2023

USING 3-DIMENSIONAL MAPPING TO DETERMINE THE POSSIBILITY OF STRUCTURAL CONTROL ON DEVELOPMENT OF THE UPPER ORDOVICIAN LEXINGTON LIMESTONE, CENTRAL KENTUCKY, U.S.A.

Sean Davis
University of Kentucky, sean_davis96@yahoo.com
Author ORCID Identifier:
https://orcid.org/0009-0009-9163-3084
Digital Object Identifier: https://doi.org/13023/etd.2023.389

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Sean Davis, Student

Dr. Frank Ettensohn, Major Professor

Dr. Kevin Yeager, Director of Graduate Studies

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THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
College of Earth and Environmental Sciences
at the University of Kentucky

By

Sean Davis

Lexington, Kentucky

Director: Dr. Frank R Ettensohn, Professor of Earth and Environmental Sciences

Lexington, Kentucky

2023

https://orcid.org/0009-0009-9163-3084

ABSTRACT OF THESIS

USING 3-DIMENSIONAL MAPPING TO DETERMINE THE POSSIBILITY OF STRUCTURAL CONTROL ON DEVELOPMENT OF THE UPPER ORDOVICIAN LEXINGTON LIMESTONE, CENTRAL KENTUCKY, U.S.A.

The upper Lexington Limestone of Late Ordovician age has been interpreted to represent a structurally controlled, complex, facies mosaic. This facies mosaic has historically been interpreted to be a carbonate buildup of shoal complexes with interbedded shale units with intertonguing facies. Due to relatively recent advances in geographic-information-systems (GIS) mapping technologies, it is possible to generate three-dimensional (3-D) compatible maps to offer insight to the complexities of the upper Lexington Limestone and to determine if structural control affected the distribution of members. The resulting two-dimensional (2-D) and 3-D maps show that basement faults likely exerted a significant influence on facies distribution and formation. The 3-D maps further suggest that post-depositional structural activity during the Alleghanian orogeny resulted in large-scale deformation of the Lexington Limestone to generate structures like the Jessamine Dome.

KEYWORDS: Three-Dimensional (3-D) Mapping, Upper Ordovician, Lexington Limestone, Structure, Esri ArcGIS Pro, Facies Mosaic.

Sean Davis

(Name of Student)

7/28/2023

Date

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By

Sean Davis

Dr. Frank Ettensohn

Director of Thesis

Dr. Kevin Yeager

Director of Graduate Studies

7/28/2023

Date

ACKNOWLEDGMENTS

My greatest appreciation and thanks to the members of my committee, Dr. Frank Ettensohn, Dr. William “Drew” Andrews, and Dr. John Hickman: to Dr. Ettensohn, for your time spent dedicated to assistance in conducting fieldwork, reviewing my writing, and guidance for presentations; to Dr. Andrews, for your mentoring in mapping and learning the new 3-D mapping process in our weekly meetings; to Dr. Hickman, for your feedback on presentations and insight into the geologic structure for this project; and to all of the committee members for their guidance and assistance in mentoring me to become a better student and researcher.

I would like to thank the KGS 3D Geoframework team for their support throughout this project. Specifically, I thank Devan Robinson for hours spent assisting in all capacities with Esri ArcGIS Pro, especially troubleshooting when issues would arise, and I thank Anna Pearson, for teaching me the basics of Esri when I was just starting this project and teaching me the framework of generating 3-D maps.

Thank you to my fellow graduate students in the Department at UK for all of the feedback, guidance, and companionship throughout the graduate-school process. Thank you to all of my friends outside of work for making the time spent in Lexington extremely enjoyable and reminding me to appreciate all aspects of life.

I especially thank the United States Geological Survey for the funding received to complete work for this project through the EDMAP program.

To Alyssa Stubbers, I am eternally grateful for all of your patience, advice, feedback, and hours spent listening to me discuss my work. Your interest in my work helped motivate me even at the toughest times, and you were always willing to be the

first to edit any rough draft or listen to me practice presentations. Building a life together during graduate school has not always been easy, but I know that this work would not have been possible without your presence.

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CHAPTER 1. INTRODUCTION

1.1 Purpose

The purpose of this thesis is to examine the nature of the upper Lexington Limestone (Tanglewood buildup) using relatively new geographic-information systems (GIS) mapping technologies to generate a three-dimensional (3-D) compatible geological framework (geoframework) to better understand how the constituent member units developed. Previous work on the Lexington Limestone suggests that the deposition of members within the upper Lexington was structurally controlled, resulting in a complex facies mosaic (Fig. 1) (Ettensohn, 1992). Integrating new digital-mapping techniques with previous work on the Lexington addresses the principle research question: Can three-dimensional mapping techniques be used to determine the presence of structural control on the distribution of members in the upper Lexington Limestone through characterization of the complex facies mosaic?

The United States Geological Survey (USGS) developed a three-dimensional geoframework initiative with the intention of creating a wholistic subsurface, 3-D, geological map of the entire United States to strengthen the scientific knowledge and understanding of the country's geology (Brock et al., 2021). The Kentucky Geological Survey (KGS) has also recently begun work on the USGS initiative in Kentucky, creating a three-dimensional geoframework of units and faults throughout Kentucky and developing a method of 3-D mapping that can be utilized in this research. Such a three-dimensional geoframework inherently must deal with geologic units that are complexly divided and units that are more uniform and widespread in nature, and the Lexington Limestone provides an example of a complexly divided geologic unit (Fig. 1). Understanding how this complexity originated, structurally or otherwise, may be used as a baseline to determine if other stratigraphic units and their facies may have been similarly influenced by reactivated structures.

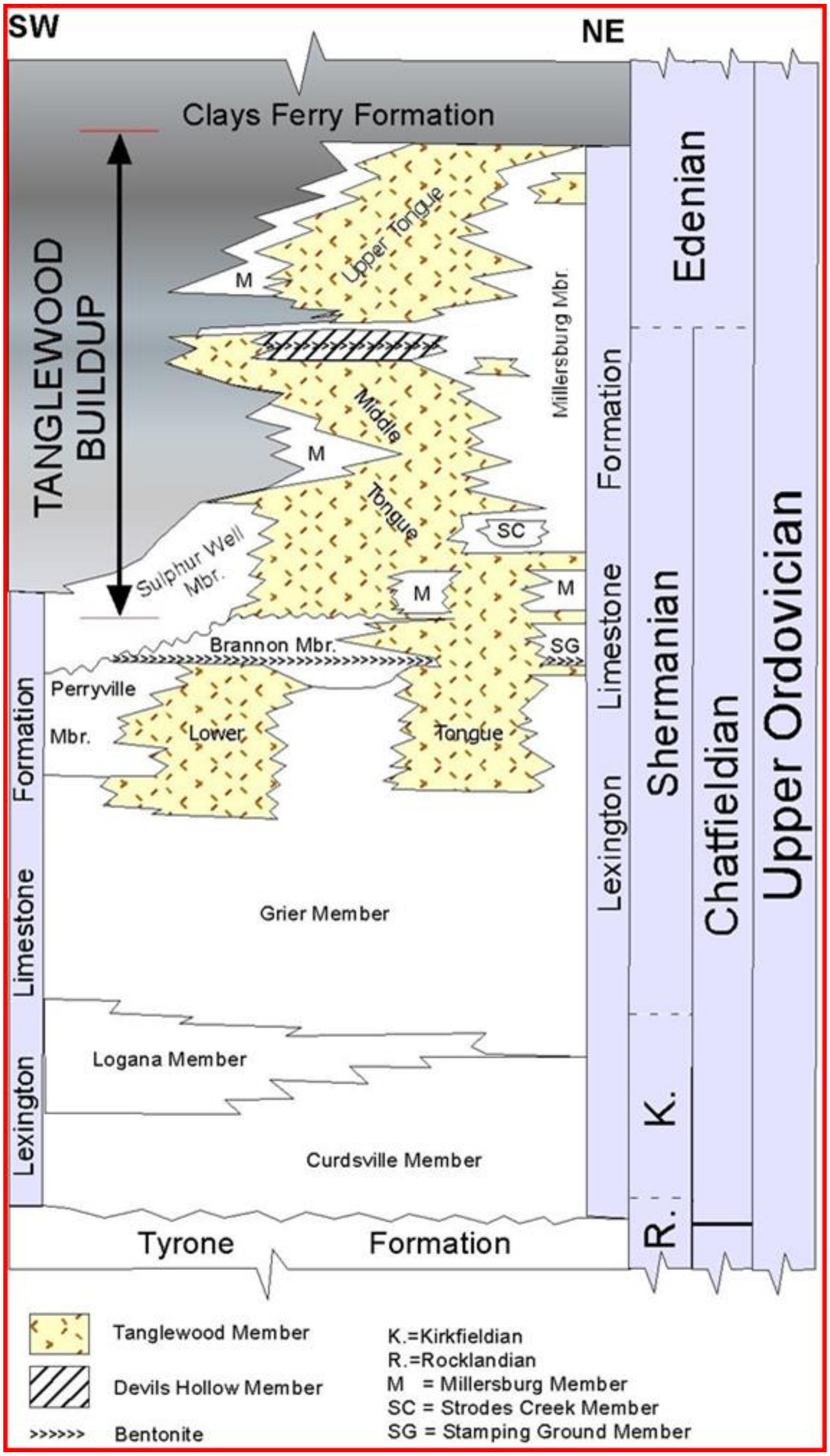


Figure 1. Schematic stratigraphic column of the Lexington Limestone showing the facies mosaic in the upper part of the unit, or Tanglewood buildup, only part of which is shown (from Ettensohn et al., 2004).

Additionally, understanding that structural reactivation in Kentucky is normally associated with major orogenic events in the Appalachian hinterland (Ettensohn et al., 2002a) could potentially signal when in the geologic record to expect facies controlled by reactivation, whereas understanding the location of possibly controlling basement structures could indicate where in the state to expect this kind of control. Data of this sort, collected and produced from this project, will be assimilated into a larger subsurface map of Kentucky, providing higher layer resolution that will contribute to an ongoing KGS statewide geoframework project. However, it will also have major geotechnical implications for understanding the distribution of karst, groundwater, and agriculturally productive soils in the Bluegrass Region of central Kentucky, and perhaps elsewhere in the Commonwealth.

The Lexington Limestone was chosen for this project due to the extensive mapping and previous work focused on the formation. From the 1960s through the 1990s, the USGS and KGS conducted a joint mapping program that holistically mapped the Commonwealth of Kentucky, providing extensive detail regarding formations and their members based upon field data collected by geologic mappers. The KGS maintained records of the maps produced by the joint mapping program and created digital databases of these geologic maps, which are available and were utilized during this research. Because of this mapping program, the Lexington Limestone also underwent several revisions of included members, as well as the renaming of members due to the complexity of intertonguing (Fig. 2) (Cressman, 1973). The recent advances in GIS mapping technology allow for this formation to be mapped in three dimensions to provide a new tool for examining these intertonguing relationships.

1.2 Geologic Setting

The Bluegrass Region of north-central Kentucky (Fig. 3), is largely underlain by the Upper Ordovician (mid-Mohawkian–lower Cincinnatian) Lexington Limestone (Cressman, 1973), although it is commonly called the Trenton Limestone in the subsurface. The Lexington Limestone was deposited during Chatfieldian–Edenian (latest Sandbian–early Katian) time during an ~4 Myr period across the Lexington Platform (Figure 4B) as a fossiliferous, largely bioclastic limestone that lies unconformably above the Tyrone

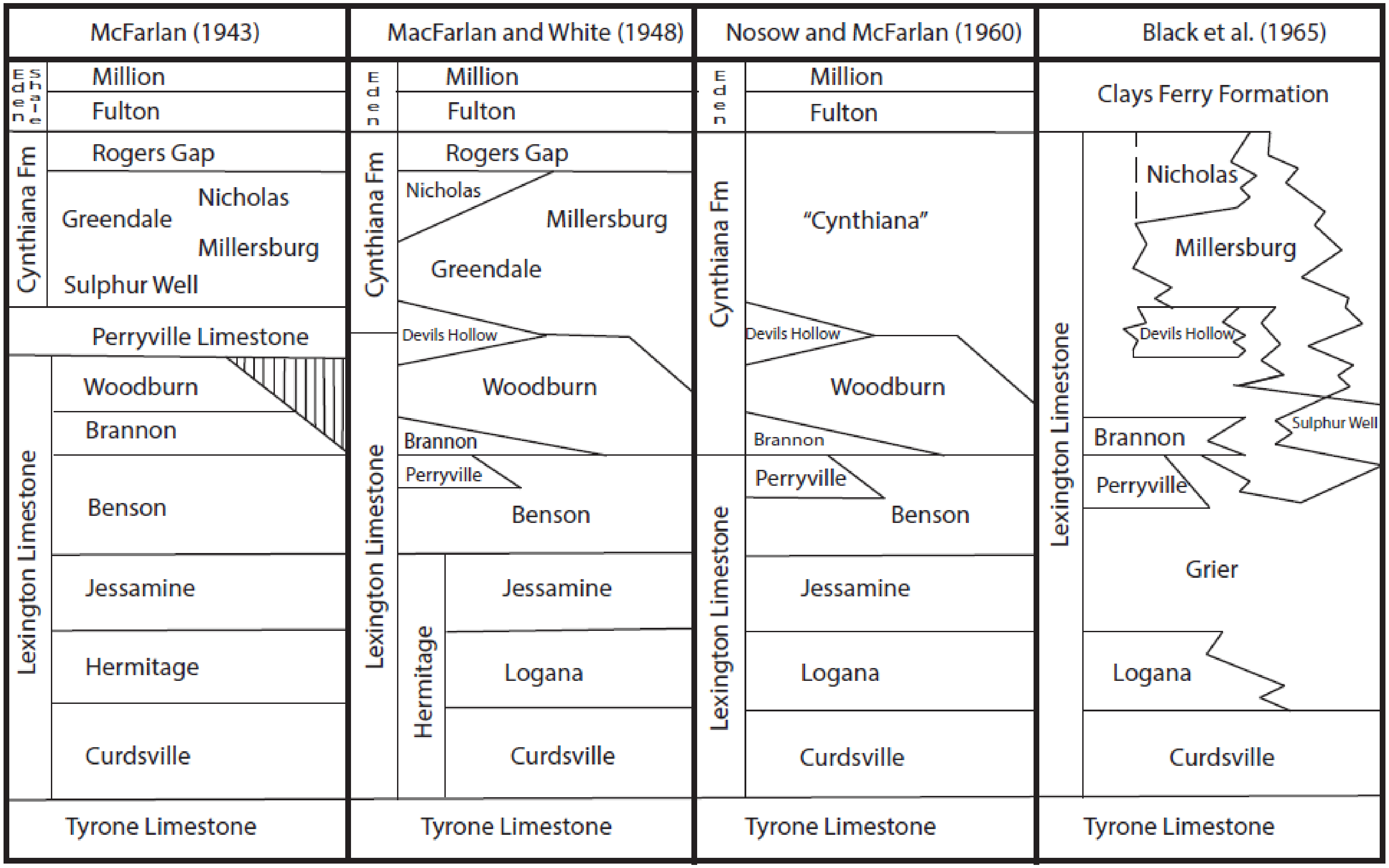


Figure 2. History of Lexington Limestone nomenclature (adapted from Black et al., 1965).

