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Surficial Mapping and Kinematic Modeling of the St. Clair Thrust Fault, Monroe County, West Virginia

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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
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Abstract

Near the Allegheny Structural boundary between the Appalachian Plateau and the Valley and Ridge Province of the West Virginian Appalachians lie four major thrust faults: the Pulaski, Saltville, Narrows, and the St. Clair all of which are associated with the Alleghenian Orogeny. Of these major thrusts, the St. Clair thrust fault represents the boundary of the Allegheny Structural Front and is one of the few major thrust faults that are exposed at the surface in the Appalachians of West Virginia.

The St. Clair thrust fault represents an example of fault-propagation folding. Within fault-propagation folding, trishear deformation and fault-bend folding can be linked to deformation. Kinematic modeling was conducted using Midland Valley's 2D Move software package to recreate the geometry of the fault and its associated fold. Modeling software was also used to determine the effects of individual parameters within trishear deformation. The parameters examined include the propagation-to-slip ratio, trishear apex angle, trishear angle, angular shear, and the number of trishear zones. Of these parameters, the propagation-to-slip ratio has the most impact on the geometry of the footwall fold. The propagation-to-slip ratio determines how much the fault propagates through the strata and also dictates what type of fold develops. A P:S ratio that is zero results in the formation of a detachment fold, a small P:S ratio results in a trishear fault-propagation fold, and a large P:S ratio results in the development of a fault-bend fold.

Through surficial mapping and kinematic modeling, it has been concluded that the St. Clair thrust fault formed in two steps involving fault-propagation folding. The overturned syncline in the footwall, the Glen Lyn Syncline, was formed by trishear deformation, with a propagation-to-slip ratio of approximately 0.25, as the fault slowly propagated through the strata. Then, the fault broke through to the surface due to an increase in the P:S ratio and a second mode of deformation occurred, fault-bend folding. This combination of trishear deformation and fault-bend folding created the present-day geometry of the St. Clair thrust fault and its associated structures.

By recreating the sequential cross-sections, it was possible to determine the amount of displacement needed for each cross-section. The southwestern most cross-section was modeled and a minimum displacement value of approximately 2300 meters was needed. Erosion has removed the hanging wall cut-off; therefore the total displacement is not constrained.

Two additional cross-sections to the northeast show evidence of an anticline in the hanging wall. The values of deformation in these cross-sections are more representative of the actual amount of displacement needed. Displacement values decreased from 7500 meters to 6700 meters toward the northeast, or by about 10%.

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This thesis has been dedicated in the memory of my grandfather,
D.E. Shrewsbury:
This is for you

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Chapter 1: Introduction

The St. Clair fault represents the boundary of the Allegheny Structural Front, as well as the approximate boundary between the central and southern Appalachians (Dean and Kulander, 1988), and is one of the few major thrust faults that are exposed at the surface in the Appalachians of West Virginia (Figures 1 and 3). The trace of the St. Clair fault ends just across the West Virginia-Virginia state line in Alleghany County, Virginia, but the northeastern extension of this same line of structural discontinuity, the Covington Lineament, extends into the Valley and Ridge of Virginia and possibly into the Shenandoah Valley (Dean, Kulander, and Skinner, 1988). The St. Clair thrust fault terminates within the core of the Wills Mountain Anticline at the junction of the southern and central Appalachians (Spraggins and Dunne, 2002).

As noted by Gustafson (1982), the hanging wall of the St. Clair fault is comprised of the Upper Cambrian Knox Dolomite through the Lower Mississippian Sandstones of the Price Formation (also known as the Pocono Formation). Also, the St. Clair fault represents a type of folding, known as a fault-propagation fold, which refers to an asymmetrical fold with one steep or overturned limb adjacent to a thrust fault (Figure 9) (Suppe and Medwedeff, 1984).

Theoretically, as the St. Clair fault dies to the northeast, the fault throw should decrease as we move from the southwest towards the northeast. I have tested this hypothesis by creating a geologic map and sequential cross-sections and by using kinematic modeling software, such as Midland Valley's 2DMove. I have also attempted to show how the strain distribution within the trishear triangle zone could be related to fracture density, which could be useful for predicting the location of possible targets for

natural gas production. This has been done in conjunction with Reed Johnsons' master's thesis "Surface and Subsurface Fracture Systems with Associated Natural Gas Production in the Lower Mississippian, Upper Price Formation, Southern West Virginia." Most importantly, I have evaluated the kinematic development of the structures that are associated with the St. Clair fault.

Figure 1: Map showing shaded relief and the location of the study area, indicated as the green box, also shown in Figure 2. Approximate locations of the Appalachian Plateau and Valley and Ridge Provinces are shown. The boundary between the two provinces, marked as a blue line, represents the Allegheny Structural Front. Coordinate system is UTM Zone 17.

Figure 2: Geological map of the study area showing general geology, corresponding USGS Quadrangle names, faults, folds, and approximate study area (shown by black box). Coordinates are UTM Zone 17 (Modified from Cardwell, et al., 1968).

Chapter 2: Location

The St. Clair fault, which is the northern segment of a 600 km long fault system, strikes in a northeasterly fashion through Russell, Tazewell and Giles Counties in Virginia, Mercer and Monroe Counties in West Virginia and Allegheny County in Virginia (Figure 3) (Butts 1940 and Gustafson 1982). The St. Clair fault, which is located in the northern end of the southern Appalachians, has been traced from its northern terminus in the core of an anticline in Allegheny County, Va. southwestward to the Clinchport and related faults of southwestern Virginia and Tennessee (McDowell and Schultz, 1989). It is in Russell County, Virginia where the St. Clair fault splits into two separate faults, the Russell Fork fault and the Honaker Thrust fault (Figure 3). The St. Clair fault is extremely well exposed on U.S. Highway 460 south of Rich Creek Va. and near Glen Lyn, Va. (McDowell and Schultz, 1989).

The area that has been mapped is located in Monroe County, WV, and covers the Gap Mills, Union, Waiteville, and Interior Quadrangles (Figure 2). Within the study area, elevation ranges from 2000 feet above sea-level just south of the town of Union, WV., to an elevation of 3900 feet along Peter's Mountain. The total vertical relief between the highest and lowest point within the study area is 1900 feet. There are several access roads that cut across the study area. The main access road is Zenith Road (CR 29), which transects the study area from east to west. Other roads of importance are Turkey Creek Road (CR 13/3), Gates Road, WV Route 3, Waiteville Road (CR 15), WV Route 219, and Crowder Road (CR 20). Turkey Creek Road cuts across the study area from Zenith Road to Gates Road. This is one of the more important roads in the study area, as it cuts across the St. Clair thrust fault just north of the town of Crimson Springs. Gates Road, WV Route 3, and WV Route 219 provide access to outcrops of the

Greenbrier Limestone and the Mauch Chunk Group. Waiteville Road and Crowder Road are important access roads, as they transect Peter's Mountain, providing a look at strata ranging from the Late Cambrian – Early Ordovician Knox Group to the Devonian Marcellus Series. Finally, the Allegheny Trail provides foot access trending along the ridge of Peter's Mountain (Figure 8).

Figure 3: Regional map showing shaded relief and the location of the St. Clair fault and other surrounding features. Study area is shown by blue box. Green represents low elevations and darker colors represent higher elevations. Modified from Gustafson, 1982 and Cooper, 1961.

Chapter 3: Stratigraphic Setting

It is noted that “nowhere along the section is a complete stratigraphic succession exposed (Late Precambrian through Pennsylvanian)” (Woodward, 1985). The strata that will be encountered in the study area range from the older Upper Cambrian to Lower Ordovician Knox Group to the younger Upper Mississippian Mauch Chunk Group.

The following are detailed descriptions of the formations (oldest to youngest) that are encountered within the study area. The following stratigraphic descriptions are compiled with the help of Kammer (2001) and McDowell and Schultz (1989). The descriptions by Kammer (2001) are for Southeastern West Virginia and the descriptions for McDowell and Schultz (1989) are for Giles County, Va. Additional descriptions have been added based on observations within the study area. A stratigraphic column for this area can be found on Figure 4 and a chart correlating the nomenclature across regions can be found in Appendix III.

Knox Group

The dolomite sequence of the Upper Cambrian through the Lower Ordovician age belongs to the Knox Group. The Knox Group was named by Safford (1869) for exposures in Knox County, Tennessee. The Knox Group is comprised of the Beekmantown Dolomite and the Copper Ridge Dolomite. For the purposes of this study, the broader Knox Group will be used. The Knox Group contains a thick sequence of gray or tan siliceous dolomite with brecciation occurring locally. The dolomite within the Knox Group is often cherty in nature.

Also, within the Knox Group, thin limestones and sandstones can be found, as well as flat-pebble conglomerates. Fossils are uncommon, except within the sandstone and limestone layers. The Knox Group represents marine shelf carbonates and range between 180 – 600 m in thickness, in Southeastern West Virginia. The thickness within the study area has been found to be in the upper portion of that range. The Knox Group overlies the Nolichucky shale and is overlain by the Middle Ordovician Limestone Group. An unconformity exists above the Knox Group, having as much as 30 m of relief. The Knox Group facies has been interpreted as being a marine shelf environment (McDowell and Schultz, 1989). Exposures of the Knox Group include areas along Zenith Road, to the west of Gap Mills and along Wallace Hollow Road, just east of the intersection of Zenith Road and Back Valley Road. These exposures are not particularly well exposed along Zenith Road, however, a few well exposed outcrops can be found along Wallace Hollow Road.

Middle Ordovician Limestone

The Middle Ordovician Limestone is composed of the New Market Limestone, Lincolnshire Limestone, and the Black River Limestone. The upper contact of the Knox Group is an erosion surface that is overlain by a sequence that is composed mostly of limestone. Within the study area the New Market Limestone may not be present. It is noted by McDowell and Schultz (1989) that in most places, the basal bed is a breccia or conglomerate that is composed of angular to subrounded clasts of light gray to black chert. The New Market Limestone (0-60 m), if present, consists of a light-gray to light-olive gray micritic limestone that is thickly bedded and might be argillaceous near the

base. Next, the Lincolnshire Limestone (14-60 m) is a dark-gray, medium to coarse grained limestone with black chert clasts and the presence of fossils, mainly brachiopods and bryozoans, but can include trilobites, echinoderms, and corals. Finally, the Black River Limestone (60-76 m) is a dark, micritic limestone with very few fossils. The Middle Ordovician Limestones often have calcite veins and are thickly bedded (more than 2 feet) within the study area. Along with the Upper Cambrian Knox Group, the Middle Ordovician Limestones form the linear valley between the northern slope of Peter's Mountain, and the southern slope of Gap Mountain. This facies represents a carbonate ramp and foreland basin deposition (McDowell and Schultz, 1989).

