susquehanna Valley revealed approximately 13% LPS shortening in surface rocks of the plateau, and 20% LPS in the Valley and Ridge (Sak et al., 2012). With that result, Sak et al. (2012) constructed a restored and balanced cross section across the central Appalachians of Pennsylvania where macroscale shortening of the Cambrian - Ordovician units in the Valley and Ridge is equal to the 20% LPS above it and an additional 24 km of that shortening is expressed as gentle folding and LPS in the Appalachian Plateau.

2.4 SEISMIC STUDIES

Seismic investigations have explored many portions of the Appalachian Plateau in Pennsylvania. Early work by Scanlin and Engelder (2003) in the southwestern Pennsylvania utilized a series of 2-D lines and well log data to support a model for the imbrication of competent Silurian - early Devonian units above the Silurian salt detachment. This area was recently revisited by Donahoe (2011) who used a 3-D seismic volume to evaluate the subsurface, confirming that the strata immediately above the salt contained both north and south dipping faults with small offsets. Analyses of high resolution 3-D seismic from central Pennsylvania (Roberts, 2013) and northeastern Pennsylvania (Gillespie et al., 2013; Mount, 2014) have produced similar results that show thrust faulting focused above the Silurian salt detachment in Silurian - early Devonian aged strata. Taken together, these previous studies demonstrate that the presence of thrust faulting in strata immediately above the Silurian Salina Group is common throughout Appalachian Plateau.

3.0 METHODS

3.1 GEOLOGIC MAPPING

This study uses a statewide geologic map (1:250,000-scale) to describe the first-order geology of Pennsylvania (Berg et al., 1980; Miles and Whitfield, 2001) across our study area. In particular, we focus on a portion of Lycoming County in central Pennsylvania that straddles the Allegheny Front (Figure 4). To represent the most detailed geology of this area, we incorporate high resolution mapping from the Pennsylvania Geologic Survey for the following quadrangles: Allenwood, Milton, Mountoursville South, Muncy, Linden, Williamsport and part of Hughesville (1:24,000-scale) (Faill and Wells, 1977; Faill, 1979; Inners, 1993). These larger scale maps subdivide the bedrock geology at a resolution not possible on the 1:250,000-scale statewide geologic map. In addition to the geologic maps, we utilize strike-and-dip data from two datasets. The first is field data collected by Sak et al., (2012) which is a tightly-spaced dataset focused along a northeast trending transect from the Valley and Ridge into the Appalachian Plateau. The second dataset, provided by Inflection Energy, LLC., was collected using high resolution imagery and elevation models to identify bedding planes and calculate strike and dip remotely.

3.2 SUBSURFACE DATA

3.2.1 Seismic

All seismic data in this study is provided by Inflection Energy, LLC. (Figure 4). These data include recently acquired high resolution 3-D seismic, spanning roughly 450 square km across Lycoming County, Pennsylvania in the Appalachian Plateau. Twelve parallel 2-D seismic sections were extracted from the 3-D seismic volume, with a spacing of 1.5 to 3 km depending on the complexity of the change in structure in adjacent sections. The section density allows us to explore how the subsurface structure in the AP is changing in both north-south and east-west directions. In addition, we incorporate two older 2-D seismic lines, which span the northernmost two anticlines of the Valley and Ridge province. The 2-D seismic data is a combination of two surveys, a Seitel Muncy Creek survey shot in November of 2010 and early 2012, and an Inflection Energy LLC. survey shot in 2014. These sections are useful for constraining how the structures of the Valley and Ridge transition into the AP.

3.2.2 Well Data

Information from 38 wells (9 vertical pilot wells, 29 lateral wells off of the pilot wells) drilled by Inflection Energy, LLC. and located in Lycoming County are used in this study (Figure 5a). These wells target the Marcellus shale, and as such contain important subsurface information on all the strata within 1,500-2,400 m of the surface. When drilling a well, the depth to each stratigraphic horizon reached along the well path is determined by drill cuttings and is recorded. The drill cutting data are used to determine the depth to critical stratigraphic

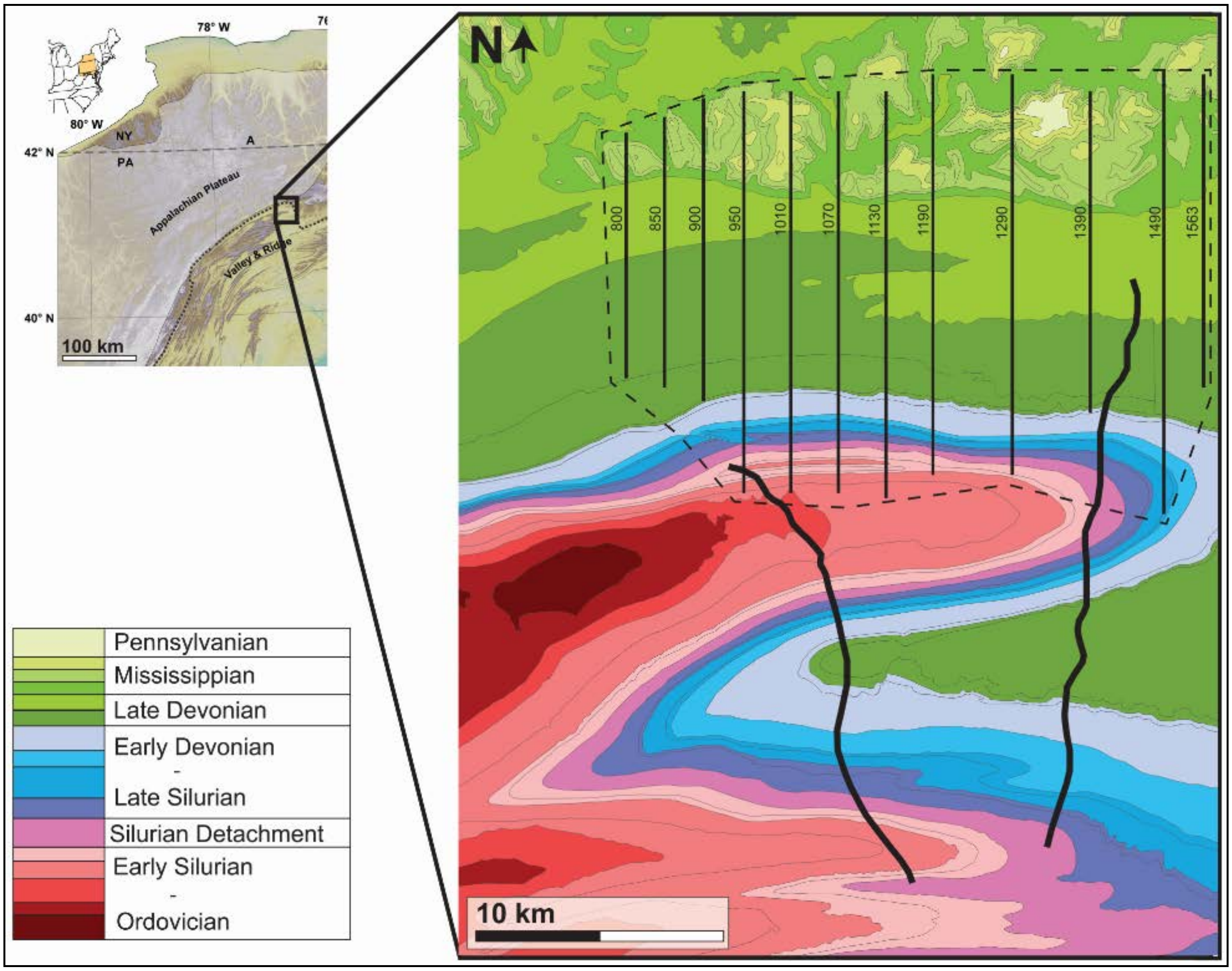


Figure 4: The plan view extent of seismic data provided by Inflection Energy, LLC. The dashed line represents the approximate extent of a 3-D volume of high resolution Appalachian Plateau seismic. The bold lines within the dashed line represent the locations of 2-D seismic lines extracted from this volume for detailed interpretations. Numbers along these lines correspond to cross section labels in appendix. Heavier sinuous lines further south represent older 2-D seismic in the Valley and Ridge. Base map (left) modified from Sak et al., (2012).

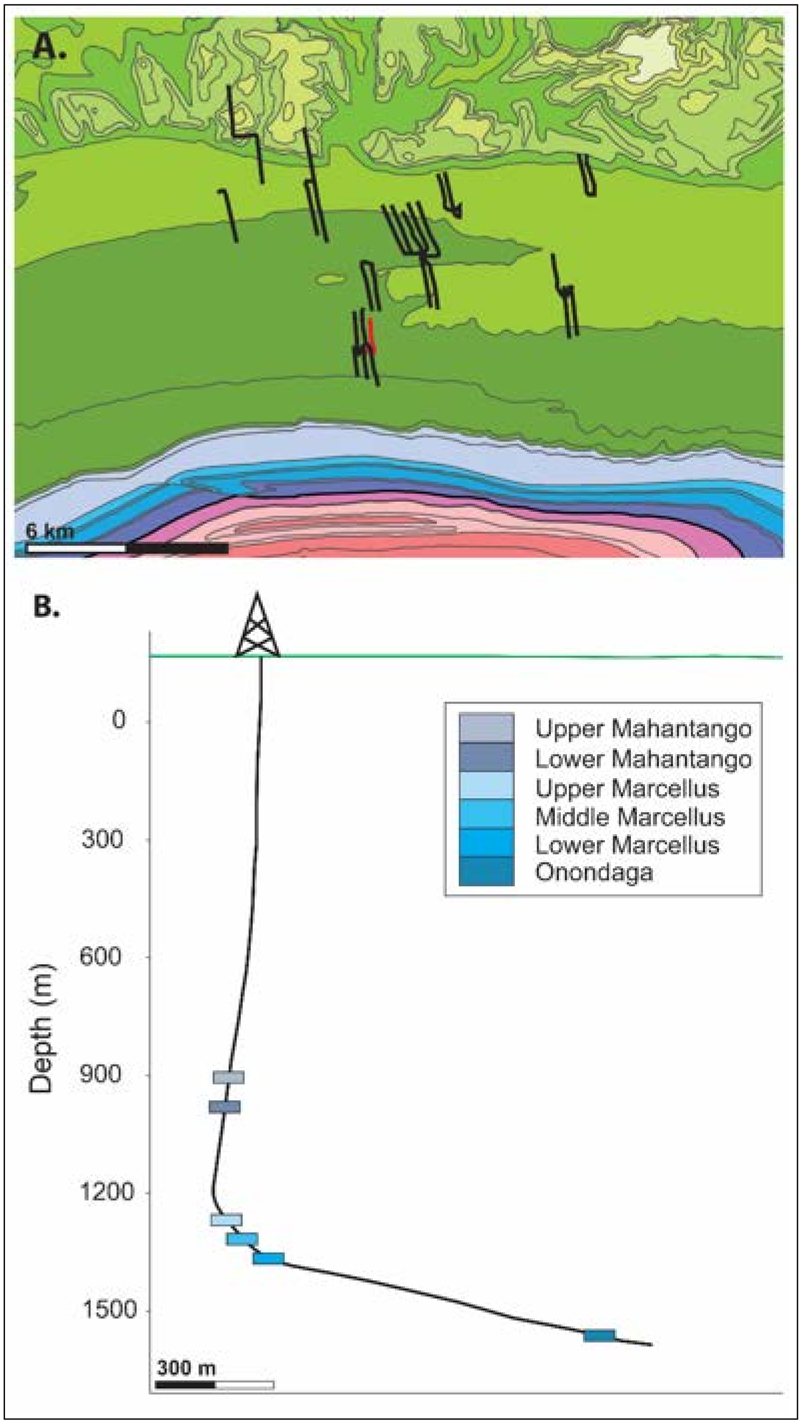


Figure 5: (A) The plan view extent of vertical and horizontal wells drilled by Inflection Energy, LLC. in Lycoming County, Pennsylvania. Refer to figure 4 for legend. (B) Horizon top data along one well path (represented by red well path in (A)) drilled by Inflection Energy, LLC. This data reveals the depth to horizons in the area of this specific well.

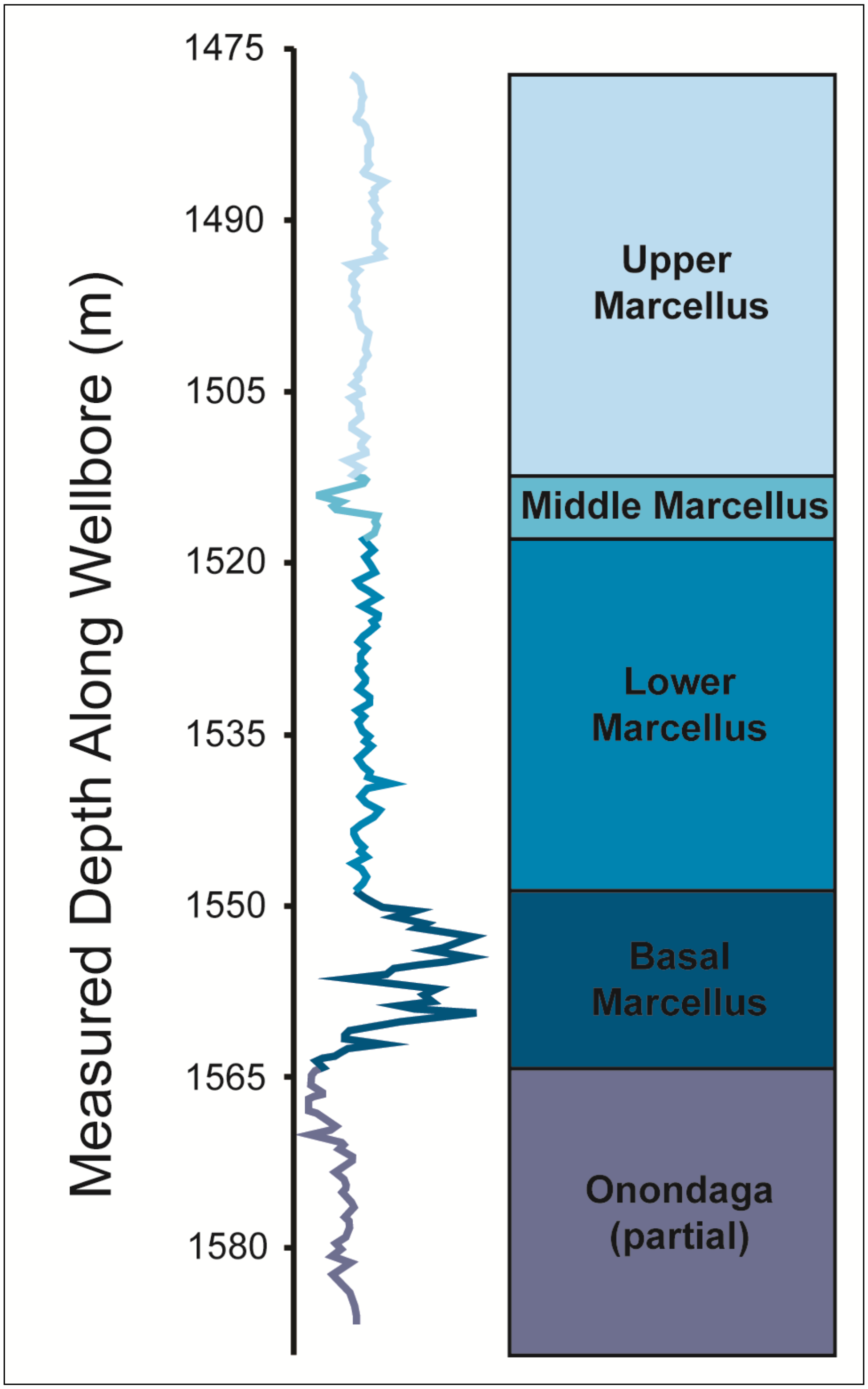


Figure 6: Vertical gamma type log for the Appalachian Plateau. This guide shows the gamma log signatures for specific units. The gamma log signature recorded while horizontally drilling is compared to this type log to understand what section the wellbore is currently in stratigraphically.

layers and tie stratigraphic units to the reflectors visible in the seismic data in 3-D space (Figure 5b).

In addition to the data indicating the top of different stratigraphic horizons, we also incorporate gamma log surveys of the wells. While drilling a vertical well, the gamma signature is recorded and compared to retrieved core data, allowing for the precise stratigraphic correlation between specific units based upon gamma log characteristics (Figure 6). This creates a type log, which is used as a guide for determining stratigraphic units without the recovered core by the comparison of gamma log signatures to the type log.

3.3 IDENTIFYING SUBSURFACE HORIZONS

Geophysics, specifically seismic reflection, provide an unprecedented view into the subsurface. However, inherent in the seismic data is the limitation that it is only measuring the two way travel time of waves of energy moving through the subsurface. Even when travel time seismic is converted into depth, seismic data does not provide in a perfect snapshot image of the exact location of units or structures in the subsurface. As a consequence, we rely upon the combination of stratigraphic horizon tops from well data and available gamma logs to inform our interpretations of stratigraphic layers from the seismic lines to ensure accuracy (Figure 7). These data are used to determine depths of subsurface units in our cross sections (Figure 7a) and relate specific seismic reflectors to stratigraphic horizons. For example, in figure 7a the first high amplitude reflector is associated with the top of the Mahantango Group. When this reflector is continuous, we can trace it throughout the section to identify the top of the Mahantango Group in areas without well data.

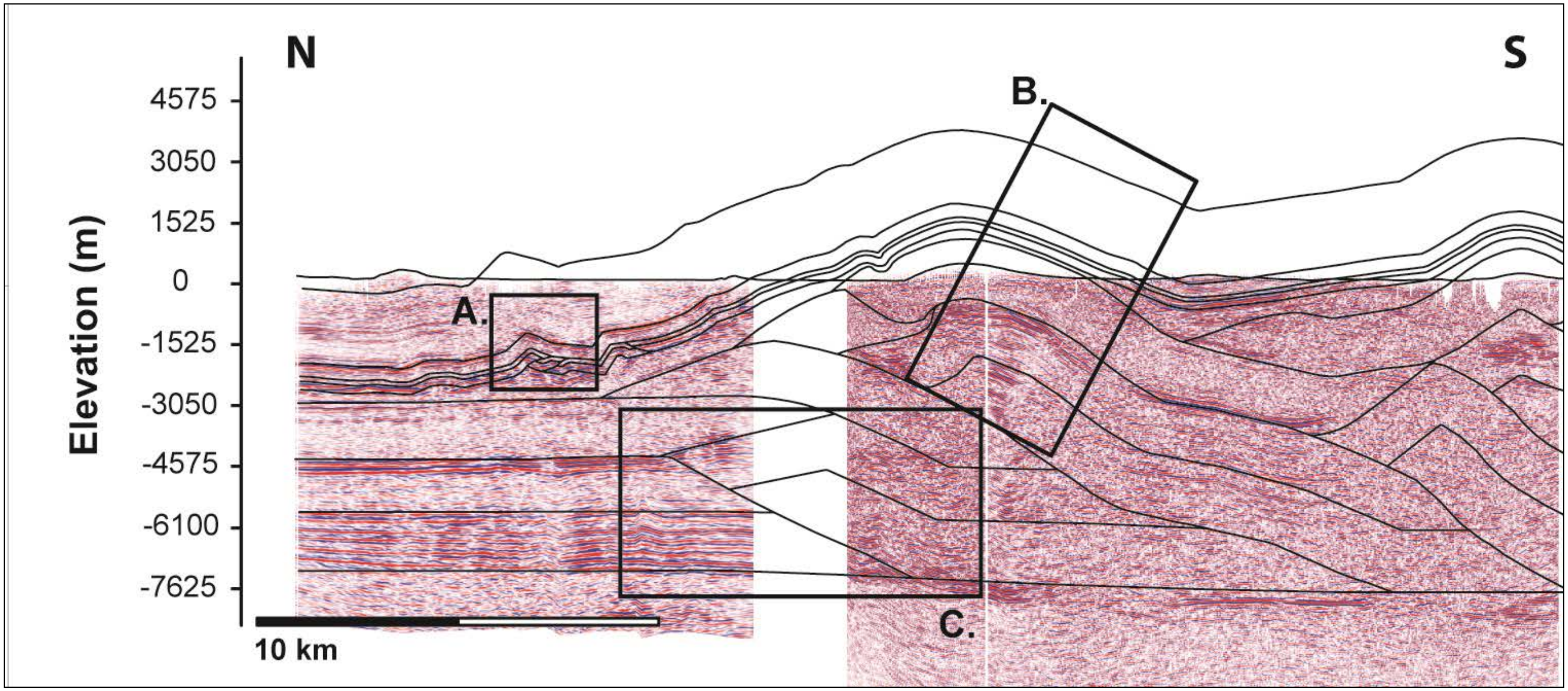
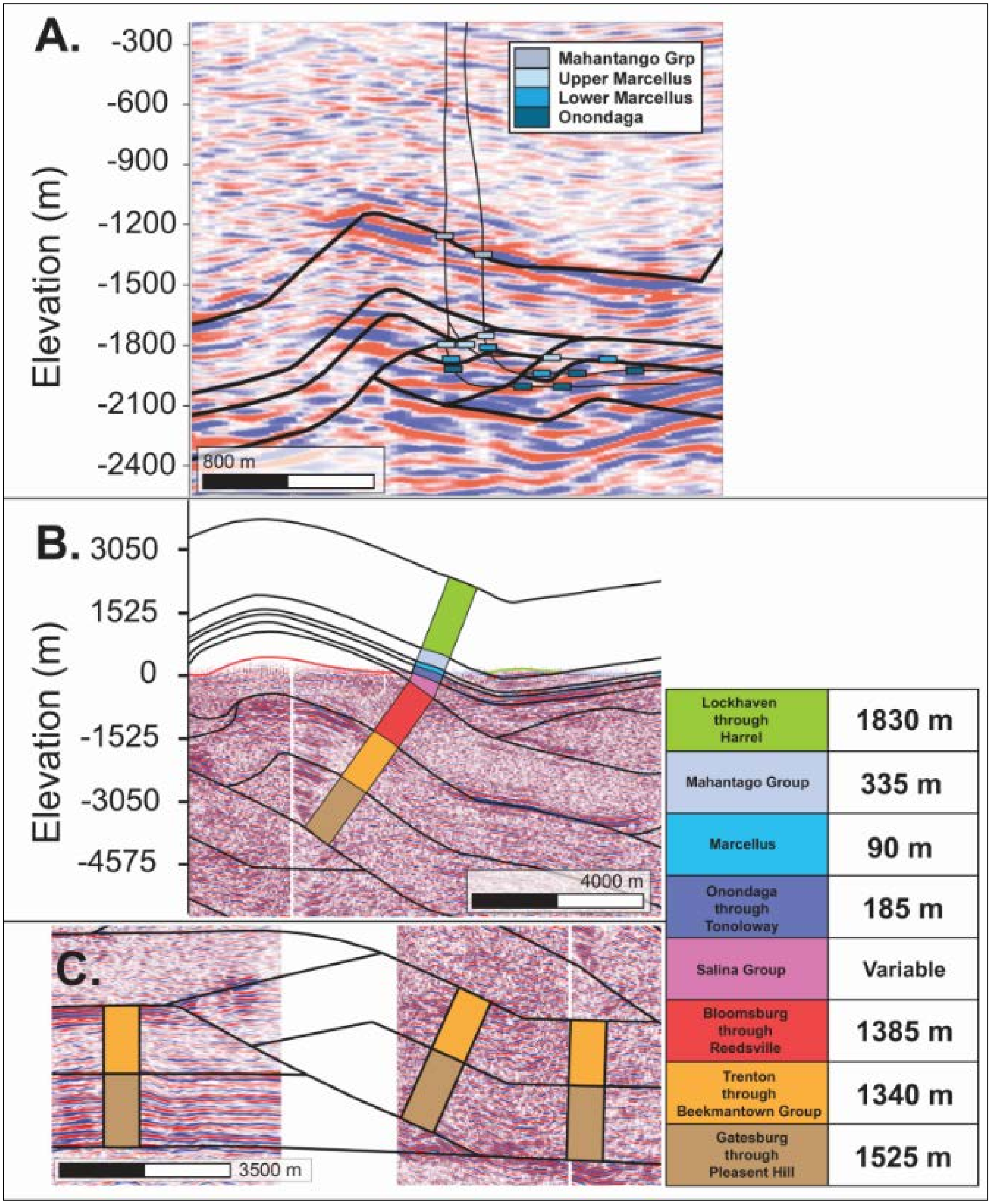


Figure 7: 2-D seismic section highlighting the Allegheny Front**.** (A) (next page) Using horizon tops provided by Inflection Energy, LLC. to interpret the depth to horizons in seismic. (B) (next page) Combining unit surface intersections and mapped stratigraphic thickness to make geologically accurate interpretations of seismic. Stratigraphic thicknesses compiled from Miller, 1961; Gwinn, 1964; Faill and Wells, 1977; Taylor, 1977; Faill, 1979; Linberg, 1985; Nickelsen, 1988; Kauffman, 1999. (C) (next page) Using stratigraphic thickness to accurately interpret a deep structure observed in seismic. Stratigraphic thicknesses compiled from Gwinn, 1964; Linberg, 1985; Nickelsen, 1988; Kauffman, 1999.