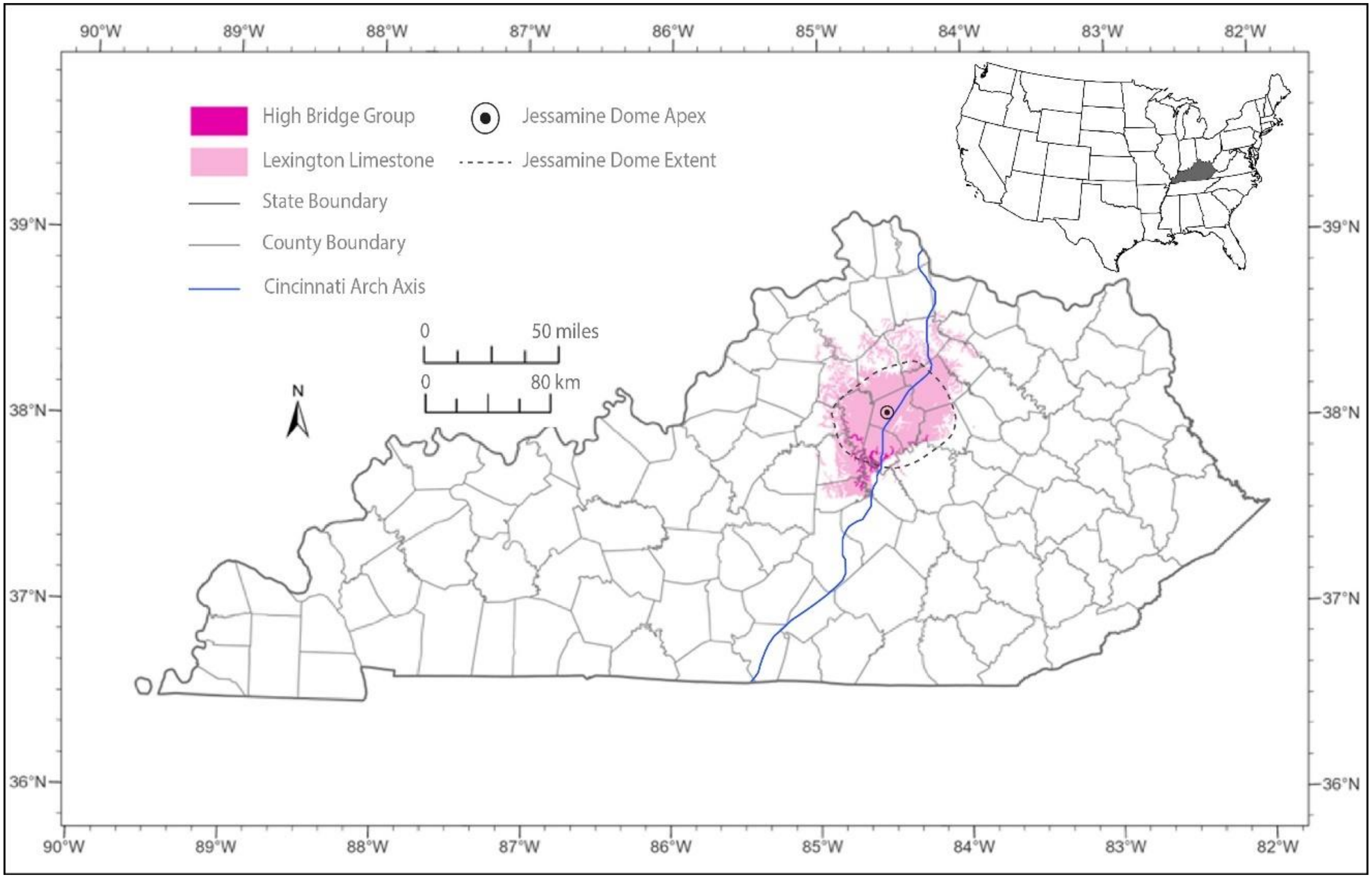


Figure 3. Distribution of the Upper Ordovician Lexington Limestone and underlying High Bridge Group, exposed on the Jessamine Dome culmination of the Cincinnati Arch. Much of the unit distribution reflects parts of the post-Trenton upper Lexington Limestone (parts above the Brannon Member; see Fig. 1) (adapted from Cressman and Peterson, 1986).

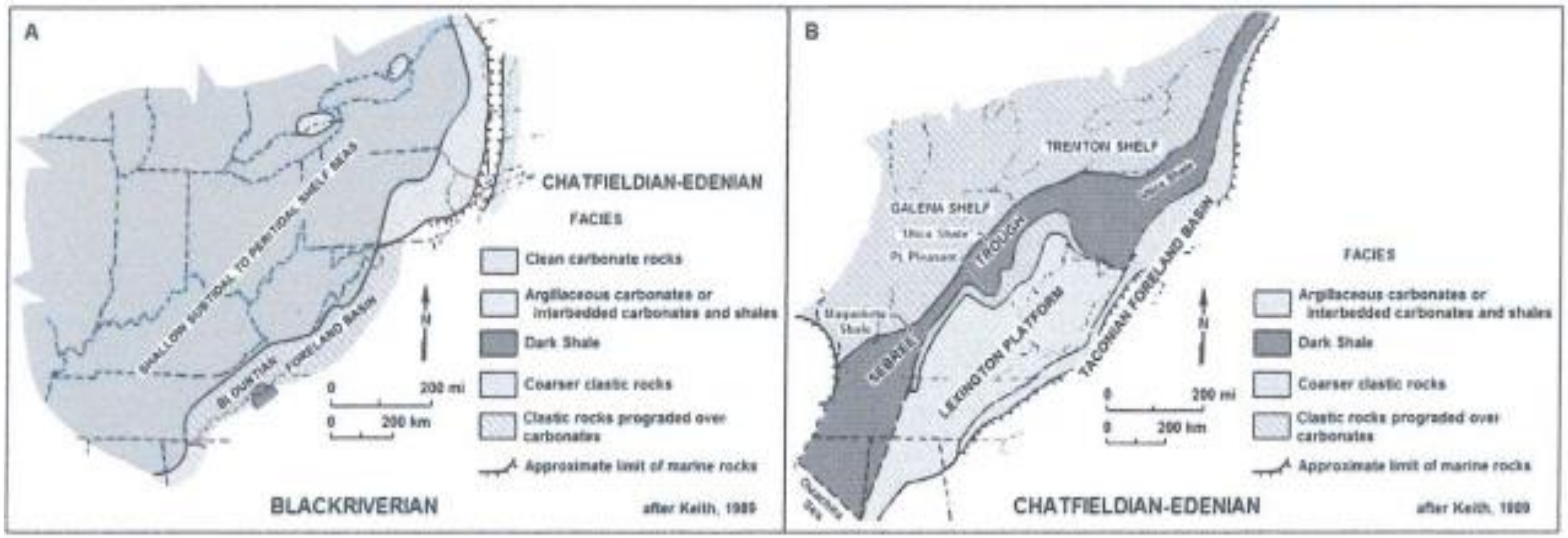


Figure 4. Paleoenvironmental interpretations of east-central Laurentia during Blackriverian (A) and Chatfieldian–Edenian (B) times, showing the stratigraphic and structural differentiation of the area due to far-field forces during the Taconic orogeny. A.) Extensive Black River carbonate platform during Blackriverian (Turinian; Late Sandbian) time; B.) Stratigraphic and structural differentiation of the Black River platform into Lexington, Trenton, and Galena platforms/shelves, as well as the Sebree trough during Chatfieldian–Edenian (mid-Mohawkian–lower Cincinnatian; latest Sandbian–early Katian) time (modified from Ettensohn et al., 2002a).

Limestone and conformably below the Clays Ferry Formation (Fig. 1). Although it is mostly thought to have been deposited as a temperate-water carbonate, deposition took place at about 25°S latitude in the subtropical, trade-wind belt (Ettensohn, 2010; Torsvik and Cocks, 2017).

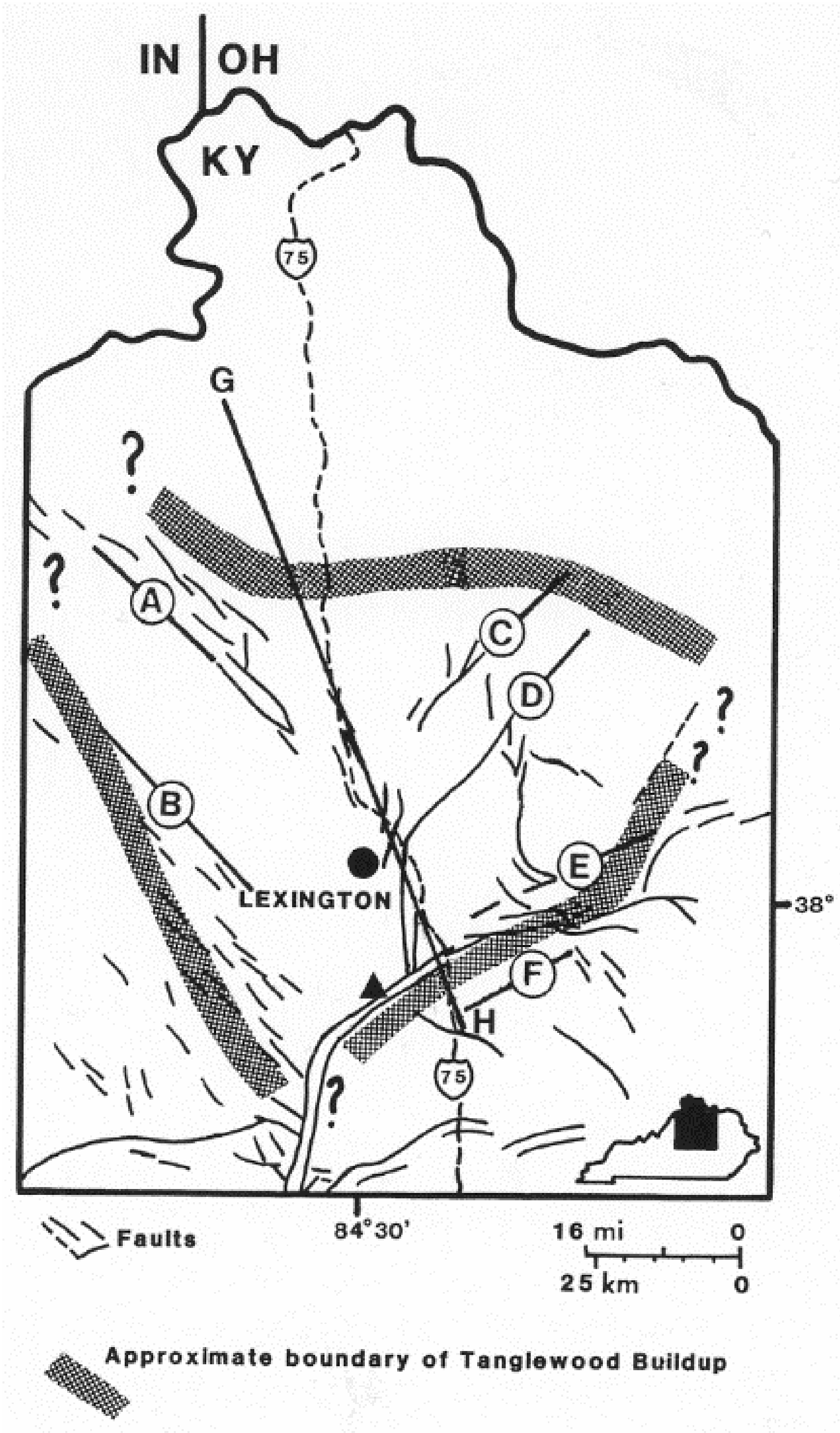
The Lexington/Trenton Limestone is unconformably underlain by the warm-water, peritidal rocks of the Tyrone Formation of the High Bridge Group (Fig. 1) (Cressman and Noger, 1976), which represents a small part of the shallow-subtidal to peritidal Blackriverian carbonate platform that extended across large parts of east-central Laurentia in pre-Lexington (Blackriverian, Turinian; Late Sandbian) time (Fig. 4A) (Keith, 1989; Ettensohn et al., 2002a).