Within the area, the Middle Ordovician Limestones are exposed along Waiteville Road on the northern side of Peter's Mountain. Also, some exposures can be found along Zenith Road, just west of the junction of Waiteville Road and Zenith Road.

Martinsburg Formation

The Martinsburg Formation has been assigned the age of Middle and Upper Ordovician. The Martinsburg Formation was named by Geiger and Keith (1891) for exposures near Martinsburg, West Virginia. The Martinsburg Formation consists of limestone with interbeds of sandstone, siltstone, and calcareous shale near the top, and ranging down to calcareous siltstones and shales near the base. The sandstones represent mostly turbidites. The contact with the underlying Middle Ordovician limestone is gradational. The Martinsburg Formation represents a shallow marine deposition, with its sediment supply possibly originating from the Taconic Orogeny (McDowell and Schultz, 1989). Kreisa (1980) attributed most of the formation to storm deposits.

Figure 4: Generalized stratigraphic column for the study area. Thicknesses shown are average thicknesses. Modified from McDowell and Schultz, 1989.

The Martinsburg Formation is found mainly on the middle and lower slopes of mountains and is generally covered by colluvium (McDowell and Schultz, 1989). In the study area, although poorly exposed due to colluvium, the Martinsburg Formation can be found trending along the northern slope of Peter's Mountain and along the south slope of Gap Mountain as a thin sliver. In southeastern West Virginia, the thickness ranges from 300-730 m. Thicknesses within the study area have been found to be approximately 550 m.

Juniata Formation

The Juniata Formation was named by Darton (1896) for its occurrence along the Juniata River in Pennsylvania. The Juniata Formation (Ordovician), also known as the Red Medina, consists of equal amounts of mudstone and sandstone, with some thin shale beds. The presence of a lagoonal facies can be found on Peters Mountain, within the study area. The lagoonal facies can be identified by the presence of ostracods and the dark red color. The mudstones of the Juniata are typically a bright red color, being made up of nonmarine redbeds. The sandstone layers are typically olive in color. The presence of glauconite accounts for the color of the sandstone layers (Gustafson, 1982). The Juniata Formation was deposited mostly as a delta-plain mudflat (McDowell and Schultz, 1989). The Juniata typically can be found on steep outcrop slopes just below the crest of ridges and is commonly covered by Tuscarora Quartzite float (McDowell and Schultz, 1989). The thickness ranges from 45-180 m. The Juniata Formation forms a gradational contact with the overlying Tuscarora Quartzite.

In the study area, the Juniata Formation is located along the northern slope of Peter's Mountain, just below the ridge. It can also be found as a thin sliver along the southern slope of Gap Mountain. An excellent exposure of the Juniata Formation can be found along WV Route 3, just north of Gap Mills, WV (Figure 5). At this location, the Juniata Formation makes up the footwall of the St. Clair fault and has been overturned. Another good exposure is located along the Hanging Rock Trail on Peter's Mountain. For this study, the contact between the Juniata and Tuscarora Formations has been placed at the first occurrence of the massive-bedded quartzites of the Tuscarora Formation.

Tuscarora Sandstone

The Tuscarora Sandstone was named by Darton (1896) for occurrences on Tuscarora Mountain, Pennsylvania. The Clinch Sandstone was named by Butts (1940) for exposures on Clinch Mountain, Tennessee. Clinch and Tuscarora both refer to the same formation, however, according to Butts (1940), the name Tuscarora applies to that formation in the Appalachian Valley north of the 38th parallel while the Clinch is used in southern Virginia and Tennessee (Gustafson, 1982). The Tuscarora Sandstone (Lower Silurian) is made up of coarse-grained, well-sorted sandstone which is quartz-rich and often displays trough and planar cross-bedding. Minor lenses of quartz-pebble conglomerate are present locally. The presence of worm burrows (*Skolithos* and *Arthropycus*) has also been noted. The Tuscarora Sandstone is very resistant and is regarded as an important mapping unit.

The ridges of Peter's Mountain and Gap Mountain are composed of the Tuscarora Sandstone. Excellent exposures of the Tuscarora Formation can be found along WV

Route 3 north of Gap Mills, WV and along the hanging rock trail along Peter's Mountain (Figure 6). The exposure near Gap Mills, WV has been overturned. Outcrops along the Hanging Rock trail expose quartz-pebble conglomerates, crossbedding, and some *Skolithos* and *Arthropycus* trace fossils. The depositional environment has been suggested to be a nearshore or shoreline deposit, possibly littoral marine or fluvial (McDowell and Schultz, 1989). Thickness ranges from 21-58 m.

Rose Hill Formation

Swartz (1923) named the Middle Silurian Rose Hill Formation for exposures at Cumberland, Maryland. The Rose Hill Formation is commonly grouped as part of the Clinton Group named from Clinton, New York. For this study, the Clinton Group will not be used. The Clinton group has been divided into the Rose Hill Formation and the overlying Keefer Sandstone. The Rose Hill consists of hematitic sandstone and shale, giving the formation a red color, in the lower portion of the Rose Hill. The upper portion of the Rose Hill Formation includes olive-green shales and siltstone. Ostracods and brachiopods can be found within the redbeds as well as the shales. The redbeds within the Rose Hill can be interpreted as lagoonal, due to the presence of ostracods and brachiopods.

Thick sandstone beds of the Rose Hill Formation form ledges on or just below ridge crests. The best exposure of the Rose Hill Formation within the study area can be found along the Alleghany National Trail, which runs parallel with the ridge of Peter's Mountain along the south slope (Figure 7). The Rose Hill Formation represents a marine transgression over the underlying Tuscarora Sandstone (McDowell and Schultz, 1989). The thickness in this area ranges from 64-150 m.

Figure 5: Outcrop along WV Route 3, just north of Gap Mills, WV showing the contact between the Juniata Formation and the overlying Tuscarora Sandstone. Note that these beds are overturned. Approximate location of picture is indicated on Figure 8.

Figure 6: Outcrop of the Tuscarora Sandstone along the ridge of Peter's Mountain. Picture was taken from the Hanging Rock Observatory, looking southwest. Approximate location of picture is indicated on Figure 8.

Keefer Sandstone

The Upper Silurian Keefer Sandstone was first named by Ulrich (1911) for exposures on Keefer Mountain, Maryland. The Keefer Sandstone, which makes up the second part of the Clinton Series, is made up of fine-grained gray-white or brown sandstone. It can also contain an upper and/or lower layer of hematite, which is around 8 inches in thickness. Some quartzite can also be found locally. There may be a presence of locally cross-bedded or ripple marked and burrowed layers (*Skolithos*) and minor reddish-brown sandstone beds.

The Keefer Sandstone forms prominent flatirons on dip slopes of ridges and locally crops out as ledges on the crests (McDowell and Schultz, 1989). Its thickness has been found to be approximately 100 m. Within the study area, outcrops of the Keefer Sandstone were not readily present. However, small outcrops were found along Crowder Road, which transverses Peter's Mountain.

Figure 7: Outcrop of the Rose Hill Formation along the Allegheny National Trail, on the south slope of Peter's Mountain. Approximate location of picture is indicated on Figure 8.

- Figure 5
- Figure 6
- Figure 7

Figure 8: Terrain map showing approximate locations for Figures 5, 6, and 7. Red star represents the location of Figure 5; Green star represents location of Figure 6; Yellow star represents location of Figure 7. Terrain map from Google Maps.

Tonoloway Limestone

The next formation is the Tonoloway Limestone (Silurian). However, between the Keefer Sandstone and the Tonoloway Limestone, it is possible to find the Rochester Shale (0-6 m), McKenzie Formation (0 -43 m), Williamsport Sandstone (0-15 m), and the Wills Creek Formation (0-67 m). These formations did not appear within the study area. The Tonoloway Limestone was named by Ulrich (1911) for outcrops on Tonoloway Ridge in Maryland. The Tonoloway Limestone is a thin, poorly exposed limestone sequence. The Tonoloway Limestone was not observed as outcrop in the study area. The presence of the Tonoloway Limestone is often indicated by reddish-brown clayey soil, small sinkholes, or a distinct slope break (McDowell and Schultz, 1989). Some calcareous shale might also be present. Near the top of the Tonoloway Limestone, calcareous siltstone and shale, cross-laminated sandstone, and fossiliferous limestone can be found. Fossils are uncommon, but occasional layers of ostracods and stromatolites can be found. Thickness within the study area can range from 30-100 m, and can be as little as 15 m.

Rocky Gap Sandstone

The Helderberg Group and the Oriskany Sandstone (Devonian) are being combined for the purpose of this project to form the Rocky Gap Sandstone. The name Rocky Gap was given to this formation by Swartz (1929) for exposures near Rocky Gap, Virginia. This is being done because the Oriskany Sandstone is only 8-23 m thick in the study area. The Helderberg Group (60-120 m) ranges from carbonate mudstone to grainstone (limestone). The Helderberg is typically fossiliferous and cherty. Fossils that can be found within the Helderberg Group include crinoid stem molds. This unit weathers

a distinct light brown color. The Helderberg Group is interpreted as being shallow water limestone.

Above the Helderberg Group, but still within the Rocky Gap Sandstone, is the Oriskany Sandstone. The Oriskany Sandstone is a medium to coarse-grained calcareous sandstone; the calcareous cement is easily removed by weathering, which leaves a friable, indistinctly bedded outcrop. Fossils might be common, which include brachiopods and crinoid stems. Outcrops of the Oriskany Sandstone occur in stream beds along Waiteville Road, on the southern slope of Peter's Mountain.

Marcellus Series

The Marcellus Series (Devonian) consists of the Huntersville Chert (9-23 m) and the Millboro Shale (46-300 m). Once again, these two formations are being combined due to the thinness of the Huntersville Chert. The Lower Devonian Huntersville Chert was first described by Price (1929) in Huntersville, West Virginia. The Huntersville Chert is a highly silicified black shale, or chert, that contains beds that are brecciated and recemented with amorphous silica. When weathered, the shales are often pink or lavender in color and the chert might be blue or blue-black. The top of the Huntersville Chert is marked by glauconitic sandstone, known as the Bob's Ridge Sandstone, which is approximately 3 ft thick. A small exposure of the Huntersville Chert can be found on the southern slope of Peter's Mountain, along Waiteville Road.

The Devonian Millboro Shale was named by Butts (1940) for exposures at Millboro Springs, Virginia. The overlying Millboro Shale is an olive-gray to grayish-black fissile clay shale that weathers gray and readily forms soil. Color can range from

brown and red to white. The shale might be sparsely fossiliferous in the study area.

McDowell and Schultz (1989) note that the Millboro Shale occurs locally just below the St. Clair thrust on the overturned limb of the Glen Lyn Syncline. The Millboro Shale is poorly exposed on the footwall block, north of Gap Mills, WV. However, on the hanging wall, the Millboro Shale is nicely exposed on the south slope of Peters Mountain. The thickness of the Millboro Shale is difficult to determine because of repetition of beds by folding and faulting, but Cooper (1961) reported a thickness of 259 to 304 m (McDowell and Schultz, 1989).