A.
Elevation (m)
-300
-600
-900
-1200
-1500
-1800
-2100
-2400
Mahantango Grp
Upper Marcellus
Lower Marcellus
Onondaga
800 m
B.
Elevation (m)
3050
1525
0
-1525
-3050
-4575
4000 m
C.
3500 m
Lockhaven through Harrel
1830 m
Mahantago Group
335 m
Marcellus
90 m
Onondaga through Tonoloway
185 m
Salina Group
Variable
Bloomsburg through Reedsville
1385 m
Trenton through Beekmantown Group
1340 m
Gatesburg through Pleasent Hill
1525 m

Stratigraphic constraints are essential for creating realistic geologic cross sections. We use mapped stratigraphic thicknesses and unit outcrops from geologic maps and transfer the exposed surface geology data into the subsurface (Figure 7b). This is permissible in our research area because the scale of our study (approximately 40 km long sections) precludes significant lateral changes in unit thickness with one notable exception. The Silurian Salina Group is comprised of interfingering mechanically weak salt and shale layers of varying thickness. As a result, this unit deforms in a ductile way and shows abrupt changes in thickness throughout the area.

The stratigraphic constraints serve the dual purpose of providing subsurface unit thicknesses and for determining deep structure where units have been deformed and uplifted from regional depths (Figure 7c). In such instances, seismic observations including tilted, uplifted, or truncated reflectors are used to identify and constrain the subsurface structure. This approach results in viable interpretations of subsurface geometry by maintaining consistent unit thickness and honoring available subsurface constraints on the position of horizon tops.

3.4 IDENTIFYING SUBSURFACE STRUCTURE

Seismic refraction is a powerful tool for identifying structures in the subsurface (Figure 8). A strong indicator of faulting is truncated seismic reflectors. In the seismic data faults are represented as abrupt terminations of strong continuous reflectors that reappear in the seismic section with some sense of offset (Figure 8a). In some instances, the resolution of the seismic section is sufficient to interpret the angle between offset beds. For example, in figure 8b we observe numerous truncations in the seismic reflectors, and those truncated segments appear to

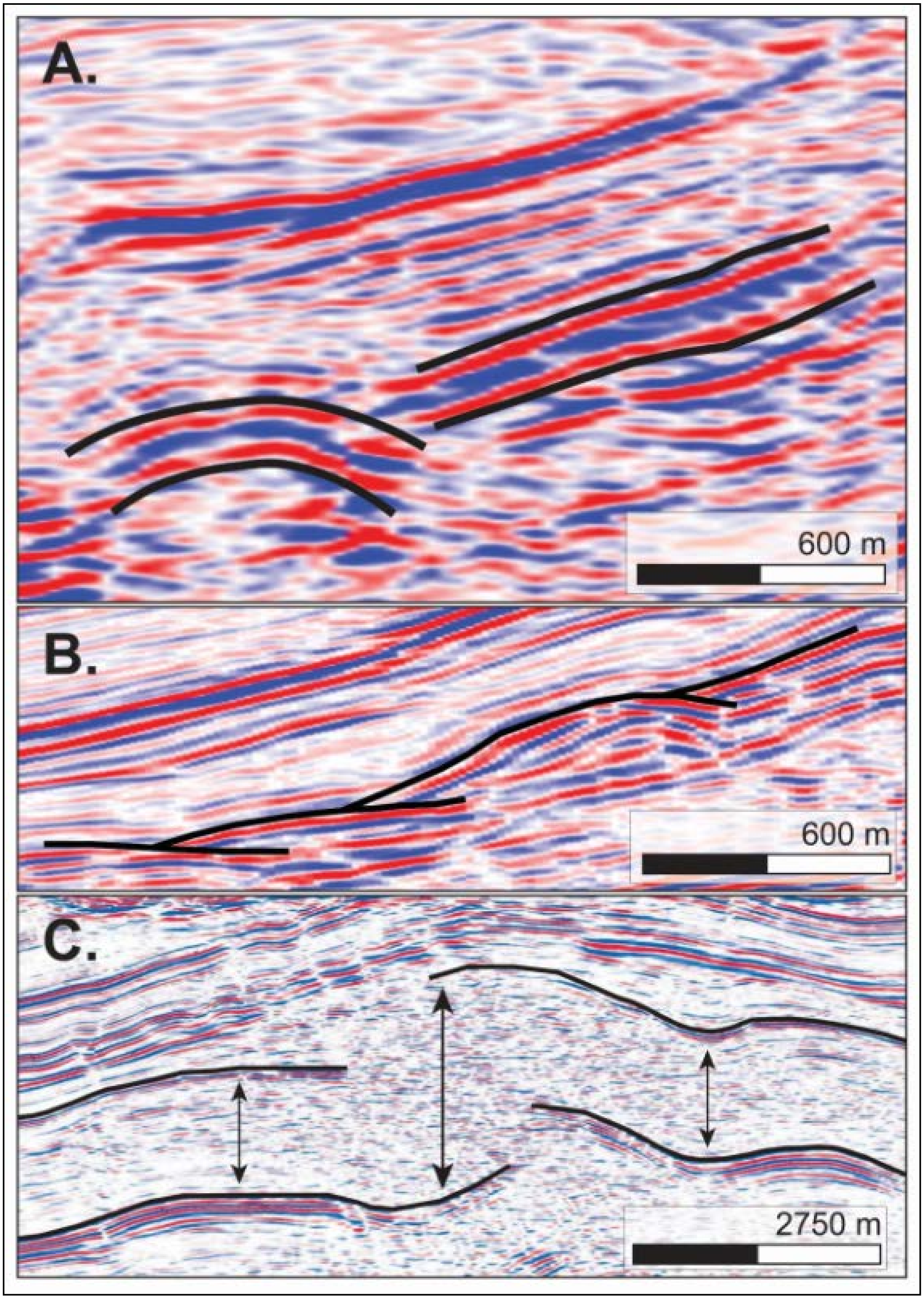

A.
600 m
B.
600 m
C.
2750 m

Figure 8 (previous page): Using observations in seismic to make structural interpretations. (A) The top strong reflector appears continuous and unbroken. In contrast, the bottom strong reflector (outlined) is abruptly truncated, reappearing with a sense of offset. (B) Truncated reflector that appears to be ramping on top of itself at low angles. (C) A very abrupt change in the vertical distance between a set of reflectors across a very small horizontal distance**.**

overlap. An abrupt change in thickness is another clear indicator of a structure. In figure 8c we can observe two sets of reflectors which represent the top and bottom of a group of beds. Abrupt thickening of beds over this scale is not geologically permissible, indicating structure must accommodate the apparent increase in thickness between these representative top and bottom reflectors.

In cases where the seismic data are insufficient to resolve the subsurface geometries, seismic data are used in conjunction with gamma log surveys to obtain the necessary resolution required to define structures. Logging while drilling (LWD) is a common industry practice where the gamma log signature is obtained while the hole is drilled to provide independent constraints on the geophysical properties of the drilled strata. In this study area, stratigraphic discontinuities in gamma signatures are observed along well paths. These discontinuities in gamma log data are interpreted as evidence of subsurface structure. In some examples we observe the gamma log signature changing from lower Marcellus to upper Marcellus, with no record of drilling through middle Marcellus (Figure 9). The omission of the middle Marcellus is interpreted as the result of faulting.

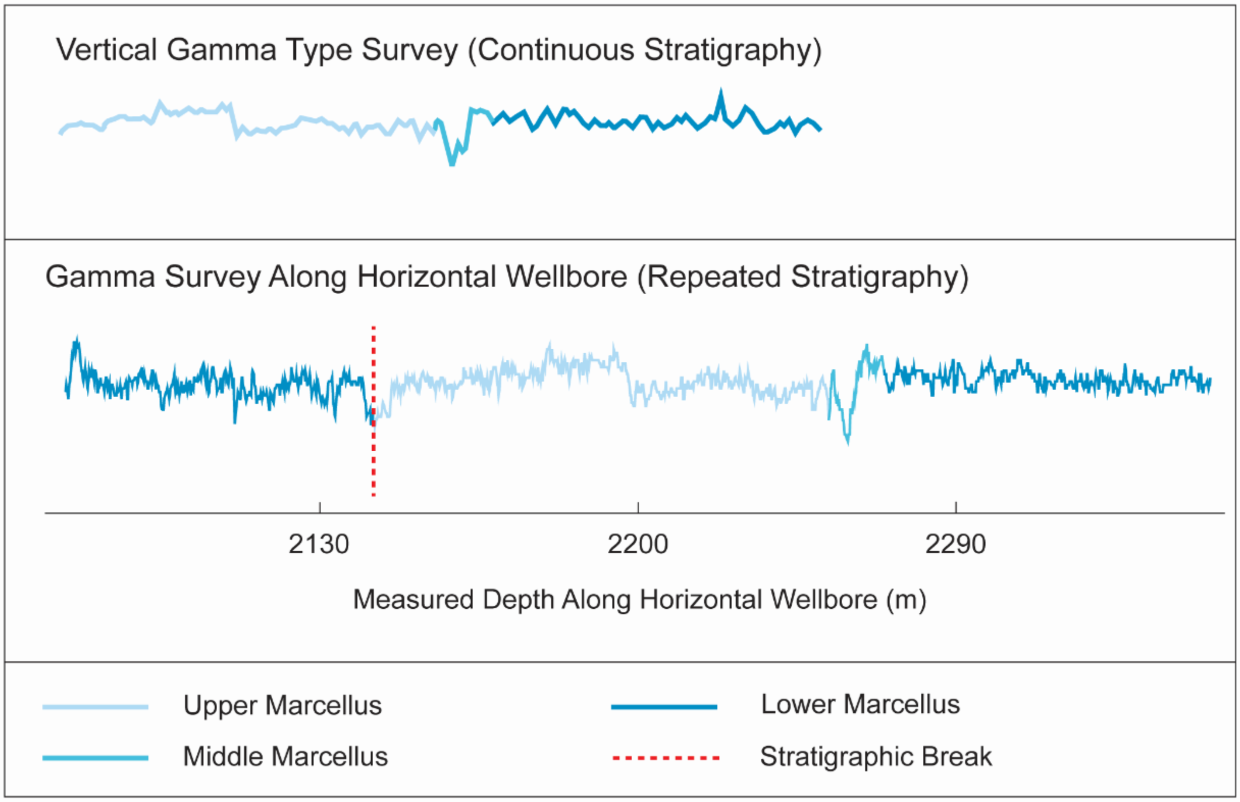


Figure 9: Comparing the vertical gamma type survey for the Appalachian Plateau (modified from Figure 6) to a horizontal well path. The horizontal well path passed through upper Marcellus shale into lower Marcellus shale with no record of middle Marcellus.

4.0 RESULTS: SUBSURFACE STRUCTURE

4.1 VALLEY AND RIDGE

4.1.1 Stratigraphic Observations

The study area is limited to the northernmost first order anticlines in the Valley and Ridge south of the Allegheny Front. In contrast to the Appalachian Plateau, the Valley and Ridge is not being extensively explored for hydrocarbon reserves so our seismic data is limited to two 2-D seismic lines (Figure 4) with no 3-D seismic or well data available. We project outcropping units and strike and dip data from geologic maps onto our line of section (Figure 7b). This allows us to correlate surface geometries with near-surface seismic reflectors. We incorporate mapped stratigraphic thickness by extending a stratigraphic column into the subsurface and find agreement between measured stratigraphic thicknesses at the surface and subsurface reflectors in the 2-D seismic sections (Figure 7b).

4.1.2 Seismic Observations

The 2-D seismic sections reveal multiple geometries that require subsurface geologic structures to produce. One of these features is discontinuous seismic reflectors. Otherwise continuous reflectors are truncated and reappear in the section with some sense of offset (Figure

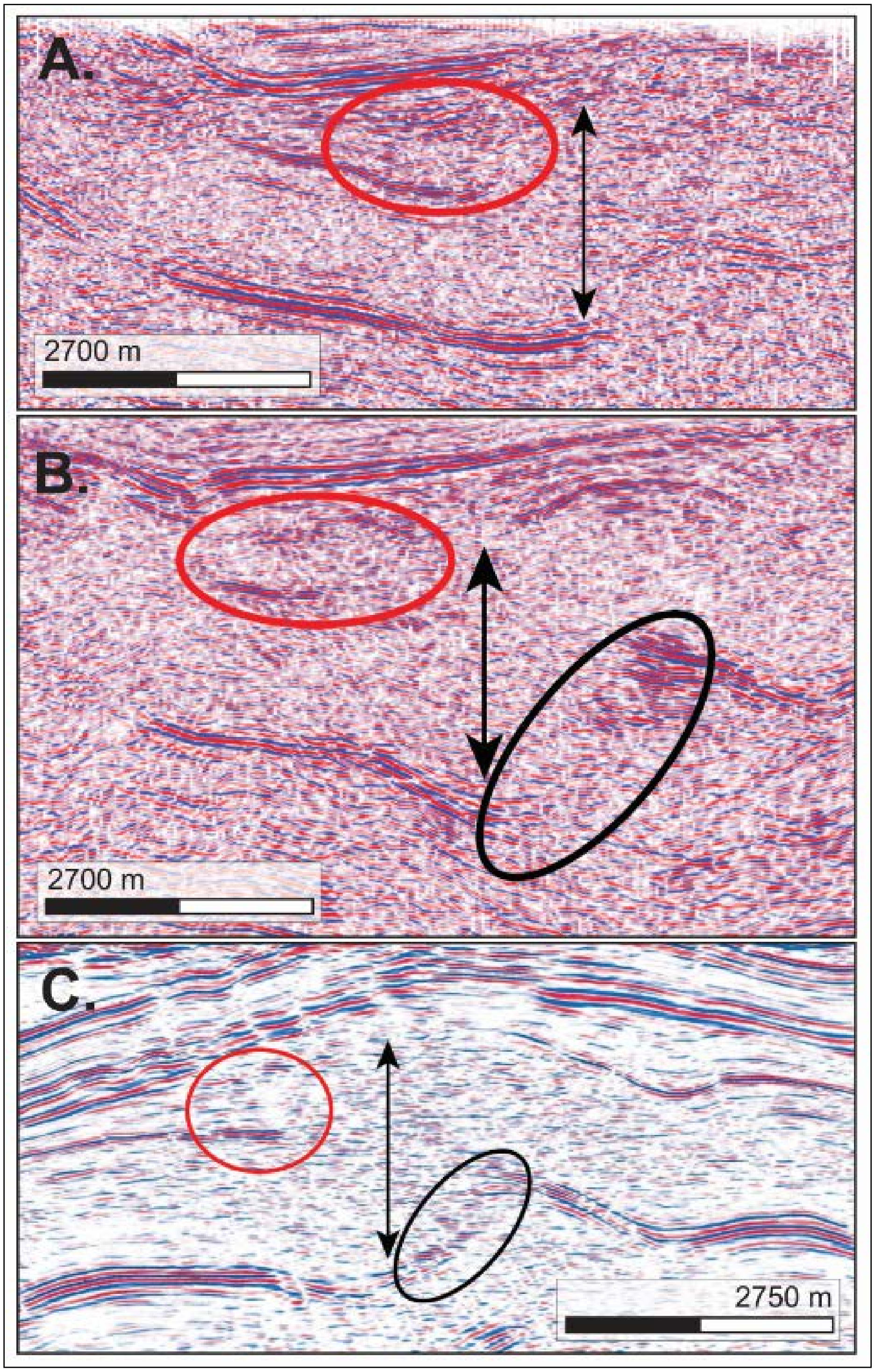


Figure 10: Indicators of subsurface structure in Valley and Ridge seismic sections. Red circles indicate 'stacked' or 'doubled' reflectors, arrows highlight abrupt changes in thickness between reflectors, and black circles show truncated offset reflectors. (A) Doubled reflectors and abrupt changes in thickness. (B) Doubled reflectors in upper seismic, truncated reflectors in lower seismic, and abrupt thickness change. (C) Abrupt change in thickness between lower truncated reflectors and doubled upper reflectors.

10). Individual truncated reflectors can be doubled or stacked (Figure 10). Seismic attributes (such as similar amplitudes and wavelengths of peaks and troughs) of these key reflectors are sufficiently unique to distinguish them as the same repeated sequence versus a separate package of reflectors that would represent a different stratigraphic sequence (either above or below). Another observation is seismic reflectors that are tilted at varying degrees, up to ~ 30^{o} (Figure 7c). We also find abrupt changes in thickness between two sets of specific reflectors. The space between these reflectors nearly doubles vertically across an ~1 km horizontal distance (Figure 10). In contrast, gradual thickening and thinning between a different set of reflectors can be seen throughout the section (Figure 11).

4.1.3 Structural Interpretation

Incorporating mapped stratigraphic thicknesses and surface geometries onto our seismic sections allows us to determine which units are represented by specific seismic reflectors (Figure

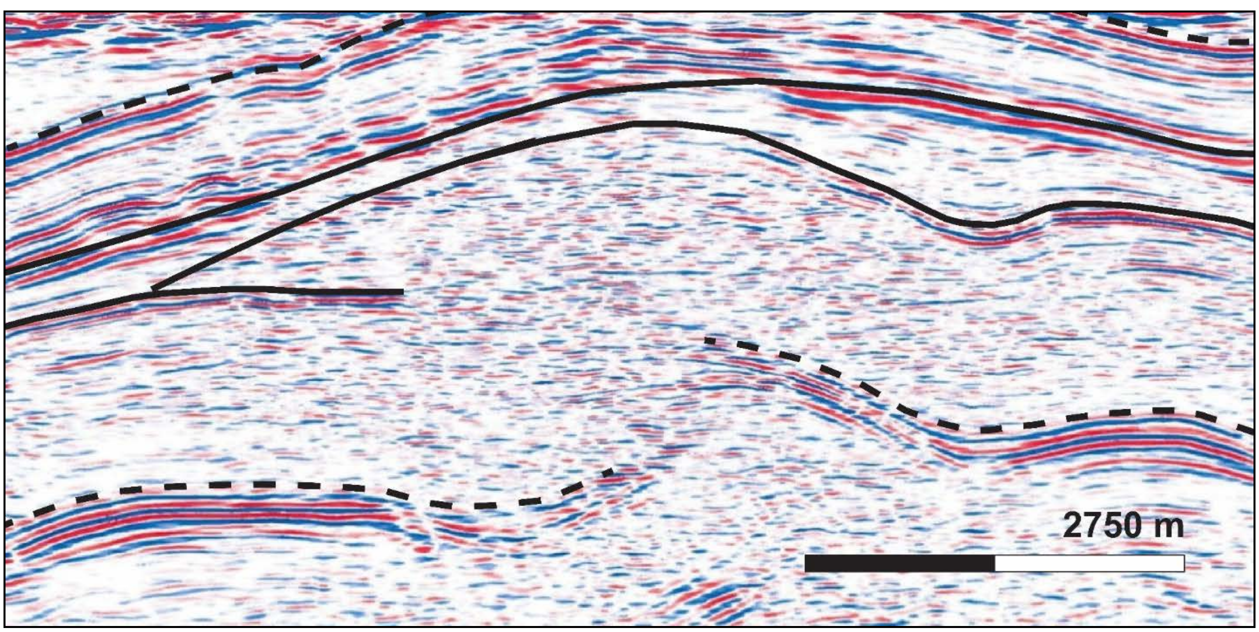


Figure 11: A gradual change in thickness is observed throughout the Valley and Ridge seismic between the two reflectors outlined by solid black lines.