1.2.1 Cincinnati Arch

The Cincinnati Arch (Fig. 3) is a broad, anticlinal structure that bisects the study area (e.g., Brett et al., 2018). The Cincinnati Arch stretches from northern Ohio to Tennessee, exposing late Upper Ordovician rocks (Brett et al., 2018, Cressman 1973). Central parts of the arch in Kentucky culminate in the Jessamine Dome (Fig. 3), exposing the Lexington Limestone at the surface in the central Bluegrass Region, even though the Cincinnati Arch was not present during deposition of the Lexington Limestone (Jewell, 2001; Borella and Osborne, 1978).

1.2.2 Jessamine Dome

The Jessamine Dome is a broad and irregular structure that occurs in central parts of the study area along the axis of the Cincinnati Arch (Fig. 3) (Borella and Osborne, 1978). This structural culmination coincides with the thickening of the Tanglewood Member and was interpreted by Cressman (1973) to be a shoal complex, which was supported by Borella and Osborne in their 1978 study. Ettensohn (1992) noted the roughly triangular distribution of the Tanglewood Member (Fig. 5), which aligned with fault zones that likely have basement precursors, further supporting the possibility of syndepositional tectonism effecting structural buildup of a regressive carbonate shoal (Fig. 6). The surface expression of these fault zones, which intersect the Jessamine Dome, include the Kentucky River Fault



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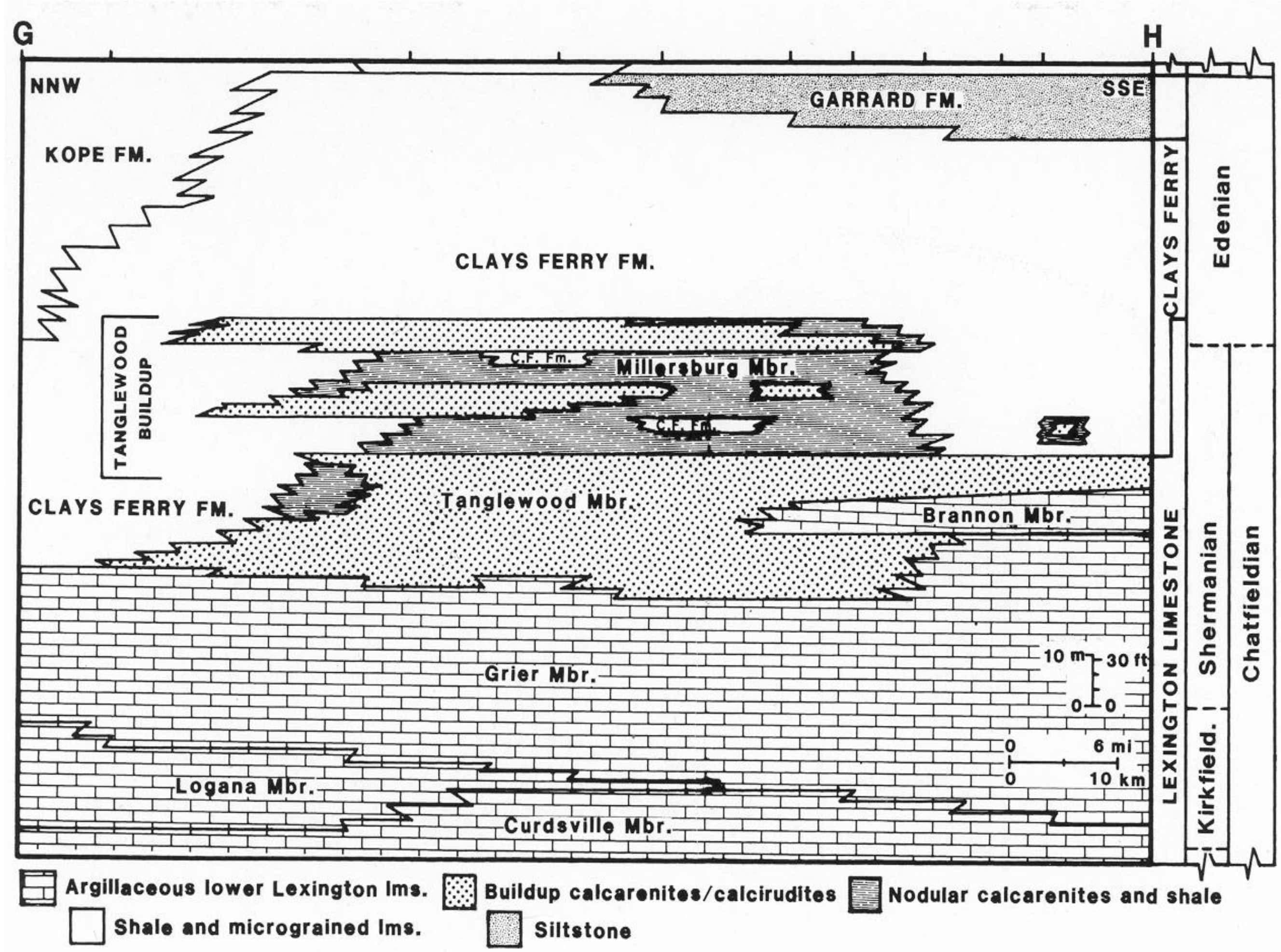

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system, the Lexington Fault system, and several other unnamed fault systems shown in Figure 5 (Borella and Osborne, 1978; Ettensohn, 1992; Ettensohn and Kulp, 1995; Ettensohn et al., 2004). These surface faults possibly represent the reactivation of preexisting Grenvillian and Iapetan basement faults (Black, 1986; Ettensohn et al., 2002ab, 2004) (Fig. 7), and it has been interpreted that reactivation of these faults during Late Ordovician time contributed to development of the Jessamine Dome (Black, 1986; Borella and Osborne, 1978).

1.2.3 Local Structure

As already noted, many of the present surface faults apparently have basement precursors (Fig. 5) that were periodically reactivated during orogenies to the east (Ettensohn et al., 2002a). Syndepositional activity on these faults has been interpreted to have influenced facies distribution in the Lexington Limestone (Ettensohn, 1992; Ettensohn and Kulp, 1995; Ettensohn et al., 2004; Koirala et al., 2016), as well as produced seismites throughout the unit (Rast et al., 1999; Jewell, 2001; Ettensohn et al., 2002b; Ettensohn et al., 2004; Jewell and Ettensohn, 2004). It is the intention of this study to use 3-D-compatible mapping to determine the possible influence of these structures on the existing geoframework.

1.3 Lexington Stratigraphy

Since the Lexington Limestone was first described by Campbell in 1898, the formation and its members have been interpreted to exhibit relatively diachronous tabular, “layer-cake” geometries (e.g., McFarlan, 1943; Nosow and McFarlan, 1960), and lower parts of the Lexington to the level of the Brannon Member (Fig. 1) are relatively diachronous tabular and widespread. Moreover, these lower parts of the Lexington are approximately equivalent to the Trenton Series of New York (Brett et al., 2004) and are called the “Trenton Limestone” in the subsurface of Kentucky (e.g., Shaver, 1985; Greb, 2017) and adjacent states. However, apparently “stray” tongues of bioclastic, calcarenitic limestone interbedded with shales and nodular limestones, which occur above the Lexington Limestone as it was designated before the USGS-KGS joint mapping program,

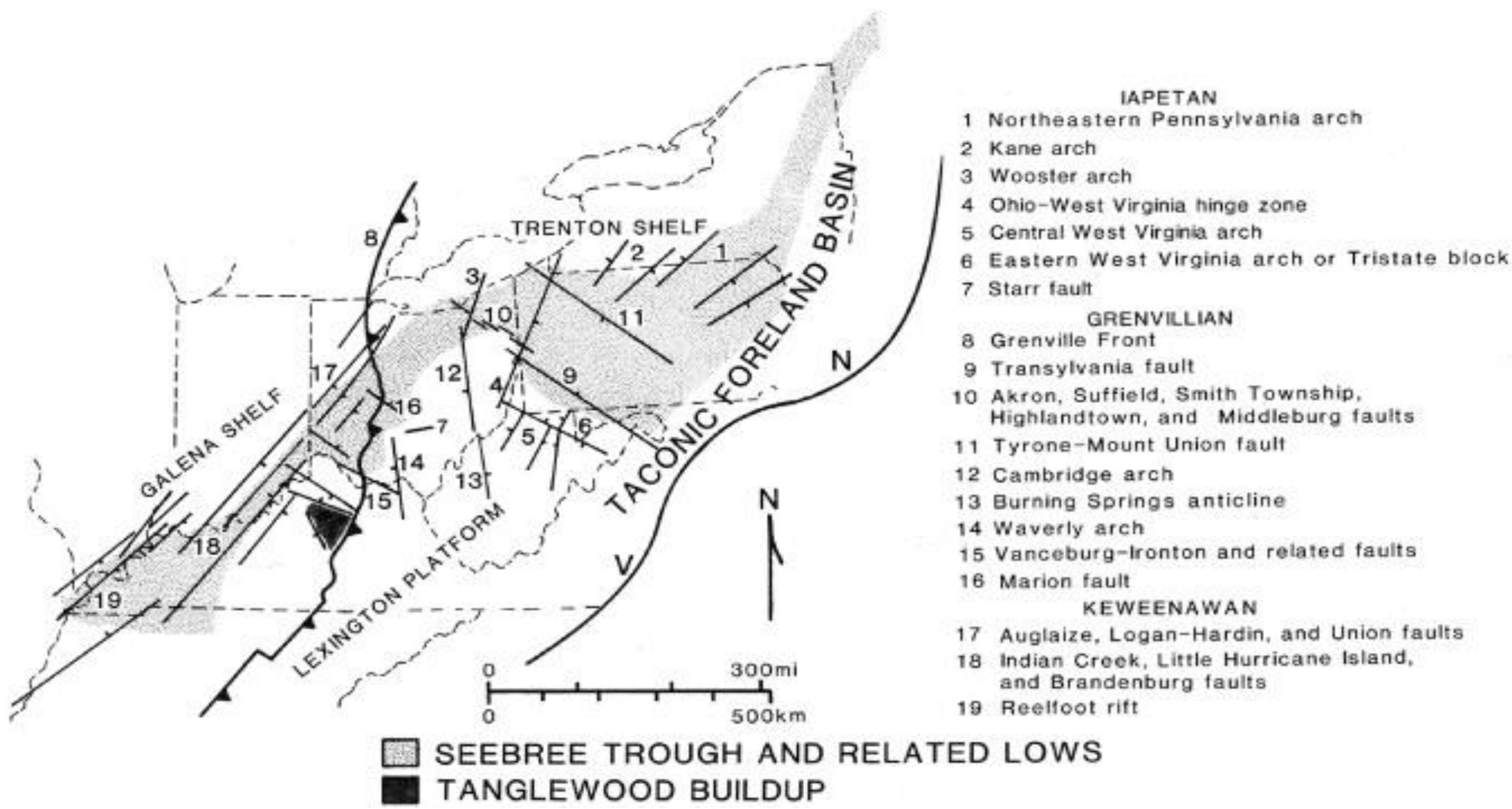


Figure 7. Important basement structures across east-central Laurentia labeled by age. It is thought that reactivation of these structures by far-field forces during the Taconic tectophase of the Taconian orogeny, which represents collision at the New York promontory (N), strongly influenced development of the Lexington Limestone and the Tanglewood buildup (dark triangle) on the Lexington Platform (Ettensohn et al., 2002a).

were included in the Cynthiana Formation, which was also interpreted to be a widespread, tabular unit (McFarlan, 1943). The Cynthiana was in turn overlain by a thick unit of interbedded, fine-grained limestones and shales, known as the Eden Shale, which extended southward into Lexington from the Cincinnati area. However, mapping during the USGS-KGS joint mapping program showed that the "stray" Cynthiana limestones above the Lexington were lithologically similar to and intertongued with parts of the Lexington Limestone below (e.g., Black et al., 1965) (Fig. 1). Hence, the term "Cynthiana" was dropped, and the various bodies of bioclastic limestone were included as the Tanglewood Member of the Lexington Limestone (Fig. 2) (Black et al., 1965), which expanded the thickness and concept of the Lexington Limestone to carbonate units younger than the Trenton equivalents in the central Kentucky area (Fig. 1).

Similarly, tongues of interbedded, fine-grained limestone and shale between the bioclastic Tanglewood bodies were shown to be intertongues of the "Eden Shale," which were determined to be lithologically different than those recognized in the Cincinnati area, and hence, were renamed the Clays Ferry Formation (Fig. 2) (Black et al., 1965; Wier and Green, 1965). These re-interpretations meant that the Lexington Limestone in the central Kentucky area was about 98 m (320 ft) thick, compared to more typical thicknesses of 61 m (200 ft) for the more tabular, subsurface Trenton equivalents. Moreover, the Lexington Limestone in the central Kentucky area was shown to intertongue on all flanks with the shales and fine-grained limestones of the Clays Ferry Formation (Fig. 6) (Black et al., 1965; Cressman, 1973; Ettensohn et al. 2002a).

The abrupt appearance of the Lexington Limestone atop the Tyrone Formation at the beginning of Chatfieldian time (Fig. 1) apparently reflects reactivation of basement structures (Figs. 1, 6, 7) by far-field forces during inception of the Taconic tectophase of the Taconian orogeny and development of the roughly rectangular Lexington Platform (Fig. 4B) (Ettensohn et al., 2002a; Ettensohn, 2010). Hence, the complex stratigraphy of the Lexington Limestone (Figs. 1, 5, 6) has been interpreted as being related to reactivated basement structures of Keweenawan, Grenvillian, and Iapetan age (Fig. 7) (Black, 1986; Ettensohn et al., 2002ab, 2004). The presence of phosphatic, temperate-water carbonates from the deposition of the Curdsville Member through the end of Lexington time suggests that the upwelling of cool, phosphate-rich waters from the adjacent Sebree Trough greatly facilitated deposition of the Lexington Limestone and Tanglewood buildup by providing important nutrients for the benthic organisms (bryozoans, brachiopods and echinoderms) whose skeletal remains largely comprise the unit (Ettensohn et al., 2002b; Ettensohn, 2010; Koirala et al., 2016).