It is beginning to become apparent that the Marcellus is a viable resource for natural gas. It has been estimated by the Potential Gas Committee that the Marcellus could increase the probable resource numbers by 50 TCF (Durham, 2008). Within the study area, the Marcellus has the most, if not only, potential for natural gas production. It has been suggested that the Marcellus will be prospective on a multiple play basis just as with the Barnett Shale (Durham, 2008). The one upside of the Marcellus is its regional extent, covering approximately 600 miles, the Barnett Shale covers only 120 miles. However, due to the large extent of the Marcellus, it will take more work to pinpoint a specific area to begin drilling (Durham, 2008).

Brallier Shale

The Upper Devonian Brallier Shale was named by Butts (1918) for exposures near Brallier Station in Bedford County, Pennsylvania. The Brallier Formation, also known as the Portage, consists of siltstones and mudstones of marine origin. Some fine-grained, thickening upwards sandstones can also be found in the Brallier Formation. The

beds are typically dark brown to gray in color. The upper contact with the Millboro Shale is gradational and is generally placed at the base of the lowest, medium-grained, cross-bedded, fossiliferous sandstone 6 ft thick, or more. McDowell and Schultz (1989) note that the Brallier outcrops along the footwall of the St. Clair thrust fault in Giles County, Va. Thickness ranges from 120-760 m. The Brallier Formation is interpreted as being distal flysch deposits, such as turbidites (McDowell and Schultz, 1989).

Chemung Formation

The Chemung Formation (Devonian) consists of thick-bedded, fine-grained, slightly calcareous sandstone with interbeds of siltstone and shale. Some of the sandstones near the top of the Chemung are highly fossiliferous, containing mostly brachiopods. Sandstones within the Chemung Formation have sole marks and may be turbidites of a proximal flysch facies (McDowell and Schultz, 1989). This sequence represents a marine depositional environment. An excellent exposure can be found along WV Route 3, a little over one-half mile north of Gap Mills, WV. A highly fossiliferous bed of the Chemung Formation is located just north of the bridge over Second Creek, along WV Route 3. The thickness ranges from 150-900 m. Above the Chemung, the Hampshire Formation (0-250 m) may be present, but not seen regionally.

Hampshire Formation

The Upper Devonian Hampshire Formation consists of entirely nonmarine sandstones, shales, and mudstones, usually being pink to bright red in color. The sandstones within the Hampshire Formation are typically cross-bedded. Thicknesses for

the Hampshire range from 0 to 250 m. The Hampshire was not expected to be located within the study area. However a thin non-mappable sliver, less than 1 meter thick, of the Hampshire Formation was found along Turkey Creek Road.

Price Formation

The Chemung and the Hampshire Formations are overlain by the Late Devonian and Early Mississippian Price Formation, which was named by Campbell (1894) for exposures on Price Mountain in Montgomery County, Virginia. The Price Formation consists of planar-cross-bedded sandstone with beds of siltstone and shales of marine origin increasing upwards. Multiple, thinly bedded, fine to medium-grained sandstone, shale, siltstone, coal, and conglomerates can be found (Johnson, 2007). Fossils are present, but not common. At the base there is often a nonmarine conglomerate known as the Cloyd Conglomerate. The Cloyd Conglomerate was deposited by a regression-transgression sequence during the late Devonian in estuarine point bar and fluvial channel environments (Bjerstedt and Kammer, 1988, Bjerstedt, 1986, and Johnson, 2007). McDowell and Schultz (1989) note that the Price Formation has been described as a regressive sequence composed of lithofacies representing eight depositional environments, ranging from marine shelf to delta plain and swamp. In southern West Virginia, the Price Formation has been interpreted as being deep water marine-deltaic in origin (Johnson, 2007).

Exposures of the Price Formation, and the Cloyd Conglomerate, can be found along WV County Route 8, just east of the study area. Another excellent exposure is located along Turkey Creek Road. The exposure along Turkey Creek Road shows cross-

bedded sandstones, layers of rip-up clasts, some fine-grained sandstone and siltstones, as well as the contact between the Price Formation and the underlying Hampshire Formation. The thickness of the Price Formation in southern West Virginia, near the town of Caldwell is 286 m (Johnson, 2007).

Maccrady Formation

The Price Formation grades upward into and interfingers with the Maccrady Formation. The Mississippian Maccrady Formation was named by Stose (1913) for the town of Maccrady, Virginia. The Maccrady Formation consists of typically bright red mudstones and sandstones of nonmarine origin. The Maccrady might contain beds of gypsum, anhydrite, and salt. The thickness of the Maccrady Formation in the study area ranges from 8-107 m. The Maccrady Formation has been interpreted as being deposited in a shallow, arid marine basin that was actively subsiding on its eastern margin (McDowell and Schultz, 1989).

Greenbrier Limestone

Although its first use is unclear, the name is derived from the Greenbrier River in nearby Greenbrier and Pocahontas Counties, West Virginia. The unit is generally given a formational rank in Virginia and a group rank in West Virginia (McDowell and Schultz, 1989). The Greenbrier Limestone (Mississippian) is composed of medium to dark-gray, locally fossiliferous limestone with chert clasts or beds. Fossils include crinoid stems. Good exposures of the Greenbrier Formation can be found along WV Route 3 between the town of Union and the first occurrence of the Maccrady Formation near the base of

Middle Mountain. Just east of the town of Union, W.V. along W.V. Route 3, few of the crinoid stems observed reached more than six inches in length. Beds of the Greenbrier Limestone which contain chert nodules can be located near the small town of Keenan, along WV Route 3. The beginning of the Greenbrier Formation was mapped by the first occurrence of limestone outcrops or the presence of sinkholes. The presence of the Greenbrier also coincides with the presence of pasture land within the study area. The Greenbrier represents a shallow water depositional environment, possibly a shallow marine shelf. Thickness of the Greenbrier ranges from 230-550 m.

Mauch Chunk Group

Above the Greenbrier Limestone is the Mississippian Mauch Chunk Formation, named by Lesley (1876) for exposures at the town of Mauch Chunk, Pennsylvania. The Mauch Chunk Group consists of the Bluefield Group (argillaceous and fossiliferous limestone and calcareous shale), Hinton Group (red, green, and gray arenaceous shale and calcareous siltstone with few beds of fossiliferous limestone and coal), Princeton Sandstone (light to medium-gray resistant sandstone or conglomerate), and the Bluestone Group (red to gray shale with lesser amounts of sandstone and siltstone and a few thin coal beds).

Exposures of the Mauch Chunk within the study area are limited to the western side of Zenith Road, near the town of Rock Cave, W.V. The Mauch Chunk Group is primarily a sequence of red and variegated shale or mudstone and sandstone and siltstone to a lesser degree. An occasional thin marine limestone with fossils can be found. The total thickness for the Mauch Chunk Group ranges from 540-1050 m.

Sequences

By the end of the Cambrian (Knox Group), a shallow sea covered essentially all of present-day West Virginia. During this time as well as most of the Ordovician Period, marine deposition was prevalent. Then, near the end of the Ordovician, the Taconic Orogeny formed a high mountainous area to the east of present day West Virginia. This mountainous area was the main source of sediments for the succeeding Silurian Period and the Early Devonian Period. Both clastics and carbonates were deposited in a mixed marine and nonmarine environment. Then, during the conclusion of the Devonian Period, the Acadian Orogeny resulted in a further source for clastic marine deposits. However, near the end of the Devonian, the sea was retreating westward and the continental redbeds of the Hampshire Formation were deposited. The Greenbrier Formation is the last marine deposit of significance in West Virginia (WVGES, 2006).

The stratigraphy of the study area can be grouped into two sequences, each consisting of a regression and a transgression. The first sequence can be located between the unconformity, between the Upper Cambrian and Lower Ordovician Knox Group and the Middle Ordovician Limestones, and the Devonian Chemung. Within this first sequence, there is a regression from the Middle Ordovician Limestones to the Silurian Tuscarora Sandstone. The Silurian Rose Hill Formation represents the first occurrence of the transgression, which continues until the Devonian Chemung Formation. The second sequence includes a regression during the deposition of the Mississippian Price and Maccrady Formations and then a transgression beginning with the Mississippian Greenbrier Formation.

Chapter 4: Structural Setting

Thrust sheets were driven westward over underlying Precambrian basement rocks during the Alleghenian Orogeny. The Alleghenian Orogeny represents the most recent of mountain building events in the study area (Kulander and Dean, 1986). Two major phases of deformation affected the Alleghenian foreland during this time. Within the study area, the major folds and faults were formed during the late phase of the Alleghenian Orogeny, which occurred during the Late Pennsylvanian and Early Permian (Shumaker, 1996).

The Allegheny structural front separates the more intensely deformed Paleozoic sedimentary strata of the Valley and Ridge structural province to the south from the much less deformed Paleozoic strata in the Appalachian Plateau structural province to the north. In the Valley and Ridge province, large scale decollements control the major structures, while smaller amplitude structures can be found in the Appalachian Plateau (Kulander and Dean, 1986; Kulander, 1987). Within the Central Appalachians, crustal shortening in the fold and thrust belt has been estimated to be between 24% and 38% depending upon the location examined (Kulander and Dean, 1986). The magnitude of Alleghenian folding and faulting decreases from east to west across the fold and thrust belt and Appalachian Plateau.

At the Allegheny structural front, the Mississippian Mauch Chunk Formation to the Devonian Beekmantown Formation is folded into a major recumbent syncline (known as the Hurricane Ridge syncline) and is cut by the St. Clair thrust fault. It was originally thought that the Hurricane Ridge syncline was synonymous with the Glen Lyn syncline (Figure 2). However, it has recently been shown by McDowell and Schultz that the

Hurricane Ridge syncline is actually a separate structure of different form, trend, and tectonic significance by R. McDowell (McDowell and Schultz, 1989). The Glen Lyn syncline is just northwest of and parallel to the St. Clair fault, where the southeastern limb is vertical to overturned, dips as low as 30° SE, and the northwestern limb is flat to gently dipping.

The foreland fold and thrust belt of the Southern Appalachian Valley and Ridge Province is characterized by a series of linear to slightly arcuate, areally extensive interleaved thrust slices that truncate regional scale anticlines and synclines (Stanley, 1983). Several thrust sheets occur within or near the study area. These include the St. Clair-Narrows sheet, the Saltville sheet, and the Pulaski sheet. It has been estimated by Stanley (1983) that there has been 4000 m of thrusting along the St. Clair fault. The St. Clair Fault represents a specific type of faulting and folding; known as fault-propagation folding, or thrust tip-line folding. Seismic data from the Southern Appalachians confirms the existence of a regional decollement beneath the Valley and Ridge Province and possibly beneath the Blue Ridge and Piedmont Provinces (Woodward, 1985). Structures in this part of the Appalachians appear to be affected primarily by Alleghenian thin-skinned tectonics above decollement horizons (Dean, Kulander, and Williams, 1979).