7b). Once the link between stratigraphy and seismic reflectors has been established, we use mapped stratigraphic thicknesses to fill available space in structural interpretations (Figure 7c). Our structural interpretations honor the observations that require structures in geophysical data and the stratigraphic constraints of geologic maps, while showing kinematically admissible geometries (Figure 12).

Incorporating stratigraphic thicknesses allows us to correlate the deep seismic reflectors with Cambrian – Ordovician strata (Figure 7). These truncated, tilted, and stacked seismic reflectors show the location of individual ramps of the Cambrian - Ordovician duplex (Figures 7b, 7c and 13). We combine the mapped stratigraphic thickness of the Cambrian - Ordovician units to accurately interpret the geometry of this duplexing sequence (Figures 7c and 14). The majority of the horses making up the duplex are southeastward dipping fault bend folds separated by seismic discontinuities that we interpret as thrust ramps that are spaced 2.9 km apart (approximately the thickness of the repeated Cambrian – Ordovician strata). To the east, the spacing between ramps observed in seismic increases to ~ 4200 m, ~1330 m thicker than the full thickness of the Cambrian - Ordovician duplexing sequence (Figure 13). Visible seismic discontinuities in these eastern sections (Figure 13) suggest additional structures that dip to the north spaced between the dominant southward dipping ramps. We interpret these structures as smaller offset backthrust ramps that accommodate additional shortening. The backthrust geometry allows us to fill the ~1330 m space between the main southward dipping ramps (Figure 15). Slip on individual ramps of the Cambrian - Ordovician duplex ranges from 1 to 8 km with lesser magnitudes of backthrusting (700 – 1400 m) on eastern sections (Figures 14 and 15).

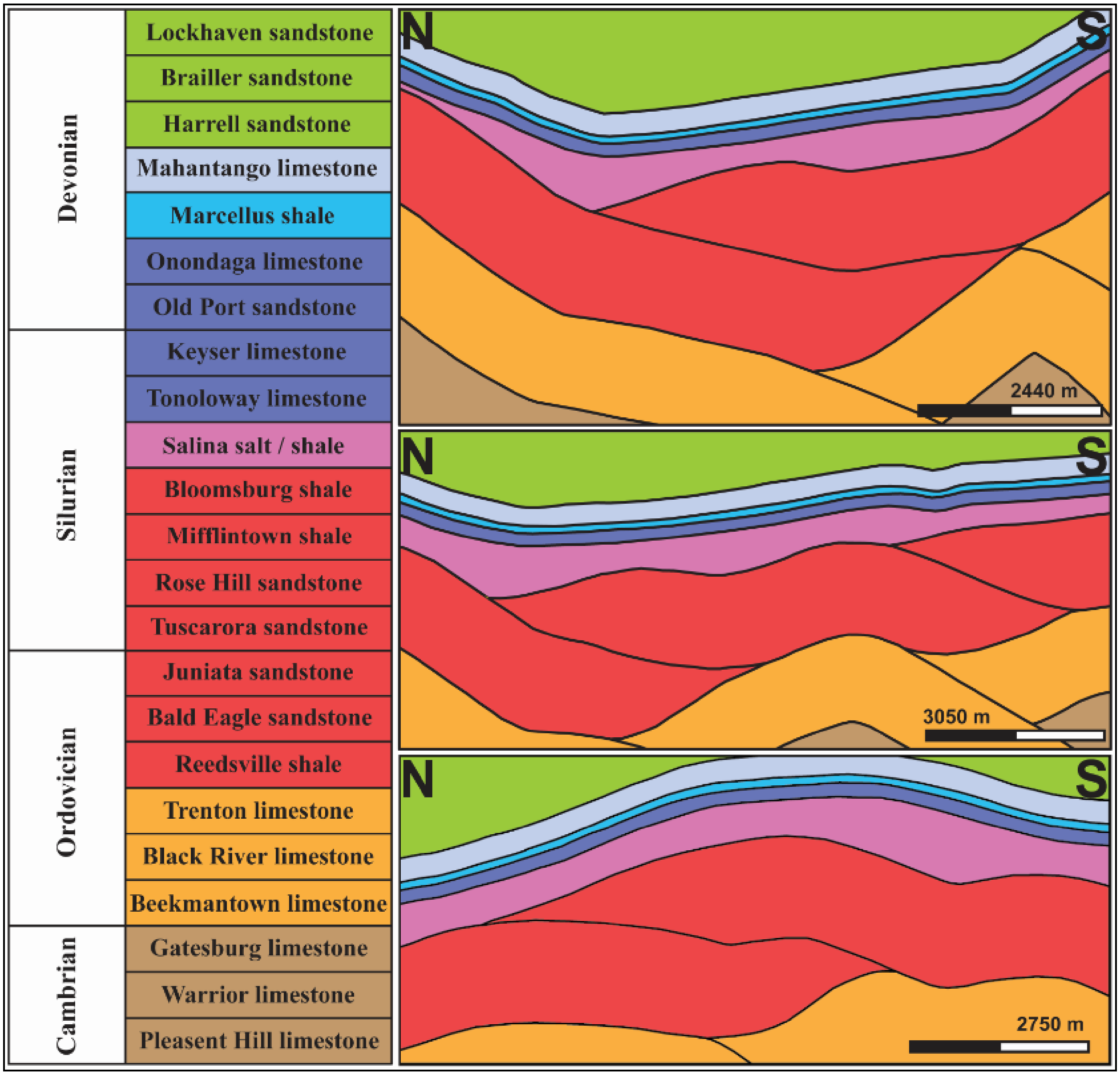


Figure 12: Structural interpretations based on geophysical data from the Valley and Ridge province.

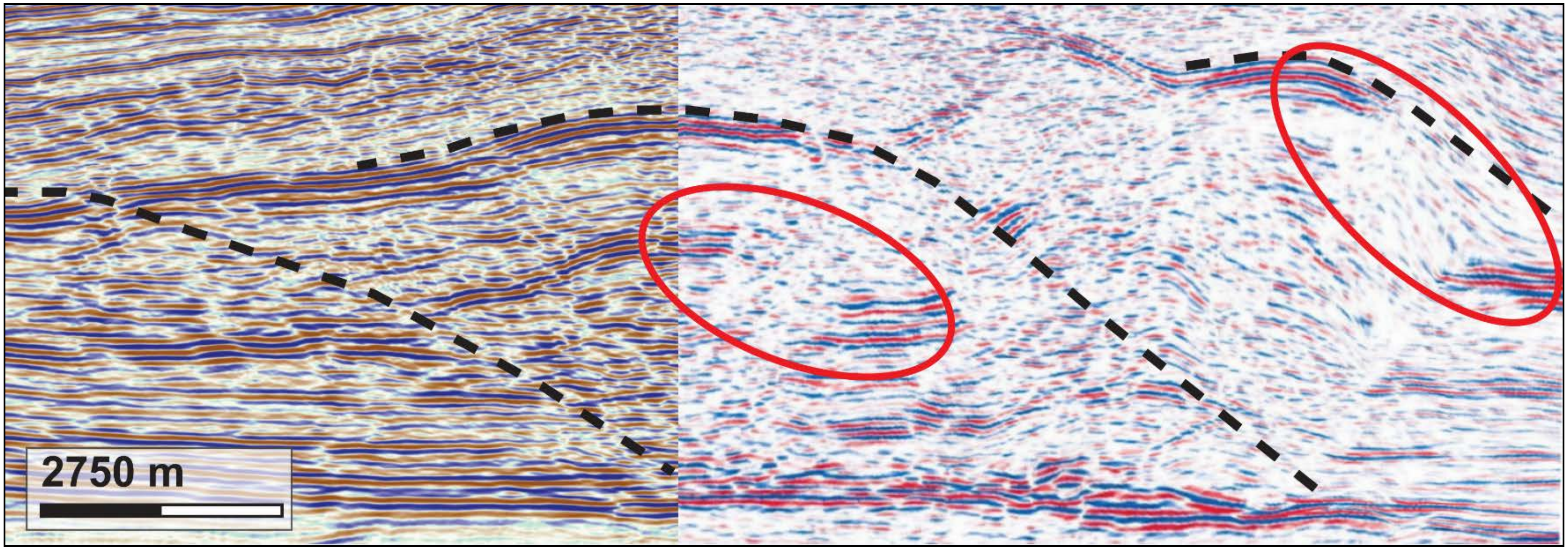


Figure 13: The location of suspected ramps shown in seismic (black dashed line) and seismic discontinuities within those ramps (red circles).

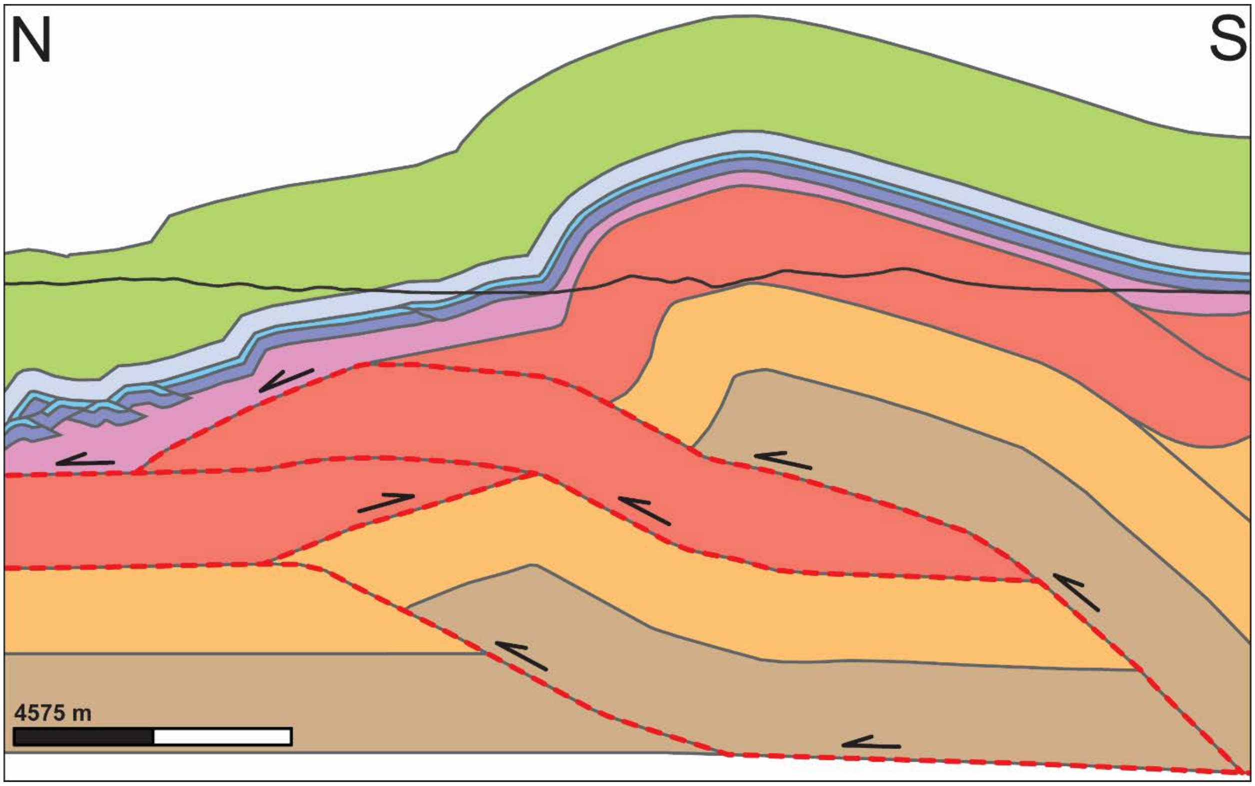


Figure 14: Depiction of how 10 km of macroscale shortening is being transferred from the Waynesboro detachment in the Valley and Ridge to the Silurian detachment in the Appalachian Plateau in the western most cross section of this study. Specific location corresponds to inline 800 in figure 4. (Refer to figure 12 for legend).

Similar truncation and stacking patterns are observed in the set of reflectors above the Cambrian – Ordovician reflectors (Figures 10, 11). We interpret these seismic characteristics as thrust faults, and we utilize stratigraphic constraints of unit outcropping and thicknesses (Figure 7b) to identify the faulted package as early Silurian to Ordovician strata (Figures 7b, 10-12). More specifically, we interpret fault ramps to extend from the Silurian Salina detachment (top) to the Ordovician Reedsville detachment (bottom). Fault ramps through early Silurian – Ordovician units dip both north and south with shortening amounts ranging from 400 to 3000 m. We relate the abrupt changes in thickness identified in the seismic sections to be a consequence of thrust faulting (Figures 10-12).

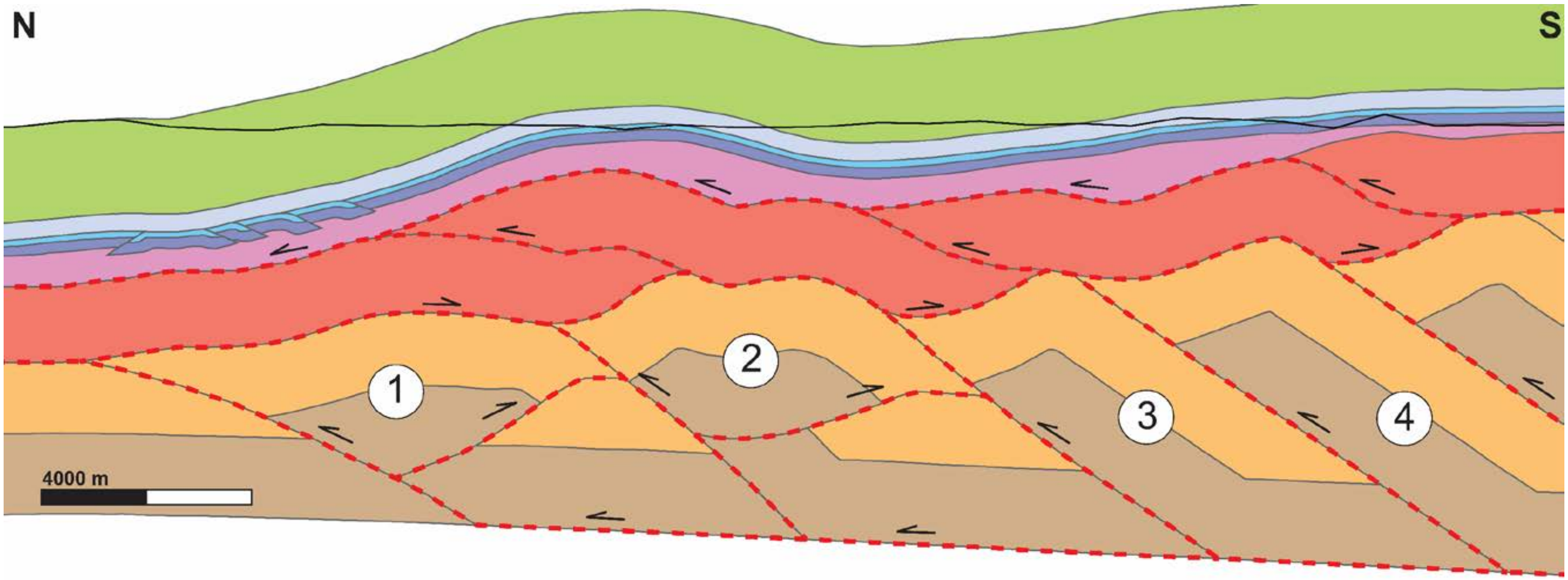


Figure 15: Illustration of how 10 km of macroscale shortening is being transferred from the Waynesboro detachment in the Valley and Ridge to the Silurian detachment in the Appalachian Plateau in the eastern most cross section of this study. Specific location corresponds to inline 1563 in figure 4. (Refer to figure 12 for legend).

The area above the early Silurian – Ordovician sequence shows gradual thickening and thinning between seismic reflectors (Figure 11). Using mapped stratigraphic thicknesses and mapped outcrops as constraints, we identify this area as the Silurian Salina Group (Figure 7b). The Salina Group is comprised of mechanically weak salt and shale. Like previous workers, we conclude that the observed gradual change in thickness is a ductile response to shortening (Prucha, 1968; Frey, 1973; Wiltschko and Chapple, 1977; Davis and Engelder, 1985; Harrison et al., 2004; Mount, 2014). The Salina salts are locally as thick as 800 meters and elsewhere can thin to 100 meters (Figures 11 and 12).

The fault geometries shown displacing the early Silurian – Ordovician units (Figures 10-12) have a fault ramp that cuts through the resistant units which becomes a decollement that parallels stratigraphy in the Silurian Salina Group (upper decollement) and the Ordovician Reedsville Formation (lower decollement). This geometry is indicative of wedge-style faulting. Wedge faulting creates a wedge shaped fault block where two fault segments (a decollement and a ramp) merge at the tip of the wedge (Shaw et al., 2006) (figure 16). We use our interpretation of wedge-style faulting in early Silurian – Ordovician units in each of our structural interpretations of the portion of the study area within the Valley and Ridge province even when seismic data is not available to reaffirm this interpretation (see appendix). Wedge-style faulting allows us to fill space between the surface geology and the duplexed Cambrian – Ordovician. Other less likely options of filling this space include anomalously thick (>2 km) amounts of Salina Group strata or additional shortening on the Cambrian – Ordovician strata. Additional displacement on faults in Cambrian – Ordovician strata would significantly increase shortening estimates of the duplexing sequence such that it would no longer balance with the cover sequence above.

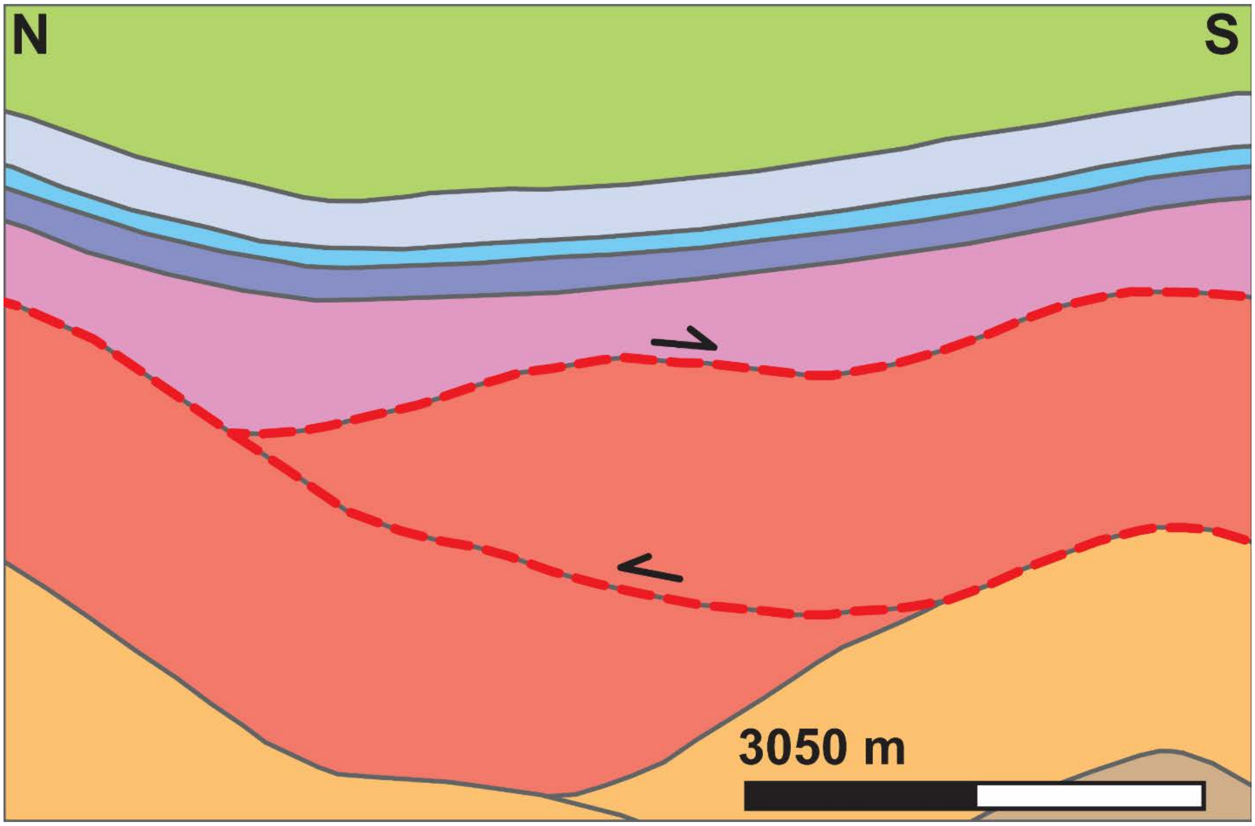


Figure 16: Two fault segments (ramp and detachment faults) merge to form the tip of the wedge block. Specific section location corresponds to inline 1070 on figure 4.

In addition, because our seismic data shows only one fault that extends from the Cambrian Waynesboro Formation to the Silurian Salina Group (Figure 7), wedge faulting between the Salina Group and Reedsville Formation is necessary as a pathway to transfer shortening in Cambrian – Ordovician units up to the Salina decollement and out onto the AP.

4.2 APPALACHIAN PLATEAU

4.2.1 Stratigraphic Observations

In map view we observe a small scale tight folding geometry exclusive to the units between the Silurian salt detachment and the top of the Marcellus shale (Figure 1). Fold wavelengths are generally < 1km with fold axes < 6 km. This surface expression is unique to the Silurian – lower Devonian sequence and is not present in map view stratigraphically above or below these units.

To correlate stratigraphy to seismic reflectors in the AP, we project bedding orientations along with unit outcropping geometries onto our line of section (Figure 17). This allows us to see the alignment of stratigraphic units with shallow seismic reflectors. The deepest observable reflector (at ~7.5-8.5 km depth) is continuous and relatively flat throughout both the Valley and Ridge and AP. Due to the apparent lack of deformation, this reflector is interpreted as the basal Waynesboro detachment. Using mapped stratigraphic thicknesses, we extend a stratigraphic column upwards from the Waynesboro detachment to align deeper stratigraphic units with seismic reflectors, which do not outcrop (Figure 18).