1.3.1 Lower Lexington Limestone

The base of the Lexington Limestone lies atop the Tyrone Formation with a sharp unconformable contact (Black et al., 1965; Jewell, 2001). The lower Lexington consists of the Curdsville through Brannon members (Fig. 1) and is delineated by another unconformity at its top, called the sub-Sulphur Well Unconformity, which truncates the Brannon Member (Fig. 1) (Ettensohn et al., 2002b, 2004). The members below the Brannon largely exhibit geometries with large, relatively flat, and tabular beds deposited in "layer-cake" fashion, which have been interpreted to be a general sequence of easterly transgressing members from the Sebree Trough (Jewell, 2001; Ettensohn et al., 2002b, 2004). These lower members comprise the Trenton equivalent in the subsurface (Ettensohn et al., 2004; Brett et al., 2004).

1.3.2 Upper Lexington Limestone

In 1992, Ettensohn examined the increase in Lexington thickness in the central Kentucky region and suggested that the extra thickness of the upper Lexington Limestone in the central Kentucky area (37 m; 120 ft) and its roughly triangular outline (Figs. 5, 6) reflected a carbonate buildup on reactivated basement structures. The coarse bioclastic limestones in the buildup were interpreted to represent shoal complexes related to periods of uplift, whereas interbedded shales were interpreted to represent eustatic highstands (Ettensohn, 1992). In contrast to the transgressive lower Lexington, the upper Lexington has also been interpreted to be largely regressive (Jewell, 2001; Ettensohn et al., 2002b, 2004). Additional mapping of Lexington members revealed that many of them had distributions and lateral extents that were apparently controlled by basement structures (e.g., Ettensohn et al., 1986; Ettensohn and Kulp, 1995; Jewell, 2001; Ettensohn et al., 2002b, 204; Clepper, 2011; Koirala et al., 2016), helping to confirm structural control across the buildup. This thickened area of Lexington Limestone in central Kentucky is now known as the Tanglewood buildup (Figs. 1, 5, 6) (Ettensohn, 1992), and the influence of Taconian structural reactivation in its formation is now well-known (e.g., Ettensohn et al., 2002a; Brett et al., 2004; McLaughlin et al., 2004; Clepper, 2011).

The above information suggests that complex relationships may exist between the various facies (units) of the Lexington Limestone (Figs. 1, 6) and basement structures (Figs. 4, 5, 7), and that three-dimensional mapping may provide the best means of fully visualizing these relationships. Because these relationships are probably best developed in the Tanglewood buildup (Figs. 1, 5, 6), which itself may reflect structural influence (Figs. 4, 7), this study will focus on those upper parts of the Lexington Limestone included in the Tanglewood buildup, specifically, the easily discerned Brannon, Devils Hollow, and upper Tanglewood tongue (Fig. 1), as well as the nature of the contact between the Lexington Limestone and Clays Ferry Formation. The generation of three-dimensional-compatible data and maps from upper parts of the formation will provide a relatively new analytical tool to interpret the formation and evolution of the Lexington Limestone.

1.3.3 Significant Stratigraphic Units

For the purposes of this study, the Brannon, Devils Hollow, Millersburg, and Tanglewood members (Fig. 1) have been marked as significant. The Devils Hollow and Brannon members are important for interpretation due to their limited geographic extents, which may offer insight into structural influences on member deposition. In 2004, Ettensohn et al. demonstrated that while the Brannon Member is relatively widespread throughout the distribution of the Lexington Limestone, the member pinches out into a tongue of the Tanglewood Member along a line that appears to coincide with basement structures (Figs. 1, 6). This member also contains evidence of soft-sediment deformation, which has been interpreted to reflect seismicity along these basement faults (Rast et al., 1999; Jewell, 2001; Ettensohn et al., 2002b; Ettensohn et al., 2004; Jewell and Ettensohn, 2004). Similarly, the Devils Hollow has a main body, with two smaller isolated bodies with locations apparently related to underlaying structures (Ettensohn et al., 2004; Clepper, 2011).

The Millersburg Member has a widespread distribution throughout the upper Lexington Limestone and exhibits two main bodies, which intertongue with the Tanglewood Member and the Clays Ferry Formation; structure apparently influenced the distribution of both bodies (Clepper, 2011; Cressman 1973). The associated Tanglewood Member is essential to this study because it largely comprises the Tanglewood buildup (Fig. 1). The Tanglewood comprises three major tongues, labeled the Lower, Middle, and Upper tongues, with several smaller tongues that intertongue with other members of the upper Lexington (Clepper, 2011; Kasl, 2001). The prevalence and distribution of this member throughout the Lexington Limestone, both vertically and laterally (Fig. 1), allow for insights into possible structural clues about the origin of the Tanglewood Buildup.

1.4 Tectonic Framework

1.4.1 Taconian Orogeny

Deposition of the Lexington Limestone was coeval with the Taconian orogeny (Fig. 4b), representing the closure of the Iapetus Ocean along two subduction zones during the Taconic tectophase (Vick et al., 1987; Ettensohn, 1991; Ettensohn et al. 2004; Ettensohn and Lierman, 2015). This subduction generated far-field and flexural forces that led to the development of the Lexington Platform and the Sebree Trough (Figs. 4b, 7) (Ettensohn et al., 2002a, 2004). These far-field forces are implied to have reactivated previous structures within the central Kentucky region and are thought to have been responsible for some of the seismic activity that caused soft-sediment deformation and seismites present with the Lexington Formation (Rast et al., 1999; Jewell, 2001; Ettensohn et al., 2002b; Ettensohn et al., 2004; Jewell and Ettensohn, 2004; Koirala et al., 2016).

CHAPTER 2. METHODS

2.1 Field Mapping Methods

Data collected at field sites include the latitude and longitude, the current geographic location of the site, the top-and-bottom elevations of the unit if both are present, thickness of the unit, either measured or collected from student theses, and any relevant information or noted features within the bed. At the start of the project, field sites were chosen to give a widespread geographic extent of the unit or beds of interest. Throughout the project, field sites were chosen for areas that lacked data or for specific areas that needed field measurements to support or reject data shown in the three-dimensional data visualization of layers.

The elevation and coordinate data were gathered using three elevation applications on a mobile device. These three applications were used to find the average elevation for a site, and each application was given more than five minutes to acclimate to the location to ensure the elevation and coordinates were precise. On average, the elevations received from these applications had an uncertainty of +/- 5–10 feet, and the elevations collected were then cross-checked against geologic quadrangle maps to maintain high confidence in these values. Geographic coordinates were recorded in decimal degrees so that when integrated into digital mapping, the data matched the coordinate system used for the digital maps. The thicknesses of the units at each site were measured using a measuring tape between the stratigraphic top and bottom contacts or obtained from previous theses.

Once all relevant information was collected, it was recorded in a field notebook and uploaded into an excel spreadsheet. This spreadsheet served as a digital record of field measurements, but also as a method to integrate field measurements into the digital maps created for this project. The inclusion of field measurements in the digital maps increased confidence in the validity of the data visualization of the three-dimensional layers generated.

2.2 Digital Mapping Methods

All digital mapping for this project was completed within Esri ArcGIS Pro, edition 3.1.1, using the coordinate system NAD 1983 State Plane Kentucky North FIPS 1601 (Meters) (Appendix 1). The data from the joint mapping program were obtained by downloading the 1:24,000 Kentucky Geologic Map available on the KGS website (Cressman and Noger, 1981), and these data were loaded into a new project within ArcGIS. Prior to converting two-dimensional (2-D) data into 3-D data, a comprehensive cross section of members in the upper Lexington Limestone was compiled based on cross sections present on geological quadrangle maps, also found on the KGS website. This comprehensive cross section allowed for quality assurance that mapped units on the 1:24,000 scale map were correctly labeled, and that the tongues of members were assigned as unique horizons to capture the complex intertonguing that occurs between stratigraphic units within the upper Lexington. The resultant 2-D and 3-D maps generated for this project reflect surface contacts, and thus, do not show information for subsurface units. Appendix 2 contains a full list of steps and tools utilized within ArcGIS for all digital-mapping methods, including the parameters used for each tool. Appendix 1 contains a glossary of all ArcGIS Pro specific mapping terms used.

2.2.1 Two-Dimensional Mapping

From the 1:24,000 map, members of the upper Lexington Limestone were selected using the "Select by Attributes" tool from the "US-KY_KGS_24K_Contacts" layer and separated into one feature class (Appendix 1) to separate only relevant stratigraphic-contact horizons (Fig 8, light-blue color). Each stratigraphic member and tongue within the upper Lexington was assigned a unique numerical code so that members and tongues could be separated into distinct feature classes within ArcGIS Pro. Within each stratigraphic member, interbedded tongues of members were also assigned unique codes relative to their elevation within the members, so that each tongue and its contact horizon could be treated as a new layer.

Once all stratigraphic contacts within the upper Lexington were assigned a code, the code was used to create a color symbology of contrasting colors within ArcGIS. Consequently, each unit or tongue in the upper Lexington was represented by a unique color in the stratigraphic column (Fig. 9), the distribution of which would later represent unit distribution on a 2-D map (Fig. 10). The distribution of each unit or tongue was reviewed across geologic quadrangle map boundaries for continuity and corrected or updated if map discrepancies were found. Each resulting unique horizon (unit or tongue) within the stratigraphic column, represented by its own color (Fig. 9), was then converted into a separate ArcGIS feature class. The distributions of each feature class (unit or tongue) were then plotted by color on a 2-D map (Fig. 10).

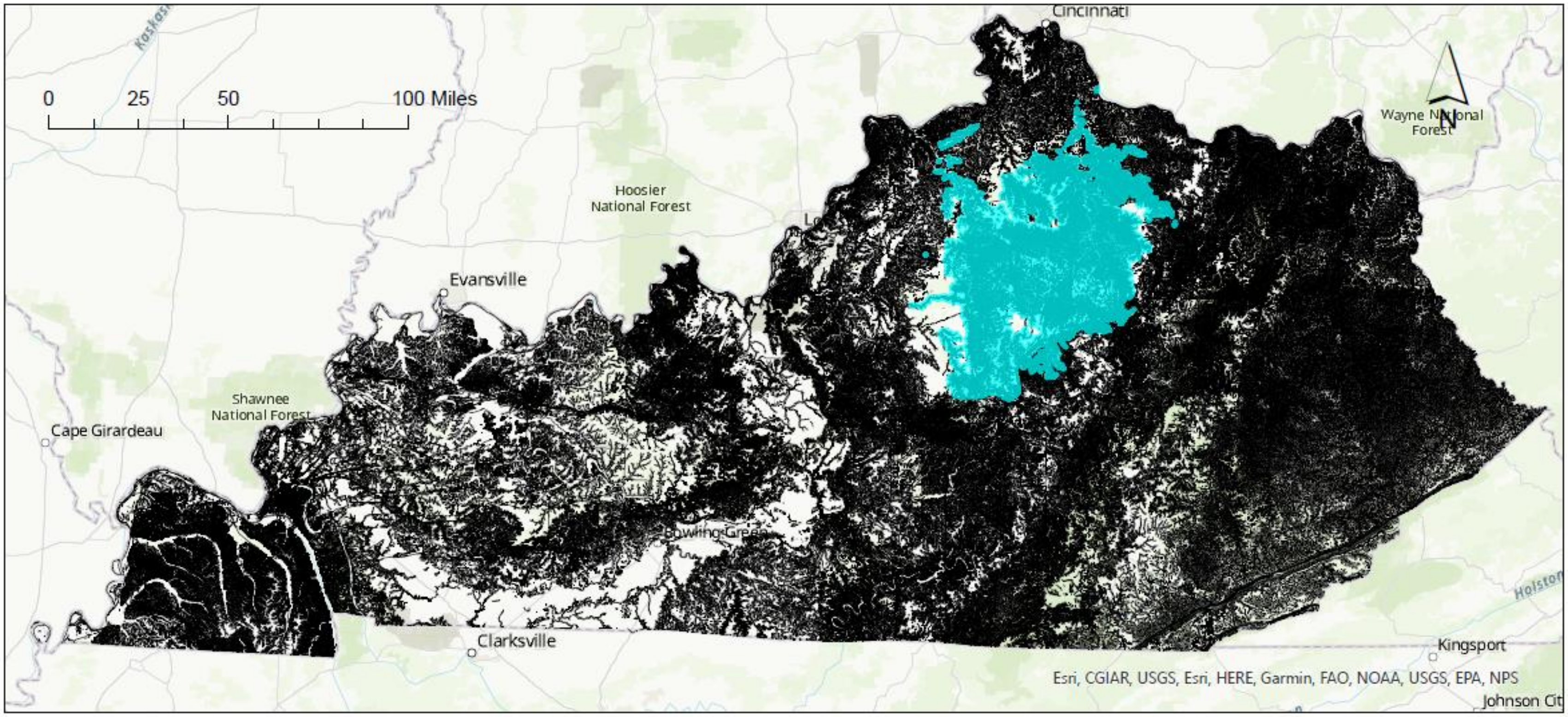


Figure 8. Stratigraphic contact map for all lithologic units within the Commonwealth of Kentucky (black lines). The stratigraphic contacts of the Lexington Limestone are highlighted in light blue.