Stanley (1983) describes two distinct types of footwall structures. The first is an areally extensive overturned block of strata bounded by faults and the second type is subthrust synclines. The Hurricane Ridge and Glen Lyn Synclines both represent subthrust synclines. Subthrust synclines, such as the Glen Lyn Syncline, present interesting geometric and kinematic problems.

Difficulties from subthrust synclines arise in attempting to model cross-sectional geometries that account for the transition from an overturned syncline at the surface to a hypothesized subhorizontal base of deformation in the subsurface (Stanley, 1983). To explain subthrust synclines, three kinematic models were examined: fault-propagation folding, trishear deformation, and faulted detachment folds.

Fault-propagation Folding

The transfer of fault related shortening to fold related shortening was first described by Dahlstrom (1969) for the Turner Valley anticline from the foothills of the Canadian Rockies (Mitra, 1992 and Dahlstrom, 1969). The term fault-propagation fold refers to a fault related fold, in which a thrust fault loses slip and terminates up-section by transferring its shortening to a fold developing at its tip (Figure 11) (Mitra, 1992). Suppe (1985) defines fault-propagation folds as folds that represent deformation that takes place just in front of the propagating fault surface (Erslev, 1991). Another way to describe a fault-propagation fold is as a fold that has been generated by the folding strains at the tip of the ramp section of the fault where the thrust displacement reaches zero. Here a distinctly asymmetric fold with a steep to overturned fore-limb is formed (McClay, 1998). The term fault-propagation folding is used to explain the common association of asymmetrical folds with one steep or overturned limb adjacent to thrust faults (Suppe and Medwedeff, 1990).

Fault-propagation folding is characterized by steep to overturned forelimbs and faulted out synclines in the footwall of the propagating thrust fault (Figure 11). Figure 11 represents the evolution of a fault-propagation fold. It is important to notice that as the fault-propagation fold evolves, and the beds begin to overturn, there is significant

thinning of the strata. It is also important to note that there is no development of a footwall syncline in the model of a fault-propagation fold. This lack of a footwall syncline makes the trishear model much more attractive.

Fault-propagation folds are common at leading edges of thrust faults (McClay, 1998). The subsurface position of the ramp structure can be predicted by projecting the axial surface of the leading synclinal fold down section to the tip line of the fault. Previous models of fault propagation folding used kink-band geometries to approximate folding in front of propagating thrusts. However, kink-band kinematics cannot replicate the curved fold surfaces and complex strain patterns in fault-propagation folds (Erslev, 1991).

Figure 10: Diagram showing trishear kinematics, the trishear zone is indicated by red lines. (Modified from Allmendinger, 1998 and Allmendinger et al., 2004)

Figure 11: The evolution of a fault-propagation fold modified from Mitra (1992). Note that there is no development of a footwall syncline. Also, the strata are thinned as they are overturned.

Trishear Deformation

Fault-propagation folds often display footwall synclines as well as changes in stratigraphic thickness and dip on their forelimbs. Previous models of fault-propagation folding used kink-fold geometries to approximate this folding in front of propagating thrusts. However, kink-fold kinematics cannot replicate the curved fold surfaces and complex strain patterns in natural and experimental fault-propagation folds (Erslev, 1991). The zone of folding within fault-propagation folds has been found to be triangular in cross section. The triangular geometry of the zone of deformation suggests that trishear deformation, formerly known as “forced folds,” may provide an alternative model for fault-propagation folding (Erslev, 1991 and Allmendinger et al., 2004).

The trishear model predicts the progressive tightening of the fold and steepening of the forelimb with time. It also suggests a steeper frontlimb in lower stratigraphic units (Mitra, 2002). Early attempts to model cases where thickness and dip change were made by geometric or kinematic exercises. However in 1991 Erslev proposed two strikingly different, kinematically explicit models for fault-propagation folds called the “trishear” model, in which many geometries can be reproduced (Allmendinger, 1998). Trishear assumes a ductile rheology within the triangular shear zone (Erslev, 1991). Erslev’s two types of trishear deformation were termed homogeneous and heterogeneous (Figure 12). Homogeneous trishear uniformly rotates the tie line throughout deformation, forming a single inclined tie line. Increased deformation in the shear zone center can be approximated by heterogeneous trishear. With heterogeneous trishear, the segments of tie lines in the center of the triangular zone rotate more than those near the triangle boundaries (Johnson, 2002). Heterogeneous trishear can be modeled by subdividing each

increment of trishear into a series of trishear stages with progressively narrowing apex angles (Erslev, 1991). Notice that in Figure 12, footwall synclines form for thrust faults and reverse fault in both the homogeneous and heterogeneous trishear models. However, the footwall syncline is much more pronounced under the heterogeneous trishear model.

Trishear deformation resembles both the geometry and the finite strain field of fault-propagation folds in thick and thin skinned provinces (Cardozo et al., 2003; Erslev, 1991; Allmendinger, 1998). Also, trishear is a powerful tool that can be used to construct balanced cross-sections of fault-propagation folds, to predict the distribution and orientation of fractures in the folds, and to estimate the nucleation point of underlying blind thrusts (Cardozo et al., 2003; Erslev, 1991; Hardy and Ford, 1997; Allmendinger, 1998).

Then in 1997 Hardy and Ford expanded Erslev's 1991 trishear model, to present a clear mathematical formulation of the problem, having analyzed the effect of variable propagation-to-slip ratio (P/S) and illustrated growth strata geometries that are associated with trishear fault-propagation folds (Allmendinger, 1998). Allmendinger (1998) stated that in the trishear model, a single fault in "basement" expands outward into a triangular zone of disturbed shear (Figure 13). The reason for the triangular shape of the shear zone must ultimately lie in the still largely unexplored mechanics of trishear." It has been shown by Erslev and Rogers (1991) that to conserve cross-sectional area the triangular zone must be symmetric with respect to the fault (Figure 10). At the top of the trishear zone, slip vectors are equal to that of the hanging wall: that is they are parallel and equal in magnitude to the master fault. At the base of the trishear zone, the slip vector varies

Figure 12: Homogeneous and heterogeneous fault propagation folding above (A) thrust, (B) reverse, and (C) normal faults (Erslev, 1991). The blue lines represent the triangle zone boundaries.

Figure 13: Changes in strain as the propagation-to-slip ratio changes. Markers within the beds indicate the orientation of the lines of no finite elongation (LNFE's). Figures created in FaultFold4.5.4 (Allmendinger 1998; Zehnder and Allmendinger, 2000).

linearly in magnitude and orientation from top to bottom (Figure 10) (Allmendinger, 1998).

The strain field within the trishear zone has been found to be heterogeneous and continuous (Figure 13). Because the shear planes are oblique to layering, the folding within the trishear zone involves changes in thickness of the layers. In general, the beds thicken during the early stages of deformation but begin to thin as they steepen and later overturn. Trishear is one of the few fold kinematic models that can predict heterogeneous strain distribution. Shear-fracture orientations appear to be very well predicted by lines of no finite elongation (LNFE's) in trishear models (Allmendinger et al., 2004). Allmendinger (1998) has suggested that lines of no finite elongation can be used as proxies for shear plane orientations.

Also, trishear is able to successfully predict small reverse faults in the hanging walls of normal faults and small normal faults in the footwalls of thrusts. It is possible to predict opening mode fractures (such as joints) by assuming that they should be orientated perpendicularly to the long axis of the finite-strain ellipse (Allmendinger et al., 2004). Therefore, this strain within the trishear zones can be used to predict fracture orientations throughout the structures (Figure 13) (Allmendinger, 1998).

Erslev (1991) notes that trishear deformation suggests several possible trajectories of fault-propagation, where zones of maximum shear and bed thinning extend from the fault tips and may guide fault-propagation trajectories. Trishear in front of thrust faults can cause relatively minor extension in the hanging wall anticline relative to the thickening in the footwall syncline. Thickening of ductile units in synclines has been observed in many thrust belts and in experiments (Erslev, 1991).

Faulted Detachment Folds

A third possible explanation, although less reasonable, of the structure seen in the study area is a faulted detachment fold. Folding prior to thrust-sheet emplacement has been proposed to explain the presence of overturned synclines in the footwalls of many thrust faults within the Appalachian foreland fold and thrust belt of southwest Virginia (Stanley, 1983). Stanley continues to state that “mesoscopic fabric data and strain states indicate rotation of bedding by folding prior to thrust sheet emplacement rather than drag folding during thrusting.”

In contrast, Mitra (2002) states that because faulted detachment folds superficially resemble fault-propagation folds, their geometry can be misinterpreted in areas of poor data quality. Mitra continues to state that characteristic features for distinguishing faulted detachment folds from fault-propagation folds includes fold-fault relationships indicating a transition from folding to faulting, such as footwall synclines and decapitated fold geometries. Fault-tip folds are characterized by blind thrusts, which terminate up section by transferring slip to an asymmetric fold forming at its tip. These structures are recognized as an important structural style in several fold belts, including in the Central Appalachian Valley and Ridge (Mitra, 2002).

Faulted detachment folds form by a transition in deformational behavior from detachment folding to progressive fault-propagation (Figure 14) (Mitra, 2002). Detachment folds form in sedimentary units characterized by significant thickness and competency contrasts (Mitra, 2002). Mitra (2002) proposed that there are two types of faulted detachment folds, which he terms Model 1 and Model 2. Model 1 faulted detachment folds involves three key elements. These elements include: a relatively thin

incompetent unit at the base, which deforms by ductile flow, overlain by a thick sequence of competent units, which deform by flexural-slip folding, accompanied by fracturing and faulting, and a thin layer of moderately competent units, which undergoes some deformation. Model 2 assumes a mechanical stratigraphy consisting of three key elements. These three elements include (from bottom to top); a thick incompetent basal unit that undergoes significant heterogeneous deformation, a moderately competent unit with a high flexural-slip, and an upper, moderately thick, incompetent unit that undergoes some amount of deformation within deformation zones.

Wiltschko and Chapple (1977) proposed for the Appalachian Plateau that within asymmetric faulted detachment folds all units sink below their regional levels within the synclines and rise within the anticlines. The extent of the synclinal downwarping depends on the ductility of the basal unit. A moderately competent basal unit generally results in less synclinal deflection, where as an incompetent basal unit results in more significant deflection (Mitra, 2002). Minor regional downwarping within the syncline has been observed with the study area, as the detachment is located within a more competent unit.