In the AP we incorporate well data to from the 38 Inflection Energy, LLC. wells to constrain near surface (1500-2500 m vertical depth) units. Projecting this well data onto seismic lines allows us to recognize what stratigraphic horizon tops are associated with specific seismic reflectors (Figure 7a).

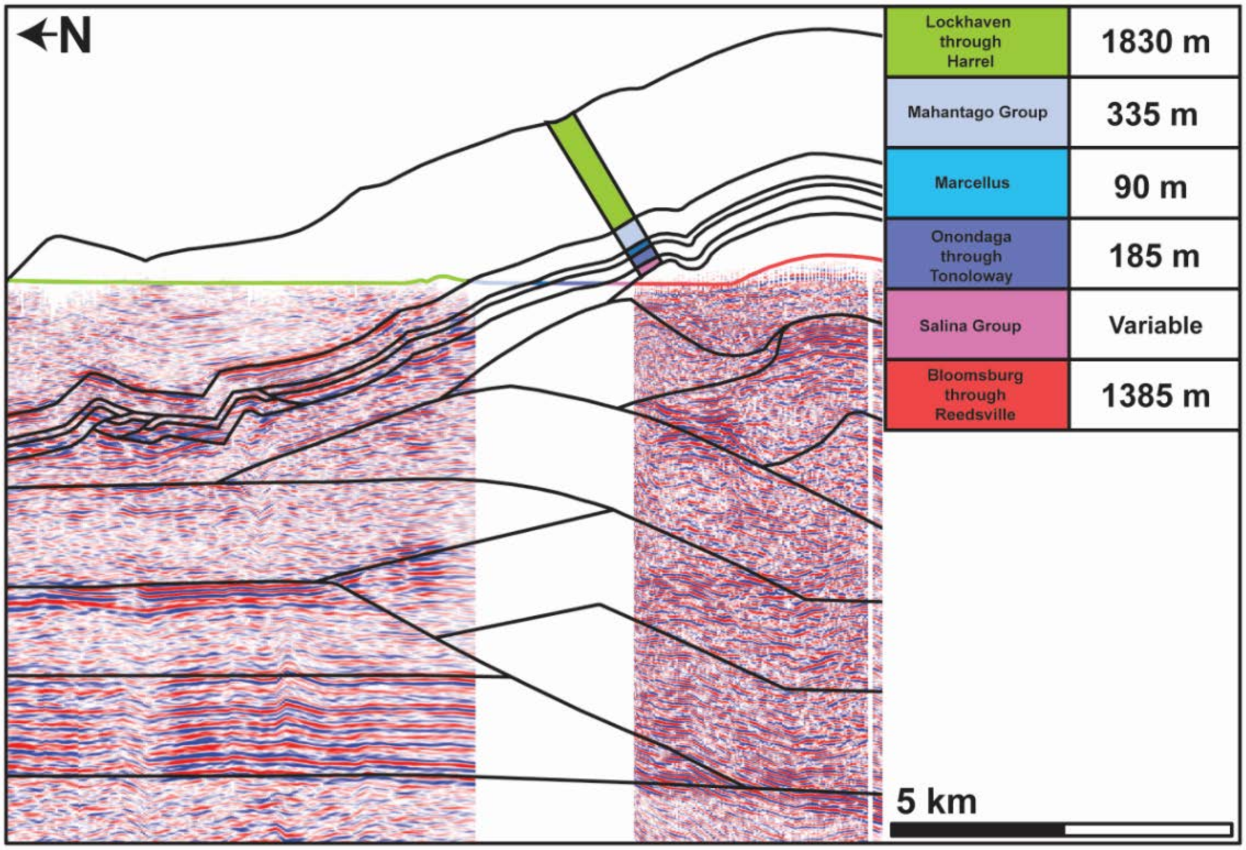


Figure 17: We project geologic outcrops onto our cross section line and integrate mapped stratigraphic thicknesses to best correlate stratigraphy with seismic reflectors in the Appalachian Plateau. Geologic contacts are projected onto the line of section. Specific section location corresponds to inline 1070 on figure 4.

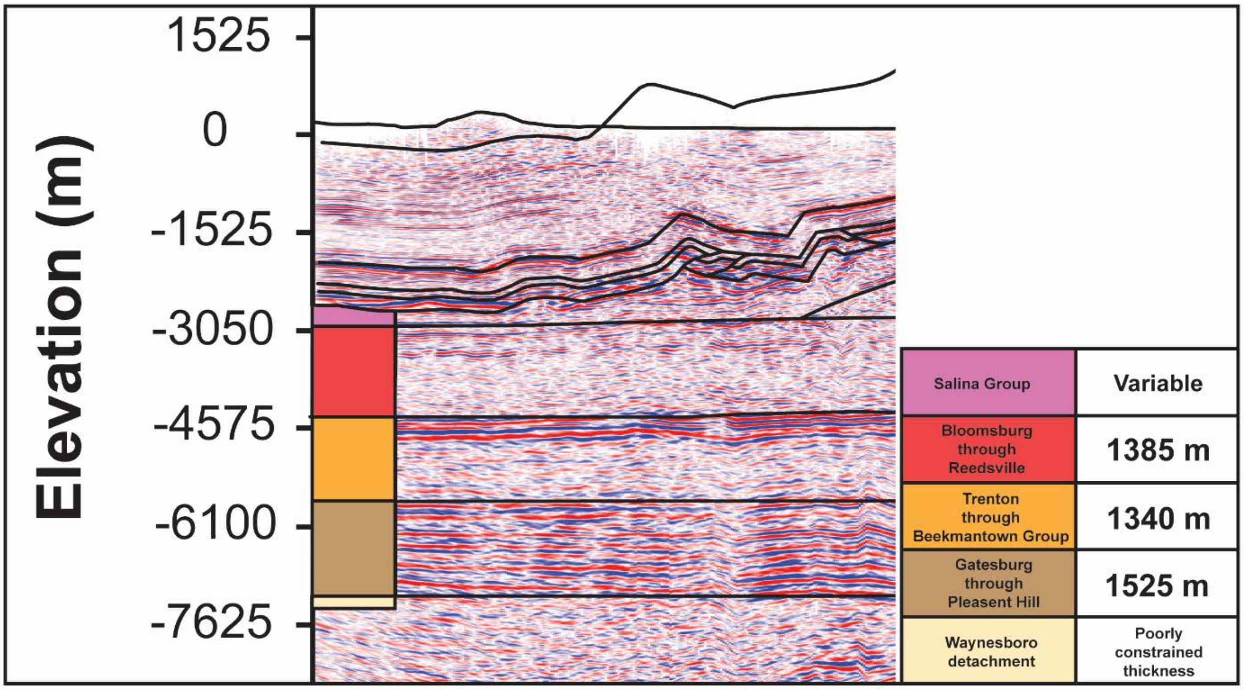


Figure 18: We utilized mapped stratigraphic thicknesses to build a stratigraphic column in the subsurface of the Appalachian Plateau. We identify stratigraphy by correlating seismic reflectors with stratigraphic thicknesses. Specific section location corresponds to inline 1070 on figure 4.

4.2.2 Seismic Observations

Seismic sections of the Appalachian Plateau are similar to the Valley and Ridge in that we detect numerous truncations and stacking patterns in a discrete package of seismic reflectors (Figure 20: set B). There are obvious breaks in strong continuous reflectors which are still present, but offset in space (Figures 8 and 19). Offset in seismic reflectors can be as large as 400 m vertically (Figures 8 and 19). Seismic data in the AP is comparable to the Valley and Ridge seismic, we see stacked and doubled seismic reflectors (Figure 8). With such high resolution data, we can approximately quantify the horizontal distance of overlapped reflectors to be as great as 400 m (Figure 8). Unlike the Valley and Ridge, truncation and stacking of seismic reflectors is only seen through one distinct group of reflectors (Figure 20: set B). A set of prominent reflectors approximately 425 m above reflector set B appear much more continuous, with no overlapping geometries (Figure 20: set A).

The set of reflectors immediately below reflector set B is also more continuous in the AP (particularly when compared to the overlying reflector) (Figure 20: set C). However, the area between these two seismic reflectors shows a gradual change in thickness from 75 to 875 m through our seismic sections (Figure 20: set C). This space can thin out to as little as 75 m, and in contrast, thicken to 875 m. Reflectors underlying this area down to the Waynesboro detachment (4250 m thick) are generally horizontal and continuous (Figures 18 and 20: set D).

The 3-D seismic volume enables us to trace these three sets of reflectors in an east west direction as well as a north-south direction to evaluate 3-D continuity. We have traced the prominent truncations highlighted in Figure 20 (set B) in the east-west direction to determine the along strike extent of the measured offsets (Figure 21). Some truncations continue along strike for as little as 5 km. In contrast the longest truncation can be traced throughout our entire study area, making the along strike extent a minimum of 25 km.

4.2.3 Structural Interpretation

To translate the geophysical observations into structural interpretations we integrate stratigraphic constraints and admissible structural geometries. By projecting well data and geologic mapping onto our seismic sections we have established a link between specific seismic reflectors and stratigraphic horizons (Figures 7a, 17). Well horizon tops constrain stratigraphy in the mid to early Devonian units (Figure 7a). The deepest unit we have well data for is the Onondaga Formation, however, we can interpret beds underlying the Onondaga Formation down to the top of the Silurian Salina Group by adding the mapped uniform stratigraphic thicknesses of the Old Port - Tonoloway Formations onto the base of the Onondaga Formation (Figure 17).

The majority of recorded well data is representative of the upper, middle, and lower Marcellus shale. Stratigraphic omissions in the well data (i.e. drilling through the lower Marcellus shale, then hitting upper Marcellus shale with no record of middle Marcellus shale (Figure 9)) indicate that the Marcellus shale has been thrust faulted.

We utilize stratigraphic thicknesses to interpret the deep 4250 m thick seismic reflectors as Cambrian - Silurian units which are undeformed in the Appalachian Plateau and bound by the Waynesboro detachment (bottom) and Silurian salt detachment (top) (Figure 18).

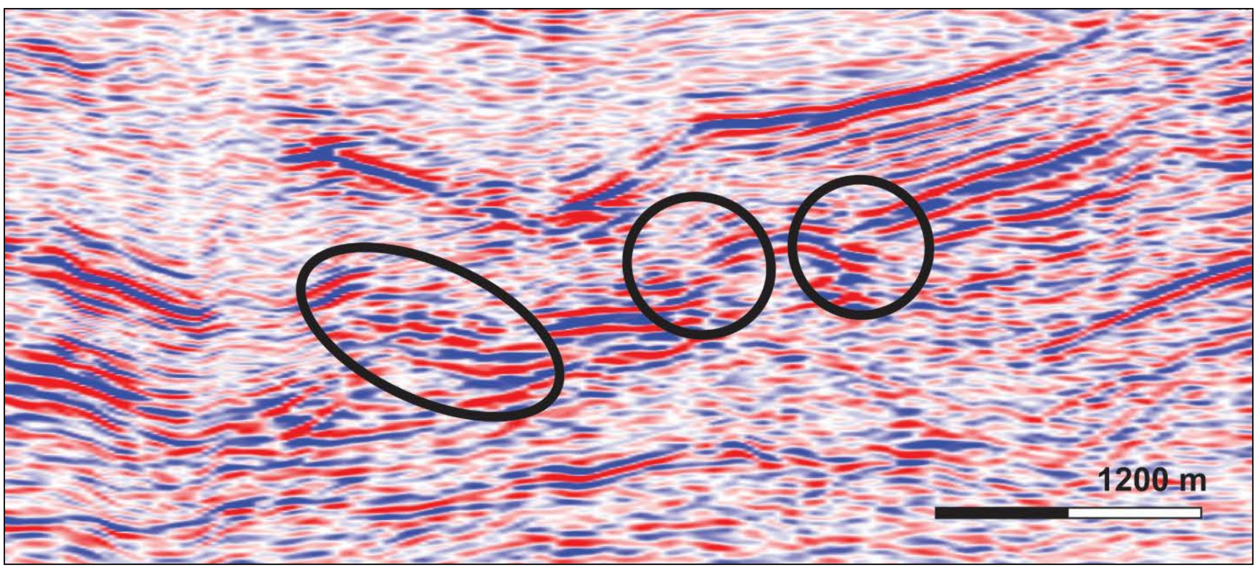


Figure 19: Indicators of subsurface structure in an Appalachian Plateau seismic section. The black circles indicate truncated offset reflectors.

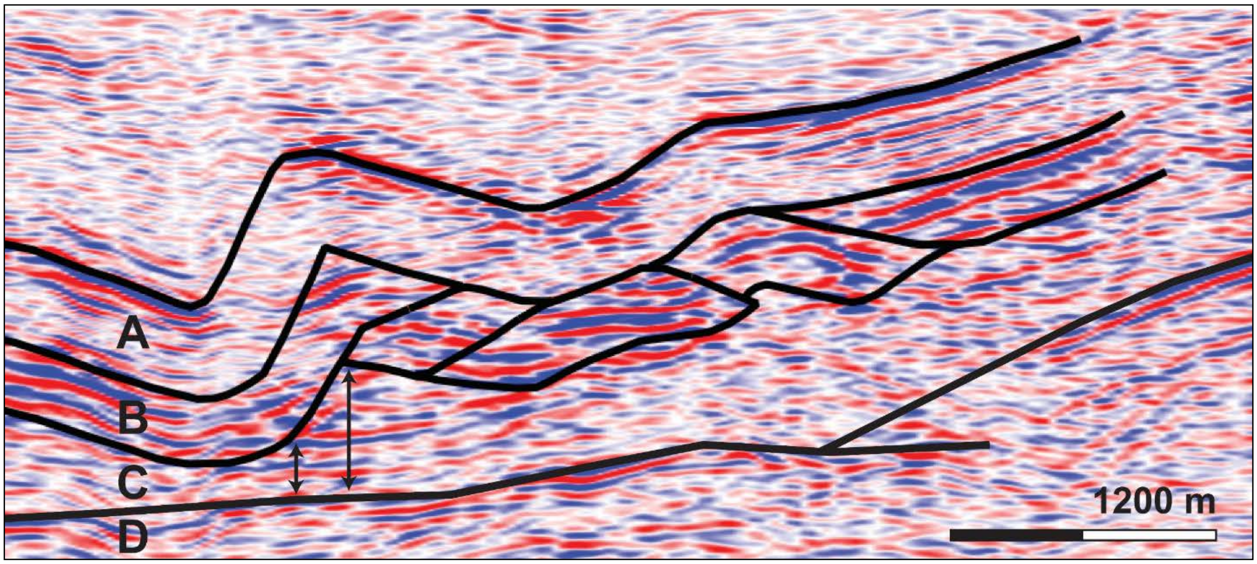


Figure 20: We observe truncation and stacking geometries in a distinct set of seismic reflectors (set B). Seismic reflectors above (set A) and below (set C) set B are relatively continuous. We see gradual changes in thickness in the area of set C.

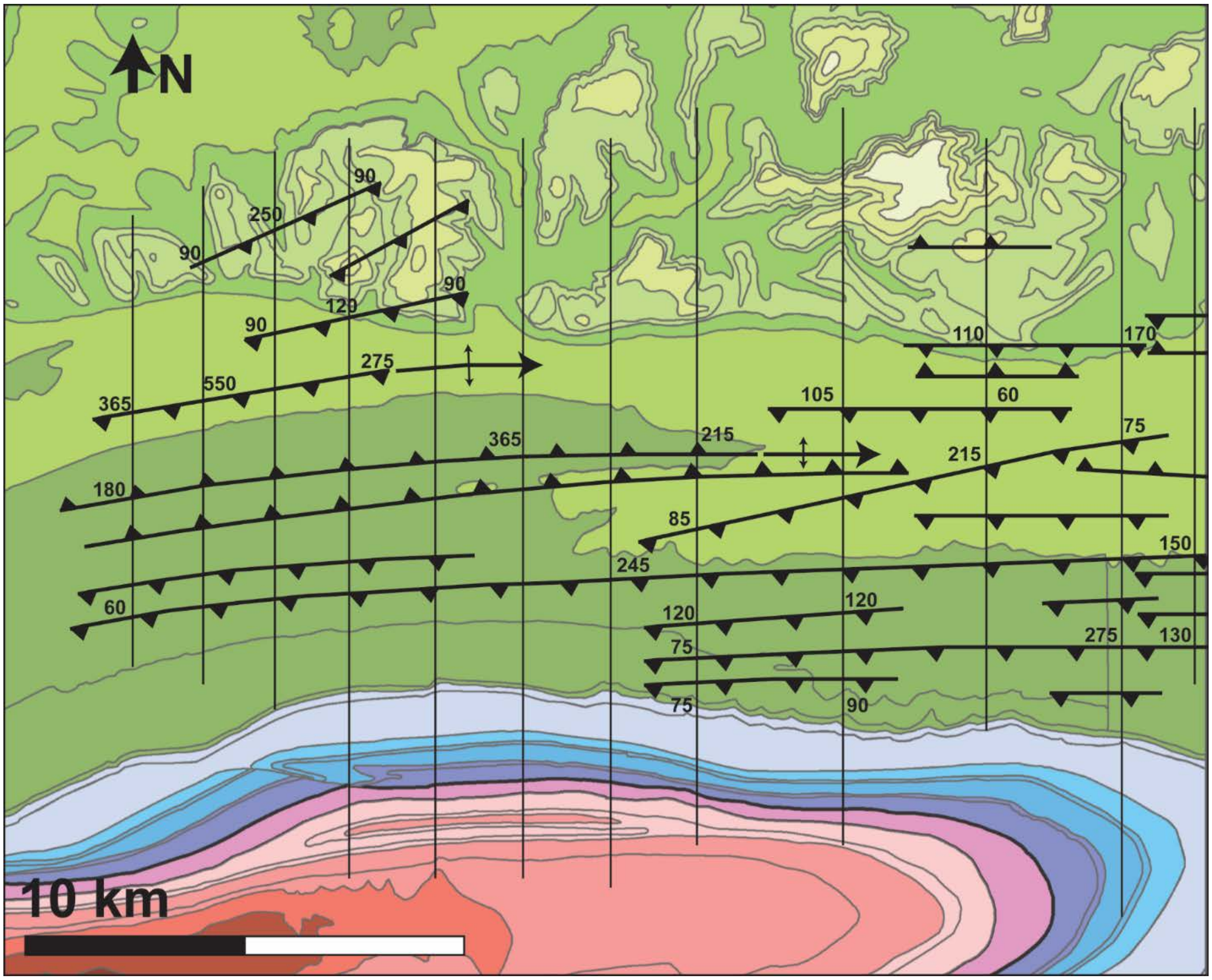


Figure 21: The along strike extent of early Devonian – Late Silurian faults in the Allegheny Front. Numbers along the fault plane indicate slip amount on fault in meters. For legend and inline identification refer to figure 4.

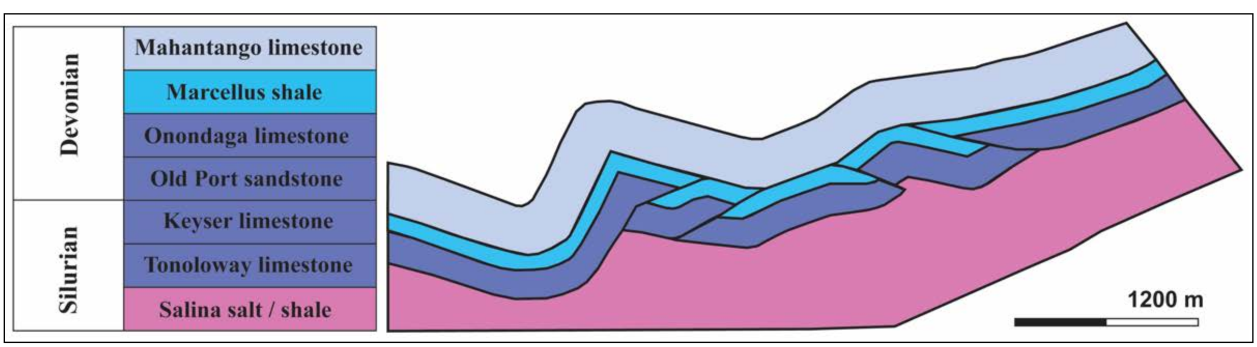


Figure 22: Structural interpretations based on geophysical and well data from the Appalachian Plateau.

Missing stratigraphy in well data indicate thrust faulting in the Marcellus shale (Figures 9 and 22), however, seismic truncations and overlapping geometries suggest that thrust faulting initiates below the Marcellus shale (Figures 19 and 20). Specifically, we propose that the beds bound between the Silurian Salina detachment (bottom) and the top of the Marcellus shale are shortening through small offset thrust faulting (Figure 22). The direction of overlapping seismic reflectors indicate both north and south dipping faults with offsets ranging from 60 to 550 m. Outcropping geometries in geologic maps and well data allow us to correlate the more continuous set of reflectors above the Marcellus shale with the Mahantango Group (Figures 7a, 17). There are a few non overlapping truncations in this set of reflectors which we attribute to steep (>30^{o}) folds which cannot be seismically imaged (Figure 20: set A). Therefore we propose a decollement horizon that facilitates the change in structures between the late Silurian – early Devonian thrust faulted units, and the overlying Mahantango Group which is simply folded (Figure 22). The change in structures between the late Silurian – early Devonian units is further supported by map view outcrop geometries (Figure 1). Surface geometries indicate small scale tight folding in this sequence, differing from the strata above and below. The change in outcrop expression evokes a change in shortening mechanism which can only be facilitated if the late Silurian – early Devonian units are bound by decollement horizons.

Stratigraphically, the units below the faulted early Devonian – late Silurian units is the Silurian Salina Group. We correlate the Salina Group to a seismic reflector package, which shows gradual changes in thickness between seismic reflectors (Figures 17 and 18). Comparable to the subsurface expression of the Salina detachment in the Valley and Ridge, we infer that the gradual change in thickness is consistent with a ductile response to shortening. Thrust faulting in the overlying early Devonian – late Silurian units results in inverted displacements, upside down fault bend folds and folding of the footwall block (Figure 23). Observing downward displacement (Figure 23) in the footwall block inverts classic fault-bend-fold geometries. This unusual relationship is plausible when rocks below the thrust-faulted section exhibit extremely weak mechanical strength and have a ductile rather than brittle response to compression, as proposed by Ramsay (1992). Downward displacement of the early Devonian – late Silurian footwall block causes the underlying Salina salts to flow into adjacent areas, thinning the unit.