For each horizon feature class (unit or tongue), the “Generate Points Along Lines” tool was used to generate a point dataset (Appendix 1) for each stratigraphic contact with a spacing of 1,000 feet between points (Fig. 11). Figure 11 and the subsequent figures are shown expressing the tool outputs for the Brannon Member for continuity. This spacing was chosen to increase the resolution (elevation and location) of the resultant feature classes generated from the point-cloud data, while maintaining a sufficiently small dataset for each feature class to ensure that the software could process the data without issue. One member, the Grier, required a point spacing of 2,000 feet between points, because the large geographic extent of the member created datasets so large, using a spacing of 1,000 feet, that the computer hardware could not process it. To create 3-D-compatible data from the point cloud of 2-D data, elevation data were assigned to each point on each feature class using the “Add Surface Information” tool and the Kentucky USGS 10-Meter Digital Elevation Model (DEM) (Appendix 1) obtained from the KGS website.

Once the point cloud contained elevation data, the “Topo to Raster” tool was used to create a raster file for each horizon (Appendix 1) (Fig. 12). The symbology (Appendix 1) for each raster file was selected to display the elevation of each horizon. To prevent ArcGIS from generating data that is not geographically close to the points along the horizon contact, the “Buffer” tool was used to generate a continuous boundary one-half-mile away from all collective points for each feature class (Fig. 13). This buffer zone (Appendix 1) was then applied using the “Clip Raster” tool to remove data within each raster that were geographically more than one-half-mile away from any data points (Fig. 14). This process increased confidence in the elevational values within each raster and prevented ArcGIS from generating data in parts of the raster where data were absent.

2.2.2 Three-Dimensional Mapping

A local scene map (Appendix 1) was created within the project in ArcGIS, and the clipped raster (Fig. 13) of each horizon was imported into the scene map. The clipped raster files were all processed with the “Raster Domain” tool to generate polygon surfaces that captured the 3-D shape of the input raster, which was used in subsequent tools to generate a 3-D surface (Fig. 15). These rasters were then processed in the “Raster to TIN” tool, which generated a triangulated irregular network (TIN) (Appendix 1) (Fig. 16). TIN files and the raster domain files for each surface were then processed in the “Interpolate Polygon

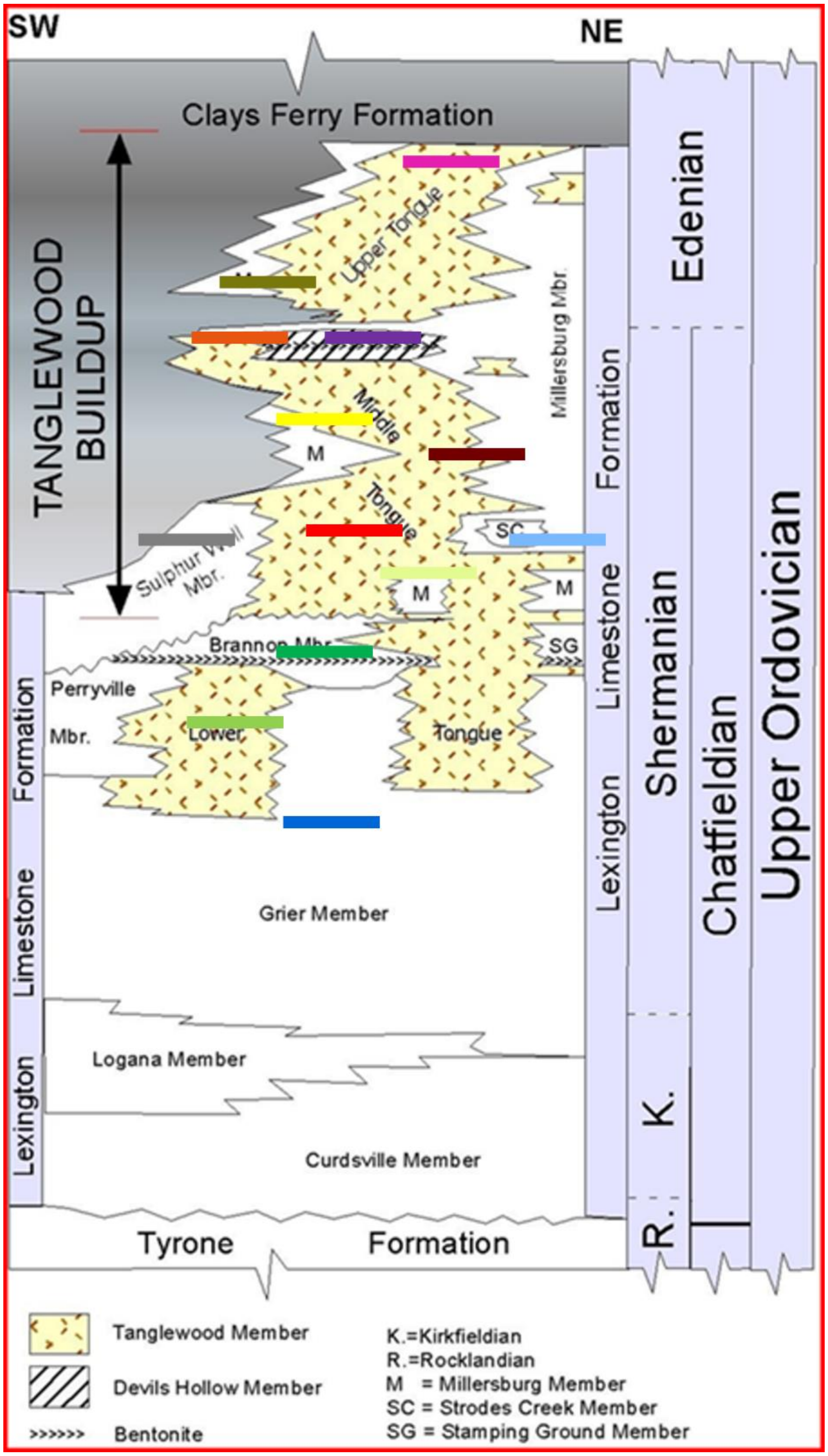


Figure 9. Modified version of Figure 1 with the assigned color values to each unique tongue or member. The colored horizontal lines represent contact horizons (Fig. 10) that were mapped as separate layers or feature classes on the final 3-D map shown in the results section (adapted from Ettensohn et al., 2004). See Table 1 for all color correlations between member and tongue contacts and associated colors.

Table 1. Full list of mapped stratigraphic contacts for members and member tongues. Colors match the color of the mapped contact on Figure 10. The code column is the unique code assigned to each tongue or member contact for sorting purposes. These numerical codes are specific to this project and have no further meaning other than for sorting contacts into feature classes during the mapping process. Numbers that are decimals represent the lower stratigraphic contact for a tongue that is mapped, but for the purpose of this project, only upper stratigraphic contact is considered.

Member or Tongue	**Color**	**Code**
Upper Tongue Tanglewood		90
Upper Tongue Tanglewood		70
Upper Tongue Tanglewood		69.5
Millersburg Tongue		63
Millersburg Tongue		62
Millersburg Tongue		61
Millersburg Tongue		60
Fossiliferous shale (fs)		130
Strodes Creek		120
Devils Hollow		100
Middle Tongue Tanglewood		53
Middle Tongue Tanglewood		52.5
Middle Tongue Tanglewood		52
Middle Tongue Tanglewood		51.5
Middle Tongue Tanglewood		51
Middle Tongue Tanglewood		50.5
Middle Tongue Tanglewood		50
Middle Tongue Tanglewood		49.5
Sulphur Well		40
Brannon		30
Lower Tongue Tanglewood		20
Grier		10

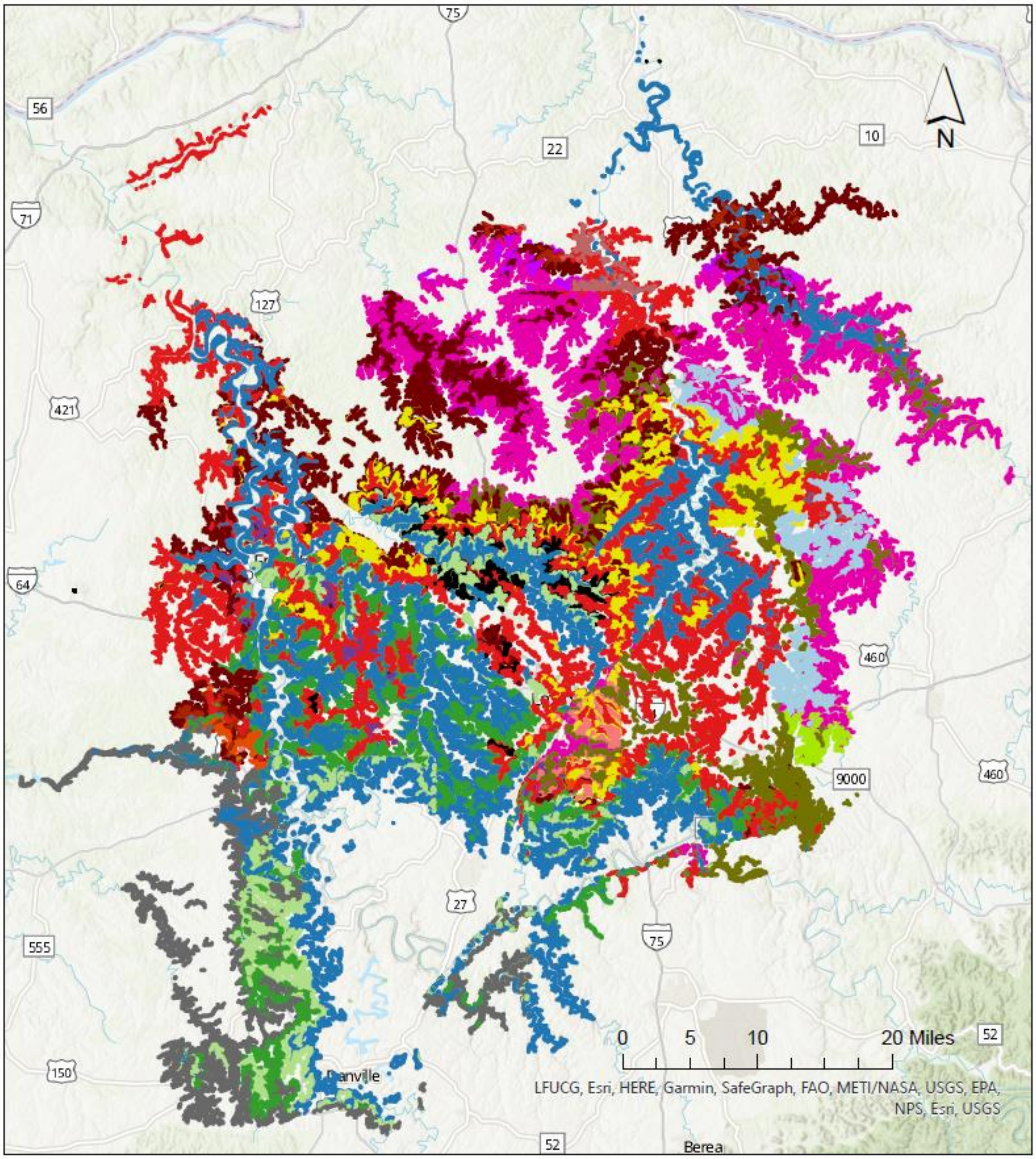


Figure 10. Aerial view of stratigraphic contacts for the upper Lexington Limestone. Each color denotes a unique member horizon in the Lexington Limestone. Figure 9 shows a modified version of Figure 1 with the colors from Figure 10 superimposed on the corresponding contact horizons. See Table 1 for all color correlations between member and tongue contacts and associated colors.

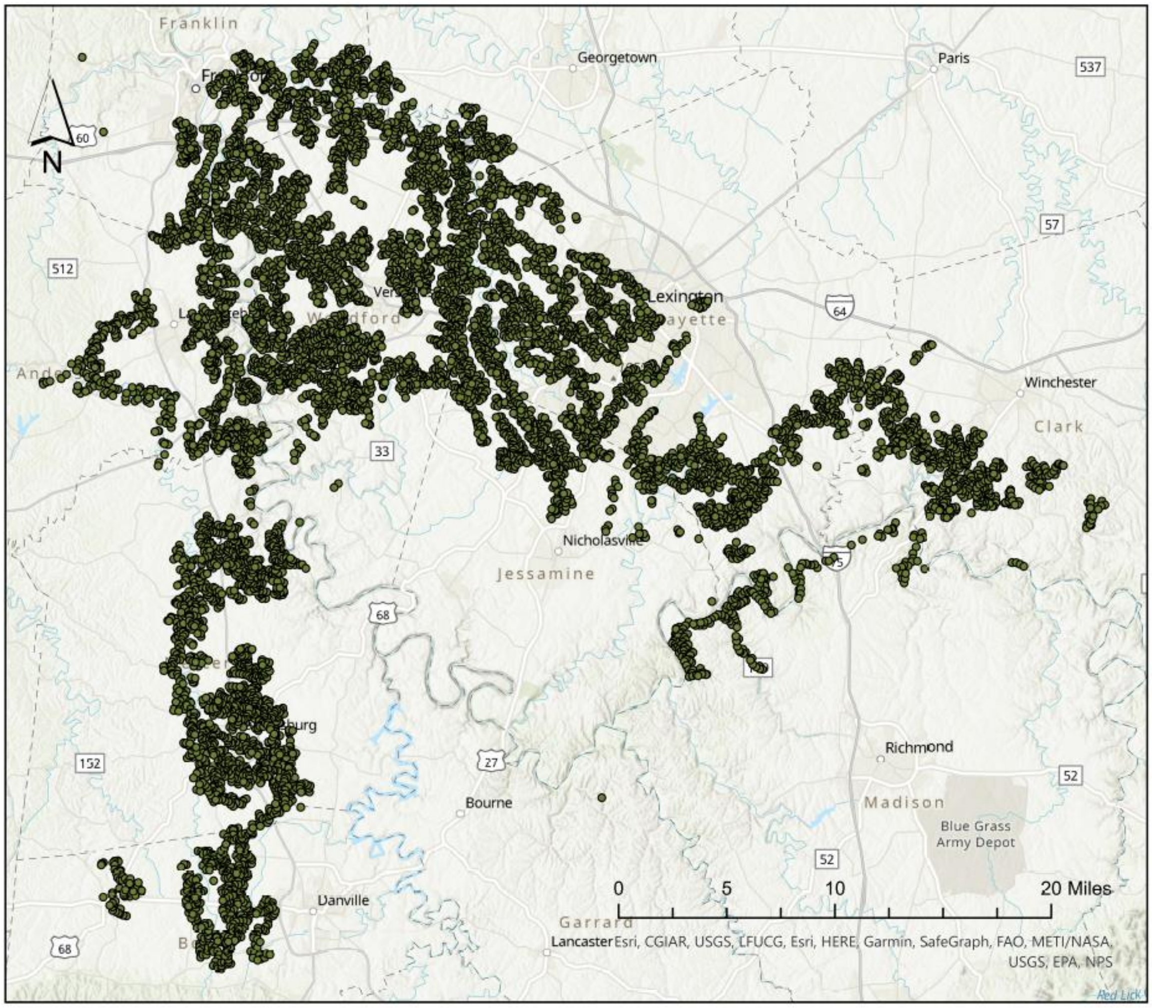


Figure 11. The "Generate Points Along Lines" tool output for the Brannon Member. Discrete points were created every 1000 feet along the mapped contact of the Brannon Member in the 1:24,000 Kentucky Geologic Map. Subsequently, elevation data were assigned to each point from the 10 Meter DEM to make the points 3-D compatible.