Figure 14: Diagram showing the evolution of a detachment fold. (a) Shows the initial step of detachment folding, where no faulting has occurred. (b) Shows second step of detachment folding, where after folding has begun, the fault then propagates through the strata (Modified from Kattenhorn, 1994).

Table 1: Comparison of Fault-Related Fold Styles (From Giffels, 2002)

Fold Model	Geometric Characteristics	Rheological Characteristics	Strain Distribution
Fault-Propagation Fold	<p>Limb thicknesses can be different in forelimb and back limb</p> <p>Angular fold shape</p> <p>Footwall strata are not folded</p> <p>A fault ramp is located in front of the forelimb, or underneath the fold core</p> <p>Interlimb angles usually range from medium(60-120 degrees) to small (<60 degrees)</p>	<p>Small mechanical strength difference between units involved</p>	<p>Moderate deformation of units in forelimb</p> <p>Strain axes orientations are the same at the top of the forelimb and at the bottom of forelimb</p> <p>Strain is the result of flexural slip</p>
Trishear	<p>Limb thicknesses are different in forelimb and back limb</p> <p>Rounded to angular fold shape</p> <p>Footwall strata may be folded</p> <p>Forelimb thickness changes with depth</p> <p>A fault ramp is located in front of the forelimb, or underneath the fold core</p>	<p>Small mechanical strength difference between units involved</p>	<p>Moderate deformation of units in forelimb</p> <p>Strain axes orientations change from the top to the bottom of forelimb</p> <p>Strain is the result of penetrative trishear</p>
Detachment Fold	<p>Limb thicknesses are the same in forelimb and backlimb</p> <p>The underlying detachment is flat</p> <p>Interlimb angles can range from small (<60 degrees) to large (>120 degrees)</p> <p>Fold wavelength is determined by thickness of the mechanically most competent unit</p>	<p>Decollement is contained in a relatively ductile unit that is overlain by a mechanically stronger unit</p>	<p>Disharmonic folding and thickening in anticline core with more parallel bedding preserved toward outside of the fold</p>

Chapter 5: Previous Work

A previous geologic map was completed in 1926 by Reger et al. which encompassed Monroe County, WV. This geologic map provided useful insight to the geology of the study area. In their map, they provide three cross-sections, two of which are on either side of the study area. This map was used as a base for the field mapping, helping fill in areas of poor exposure and areas that were not accessible.

Several studies have been conducted on the St. Clair thrust fault. In 1982, Thomas K. Gustafson wrote a paper titled, “Geology and Structural Analysis between the Narrows and St. Clair thrust faults in the Narrows Quadrangle, Giles County, Virginia.” In his paper, Gustafson states that the structures associated with the hanging wall of the St. Clair fault involve the Upper Cambrian Knox Dolomite [Beekmantown] through the Lower Mississippian Sandstones of the Price Formation. He indicates that the footwall of the St. Clair fault ranges from the Upper Ordovician Juniata Formation to the Lower Pennsylvanian Lee Formation within the Hurricane Ridge syncline. Gustafson also notes that the St. Clair can be easily delineated by the easily distinguishable lower section of the Knox Group on the hanging wall and the deformed shale and siltstone of the Devonian Chemung Formation on the footwall.

Another paper that involves the St. Clair fault was written by Andrew Leigh Mehlhop in 1996 titled, “Extensional Structures along the Allegheny Front in Virginia and West Virginia near the Giles County seismic zone.” Mehlhops’ study focused on the structures that are exposed in the footwall of the St. Clair thrust fault. In his paper Mehlhop provides several useful figures, including a schematic block diagram that illustrates the major structures in his study area, a generalized stratigraphic column,

detailed lithologic descriptions, and a cross-section of his study area. Although the St. Clair fault is not an extensional structure, the figures presented by Mehlhop (1996) are helpful in understanding the stratigraphy and structure within the study area. Mehlhop (1996) is more concerned with the Lindside Fault Zone than he is with the St. Clair fault. The structures of the Lindside Fault Zone are important to this study as these structures relate to the strain that is present in the footwall. These footwall structures are the same structures that are trying to be explained by using trishear deformation.

Kulander and Dean (1988) examined a series of thrust faults just south of the map area, namely the North Mountain-Pulaski fault system. They note the Blue Ridge and Great Valley of western Virginia are part of a detached master thrust sheet that extends through the central-southern Appalachian change of trend and has a root zone situated east of the Blue Ridge under the Piedmont (Figure 9). They have suggested that, just like the St. Clair thrust in the map area, displacement on the Pulaski fault increases from northeast to southwest (or as stated earlier, decrease from southwest to northeast) (Kulander and Dean, 1988). One significant problem with the work of Kulander and Dean is that the series of cross sections they created were not balanced before being analyzed. The transition from the central Appalachian structural grain of N30E to the southern Appalachian structural trend of N60E occurs within the V-shaped Roanoke Recess north of Roanoke, V.A. It is at this location where thrusts such as the Saltville and St. Clair faults that characterize the structural style of the southern Appalachians terminate, and sedimentary rock cover shortening is increasingly accommodated by folding in the central Appalachians (Kulander and Dean, 1988). The evidence of this

occurring is the presence of increased fold frequency and widening of the fold belt to the northeast (Kulander and Dean, 1988).

Spraggins and Dunne (2002) indicate that within the Appalachians, emergent thrusts give way to map-scale folds above blind duplexes. Within the study area, it has been observed that the Narrows thrust fault transferred its strain from faulting to folding, creating the Fork Mountain Anticline. Within their article, the authors provide a regional map showing the locations of the central and southern Appalachians, the St. Clair thrust fault, and the Wills Mountain Anticline (Figure 15). Three sequential cross-sections are also provided, each giving insight to the nature of the St. Clair thrust fault. The authors state that the Appalachian Plateau in the recess was an area of active blind thrusting during the late Paleozoic formation of the Appalachian portion of the Alleghenian thrust belt (Figure 16c). They provide two possible explanations for the St. Clair thrust fault.

The first is that displacement from the southern Appalachian portion of the Alleghenian thrust belt was not substantially transferred into the Appalachian Plateau. Therefore, up to 20 km of thrust displacement for the southern Appalachian St. Clair thrust sheet emerges through the surface trace of the St. Clair thrust in front of the plateau (Figure 16a) (Spraggins and Dunne, 2002). A second hypothesis provided by Spraggins and Dunne (2002) is that the St. Clair thrust is only an imbricate fault of a blind thrust flat, which continues into the Appalachian Plateau (Figure 16b). Finally, they state that the St. Clair thrust fault terminates in a regional anticline at the junction of the southern and central Appalachians (Figure 16c). Couzens and Dunne (1994) suggest that this termination is the result of displacement transfer to a blind thrust instead of simply a displacement decrease to zero for an emergent thrust (Spraggins and Dunne, 2002).

Their conclusion is that the existence of a blind fault supports an interpretation that the St. Clair thrust sheet and the Wills Mountain duplex are a continuous structure (Spraggins and Dunne, 2002).

Figure 15: (a) Map showing the locations of the Central and Southern Appalachians, St. Clair thrust, Wills Mountain Anticline, and other structural elements. Letters a, b, and c represent locations of sequential cross sections (shown in Figure 16). (b) Map showing close-up of study area. (Spraggins and Dunne, 2002)

Figure 16: Sequential cross sections along the St. Clair thrust fault. Locations of cross sections indicated in Figure 15. It is important to note that in (a) and (b) the St. Clair thrust fault breaches the present-day surface. In cross section (c), the St. Clair thrust fault does not reach the surface. Faulting has been transferred to folding. SCT-St. Clair thrust, WMA – Wills Mountain Anticline. (Spraggins and Dunne, 2002).

Chapter 6: Surface Research

Background Information

The St. Clair fault has been geologically mapped at a scale of 1:24,000 as per EDMAP requirements in Monroe County, West Virginia (at total area of 12 x 16 km, Figure 2). The mapping has encompassed most of the Gap Mills Quadrangle and small portions of the Union, Waiteville and Interior Quadrangles. The geological map was then transferred into a shapefile for use in GIS applications. This was done using the ArcGIS software package. As noted before, this strain information has been used to estimate the fracture density along the fault and to potentially be used to predict possible targets for natural gas production. The strain distribution along the fault has been estimated by utilizing Allmendinger's Fault/Fold software package, which provides strain ellipses for strata within the triangular zone of a fault.

As noted above, Midland Valley, Inc.'s 2D move software has been used to analyze the data. To use 2D move, the user first imports his/her data, then through model conditioning and jigsaw restoration, can utilize kinematic restoration and analysis to create a final structural model. The final structural model can then be subjected to forward modeling and analysis, which includes fracture prediction, kinematic analysis, and volume analysis, to create a present day structural architecture (Figure 17).

Figure 17: Flow chart for the kinematic modeling software, 2D Move (From 2DMove manual).

Surficial Mapping and Modeling

Data for this project has been collected solely through surficial observations; no seismic or well data were available for use. In conjunction with these surficial observations, several items have been noted. These include: strike and dip data, UTM locations for data points, formation descriptions (which includes lithologies), and hand samples of the formations that are to be described (Appendix I). Observations were taken and mapped using the Universal Transverse Mercator 1927, Zone 17, North American Datum (NAD 27). The collected data were used to create a geologic map and three subsequent cross-sections. To aid in the field mapping, aerial photographs were used.

The geologic map was initially created on hard copies of the topographic maps by transferring the observed data onto them, which includes locations of each data point and strike and dip data. The geologic map was then traced onto a clear Mylar paper and scanned to create an image file for each quadrangle. These image files were imported into the ESRI ArcGIS software package and georeferenced for future use.

Georeferencing allows data to be viewed, queried, and analyzed with other geographic data. Once the images were imported into the ArcGIS software package, the contacts were converted into an ArcGIS shapefile. This was done using Arc and ArcCatalog. Using ArcCatalog, the images were exported to a coverage. Then Arc was used to build, clean, and describe the coverages. Once the coverages were created, ArcCatalog was once again used to convert the coverage into a single shapefile.

Then using the editor option within ArcGIS, it was possible to make minor adjustments within the shapefile, such as closing small holes and removing any unwanted marks. The contacts were then closed in using a newline, which is a border that is drawn to delineate and define the extent of geographic data on a map. The newline allowed each formation to be designated a specific color. This shapefile was then draped over the 3-meter digital elevation model to provide topography to the map. Also added to the map were folds, faults, major and minor roads, streams, and strike and dip markers. The completed map can be seen in Figure 18.

Figure 18: Completed geologic map of the study area. St. Clair thrust fault and other major folds are labeled. Lines of cross section are shown as A-A' on map. Corresponding cross-sections are shown in Figure 19.