Through these structural interpretations, we suggest that the fault ramps offsetting early Devonian – late Silurian units are linking the Silurian salt detachment and an additional detachment along the top of the Marcellus shale (Figure 23). This geometry creates a wedge tip where the ramp fault segment merges with the Marcellus shale detachment. Shortening on both fault segments allows for the propagation of the wedge tip, causing folding in the footwall block

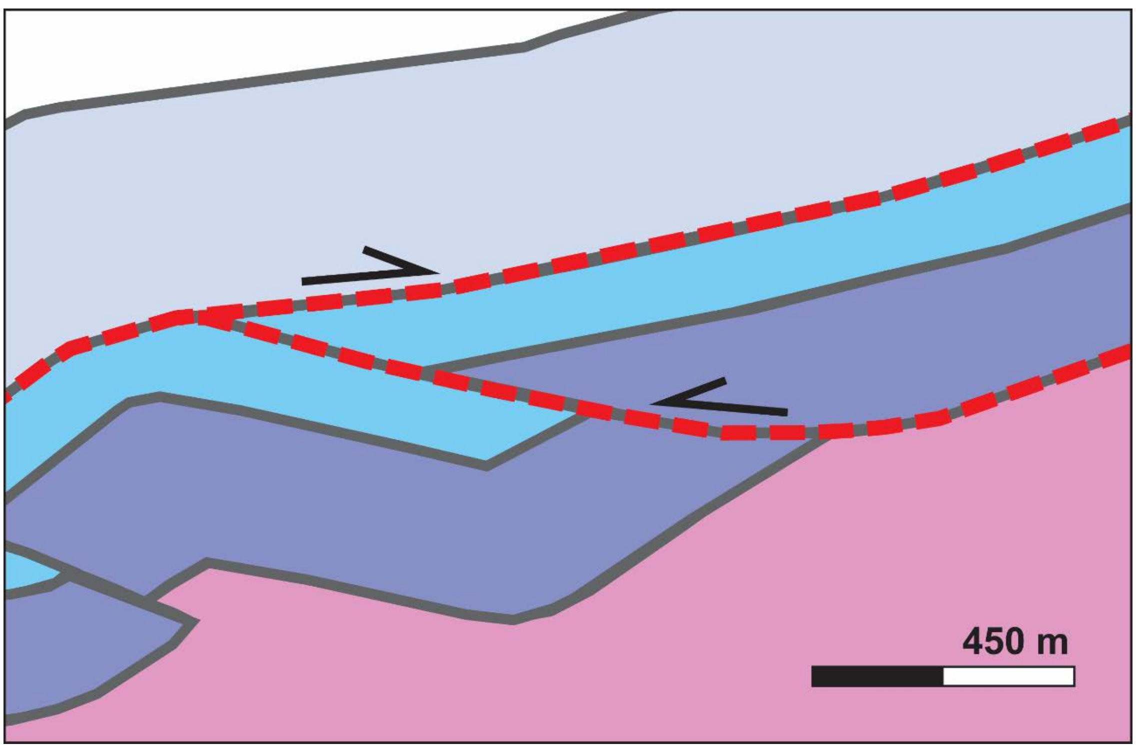


Figure 23: Two fault segments (ramp and detachment faults) merge to form the tip of the wedge block. We interpret the down displacement and folding of the footwall block above the ductile Salina salts which is a characteristic of wedge style faulting (Medwedeff, 1992; Ramsay, 1992; Shaw et al., 2006). Refer to figure 22 for legend.

(Ramsay, 1992; Shaw et al., 2006). Characteristics such as downward deflection and folding of the footwall, an extremely mechanically weak detachment horizon, and two fault segments merging at a tip (Medwedeff, 1992; Ramsay, 1992; Shaw et al., 2006) allow us to propose wedge style faulting in the early Devonian – Silurian units.

4.2.4 Ubiquity of Structure

The large extent of the 3-D seismic volume used in this study allows us to recognize the existence of the small scale wedge faulting in Silurian to early Devonian strata throughout the area (refer to appendix for all sections). The along strike extent in our fault segments range from 5 km to ≥ 25 km, with the majority extending < 25 km (Figure 21). Thus the faults interpreted in the western portion of our section are different than faults in the eastern portion with only a few faults that continue across the volume. On a regional scale, we show that the deformational style through our study area is consistent, however, the individual structures change along strike.

5.0 RESULTS: BALANCING THE SECTION

Rocks exposed at the surface in the Appalachian Plateau record 13% LPS (Nickelsen, 1996; Engelder and Engelder, 1977; Slaughter, 1982; Geiser, 1974). The LPS on the AP is kinematically linked to macroscale faulting in the Valley and Ridge, i.e the 13% LPS in the AP needs to be balanced by equivalent amount of shortening in rocks that experienced no LPS (Sak et al., 2012). To translate 13% LPS into kilometers, we begin with a deformed cross section which spans the entire extent of the salt basin, and equal to the entire extent of strata recording LPS (Figure 24). Our deformed section utilizes the two units of the cover strata which outcrop most frequently to best reconstruct the geometry of the broad Appalachian Plateau folds. We restore this section by flattening out each fold and undoing each fault to return to the section to the undeformed horizontal geometry to quantify the magnitude of shortening accommodated by gentle folding in the AP. At this scale there is a minimal (< 5 km) difference in bed length between the deformed and restored (Figure 24) cross section, indicating that LPS must be the dominant shortening mechanism on the AP. To quantify the amount of LPS we take 13% of the restored 180 km length to determine the magnitude of LPS is 24 km. Thus 24 km of shortening is being fed to the Silurian Salina detachment from the Valley and Ridge. This methodology and result are consistent with Sak et al., (2012).

For a balanced section to be admissible and viable requires a clear path for displacement along faults, and the ability to show that displacement along those paths are conserved throughout the entire system (Dahlstrom, 1969; Boyer and Elliott, 1982). This can

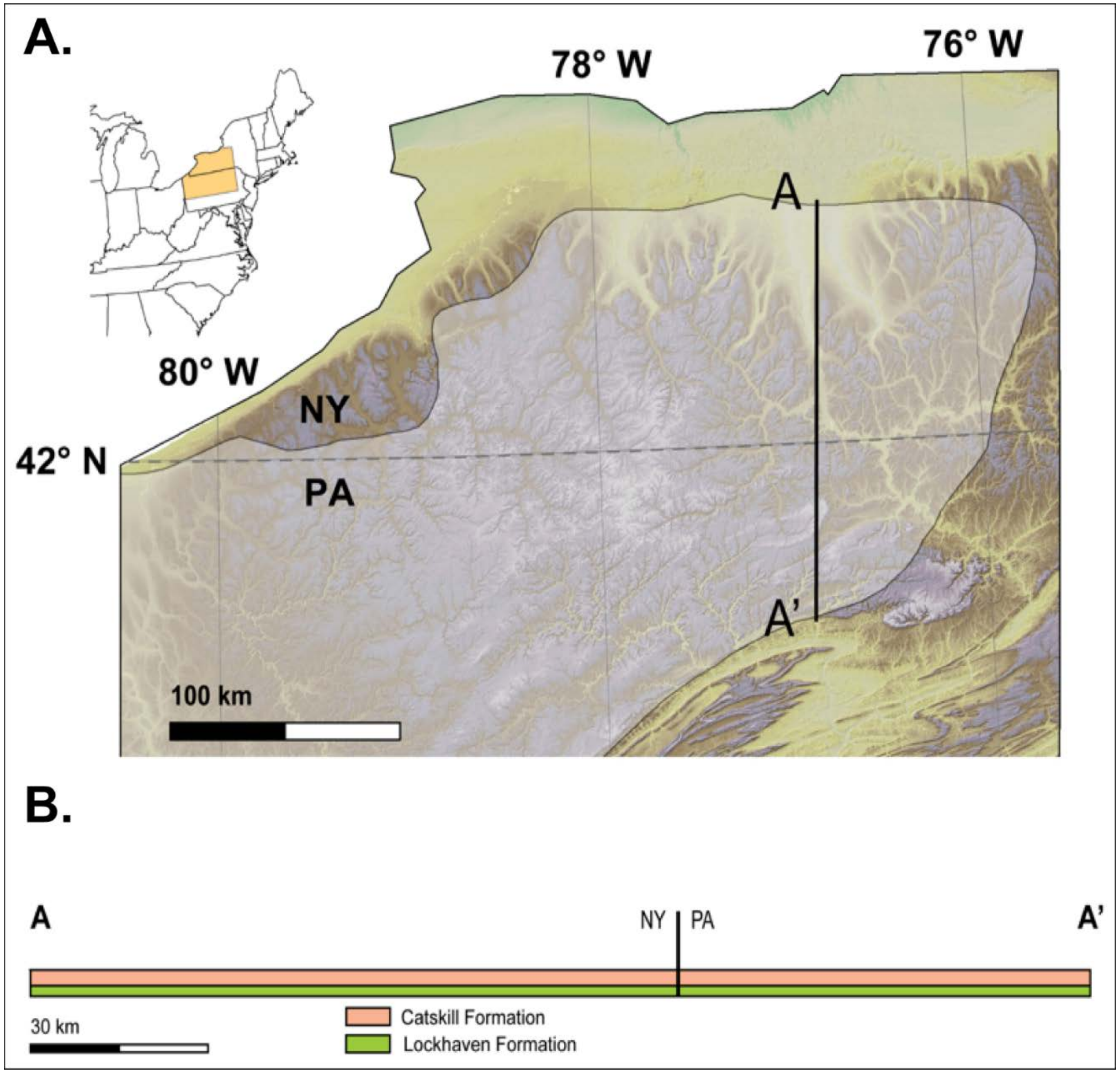


Figure 24: Appalachian Plateau restoration along the Silurian salt basin. Extent of the salt basin is the area of the gray polygon. (A) Plan view of the transect for the Appalachian Plateau restoration. Figure modified from Sak et al., (2012). (B) Restored cross section.

prove difficult in blind fold and thrust belts as fault slip will commonly be expressed as folding or LPS in overlying units (Sak et al., 2012). Tracking shortening across the Allegheny Front means determining a clear path for slip to be transferred from the basal decollement in the lower shales in the Cambrian Waynesboro Formation up to the Ordovician Reedsville Formation detachment, and ultimately up to the Silurian Salina Group salt detachment. The location where the main decollement horizon transitions from the Waynesboro and Reedsville Formations to the Salina Group ultimately represents the transition from the Valley and Ridge province into the AP.

Balanced cross sections also require that the geometries in the deformed section are able to be restored, (i.e., footwall block and hanging wall block lengths must be equal, and upon restoration must represent the original thickness of the bed) (Dahlstrom, 1969). A balanced section will show the same magnitude of shortening in each layer and equal bed lengths upon restoration under the assumption that each bed was the same length prior to shortening (Dahlstrom, 1969). To assure that the geometries in these geologic cross sections are viable, the sections in this study were kinematically restored and balanced. Traditional balanced cross sections account for total shortening through the entire system of the mountain belt. The scale and focus of this study are not amenable to accounting for total shortening of either the Valley and Ridge or AP. Instead, we show that the units in our study area are all shortening at equal magnitudes, regardless of the mechanism. We show this by taking a conservation of bed length or ‘line length’ approach. We can show that upon the restoration of beds between two points, that all of the final restored bed lengths are equal. Through this process we must account for microscale LPS amounts in addition to macroscale faulting and folding.

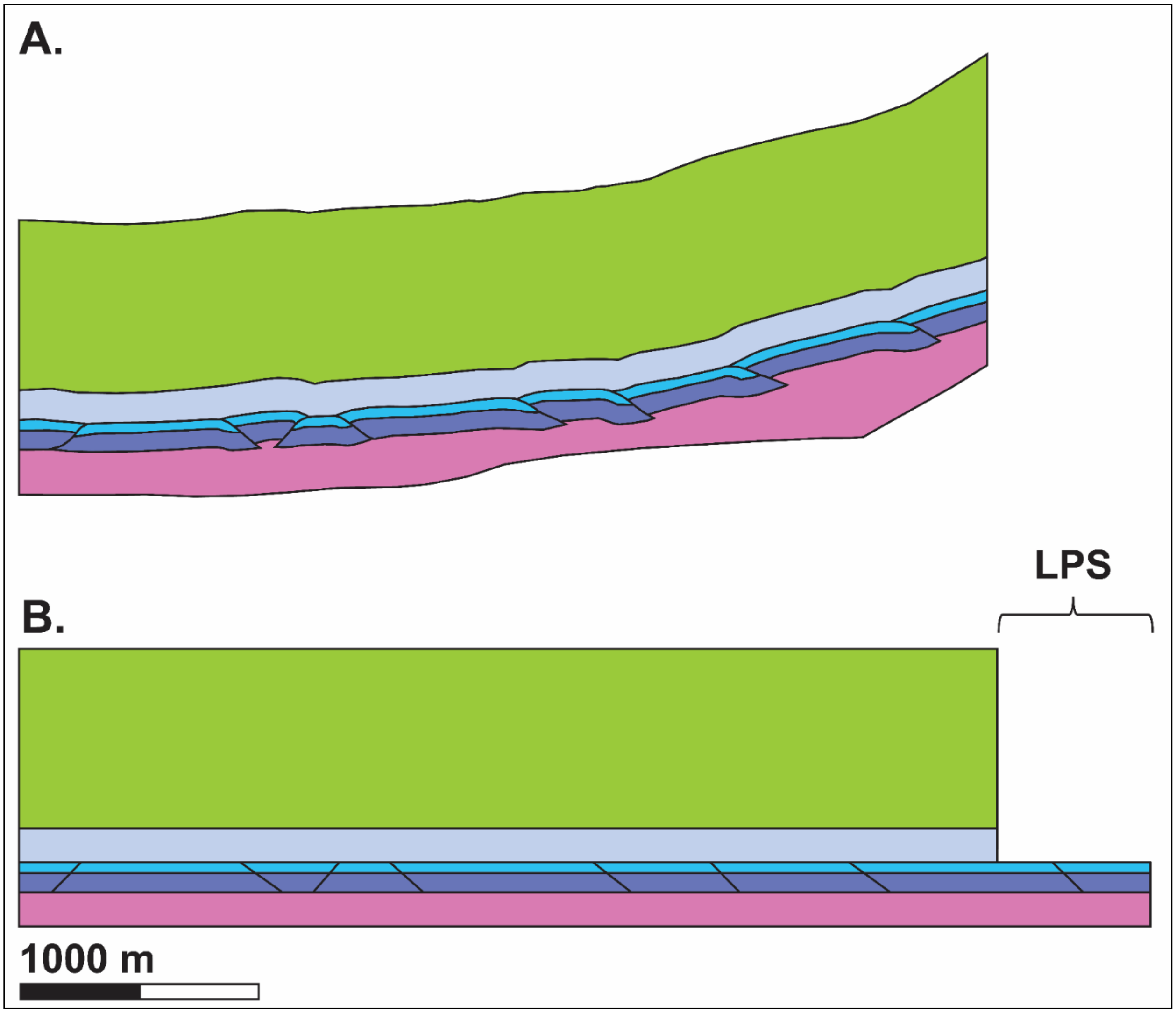


Figure 25: Restoration of a geologic cross section of the Appalachian Plateau. (A) Deformed cross section. (B) After restoring shortening through faulting and folding, the light blue and green beds are shorter. It is inferred that they are shortening 13% via LPS. Specific location of section corresponds to inline 1390 in figure 4. (refer to figure 12 for legend).

5.1 APPALACHIAN PLATEAU

In the absence of high resolution seismic and well data, workers (e.g., Sak et al., 2012) were left to hypothesize which rocks in the subsurface were shortening via LPS and proposed that all of the rocks above the Salina Group deformed by LPS. We test this assumption by conducting a simple line length restoration of our cross sections, restoring all the macroscale shortening via folding and faulting. In all 12 sections in this study (see appendix), such efforts at line length restoration result in restored cross sections characterized by beds in the interval spanning from the top of the Marcellus shale through the Salina Group that are consistently longer than the overlying sequence (Figure 25). Consistently, the faulted Marcellus through Salina package is 13% longer than the beds above it in every section. At the surface documented LPS is accommodating 13% of the total shortening. By combining these two shortening mechanisms in our cross sections of the AP, macroscale wedge faulting in the Silurian through early Devonian strata, and microscale LPS in the rocks above the Marcellus shale, our sections balance (Figure 25). Having these high resolution data permit us to refine earlier interpretations of the plateau which assume that all strata above the Silurian Salina salt detachment is shortening via LPS. Our observation of macroscale structure in the seismic data and ability to quantify the magnitude through balanced cross sections allow us to identify the dominant shortening mechanisms and show that the magnitude of shortening and the shortening path balance.

5.2 VALLEY AND RIDGE

As stated previously, 13% of LPS across the width of the Silurian salt basin (Figure 24) translates to 24 km of shortening above the Silurian Salina salt detachment in the Appalachian Plateau. Of the 24 km, it was hypothesized that 14 km were transferred from the Waynesboro detachment to the Salina detachment along two fault-bend folds further south in the Valley and Ridge and this shortening was expressed as early LPS in the Silurian and younger rocks on in the Appalachian Plateau (Sak et al., 2012). The proposed ramps are south of this study area (Sak et al., 2012) and therefore, this 14 km of shortening will not be accounted for in this study. However, Sak et al. (2012) hypothesize that the remaining 10 km, which is expressed as LPS in the AP, was transferred from the Valley and Ridge along a thrust ramp under the Nittany Anticline, which provides a pathway to feed slip from Cambrian to Silurian strata. The Nittany Anticline marks the northwestern extent of the Valley and Ridge, and is regarded as the northern most major anticline south of the Allegheny Front and within the 3-D seismic volume. With the aid of seismic profiles to constrain subsurface geometries we will account for 10 km of shortening being transferred from the Valley and Ridge to the plateau in our sections.

Our geologic cross sections accommodate 10 km of shortening in the region of the Nittany Anticline, however our interpretation of specific subsurface structures beneath the anticline and pathway along which slip is transferred differ from that presented by Sak et al. (2012) due to constraints provided by high resolution seismic data. In addition, the available 2-D seismic profiles south of the 3-D volume, spaced 15-25 km apart across the Nittany Anticline, highlight west to east changes in structure as the anticline plunges to the east. To highlight these changes, we compare our westernmost and easternmost cross sections, which parallel one another and are separated by 25 km (Figure 4). These two sections can be thought of as end members on the spectrum of Valley and Ridge structure. The 12 cross sections (see appendix) analyzed for this project highlight small variations in the macroscale geometry of structures under the Nittany Anticline to reconcile the different geometries required by the 2-D seismic lines (Figures 7 and 13). These small variations allow for a smooth and kinematically viable transition between the western-most and eastern-most cross section.

In the westernmost cross section we interpret a ramp within Cambrian – Ordovician strata immediately north of the Nittany Anticline (Figure 14). This structure transfers 3 km of slip to the Silurian Salina detachment in the AP through a triangle zone. Slip is fed toward the foreland along the deepest ramp segment and hinterlandward along the passive Reedsville cover detachment, and ultimately forelandward again along a ramp segment through the Reedsville detachment up to the Silurian salt detachment in the AP (Figure 14). The remaining 7 km of shortening is transferred to the Silurian Salina Group along the ramp of the Nittany Anticline as argued by Sak et al. (2012). Moving to the east, we interpret that the 10 km of shortening is facilitated by a greater number of structures. In Figure 15 we track 10 km of shortening across four horses (two of which have additional shortening through backthrusting). Like the section to the west, this shortening is fed to the Silurian Salina detachment through a much more complicated, northward expanding triangle zone with shortening transferred initially towards the foreland from the Waynesboro detachment to the Reedsville detachment, then hinterlandward along the Reedsville detachment, and toward the foreland along three separate ramp segments in late Ordovician to Silurian age strata (Figure 15).

Grouping units in the Appalachians by amounts of LPS shows relative magnitudes of shortening (Figure 26). We show that the cover sequence above the duplexing Cambrian – Ordovician sequence is shortening 20% via LPS. The units above the Marcellus shale to the surface undergo an additional 24 km of LPS which is fed to the Silurian salt detachment via large scale wedge faulting in the late Ordovician – early Silurian units in the Valley and Ridge (Figures 14 and 15). Shortening is then transferred from the Silurian salt detachment to the Devonian Marcellus detachment via small scale wedge faulting in the AP (Figures 14 and 15). The scope of our study only permits us to show the last 10 km of shortening in the late Ordovician – early Silurian units and the pathways for shortening to reach the Silurian salt detachment (Figures 14 and 15). Sak et al. (2012) hypothesized that the 10 km of shortening on the Nittany Anticline was transferred from the Waynesboro detachment to the Salina detachment along one large fault bend fold and proposed that remaining 14 km of shortening is transferred to the Silurian salt detachment along two fault-bend folds south of our study area, at the southern edge of the Valley and Ridge. Seismic data for the northern limit of the Valley and Ridge highlight that the structure at the Nittany Anticline is more complex and that several macroscale wedge faults in the late Ordovician – early Silurian units help transfer slip between the Waynesboro detachment to the Salina detachment (Figures 14 and 15). Wedge faults in late Ordovician – early Silurian strata present an alternative way of transferring slip from the Cambrian to the Silurian detachments, eliminating the need for any given fault, such as the two southernmost faults proposed by Sak et al. (2012) to extend from the Cambrian to the Silurian. Therefore, we propose that large scale wedge faulting in late Ordovician – early Silurian strata is ubiquitous through the Valley and Ridge eliminating the need for early LPS to be transferred ~ 200 km to the AP. We suggest that the total 24 km of shortening accommodated by the wedge faults balances the 24 km accommodated via LPS in the AP.