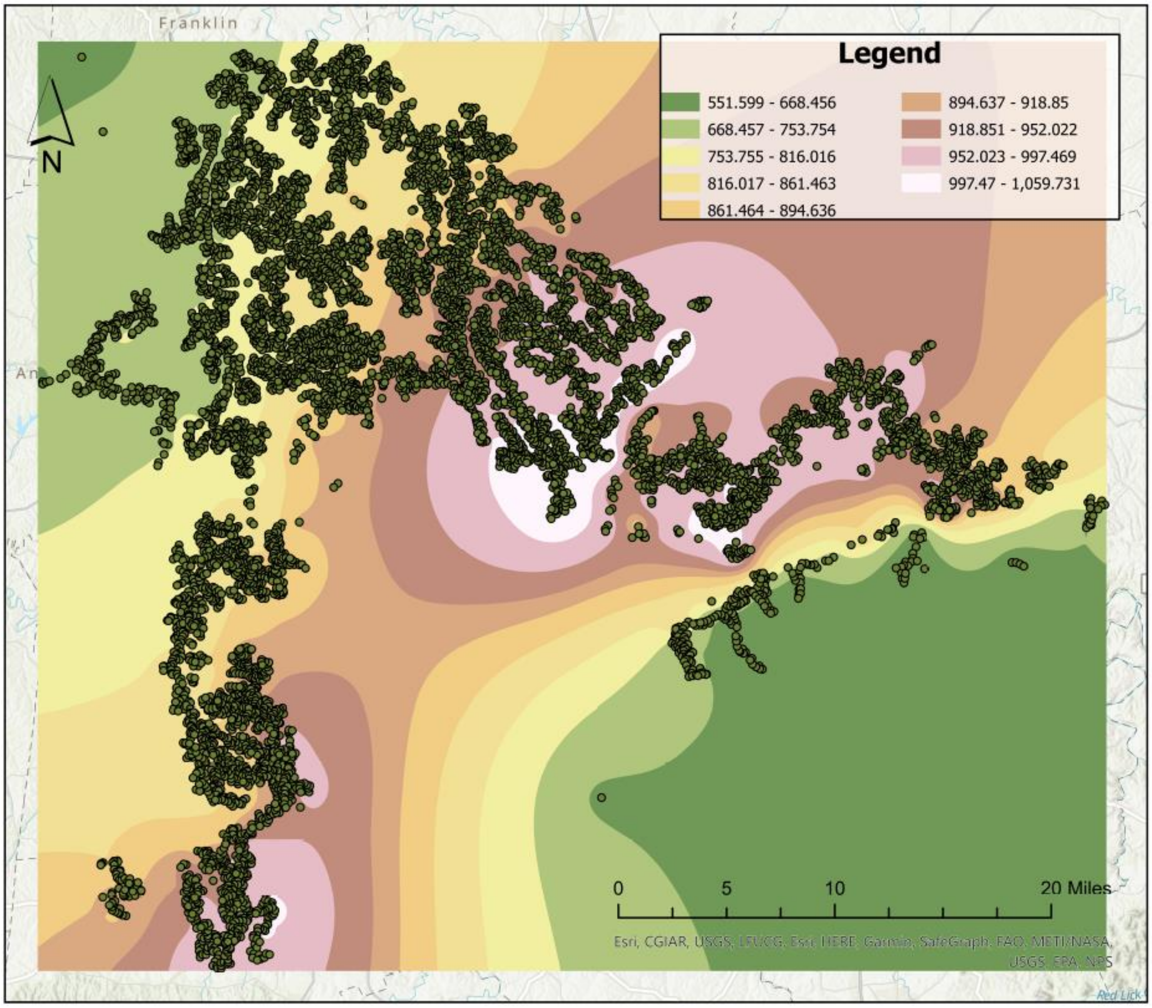


Figure 12. The output of the "Topo to Raster" tool for the Brannon Member with the points from the 3-D-compatible "Generate Points Along Lines" output of the Brannon Member superimposed above the raster file. The bands of color on the map represent ranges of elevation in feet above sea level for the region generated by Esri ArcGIS Pro based on data interpolation.

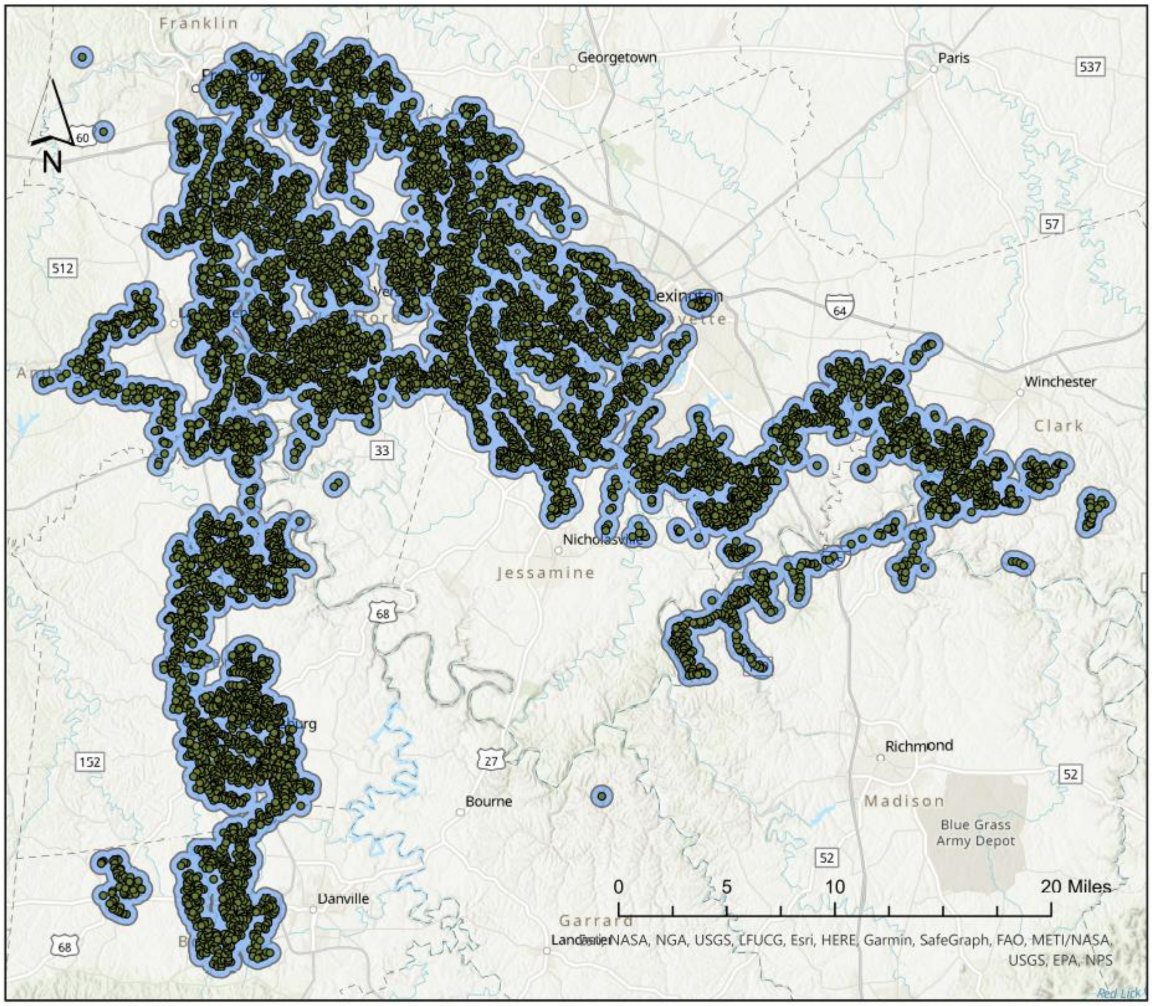


Figure 13. The output of the “Buffer” tool for the Brannon Member with the points from the 3-D-compatible “Generate Points Along Lines” output (green points) of the Brannon Member superimposed above the buffer zones (light blue).

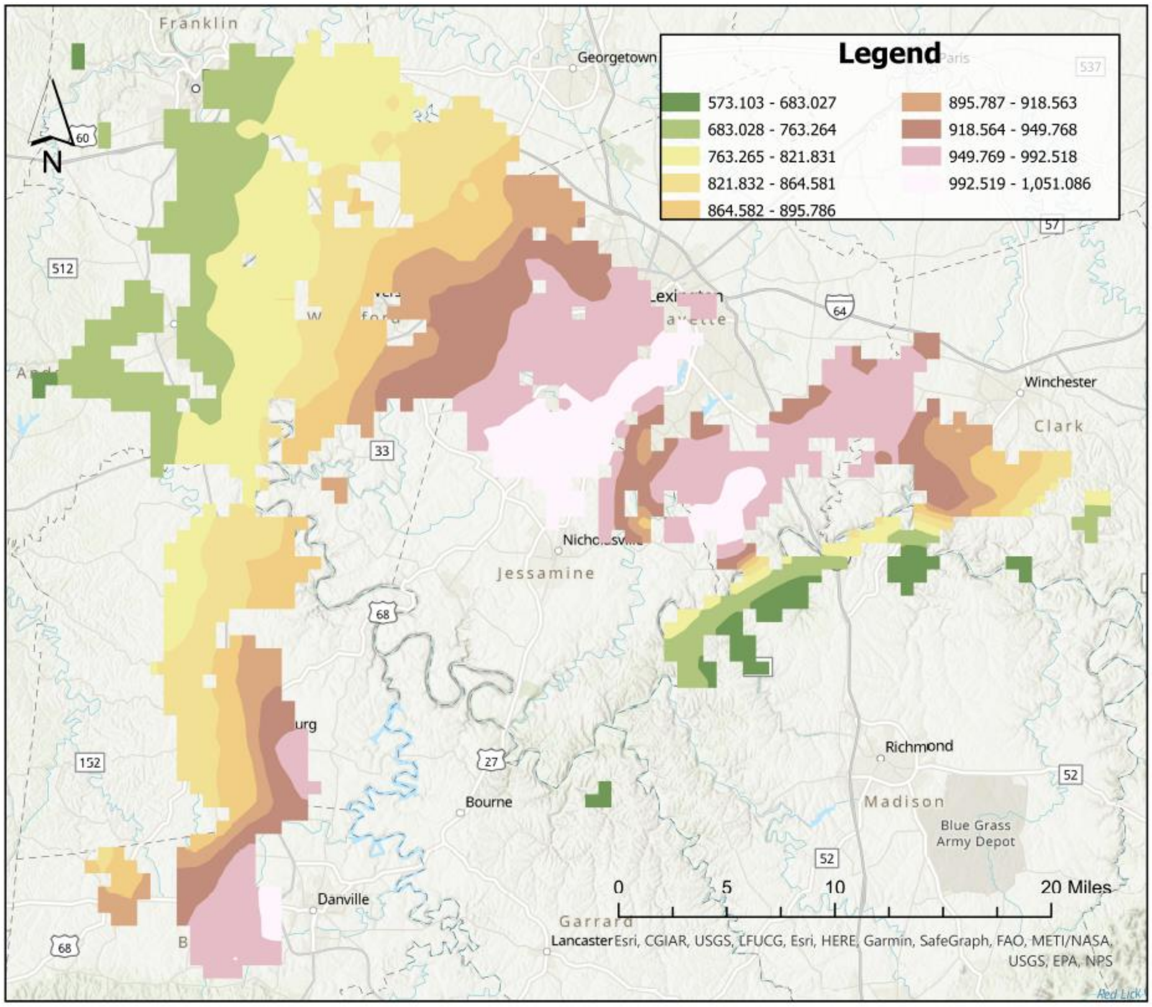


Figure 14. The output of the "Clip Raster" tool for the Brannon Member. Bands of color represent ranges of elevation in feet above sea level for regions of similar elevation. The extent of the raster file has been clipped to the geographic lateral extent of the "Buffer" output from Figure 13.