Cross-sections:

To aid in the creation of the sequential cross-sections, the topographic profiles were created using a 3 meter digital elevation model (DEM) and the ArcGIS software suite. This was done by opening the 3-meter DEM of the area and also opening the 3D Analyst extension with ArcMap. Then the correct DEM layer was selected and the interpolate line function was selected. Two endpoints were then located and marked in the DEM. Finally, the histogram button was selected to create the profile. The 3 meter DEM files were obtained from the West Virginia GIS Technical Center. The created topographic profiles were then imported into Adobe Illustrator and were adjusted to be on a 1:1 scale.

Once the sequential cross-sections had been created, it was necessary to check the validity of these cross-sections, that is, checking for geometric acceptability. This has been done through a process known as balancing a cross-section. To obtain a balanced cross-section, one flattens out the deformed beds and returns them to their depositional position. If this restoration can be completed, it is possible to conclude that the cross-section is geometrically feasible (Dahlstrom, 1969). Dahlstrom continues to state that, “It should be emphasized that a cross-section which passes the geometric tests is not necessarily correct, because completely ridiculous cross sections can be drawn which abide the law of conservation of volume. However, if a cross-section passes the geometric tests, it could be correct...and on the other hand a cross-section that does not pass the geometric tests could not possibly be correct” (Dahlstrom, 1969).

It is important to assure that the completed cross-sections are balanced, as the quality of structural cross-sections can be improved by testing them for geometric

validity (Dahlstrom, 1969). Balanced cross-sections provide a powerful constraint in the interpretation of complex structures characterized by poor data quality. Fold and thrust belts are characterized by complex structures, so available surface data is usually poor quality (Mitra, 1992). Balanced cross-sections provide a link between the deformed and undeformed states.

The cross-sections have been analyzed using Midland Valley, Inc.'s 2DMove software. As noted in the 2DMove manual, "2DMove is a structural analysis and modeling program that allows line-length and area balancing of cross-sections." Both structural restorations and forward modeling can be carried out with 2DMove. The 2DMove software is capable of balancing cross-sections, providing strain data (fracture prediction), kinematic analysis, and volume analysis as well as other information. 2DMove also includes kinematic models for trishear deformation and for fault-parallel flow. It is necessary to incorporate both trishear deformation and fault-parallel flow to model the hanging wall and footwall of the St. Clair fault.

In order to recreate the cross-sections, it was necessary to incorporate a step in the fault. In cross-section A-A', the St. Clair thrust fault is located at the base of the Martinsburg Formation (Figure 19a). For the other cross-sections, the St. Clair thrust fault needed to step down into lower stratigraphic units to allow the presence of the Middle Ordovician Limestone in the footwall (Figures 19b and c). Completed sequential cross-sections are located in Figure 19 as well as in a pouch at the back.

(a)

(b)

(c)

0 1000 2000 3000 Feet
0 500 1000 Meters

Figure 19: Sequential cross-sections across the study area. Lines of cross-sections are shown on figure 18.

Chapter 7: Interpretations from Computer Modeling

It has become apparent that the structures that are associated with the St. Clair thrust fault have formed through a combination of processes. Through examination of the observed field data and the modeled cross-sections, it has been possible to rule out the idea that the St. Clair thrust fault formed as a result of a faulted detachment fold. With faulted detachment folding, there is no change in thickness between the forelimb and backlimb. Observations and modeling support the idea that there is a significant thickness change along the overturned footwall syncline. It has been interpreted that the St. Clair thrust fault has formed by a combination of fault-bend folding and trishear deformation. It is important to understand how each parameter affects the overall structure being formed. Therefore, the various parameters were adjusted individually, to find the effects of each parameter. These parameters include the propagation to slip ratio (P:S ratio) of the fault, the trishear apex angle, angular shear, the trishear angle, and the number of trishear zones.

Propagation-to-Slip Ratio

Unlike parallel-kink fault-propagation, which uses a fixed propagation-to-slip ratio based on fault geometry, trishear allows great flexibility in the choice of the propagation-to-slip ratio. With trishear, it is possible to specify any propagation-to-slip ratio for any fault geometry (Allmendinger et al., 2004). The P:S ratio describes how much the fault propagates through the strata as displacement is added. A change in the P:S ratio of just 0.3 produces a change in fold shape that is equivalent to that produced by a 15-20° change in trishear angle (Allmendinger, et al., 2004). The Propagation-to-slip ratio exerts the most important control on the amount of strain in a trishear structure. The

lower the P:S ratio is, the more opportunity the ductile layers will have to deform (Allmendinger et al., 2004).

If a P:S ratio of zero is used the fault does not propagate into the overlying strata as displacement is added. A P:S ratio of 0.5 depicts that the fault is propagating forward half as much as the fault displacement. Likewise, a P:S ratio of 1.0 indicates that the fault is propagating forward as much as the fault displacement. The geometry of the resulting fold changes significantly as the P:S ratio is increased. A small P:S ratio results in an overturned syncline and anticline pair. The footwall syncline in a small P:S ratio fold displays thickening of the strata as they are folded and thinning as they overturn. When a small P:S ratio is used, more deformation occurs on the forelimb. When a larger P:S ratio is used, the thickening of the strata as they fold is still present, but instead of thinning as they overturn, the strata are cut by the propagating fault. Diagrams showing the affects of changing P:S ratios are shown in Figure 20.

It has been found that the difference between a detachment fold, a fault-bend fold and a trishear fault-propagation fold lies within the propagation-to-slip ratio. A propagation-to-slip ratio of zero indicated the development of a detachment fold (Figure 21a). A small propagation-to-slip ratio tends to develop a trishear fault-propagation fold (Figure 21b). Finally, as the propagation-to-slip ratio increases, as shown by Allmendinger et al. (2004), the development of a fault-bend fold occurs (Figure 21c).

Figure 20: Effects of changing propagation to slip ratio, while displacement remains constant. (a) P:S ratio of 0.0, note that the fault does not propagate through the strata. Deformation is entirely by folding (b) P:S ratio of 0.5, the fault begins to propagate upwards through the strata. Strata in the footwall beginning to thicken as they overturn. (c) P:S ratio of 1.0, the fault propagates through most of the layers, creating smaller folds along the fault and increased thickness changes in front of the fault. (d) P:S of 3.0, the fault has now propagated entirely through the strata. Very little folding is present.

(a) $P:S = 0$; Detachment fold

(b) $P:S = 1.5$; Trishear fault-propagation fold

(c) $P:S = 15$; Fault-bend fold

Figure 21: Diagram showing the relationship between the propagation-to-slip ratios to the type of fold that develops. The red lines represent faults; the blue lines represent the triangle zone. (a) Shows a $P:S$ ratio of zero, which leads to the development of a detachment fold. (b) Shows a small $P:S$ ratio, leading to the development of a trishear fault-propagation fold. (c) Shows how a large $P:S$ ratio leads to the development of a fault-bend fold (Allmendinger et al., 2004).

Trishear Angle

Another important factor is the trishear angle. While the entire anticline-syncline pair is getting deformed by flexural-slip-folding, the trishear zone undergoes a different type of strain. Within the triangle zone, the strata experiences inhomogeneous, distributed strain. The trishear angle directly impacts the area that is folded by the propagating fault. If the trishear angle is small, there is a small area in front of the fault that is deformed by distributed strain. On the other hand, if the angle is large, there is a large area in front of the fault that is deformed by distributed strain. Figure 22 illustrates changes in the fold geometry as the trishear angle changes.

Trishear Apex Angle

Changing the trishear apex angle changes the angle at which the fault propagates through the strata. This also greatly affects the fold geometry. A trishear apex angle of small value produces a footwall syncline, which shows little to no overturning. As the trishear apex angle increases, the footwall syncline begins to overturn. Eventually, as the apex angle reaches the vertical, the fault rapidly cuts through the strata, producing some minor folding in the footwall. The majority of the deformation here occurs as faulting. Figure 23 illustrates how changing the trishear apex angle affects the geometry of the fault and fold.

Figure 22: Diagram showing the effects of changing the trishear angle, all other variables remained constant. (a) Has a trishear angle of 10, (b) has a trishear angle of 50, and (c) has a trishear angle of 90. The trishear angle directly impacts the area that is folded by the propagating fault.

Figure 23: Diagram showing the effects of changing trishear apex angle, all other variables remained constant. Trishear Apex Angles are (a) 10, (b) 45, and (c) 65.

Number of Trishear Zones

The number of trishear zones used determines whether the model is deformed using homogeneous or heterogeneous trishear. During modeling, using one trishear zone indicates that the model is undergoing homogeneous trishear (Figure 24). Likewise, using a larger number indicates heterogeneous trishear. It is been found that using a larger number of zones increases the resolution of the model.

Figure 24: Diagram showing the subdivision of a single trishear zone into 5 nested zones (From Midland Valley 2DMove Help Files)

Angular Shear

Finally, changing the angular shear within the strata affects the angle at which the strata are pushed toward the fault. An angular shear of zero represents the strata being pushed evenly from the top to the bottom. Adding a positive angular shear pushes the strata more towards the bottom than the top. On the other hand, adding a negative angular shear pushes the strata more from the top than the bottom. Figure 25 illustrates how inducing angular shear into the model affects the fold geometry. It is reasonable that some combination of the above parameters will be needed to correctly model the footwall syncline.

Figure 25: Diagram showing how a change in angular shear affects the geometry of the fold, all other variable remained constant. (a) Represents an angular shear of -45. Notice how the beds have been pushed more from the top than the bottom. (b) Represents an angular shear of 45. Here the beds have been pushed more from the bottom than the top.

Footwall:

To model the footwall of the St. Clair fault, the trishear algorithm within 2DMove was used. It was necessary to begin with a hand-drawn cross section based on observed field data (Figure 26a). Then the fault geometry was digitized and horizontal strata were drawn at the correct thicknesses (Figure 26b). Then the strata that are cut by the fault were split, making it possible to model the hanging wall and footwall separately (Figure 26c).

As noted previously, trishear deformation has been found to be responsible for the overturned footwall syncline, the Glen Lyn Syncline, of the St. Clair thrust fault.

Trishear deformation has allowed for the changing of thicknesses as well as the rounded to angular fold shape. Several possibilities of combinations of parameters have led to similar final models, such as changing the apex angle, the number of trishear zones, and the trishear angle. As the ancestral St. Clair thrust fault began to propagate through the strata, the triangular zone in front of the fault tip began to deform the footwall strata. It has been determined through kinematic modeling that as the fault propagated through the strata, the trishear angle and the apex angle changed with time. Also, a small propagation- to-slip ratio was needed to produce the overturned syncline, as the fault did not reach the present day surface via trishear deformation.

(a)

(b)

(c)

Figure 26: Beginning steps of kinematic modeling with 2DMove. (a) Is a hand-drawn cross section based on observed field data. (b) Represents 2nd step in modeling. Horizontal layers are drawn at the correct thicknesses and the interpreted fault position is traced. (c) Is the final model to be used in 2DMove. Notice that all layers are horizontal.