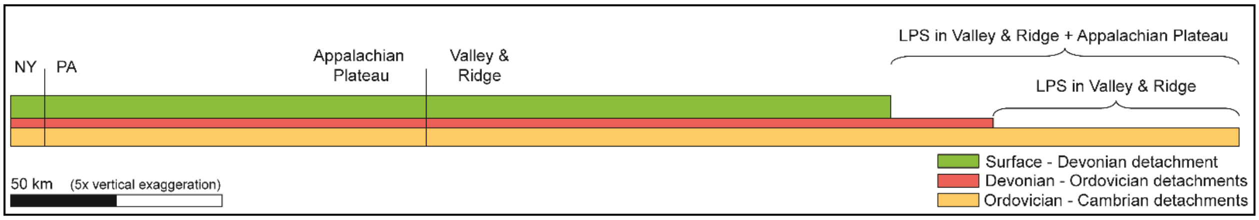


Figure 26: LPS amounts in units between specific detachment horizons on a regional scale.

6.0 DISCUSSION

6.1 WEDGE FAULTING ON A VARIETY OF SCALES

Similar wedge-style faulting is observed in both the Valley and Ridge and Appalachian Plateau structural provinces (Figures 16 and 23) although at different scales. In the AP wedge faulting occurs at a smaller (60 – 550 m shortening) scale, offsetting the competent Onondaga through Tonoloway Formations between the Salina and Marcellus detachments. Wedge faulting in the Valley and Ridge occurs at a larger (400 – 3000 m shortening) scale, offsetting the more rigid Bloomsburg through Bald Eagle Formations between the Reedsville and Salina detachments. We contend that wedge faulting at a wide range of scales is ubiquitous through this part of the Appalachians including outcrop scale structures. Outcrop scale examples of wedge faulting highlight several of the features present in macroscale wedge faults observed in seismic data (Figure 27). We observe large scale wedge faulting in which a package of numerous resistant sandstones and limestones are offset and shortening is transferred into the overlying shales, which act as accommodation zones (Figure 27a). In contrast we also observe small-scale wedge faulting that is no thicker than a single bed (Figure 27b). In both cases we can track shortening into mechanically weaker bounding beds which accommodate shortening via ductile deformation in contrast to brittle faulting. We conclude that the successions of mechanically

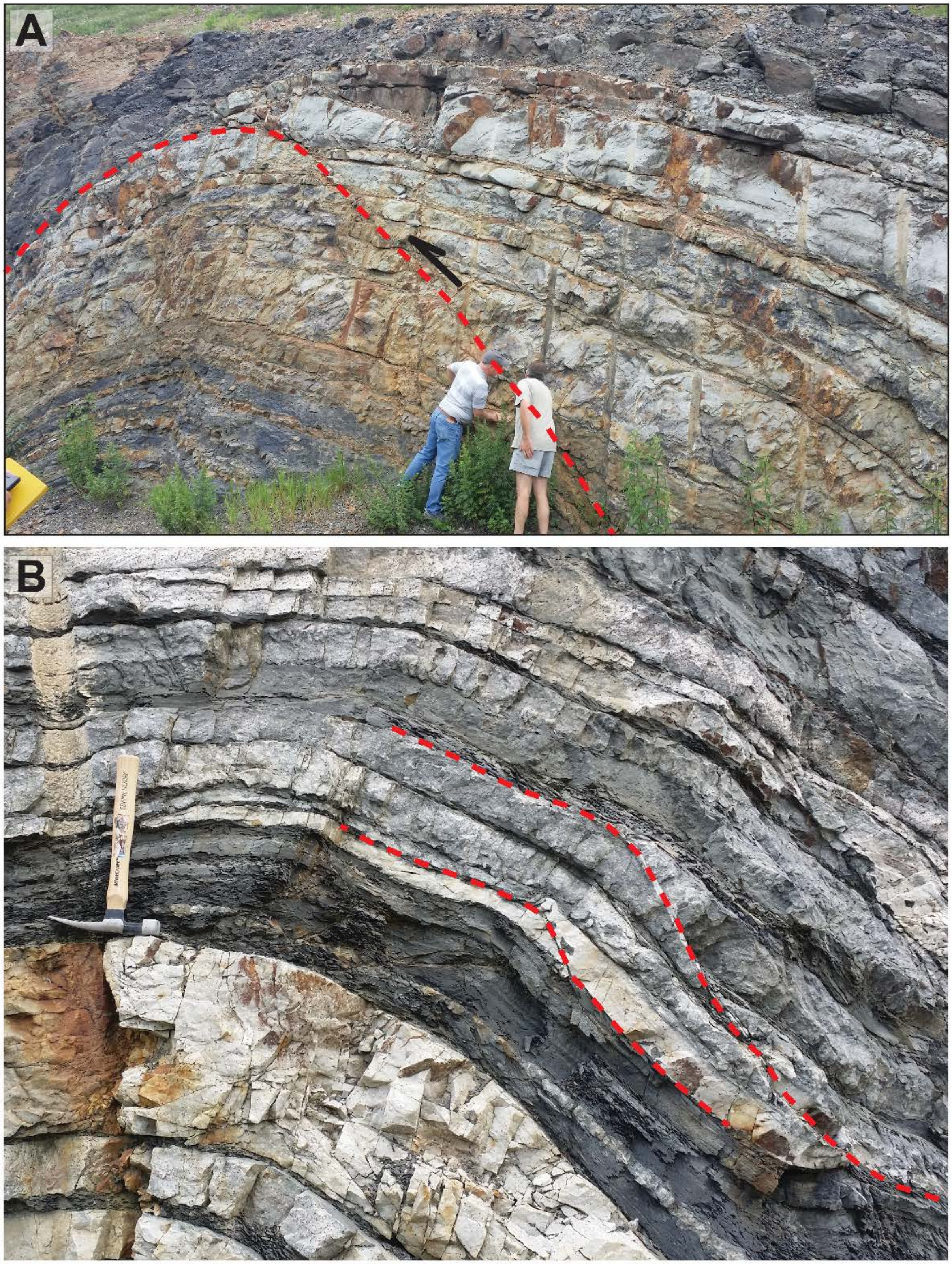

A
B

Figure 27 (previous page): Wedge faulting observed in road cuts in the Valley and Ridge, central Pennsylvania. (A) Large scale wedge faulting. We observe the stronger beds (light tan) offset, and track the shortening into the shales above which are acting as accommodation zones. (B) Two small scale wedge faults offsetting single beds within a formation. Similarly to large scale wedge faults, we observe the offset in resistant beds, and the bounding shales are acting as accommodation zones.

weak and strong beds throughout the Appalachians promotes wedge-style faulting across a range of scales.

6.2 REGIONAL IMPLICATIONS

Although our study focuses on 450 km^2 area of Lycoming County covered by the 3-D seismic volume, comparisons with previously published investigations (e.g., Scanlin and Engelder, 2003; Donahoe, 2011; Gillespie, 2013; Roberts, 2013; Mount, 2014) suggest that this area is representative of the region. Figure 28 highlights the spatial extent of the Salina salt, locations of previously published seismic studies (Scanlin and Engelder, 2003; Donahoe, 2011; Gillespie, 2013; Roberts, 2013; Mount, 2014) that show small truncations and stacked geometries in seismic reflectors, and the location of measured LPS on the AP and the location of our study area. Interpretations of previously published seismic data have also identified truncated and stacked seismic reflectors, tied these reflectors to early Devonian – late Silurian units, and interpreted macroscale faulting in units above the Silurian salt detachment and below the Devonian Mahantango Group (Scanlin and Engelder, 2003; Donahoe, 2011; Gillespie, 2013; Roberts, 2013; Mount, 2014). These previously published observations for both seismic and LPS allow us to extend our model of how shortening in the Salina Group through Marcellus shale is balanced by LPS in the strata above the Marcellus shale across a much larger portion of the AP to include the extent of the previously published

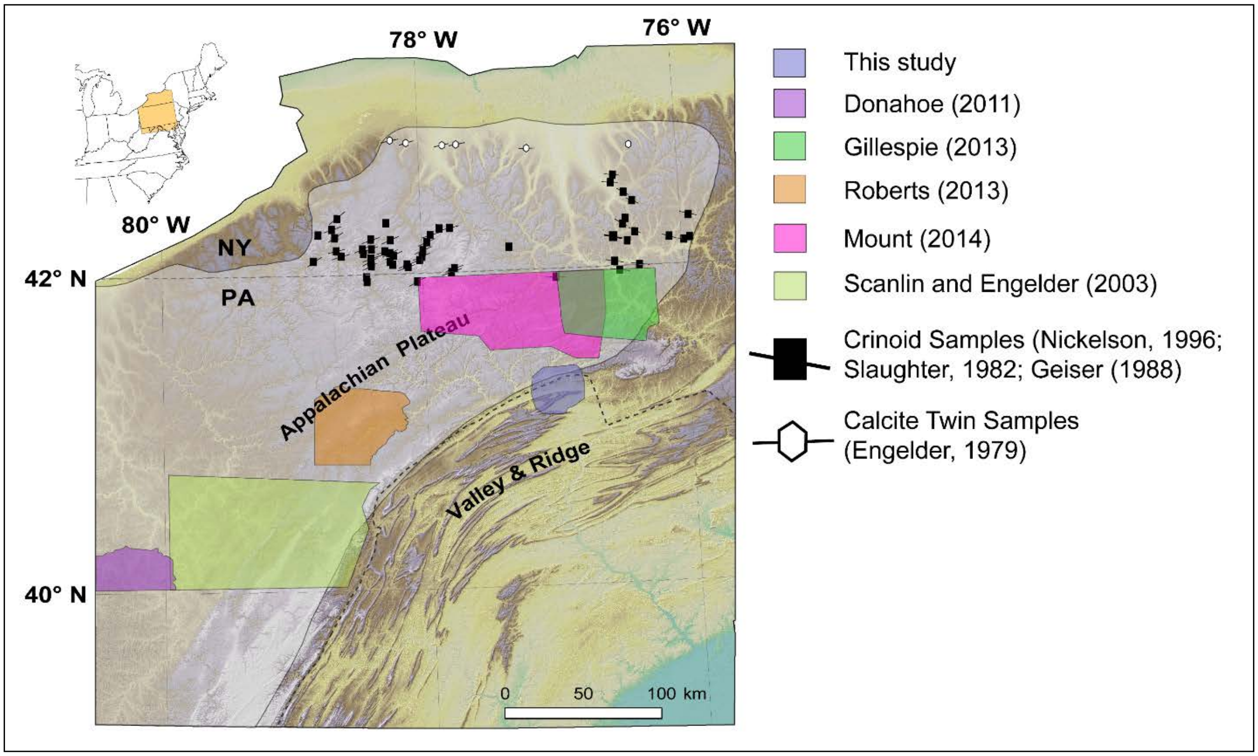


Figure 28: Spatial distribution of LPS data and recently published seismic studies in Pennsylvania. Base map is modified from Sak et al., 2012.

studies (Figure 28). Published work agrees that fault segments are initiating in the weak Silurian strata and offset Devonian-aged strata. An important distinction between our interpretations and previously published interpretations (Scanlin and Engelder, 2003; Donahoe, 2011; Mount, 2014) is the extent of the faults into the overlying stratigraphy. While previous studies (Gillespie, 2013; Roberts, 2013) report that faults terminate at the top of the Marcellus Formation, consistent with our findings, others (Scanlin and Engelder, 2003; Donahoe, 2011; Mount, 2014) argue that a few of the faults segments cut upsection and displace the overlying Mahantango Group. Implicit in this interpretation are implications regarding shortening styles within the Mahantango Group. For example, assuming none of the shortening within the Mahantango Group is accommodated via LPS and that this stratigraphic package contains a lesser degree of macroscale faulting than the subjacent units then the sections do not balance. Alternatively, if the Mahantango Group displays macroscale shortening plus 13% LPS, the sections do not balance. Roberts (2013) evaluated the probability of faulting in the Mahantango Group by evaluating a suite of seismic attributes, such as variance and ant tracking. These methods highlight discontinuities in seismic reflectors and evaluate how continuous and significant these discontinuities are. Comparing the seismic attributes of the Mahantango Group to clearly faulted units such as the Marcellus Formation strongly suggest that at the macroscopic scale, the Mahantango Group is not faulted (Figure 30a) (Roberts, 2013). This requires that the Mahantango Group must be shortening via a separate microscale mechanism, consistent with our interpretation.

Some published seismic sections (Donahoe, 2011; Mount, 2014) do show perturbations in the top reflector of the Mahantango Group (Figure 29). We propose three potential explanations for perturbations of seismic reflectors in the Mahantango Group: seismic artifacts, steep folding, and negligible amounts of offset. Long lineations that extend across seismic profiles and create small perturbations in reflectors are an example of potential seismic artifacts, which form during acquisition and processing of seismic data (Figure 29a). A 3-D dataset would be useful in determining whether a lineation (Figure 29a) continues in 3-D space, which would be consistent with the presence of an actual structure. A lineation appearing on a 2-D section which does not exist on neighboring sections may reflect a seismic artifact. Steep bedding planes are another example of a structure which may appear to be a fault in seismic section (Figure 29b). Steeply dipping (>30°) folds cannot be seismically imaged and can appear as a truncation, as is observed in our own seismic data (Figure 20). An alternative interpretation to certain truncations in the Mahantango Group reflector (i.e. Figure 29b) is that the beds are steeply folded

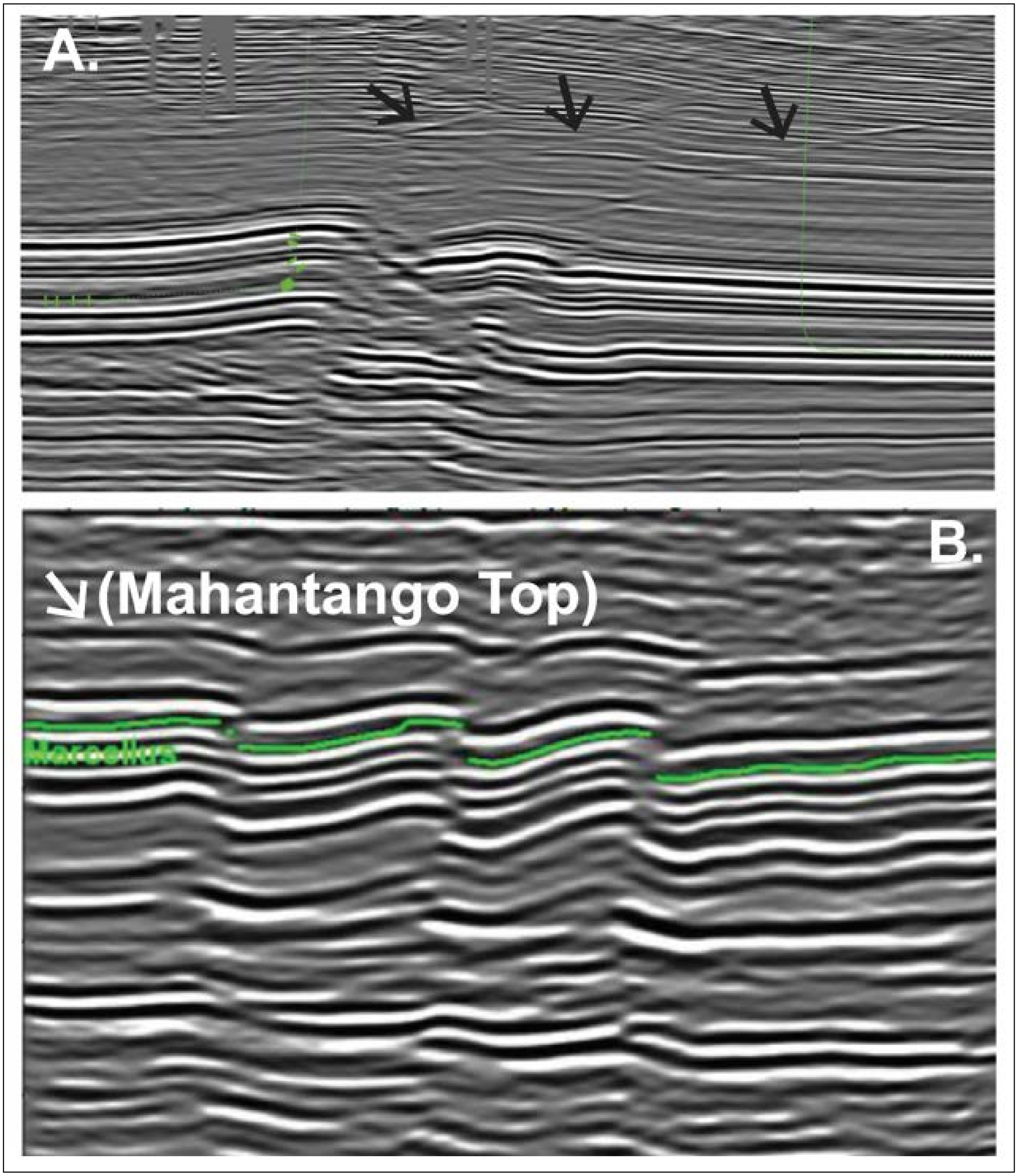


Figure 29: Evidence of shallow faults in previously published studies. (A.) From Mount, 2014. Black arrows show location of seismic lineations that were interpreted by Mount (2014) to be shallow faults initiating from the Mahantango Group and terminating in the overlying Lockhaven Formation. Green lines are Marcellus Shale wells. Figure is unedited from original version. (B.) From Donahoe, 2011. Green lines outline Marcellus Shale top. Figure is unedited from original version except for the addition of the white arrow and label indicating the top of the Mahantango Group top.

to accommodate shortening from thrust faulting in the underlying early Devonian – late Silurian package. If the Mahantango Group faults proposed by Scanlin and Engelder, 2003; Donahoe, 2011; Mount, 2014 (Figure 29) do exist, we argue that the magnitude of shortening on these faults is considerably less than the magnitude of macroscale shortening on early Devonian – late Silurian units that the quantification of shortening (<10 m) would be relatively negligible.

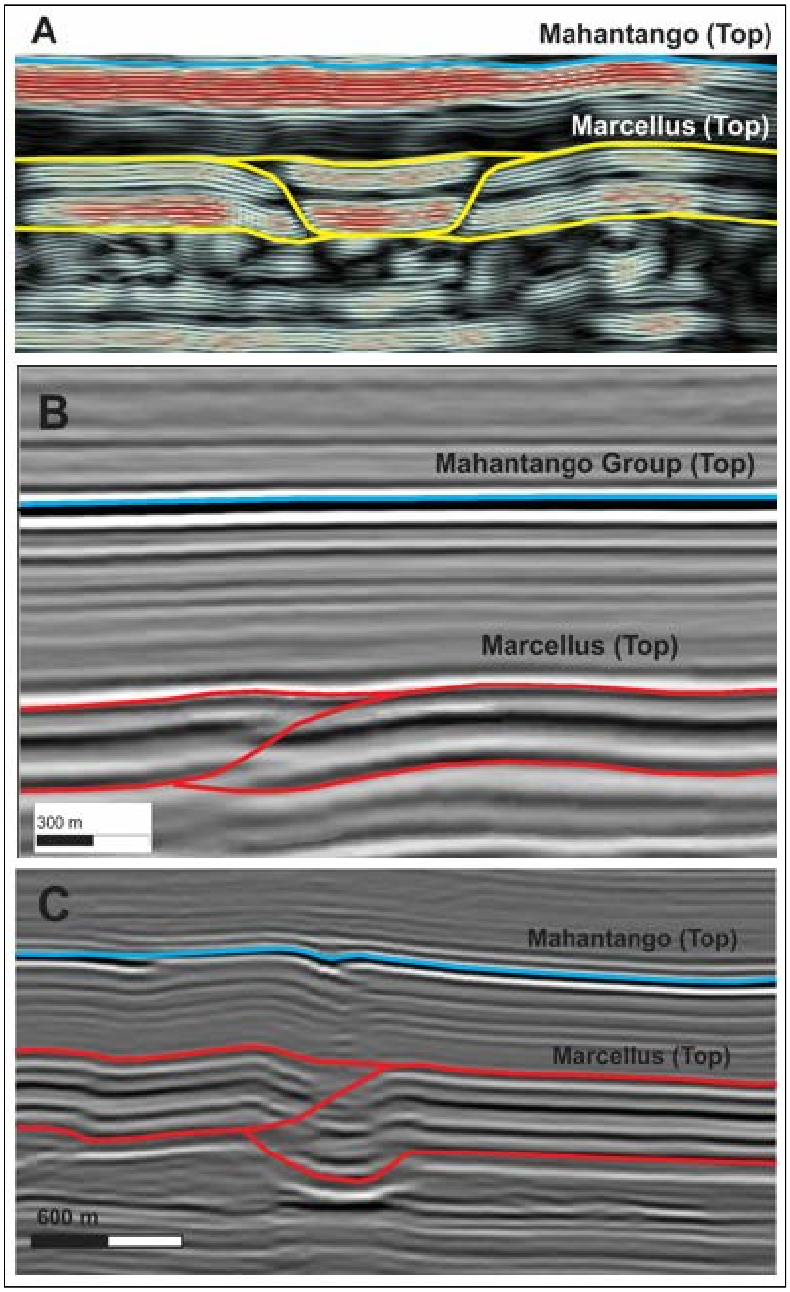


Figure 30: Examples of reinterpretations of previously published seismic reflection profiles, refer to figure 28 for general locations. Profile (A) is characterized by unbroken Mahantango Group and wedge-style faulting beginning at the top of the Marcellus shale. The tapered hanging wall and footwall cutoffs are an interpretation, but necessary to maintain uniform thickness of all beds while accommodating shortening. Seismic reflection from Roberts (2013). (B) Similarly, in the seismic reflection profile collected in Bradford, Gillespie (2013) presents a similar geometry. Here the top of the Mahantango Group is marked by a strong continuous reflector representing the overlying beds beginning at the top of the Marcellus Formation. (C) A seismic reflection profile from Mount (2014) reveals characteristics of wedge-style faulting beginning at the top of the Marcellus Formation, including downward displacement and folding of the footwall block. We interpret that the underlying ductile salt detachment is displaced to accommodate this structure.