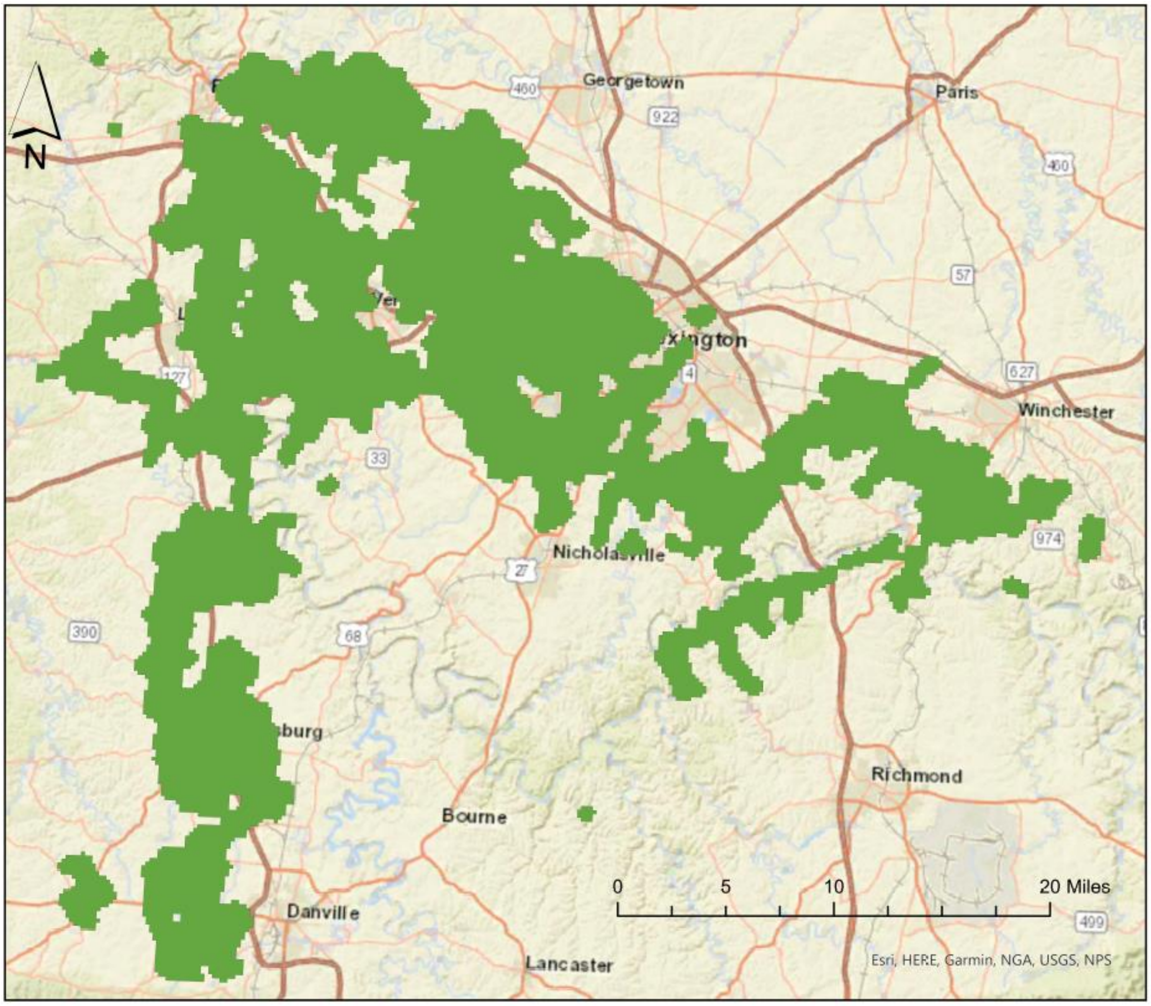


Figure 15. The output of the “Raster Domain” tool for the Brannon Member. This green layer represents an aerial view of the Brannon Member as a 3-D-polygon surface that marks the elevations present across the mapped member.

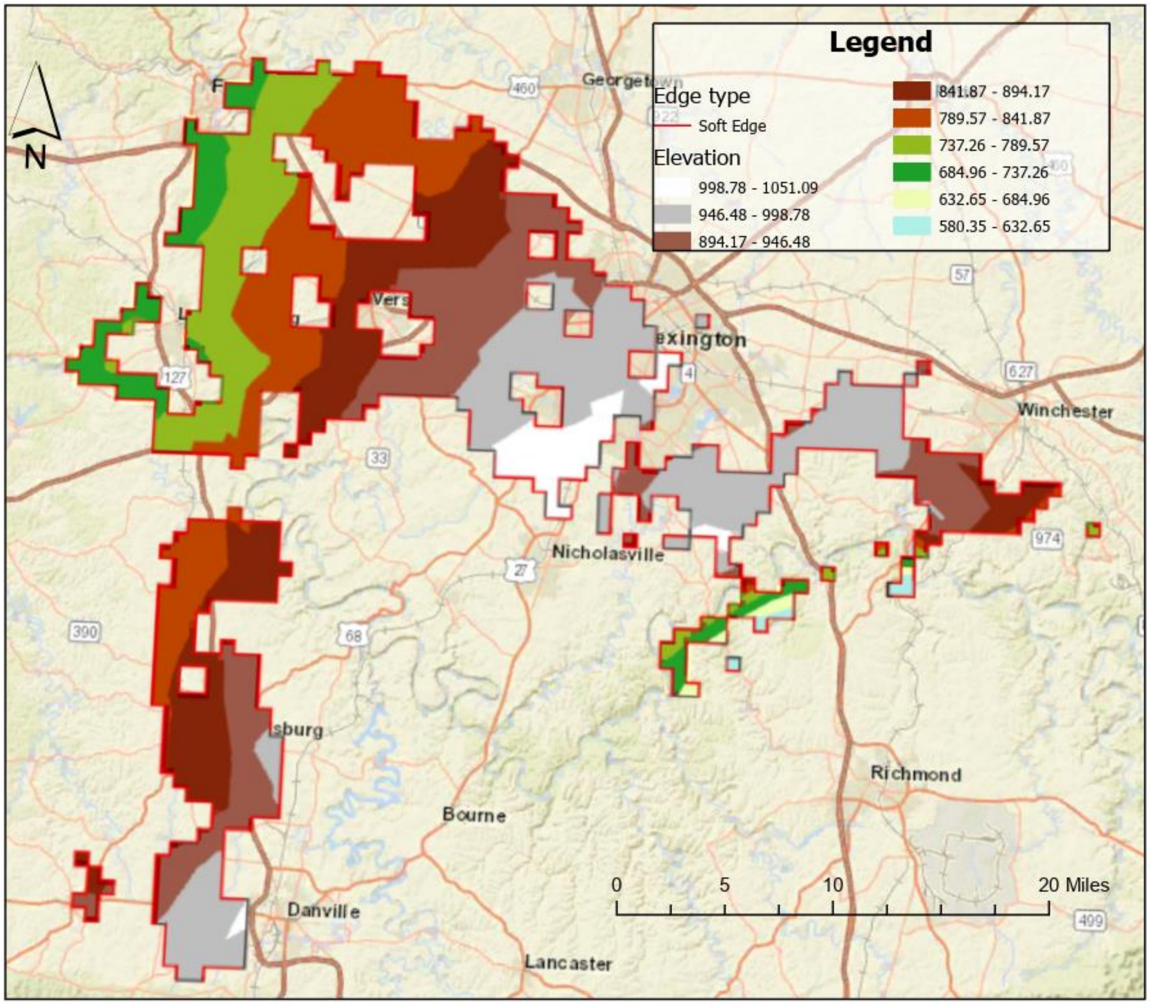


Figure 16. The output of the “Raster to TIN” tool for the Brannon Member, which generated a triangulated irregular network (TIN) for the member. Bands of color represent ranges of elevation in feet above sea level for triangular-prism polygons in regions of similar elevation.

to Multipatch" tool to generate triangular-prism polygons that were draped over the TIN file to provide enveloping layers that represent the surface topography of each horizon member with their respective surface morphology and elevations (Fig. 17).

The creation of 3-D layers for each member allowed for analysis of the relative elevations of each stratigraphic horizon and how the horizons met and interacted at facies boundaries. To increase ease of analysis, the vertical exaggeration for each layer was increased to twenty times the true values, because the layers within the formation are relatively thin and flat and do not capture intertonguing relationships easily at base-level elevations (Fig. 18). A 3-D-generated fault model of known faults within the study area was obtained from KGS and imported into the scene map to analyze the trends between elevation and geographic proximity to known faults (Kentucky Geological Survey, 2023).

2.3 Analysis

The process of data analysis within this project was purposefully done manually instead of utilizing software or automated processes. This manual approach ensured that the 3-D data visualization was as geologically accurate as possible in relation to the units and tongues, which also allowed for the use of field work to supplement any uncertainty in the data. The automation process, while capable of the same geological precision, has a steep learning curve for automating tools and workflows within ArcGIS Pro using arcpy Jupyter Notebooks. The hybrid model of using both field and digitized-map data increases confidence in not only the digital mapping, but also in the methodology used within the project.

To analyze elevation trends within each horizon, the "Slope" tool was used on each clipped raster file within the 2-D map. This created a surface which highlighted the percentage of hillslope present across the stratigraphic surface related to changes in elevation (Figure 19). The "Create Feature Class" tool was used to create layers for each respective stratigraphic horizon. Within these new feature-class layers, the "Create Features" tool was used to create polylines (Appendix 1) that delineate trends within hillslope data so that the location of these trends and the percentage of slope change could be compared to the proximity of known faults in the study area. The trends for all layers

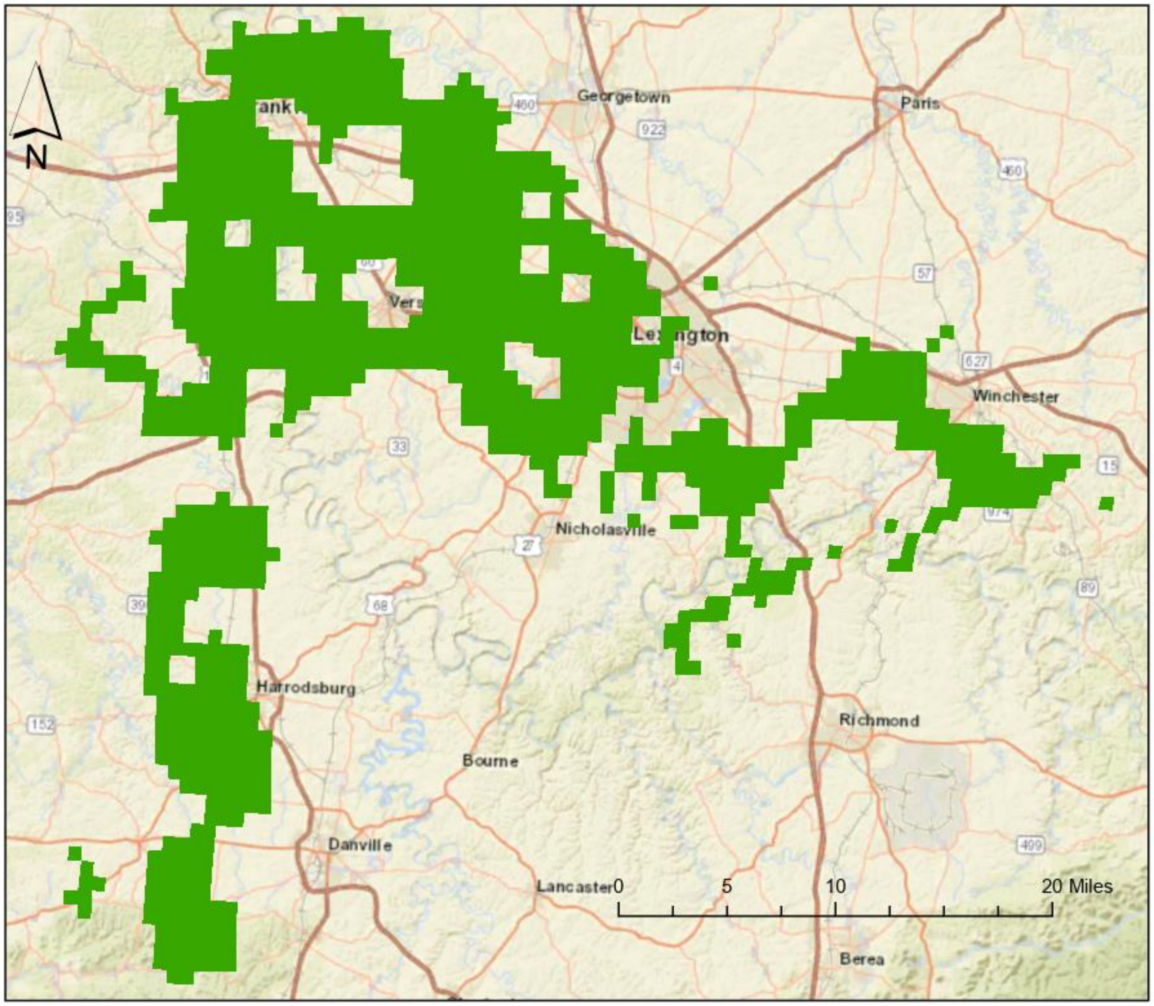


Figure 17. The output of the “Interpolate Polygon to Multipatch” tool for the Brannon Member. The green layer shows a polygon surface that is draped over the TIN file (Fig. 16) to provide an elevational layer as viewed from above that represents the Brannon Member with the respective surface morphology and elevation.