This combination of parameters created an overturned syncline with an angular fold (Figure 28a). A model of this type was necessary to deform horizontal layers into the correct geometry needed to reproduce the observed data. It has been found that for cross-section A-A', approximately 2000 meters of displacement was needed. It is believed that after the footwall was deformed, the strata were then slightly tilted in a southerly direction.

Other models were created, each differing slightly, but resulting in the same general geometry. These models each created an overturned syncline with a very angular fold. It is believed that in these models, splay faults near the beginning of the fault ramp were formed to accommodate folding and the stratigraphic changes in thickness. The stratigraphic thickness changes found with the kinematic modeling match very well with the observed field data.

The amount of deformation found in cross-section A-A' is not indicative of the total amount of deformation that occurred, as there is no evidence of a fold in the hanging wall. Therefore, the final 2 cross-sections were modeled using the same technique. These models provide a more precise value of deformation, as folding is evident in the hanging wall. As noted before, a step was incorporated into these final two models to allow for the older strata to appear in the footwall. For the second cross-section, B-B', a displacement value for the footwall ranged from 3300-3500 meters (Figure 27a). For the final cross-section, the displacement slightly decreased to a value of 2700-3150 meters (Figure 27b).

Hanging Wall:

As the mode of deformation shifted from trishear towards fault-bend folding, the St. Clair thrust fault propagated through the remaining strata, due to an increase in the propagation-to-slip ratio. To model the hanging wall, the *fault-parallel flow* model in the 2D Move software package was used. The propagation of the fault through the strata allowed the hanging wall to be continually thrust along the fault, without affecting the footwall. For the hanging wall, in cross-section A-A', to have been thrust upon the footwall and to have placed the strata to its present day position, a minimum of 850 meters of displacement was needed (Figure 28b). As noted before, due to the lack of evidence of an anticline in the hanging wall, this value is the minimum amount of displacement that occurred. The values found for the two remaining cross-sections provide a more accurate displacement value, as an anticline is apparent in the hanging wall. A displacement value of 3200-4000 meters was found for cross-section B-B' and a value of 4000-5000 meters was found for cross-section C-C'.

There are several uncertainties within the hanging wall of the St. Clair thrust fault. These uncertainties arise from folding and faulting just south of the map area. It is believed that the Narrows thrust fault terminates just west of the study area, where faulting is transferred to folding. The exact location of the termination of the Narrows thrust fault is unknown, as it is either not exposed at the surface in the study area or it terminated prior to entering the study area. Previous models (Woodward, 1985) have suggested that the Narrows thrust fault transfers its deformation to folding just below the present day surface. Others have suggested that the Narrows thrust fault reaches the present day surface.

Another uncertainty within the hanging wall is the geometry of the first ramp of the St. Clair thrust fault. It has been found that a ramp with a low angle is capable of reproducing the observed hanging wall geometry. Other possibilities include the presence of a duplex along the ramp, which could create a repetition of older strata, (Woodward, 1985) or a steeper ramp angle. The overturned anticline that was produced by the fault parallel flow in the hanging wall is not present in the study area. This is due to the extent of erosion the overturned anticline was subjected to. In the models produced, the final position of the overturned anticline was located above the present day topography, suggesting that it has been eroded away (Figure 28c).

Figure 27: Cross-section B-B' and C-C' showing the step in the St. Clair thrust fault and the recreation of the footwall geometry. (a) Represents cross-section B-B' and (b) represents cross-section C-C'.

Figure 28: Diagram showing the evolution of the modeled cross-section A-A'. (a) Shows 1st step in modeling, here the footwall has been recreated. (b) Shows the break-through of the fault and the continued thrusting of the hanging wall. (c) Shows the final stage in modeling, with present-day topography shown.

Chapter 8: Conclusions and Further Studies

1. The St. Clair thrust fault trends in a southwest to northeast direction through the map area, terminating just east of the West Virginia-Virginia border, in Allegheny County, Virginia. The hanging wall within the study area is comprised of the Late Cambrian-Early Ordovician Knox Group through the Devonian Marcellus Series. The footwall of the St. Clair thrust is comprised of the Middle Ordovician Limestone to the Middle Mississippian Greenbrier Limestone and the Late Mississippian Mauch Chunk Group. The St. Clair thrust fault terminates within the core of the Wills Mountain Anticline (Spraggins and Dunne, 2002).
2. The St. Clair thrust fault formed as a combination of trishear deformation and fault-bend folding. The overturned footwall syncline was formed by trishear deformation as the fault slowly propagated through the strata. The hanging wall was then thrust upon the footwall as the propagation-to-slip ratio increased and the mode of deformation switched from trishear to fault-bend folding and the fault broke through to the surface.
3. By recreating the sequential cross-sections, it was possible to determine the amount of displacement needed for each cross-section. Cross-section A-A' was modeled and a displacement value of approximately 2300 meters was needed. This value is of less

significance as it represents the minimum amount of displacement needed as there is no evidence of an anticline in the hanging wall.

4. Two additional cross-sections were modeled, each that show evidence of an anticline in the hanging wall. The values of deformation in these cross-sections are more representative of the actual amount of displacement needed. Cross-section B-B' had a total displacement value of approximately 7500 meters and C-C' had a value of approximately 6700 meters.
5. Cross-sections B-B' and C-C' show evidence that the displacement value is decreasing to the northeast. A decrease in displacement of 800 meters was found, or 10.66 percent.
6. Using R.W. Allmendinger's trishear modeling program, Fault/Fold, it has been possible to estimate the strain within the trishear triangle zone (Allmendinger, 1998; and Zehnder and Allmendinger, 2000). Through kinematic modeling it has been determined that during the initial trishear deformation, the St. Clair thrust had a small propagation-to-slip ratio before the mode of deformation shifted to fault-bend folding. This small P:S ratio suggests that the strata in the footwall underwent more strain than if the P:S ratio was larger.
7. Areas where intense trishear deformation has occurred, and hence have undergone significant strain, could be possible areas of intense fracturing. These areas of intense

fracturing are possible targets for natural gas production. One possible location within the study area is in the overturned footwall of the St. Clair thrust fault and between the Glen Lyn and Hurricane Ridge Synclines, where the Marcellus Series is present.

Possibilities for additional research include:

1. The acquisition of seismic reflection data to aid in the interpretation of the overturned footwall syncline and to better constrain the thicknesses of the strata. In addition, this would allow for a more precise location of the St. Clair thrust fault itself and a better understanding of the fault geometry.
2. Additional studies to the south would indicate the effect of other geologic structures. Areas of interest could be: what are the effects of the Narrows thrust fault, the Saltville thrust fault, or any of the other structures on the geometry of the St. Clair thrust fault.

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Appendix I: Field observations

Formation_	UTM_Zone	UTM_Easting	UTM_Northing	Lithology	Fossils/Other	Strike	Dip	Direction	Strike_Cor	Date_Recorded	Stop
Chemung	17	551130	4158665	Sandstone	None	88	50	SE	268	9/16/2006	1
Chemung	17	551078	4158903	Sandstone	Brachiopods	154	13	NE	334	9/16/2006	2
Greenbrier	17	549474	4159374	Limestone	None	0	0		0	9/16/2006	3
McCrary	17	557480	4163273	Shale	None	34	89	SE	214	9/16/2006	4
Price	17	557484	4163008	Siltstone/SS	None	90	56	SE	270	9/16/2006	5
Price	17	557531	4162945	Cong/SS	None	68	90	SE	248	9/16/2006	6
Price	17	557657	4162425	SS	None	80	66	SE	260	9/16/2006	7
Juniata	17	551986	4157237	Siltstone/SS	None	70	50	SE	70	9/16/2006	8
Tuscarora	17	551973	4157211	Cong/SS	None	48	52	SE	48	9/16/2006	9
Tuscarora Float	17	555211	4155682	Cong. Boulder	None	0	0		0	9/16/2006	10
Tuscarora Float	17	556460	4155636	Cong/SS boulder	None	0	0		0	9/16/2006	11
Rose Hill	17	557229	4155484			0	0		0	9/16/2006	0
Rose Hill	17	557226	4155229	White Shale	None	0	0		0	9/16/2006	12
Rose Hill	17	556583	4154680	Red SS/MS/Sh	Ostracods	0	0		0	9/16/2006	13
Oriskany	17	556765	4154503	SS w/ Hematite	None	70	26	SE	70	9/16/2006	14
Oriskany	17	557160	4154809	SS		70	42	SE	70	9/16/2006	15
Brallier	17	550266	4149643	Siltstone/Shale		60	54	SE	60	9/16/2006	17
Marcellus	17	541407	4150695			80	28	SE	80	9/16/2006	18
Greenbrier	17	538397	4151511	Limestone		68	52	SE	68	9/16/2006	19
Mauch Chunk	17	538803	4152623	Black Shale		70	16	SE	70	9/16/2006	20
Greenbrier	17	540639	4154347	Limestone		58	75	SE	58	9/16/2006	21
Greenbrier	17	540745	4154204	Limestone		70	8	SE	70	9/16/2006	22
Greenbrier	17	540927	4158029	Limestone	Burrows	136	12	SW	136	9/16/2006	23
Greenbrier	17	541123	4160312	Limestone	Crinoids	49	12	NW	229	9/17/2006	24
Greenbrier	17	544897	4159543	Limestone	Chert Nodules	46	8	SE	226	9/18/2006	25
Greenbrier	17	544837	4157852	Limestone		30	6	W	210	9/19/2006	26
Chemung	17	547358	4156094	Sandstone	Iron Staining	72	68	S	72	9/20/2006	28
Tuscarora Float	17	547699	4156041	SS		0	0		0	9/21/2006	29
Tuscarora Float	17	547508	4155912	SS		0	0		0	9/22/2006	30
Greenbrier	17	542796	4156538	Limestone		130	10	NE	310	9/23/2006	32
Greenbrier	17	548543	4159739	Limestone		220	18	NW	220	3/25/2007	40
Price	17	548905	4162736	SS		220	20	NW	220	3/25/2007	41
Maccrady	17	548762	4162756	Mudstone		0	0		0	3/25/2007	42
Maccrady	17	548544	4162723	SS		20	20	SE	20	3/25/2007	43
Greenbrier	17	547398	4162247	Limestone		0	0		0	3/25/2007	44
Maccrady	17	546397	4156320	Mudstone		0	0		0	3/25/2007	45