We reinterpret previously published seismic sections (Scanlin and Engelder, 2003; Donahoe, 2011; Gillespie, 2013; Roberts, 2013; Mount, 2014) to provide a more complete sense of potential geometries. We outline the top of the Mahantango Group in blue (Figure 30 A-C) to highlight the continuous, unfaulted reflector. We also highlight truncated reflectors beneath the Mahantango Group which begin at the top of the Marcellus shale. Figure 30 A (in yellow) and C (in red) show the full thickness of the Marcellus through the top of the Salina detachment. Figure 30 B (red lines) only shows the partial thickness of the Marcellus through Salina package due to the image extent and placement of scale bar in the source publication (Gillespie, 2013). We show tapered hanging-wall and footwall cutoffs in all interpretations (Figure 30 A,C [red lines], B [yellow lines]). This interpretation is necessary to maintain constant stratigraphic thickness of the continuous overlying Mahantango Group while accommodating shortening on faults within Marcellus – Salina units. This change in deformation style requires that the top of the Marcellus shale is a detachment horizon. We can recognize a similar style of wedge faulting as reported in our dataset throughout this reanalysis (Figure 30).

The recognition of the top of the Marcellus Formation as a regionally extensive detachment surface carries broad implications. The mechanical strength of the units involved in our wedge fault interpretations allows for the downward displacement of the rigid footwall block, displacing the underlying ductile Silurian salt detachment rather than adding structural relief to the overlying beds. This structural style results in little expression of faulting or folding in rocks at the surface, aside from the areas where the faulted strata actually outcrops (Figure 1). Because these units rarely do outcrop, and their structure creates no surface expression, we must rely on subsurface data to recognize it. We have shown that although wedge faulting is the dominant shortening mechanism in Silurian – early Devonian units in the AP, the individual structures rarely extend beyond 25 km along strike (Figure 21) hindering recognition of these structures at a regional scale. Therefore, it is possible to infer that this style of structure is present throughout the AP in late Silurian to Devonian aged strata, by linking our observed subsurface structure to the spatial distribution of LPS data (Figure 28). We postulate that shortening throughout the AP is balanced between macroscale shortening via wedge faulting in late Silurian to early Devonian aged strata and equal magnitudes of shortening via LPS in Devonian through Carboniferous rocks such as those exposed on the surface of the AP.

7.0 CONCLUSION

Due to the lack of high resolution subsurface data, structural details of deformed rocks not exposed at the surface of the Appalachian Plateau have been a mystery. Traditionally the subsurface structures have been simplified to solely detachment folding over the ductile Silurian salt detachment. It is known that LPS is shortening rocks at the surface of the AP (Nickelsen, 1996; Engelder and Engelder, 1977; Slaughter, 1982; Geiser, 1988) and previous seismic strongly suggest the presence of macroscale faults. Through the use of new high resolution 3D seismic data, macroscale shortening structures have been revealed and documented specifically in the late Silurian to early Devonian units.

Our structural interpretations of geophysical data can be supported from a variety of observations beyond that seen in seismic data. Map data from the Nittany Anticline shows unique fold geometries in rocks immediately above the Salina Group strongly suggesting that more than one shortening mechanism exists in units in the AP above the Silurian salt detachment (Figure 1). These small scale, tight folds are seen in surface expressions and are limited to just the Silurian – early Devonian units. Macroscale faulting confined to these units is confirmed by stratigraphic discontinues in the Marcellus shale in gamma log surveys, which were recorded via LWD (Figure 9). The recorded gaps in stratigraphy are indicative of thrust faulting.

We utilize 3-D seismic data to determine the geometry, extent and magnitude of shortening accommodated above the Salina Group and below the Mahantango Group. We document a range of fault offsets (60 m to 550 m) and show that the along strike extent of the faults are generally < 25 km. These faults do not extend stratigraphically above the Devonian Marcellus Formation. Therefore, we interpret an additional detachment horizon at the top of the Marcellus shale, and that the units above this detachment are shortening via LPS. The geometry of these thrust faults contained between two detachments argue for wedge-style faulting repeating the late Silurian to early Devonian units. The magnitude of macroscale shortening in these Silurian to lower Devonian units is equal to the magnitude of shortening via grain scale LPS measured in the overlying units. On a regional scale, all the strata above the Marcellus shale detachment in the AP have shortened 24 km via LPS. We trace the 24 km of LPS back to 24 km of shortening via macroscale wedge-style thrust faulting in Ordovician – Silurian units above the Reedsville shale detachment in the Valley and Ridge.

The interpretations developed within the 450 km^2 seismic volume are exportable to previously published seismic studies elsewhere on the AP suggested the presence of a regional scale mechanism for accommodating shortening about the Silurian salt detachment. Pairing a large swath of LPS data in the surface rocks of the Appalachian Plateau with a large swath of late Devonian to Silurian shortening observations in recently published seismic throughout the region, we argue that small scale wedge faulting is occurring in units between the upper Marcellus shale and the top of the Silurian salt detachment across the entire plateau, and that the system is balanced because shortening accommodated via wedge faulting equals the amount of LPS in the overlying strata.

APPENDIX

Included in this section is each full geologic cross section constructed in this study. The cross sections shown are organized spatially from west to east.

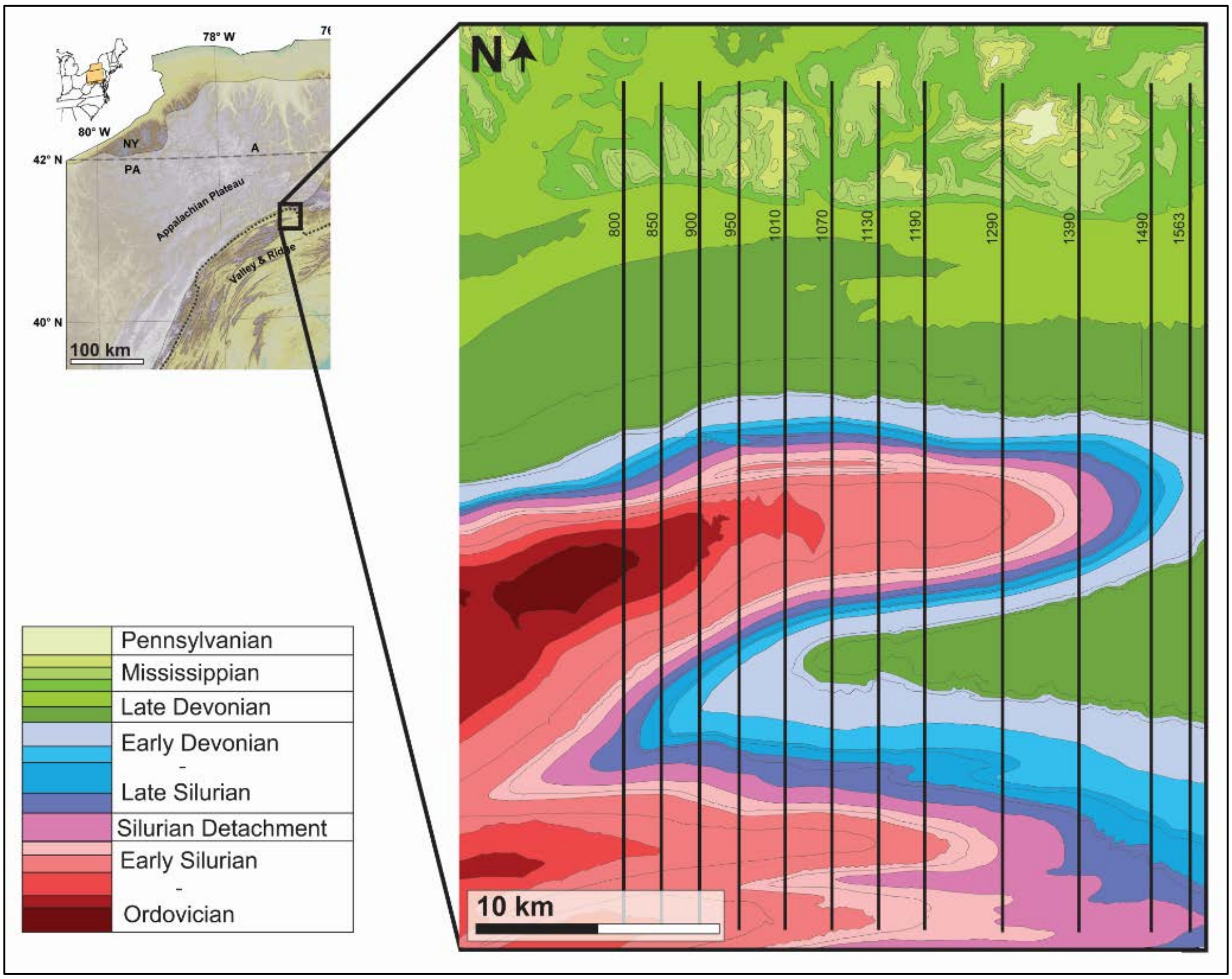


Figure 31: Overview of the locations of the geologic cross sections shown in appendix.