Appendix I: Field observations, continued

Formation_	UTM_Zone	UTM_Easting	UTM_Northing	Lithology	Fossils/Other	Strike	Dip	Direction	Strike_Cor	Date_Recorded	Stop
Greenbrier	17	545944	4156742	Limestone		350	90		0	3/25/2007	46
Greenbrier	17	542780	4156536	Limestone		220	10 NW		220	3/25/2007	47
Greenbrier	17	543418	4155405	Limestone		54	74 S		74	3/25/2007	48
Maccrady	17	544035	4154367	SS		0	0		0	3/25/2007	49
Price	17	543763	4153614	SS		50	32 SE		32	3/25/2007	50
Price	17	543797	4153590	Shale		50	30 SE		30	3/25/2007	51
Price	17	543801	4153591	SS		50	32 S		32	3/25/2007	52
Price	17	543828	4153532	SS		0	0		0	3/25/2007	53
Price	17	543855	4153517	SS		80	50 S		50	3/25/2007	54
Hampshire	17	543869	4153502	SS		0	0		0	3/25/2007	55
Chemung	17	543985	4153360	SS		56	12 SE		12	3/25/2007	56
Chemung	17	544250	4153227	SS	Brachiopods	60	34 S		34	3/25/2007	57
Brallier	17	544506	4152914	Siltstone		52	30 S		30	3/25/2007	58
Marcellus	17	544586	4152894	Shale		0	0		0	3/25/2007	59
Marcellus	17	545331	4152415	Siltstone		0	0		0	3/25/2007	60
Tuscarora	17	545826	4152251	SS		0	0		0	3/26/2007	61
Beekmantown	17	545902	4152605	Limestone		0	0		0	3/26/2007	62
Rose Hill	17	545761	4152255	SS		0	0		0	3/26/2007	63
Rose Hill	17	545750	4152258	SS		0	0		0	3/26/2007	64
Rose Hill	17	545735	4152264	Mudstone		200	90		200	3/26/2007	65
Rose Hill	17	545737	4152268	Mudstone		0	0		0	3/26/2007	66
Rose Hill	17	545635	4152408	SS		220	70 SE		220	3/26/2007	67
Rose Hill	17	545628	4152446	Siltstone		0	0		0	3/26/2007	68
Keefer	17	545596	4152501	SS		0	0		0	3/26/2007	69
Keefer	17	545531	4152477	Mudstone		0	0		0	3/26/2007	70
Rose Hill	17	545474	4152444	Mudstone		0	0		0	3/26/2007	71
Keefer	17	545331	4152419	Siltstone		0	0		0	3/26/2007	72
Marcellus	17	545199	4152435	Siltstone		220	50 SE		220	3/26/2007	73
Marcellus	17	545141	4152443	Siltstone		72	46 SE		252	3/26/2007	74
Keefer	17	545001	4152458	SS		89	30 SE		89	3/26/2007	75
Mauch Chunk	17	540304	4153965			0	0		0	3/26/2007	76
Price	17	539153	4152653	SS		80	20 SE		260	3/26/2007	77
Mauch Chunk	17	538808	4152634	Mudstone		0	0		0	3/26/2007	78
Mauch Chunk	17	538410	4151751	SS		68	20 S		248	3/26/2007	79
Greenbrier	17	538402	4151724	Limestone		72	40 SE		0	3/26/2007	80
Greenbrier	17	538404	4151683	Shale		0	0		0	3/26/2007	81

Appendix I: Field observations, continued

Formation_	UTM_Zone	UTM_Easting	UTM_Northing	Lithology	Fossils/Other	Strike	Dip	Direction	Strike_Cor	Date_Recorded	Stop
Greenbrier	17	538411	4151668	Limestone	Crinoids	0	0		0	3/26/2007	82
Greenbrier	17	538390	4151516	Limestone		64	48 S		0	3/26/2007	83
Greenbrier	17	538375	4151496	Limestone		68	54 S		0	3/26/2007	84
Price	17	540586	4150471	SS		26	40 SE		0	3/26/2007	85
Tuscarora	17	550384	4151514	SS		40	38 SW		0	3/26/2007	86
Rose Hill	17	550563	4151596	SS		72	42 N		0	3/26/2007	87
Rose Hill	17	551836	4152335	SS		72	48 N		0	3/26/2007	88
Tuscarora	17	552393	4152579	SS		0	0		0	3/26/2007	89
Tuscarora	17	549528	4151255	SS		84	70 S		0	3/26/2007	90
Tuscarora	17	548797	4150902	SS		78	50 S		0	3/26/2007	91
Tuscarora	17	548610	4150898	SS		88	48 S		0	3/26/2007	92
Tuscarora	17	548309	4150752	SS		86	32 S		0	3/26/2007	0
Rose Hill	17	549467	4150866	SS		74	22 S		74	6/16/2007	93
Oriskany	17	550253	4151064	SS		0	0		0	6/16/2007	94
Oriskany	17	550142	4150913	SS		79	30 S		79	6/16/2007	95
Oriskany	17	550108	4150862	SS	Burrows	74	26 S		74	6/16/2007	96
Oriskany	17	550063	4150835	SS		82	22 S		82	6/16/2007	97
Oriskany	17	550030	4150861	SS		70	29 S		70	6/16/2007	98
Oriskany	17	549748	4150497	SS		0	0		0	6/16/2007	99
Marcellus	17	549775	4150436	SS/Siltstone	Marcellus	69	20 S		69	6/16/2007	100
Marcellus	17	549649	4150164	Shale	Millboro	0	0		0	6/16/2007	101
Marcellus	17	549597	4150104	Shale		0	0		0	6/16/2007	102
Brallier	17	551069	4147519	Shale		85	22 S		85	6/16/2007	103
Brallier	17	551065	4147275	Shale		0	0		0	6/16/2007	104
Tuscarora Float	17	543157	4151032	SS		0	0		0	6/16/2007	105
Price	17	539032	4150650	SS		65	56 S		65	6/17/2007	106
Beekmantown	17	539051	4149326	Dolomite		0	0		0	6/17/2007	107
Beekmantown	17	539103	4149457	Dolomite		0	0		0	6/17/2007	108
Price	17	539189	4149824	SS/Siltstone		80	42 S		80	6/17/2007	109
Price	17	539252	4149870	Siltstone		0	0		0	6/17/2007	110
Price	17	539312	4149939	Siltstone		71	16 S		71	6/17/2007	111
Beekmantown	17	539834	4149792	Dolomite		0	0		0	6/17/2007	112
Beekmantown	17	544892	4150910	Dolomite		96	14 S		96	6/17/2007	113
Price	17	549333	4162957	Sandstone		0	0		0	8/14/2007	114
Maccrady	17	547627	4162319	Mudstone		0	0		0	8/14/2007	115
Greenbrier	17	546185	4162064	Limestone		0	0		0	8/14/2007	116

Appendix I: Field observations, continued

Formation_	UTM_Zone	UTM_Easting	UTM_Northing	Lithology	Fossils/Other	Strike	Dip	Direction	Strike_Cor	Date_Recorded	Stop
Marcellus	17	550267	414936	Siltstone		50	44	SE	50	8/14/2007	117
Ordovician Limest	17	549372	4151575	Limestone	Calcite veins	0	0			8/14/2007	118
Martinsburg	17	549254	4151691	Limestone		0	0			8/14/2007	119
Ordovician Limes	17	549163	4152494	Limestone	New Market LS	80	30	SE	80	8/14/2007	120
Ordovician Limes	17	548521	4152453	Limestone	New Market LS	76	28	SE	76	8/14/2007	121
Ordovician Limes	17	547889	4152387	Limestone		86	30	SE	86	8/14/2007	122
Tuscarora	17	541679	4150650	Sandstone		0	0			8/14/2007	123
Rose Hill	17	541625	4150634	Sandstone		0	0			8/14/2007	124
Price	17	551093	4158923	Sandstone		0	0			8/14/2007	125

Appendix II: CMYK Values used for geologic mapping

Formation	CMYK Values
Mmch	32A0
Mg	42A0
Mmcc	5310
Mp	21A0
Dch	3300
Db	4400
Dm	6500
Drg	2200
Sk	2300
Srh	34A0
St	4600
Oj	0310
Om	0410
Omls	A510
Obk	A330
Cnh	0430

A = 8%	1 = 13%	2 = 20%	3 = 30%	4 = 40%	5 = 50%	6 = 60%	7 = 70%	X = 100%
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CMYK values used in geologic mapping, from “U.S. Geological Survey Time Color Scheme.”
(Walker and Cohen, 2006)

Appendix III: Regional Changes in Nomenclature

System	Mercer, Monroe, and Summers County, WV. (Reger, 1926)		Giles County, VA., and Mercer County, WV. (Cooper, 1961)	Botetourt County, VA. (McGuire, 1970)	Study Area	
Mississippian	Mauch Chunk Series	Bluestone Group	Bluestone Formation	Not Exposed	Mauch Chunk Group	
		Princeton Conglomerate	Princeton Formation			
		Hinton Group	Hinton Formation			
		Bluefield Group	Bluefield Formation			
	Greenbrier Series		Casper Limestone			Greenbrier Limestone
			Ste. Genevieve Limestone			
			Hillsdale Limestone			
			Little Valley Limestone			
	Maccrady Series		Maccrady Formation			Maccrady Formation
Pocono Series		Price Formation	Price Formation	Price Formation		
Devonian	Chemung Series		Parrot Formation	Chemung Formation	Hampshire Formation	
			Chemung Formation		Chemung Formation	
	Portage		Brallier Formation	Brallier Formation	Brallier Shale	
	Genessee-Hamilton-Marcellus Series		Millboro Formation	Millboro Formation	Marcellus Series	
			Huntersville Formation	Needmore Formation		
				Ridgely Sandstone		
	Oriskany Series Helderberg Series		Rocky Gap Sandstone	Licking Creek Formation	Rocky Gap Sandstone	
				Healing Springs Sandstone		
				New Creek Limestone		
	Silurian	Clinton Series		Keyser Formation		Tonoloway Limestone
Tonoloway Limestone					Tonoloway Limestone	
Keefer Formation				Keefer Sandstone	Keefer Sandstone	
		Rose Hill Formation	Cacapon Formation	Rose Hill Formation		
White Medina Series		Tuscarora Sandstone	Tuscarora Formation	Tuscarora Sandstone		
Ordovician	Red Medina Series		Juniata Sandstone	Juniata Formation	Juniata Formation	
	Martinsburg Series	Lower Maysville Group	Martinsburg Formation	Martinsburg Formation	Martinsburg Formation	
		Eden Group				
		Trenton Group				
	Moccasin Series		Eggleston Formation	Eggleston Formation	Middle Ordovician Limestones	
	Stones River (Chickamauga) Series		Moccasin Formation	Edinburg Formation		
			Witten Limestone			
			Gratton Limestone			
			Benbolt Limestone			
			Pearisburg Limestone	Lincolnshire Limestone		
			Lincolnshire Limestone			
			Five Oaks Limestone			
			Elway Limestone	New Market Limestone		
	Blackford Formation					
	Beekmantown Series		Knox Group	Beekmantown Formation	Knox Group	
				Chepultepec Formation		
				Conococheague Formation		
Copper Ridge Formation						

-Modified from McDowell and Schultz, 1989