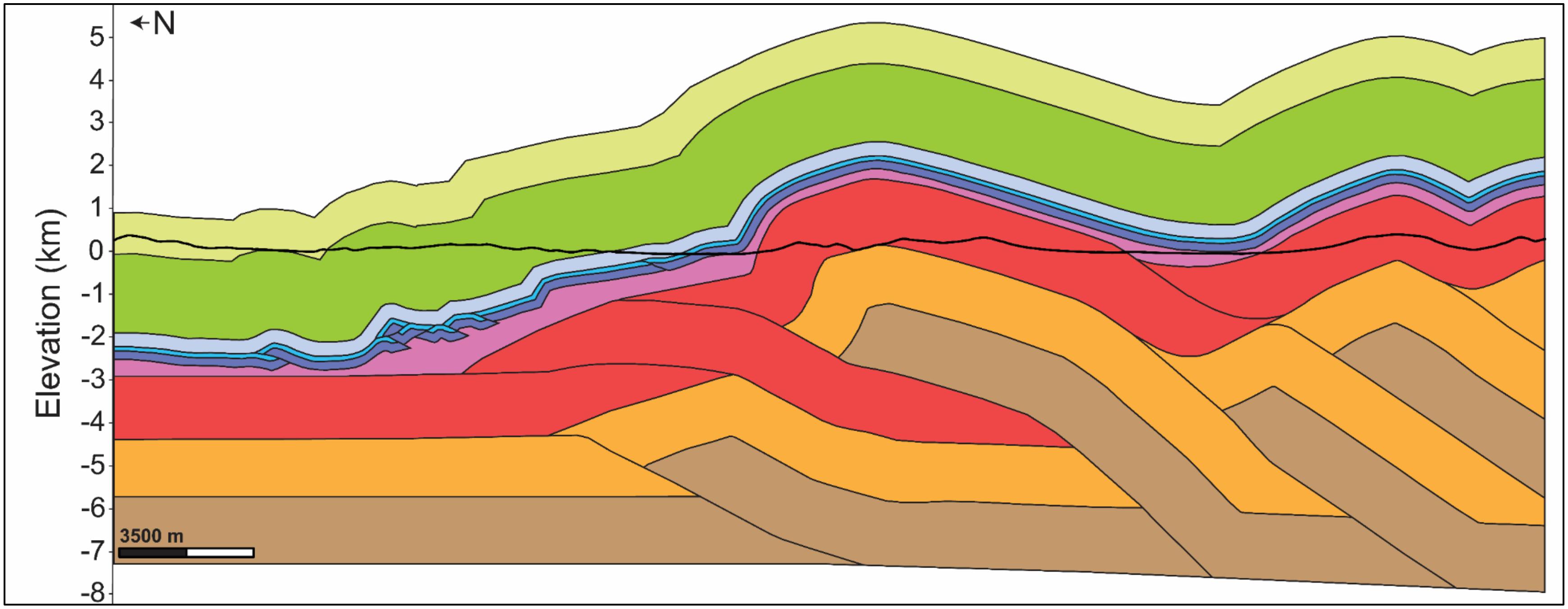


Figure 32: Inline 800

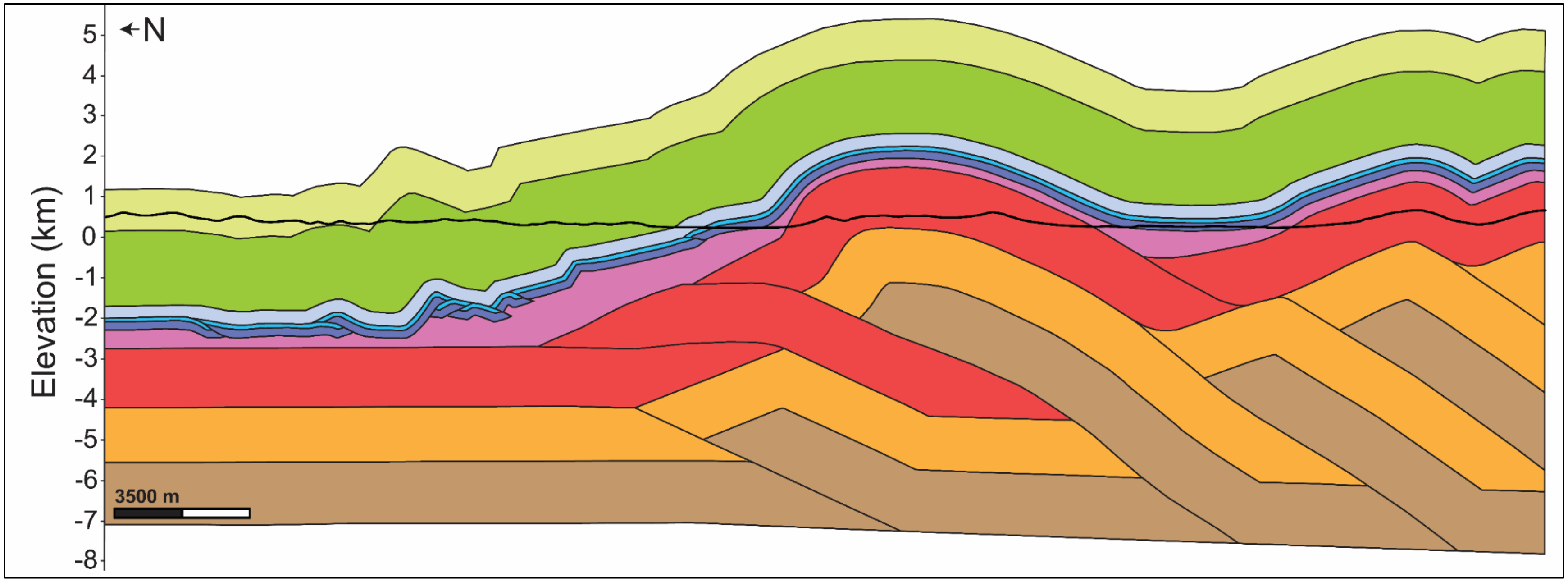


Figure 33: Inline 850

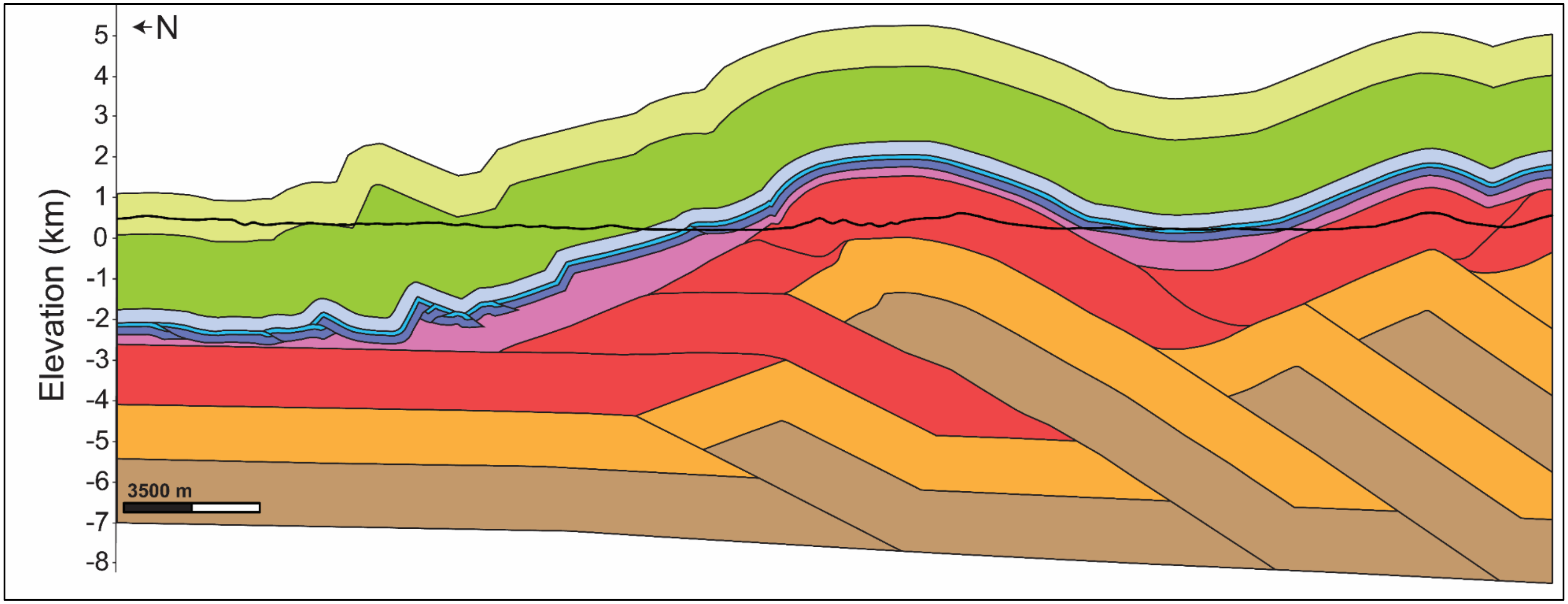


Figure 34: Inline 900

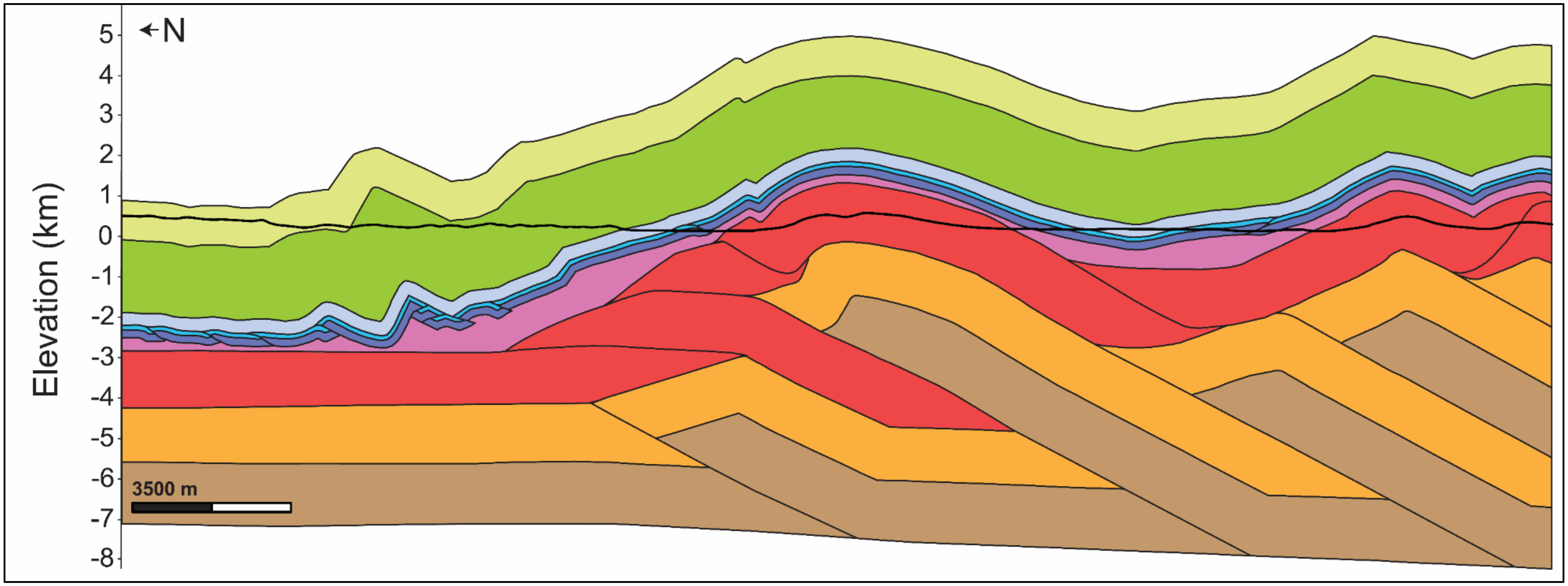


Figure 35: Inline 950

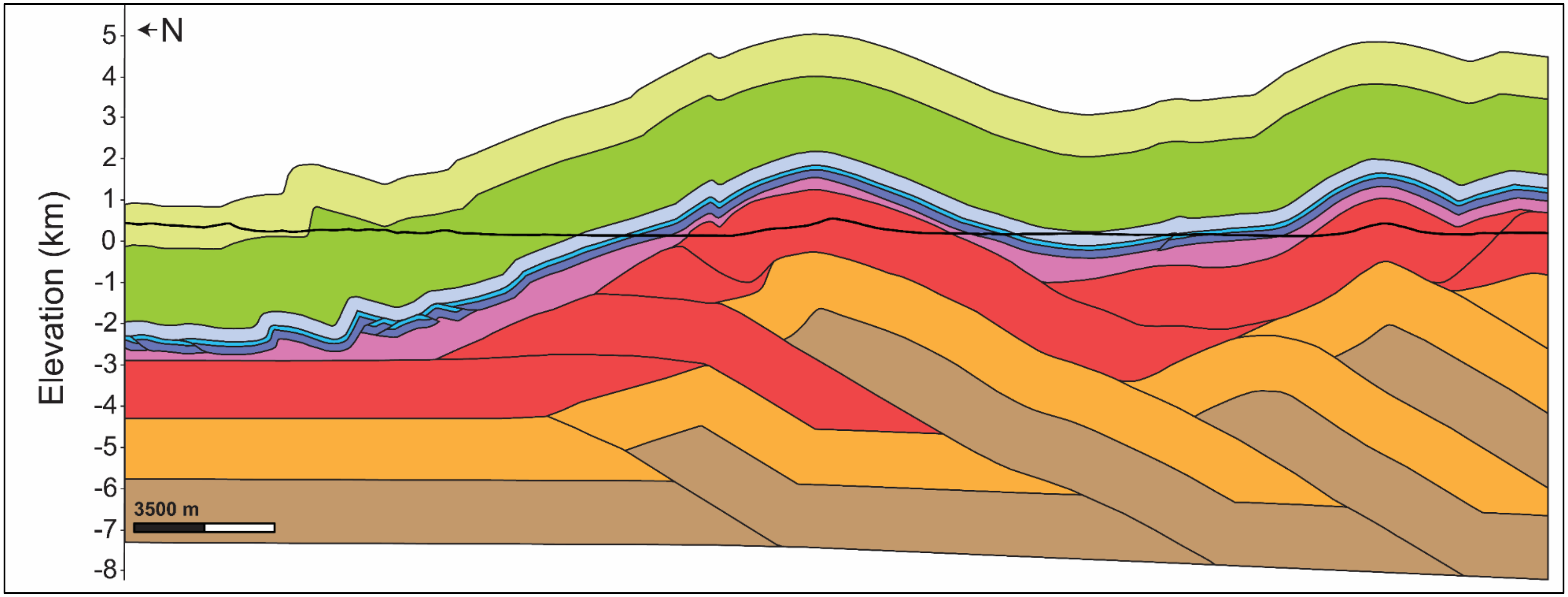


Figure 36: Inline 1010

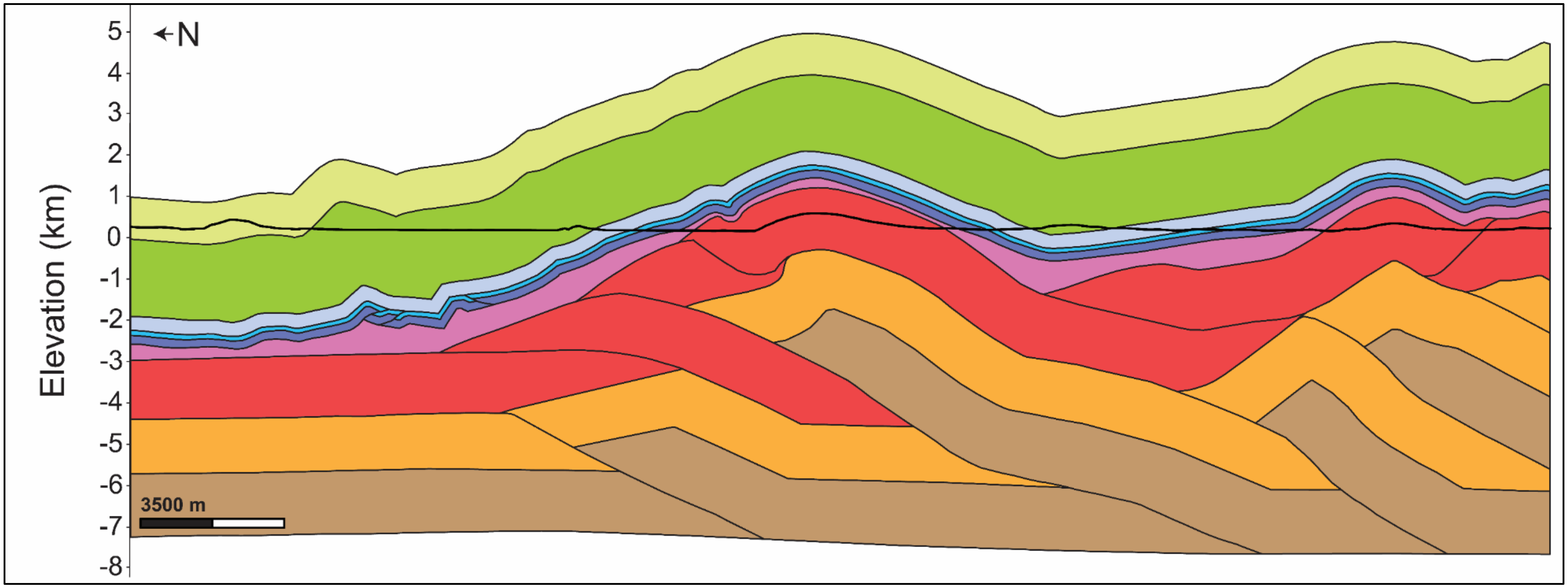


Figure 37: Inline 1070

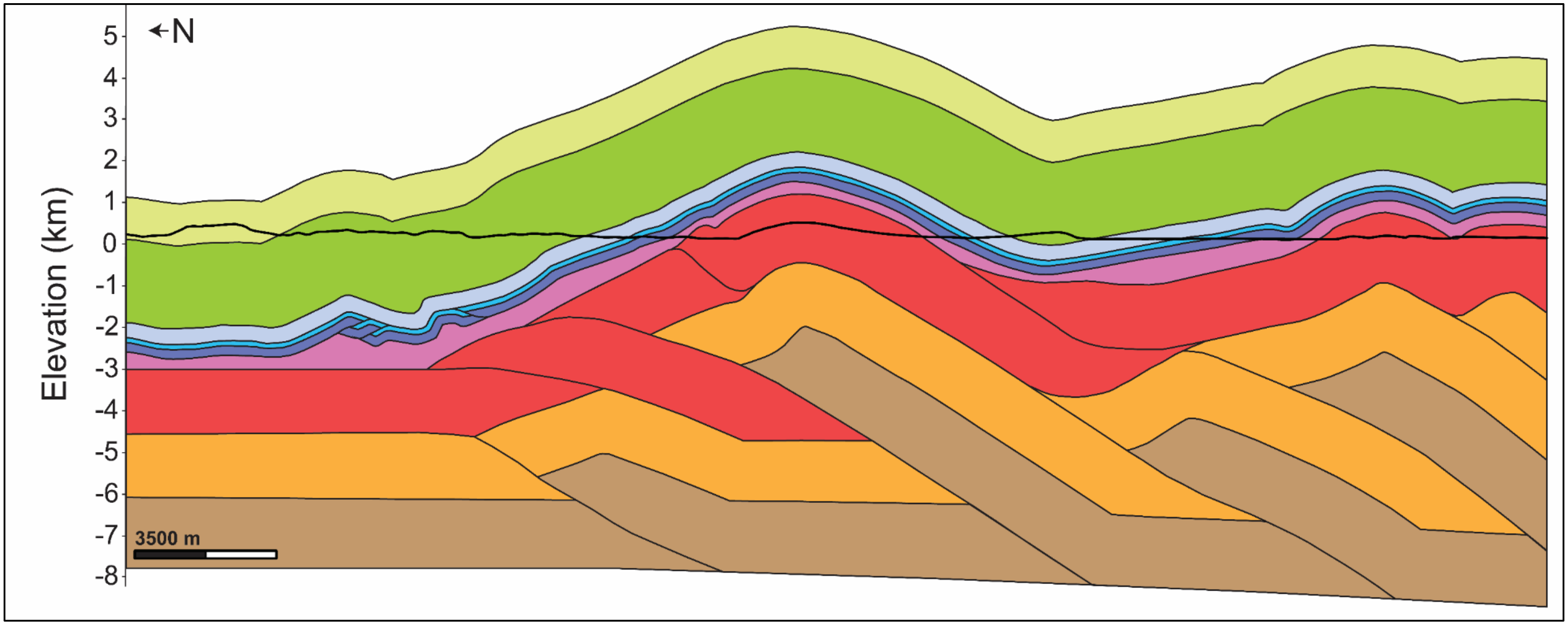


Figure 38: Inline 1130

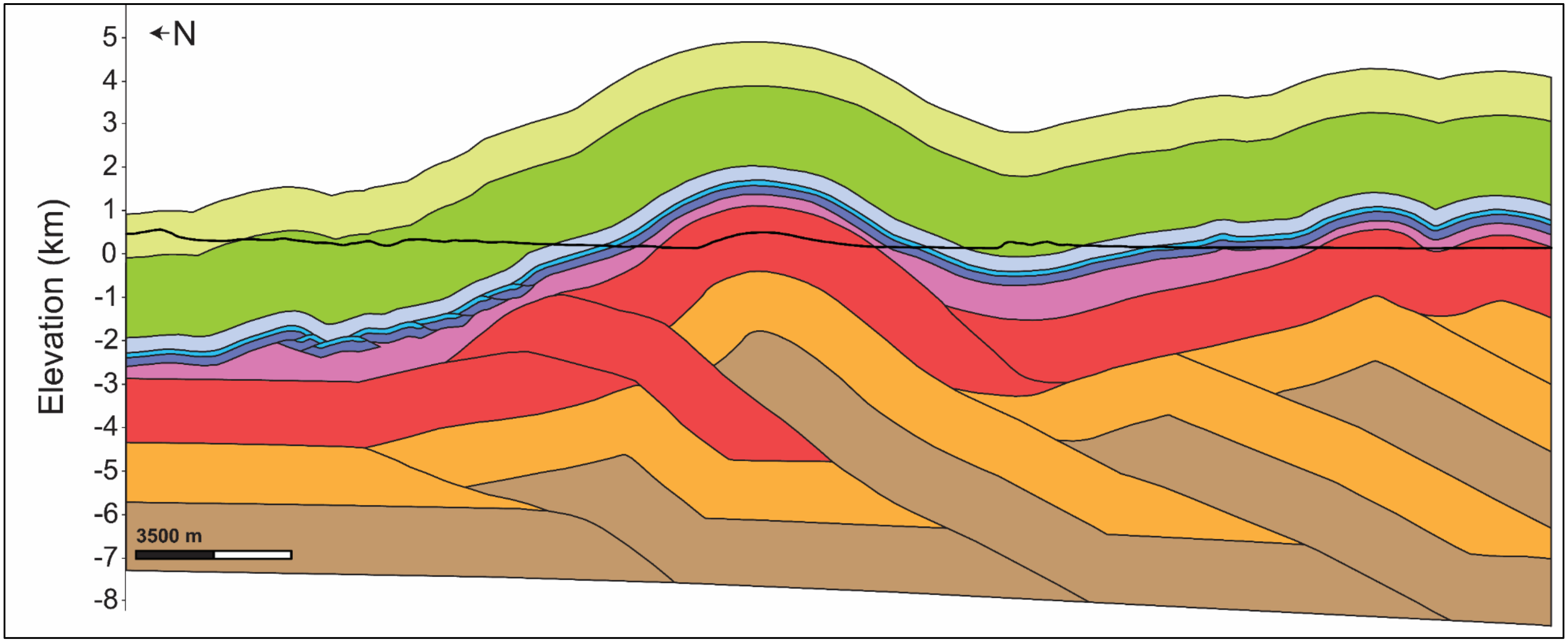


Figure 39: Inline 1190

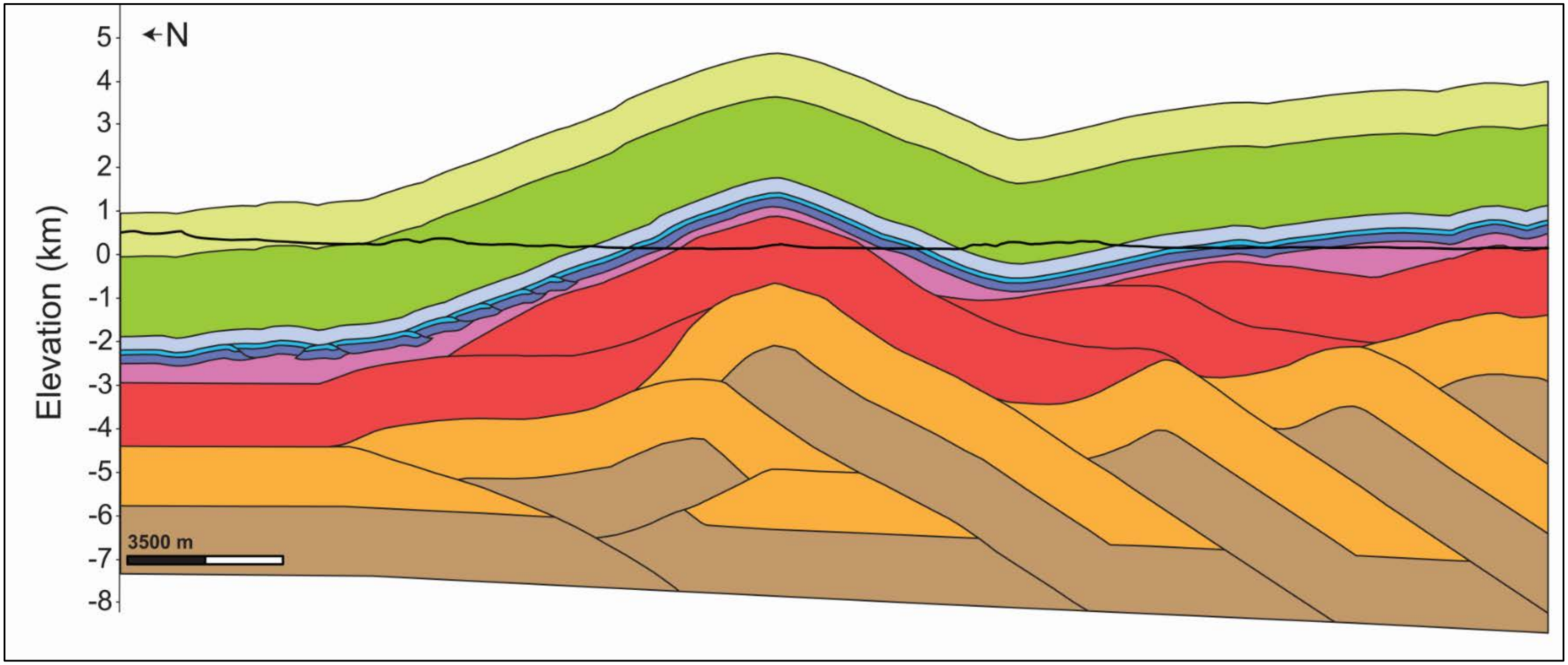


Figure 40: Inline 1290

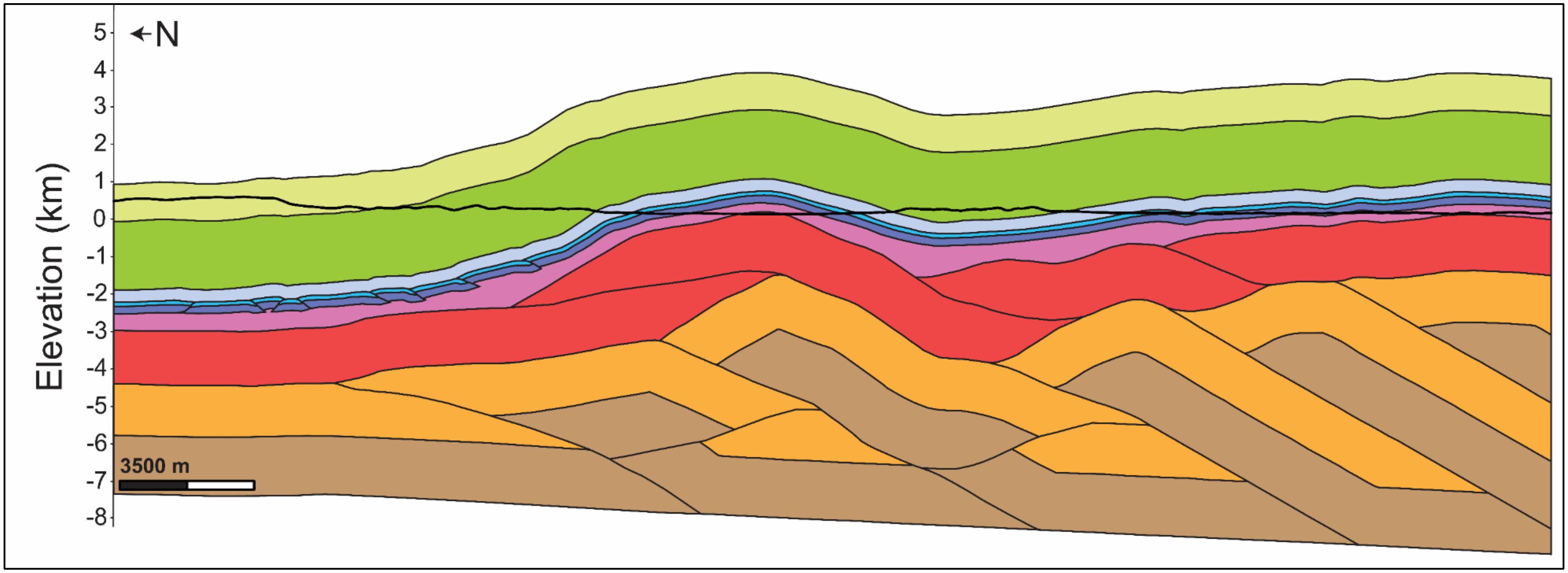


Figure 41: Inline 1390

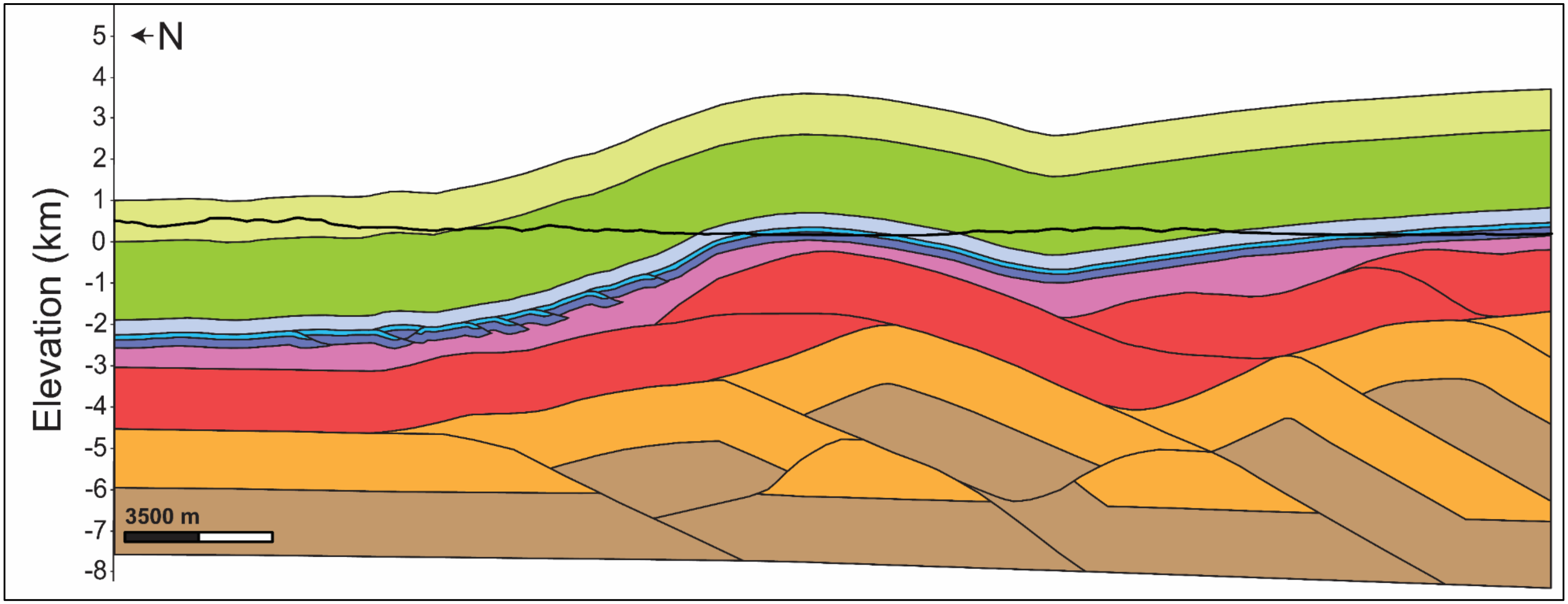


Figure 42: Inline 1490

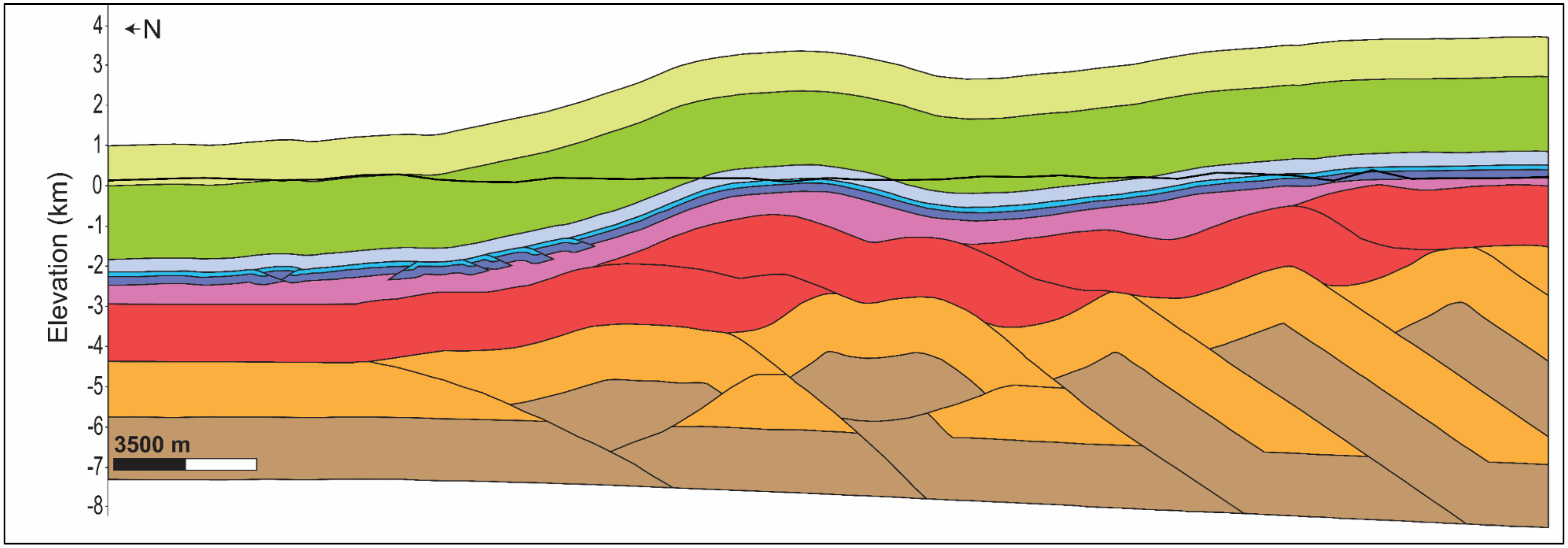


Figure 43: Inline 1563

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