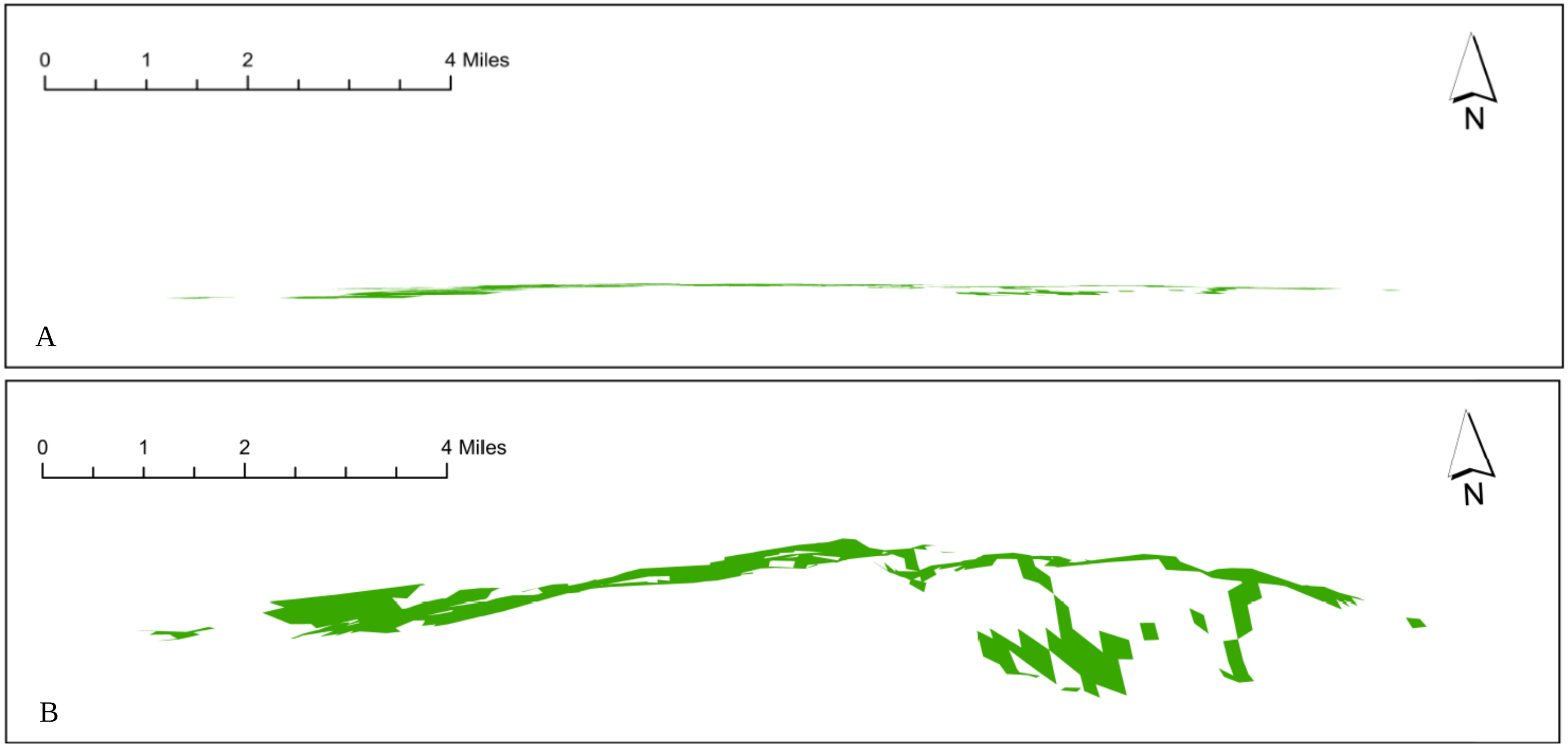


Figure 18. A.) The 3-D visualization of the Brannon Member, viewed with no vertical exaggeration. The Brannon Member is shown viewed from south of the member, and looking northward. Due to the relatively small differences in elevation, changes in surface topography are not visible at this scale. B.) The 3-D visualization of the Brannon Member, viewed at twenty-times vertical exaggeration. The Brannon Member is shown viewed from south of the member, and looking northward. All members will be shown at twenty-times vertical exaggeration to highlight changes in the surface topography.

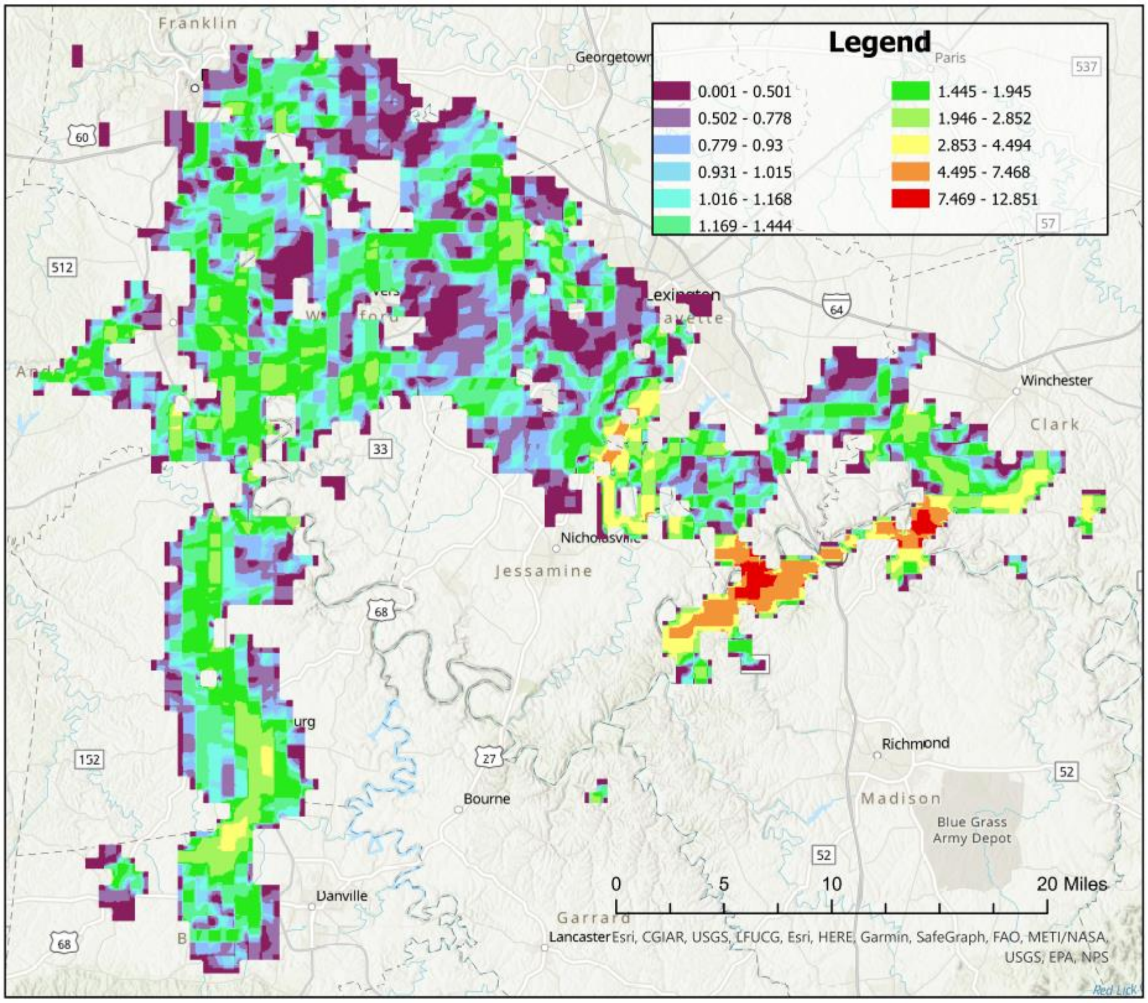


Figure 19. Output of the "Slope" tool for the clipped-raster extent of the Brannon Member from Figure 14. The colors within the legend represent percent rise in slope for the surface topography, with a flat surface represented by 0 percent, and a 45-degree surface represented by 100 percent.

were viewed at once to determine where any geographic overlap occurred so as to indicate where a through-going control affected multiple members. These slope-feature classes were then compared to structure-contour lines from the digital 1:24,000 Kentucky Geologic Map for possible correlation between trends and mapped structure-contours.

CHAPTER 3. Results and Discussion

3.1 Two-Dimensional Map

The product of the two-dimensional map (Fig. 10) shows the lateral extent of the surface expression of stratigraphic contacts of members and member tongues in the upper Lexington Limestone. Figure 10 shows that several members of the upper Lexington are terminated locally within the formation and are not continuous throughout the entire geographic extent. The Grier (blue), however, is distributed throughout the entire geographic extent of the Lexington Limestone and does not appear to be constrained (Fig. 20). Figure 20 is the 2-D-map version of Figure 10, showing the general trends of a few members and tongues, whose extents are terminated near dashed lines that align with basement structural lineaments A and B from Figure 5.

Structural lineaments A and B in Figure 20 align with the lateral extent of the Sulphur Well, Devils Hollow, and Brannon members. The Sulphur Well Member is only present south of lineament B and is the only member of the upper Lexington that is present south of this lineament. The Devils Hollow member is geographically constrained between lineaments A and B and is not present elsewhere within the Lexington Limestone. Lineament A also denotes the northern extent of the Brannon Member. The Strodes Creek Member is constrained to the eastern side of lineament I (Fig. 20).

The mapped surface faults from the 1:24,000 Kentucky Geologic Map were included in the 2-D map to examine the proximity of faults to the distribution of members in the upper Lexington (Fig. 21) with three major fault systems in the region (Brumfield, Kentucky River, Lexington). The Brumfield Fault coincides with the southernmost surface expression of the Lexington Limestone, and specifically of the Sulphur Well

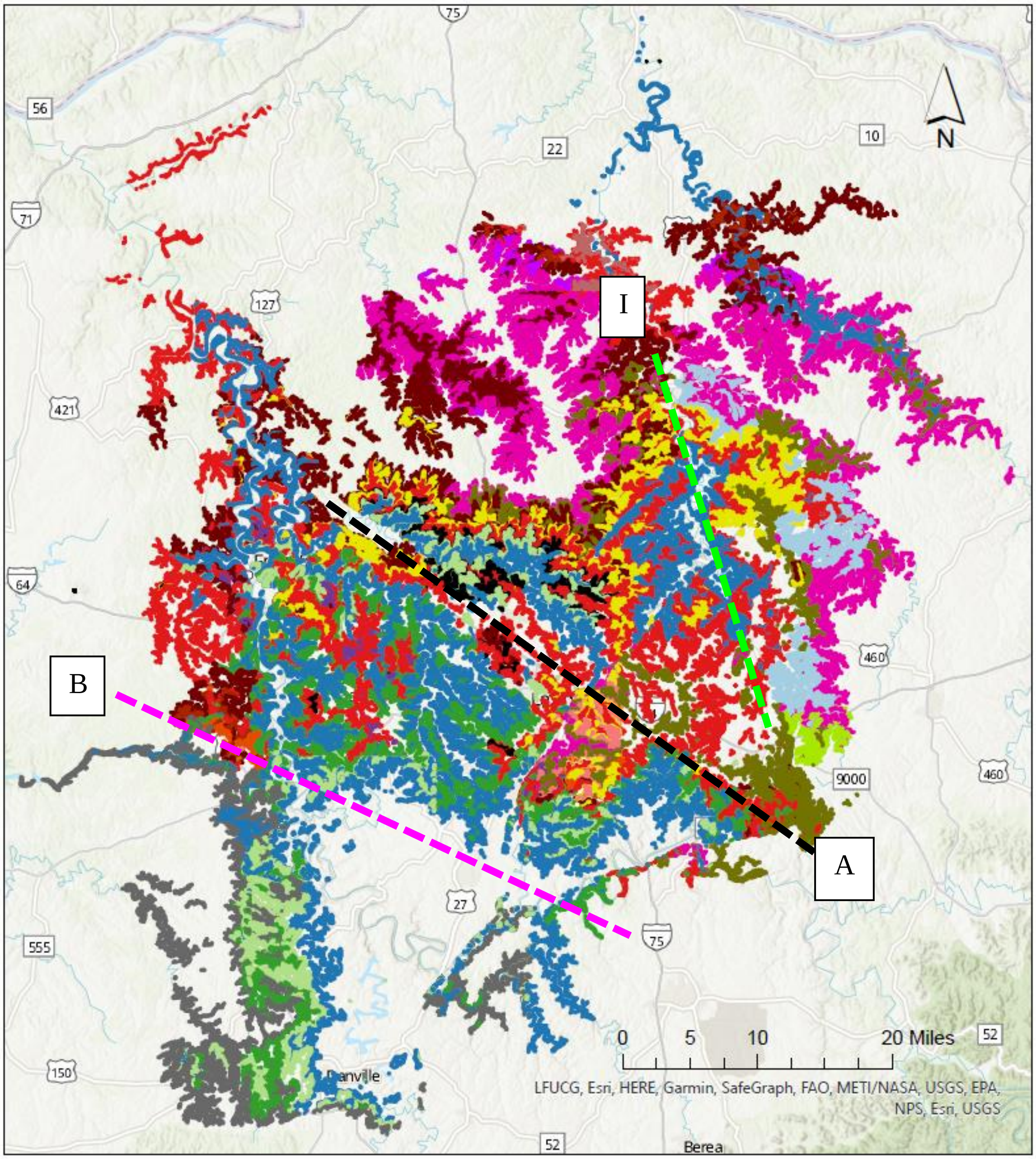


Figure 20. Adapted version of Figure 10. Colored dashed lines A (black), B (pink), and I (lime green) outline regions where tongue or member distributions terminate and represent basement structural lineaments from Figure 5. Lineament I represents smaller, unnamed faults that were not previously labeled. Lineament B denotes the northern limit of the Sulphur Well Member (grey). However, no other members of the upper Lexington occur south of lineament B. Lineament A defines the northern extent of the Brannon Member (dark green). The Devils Hollow Member (purple) only occurs geographically between lineaments A and B, and lineament I marks the westward limit of the Strodes Creek Member (light blue).

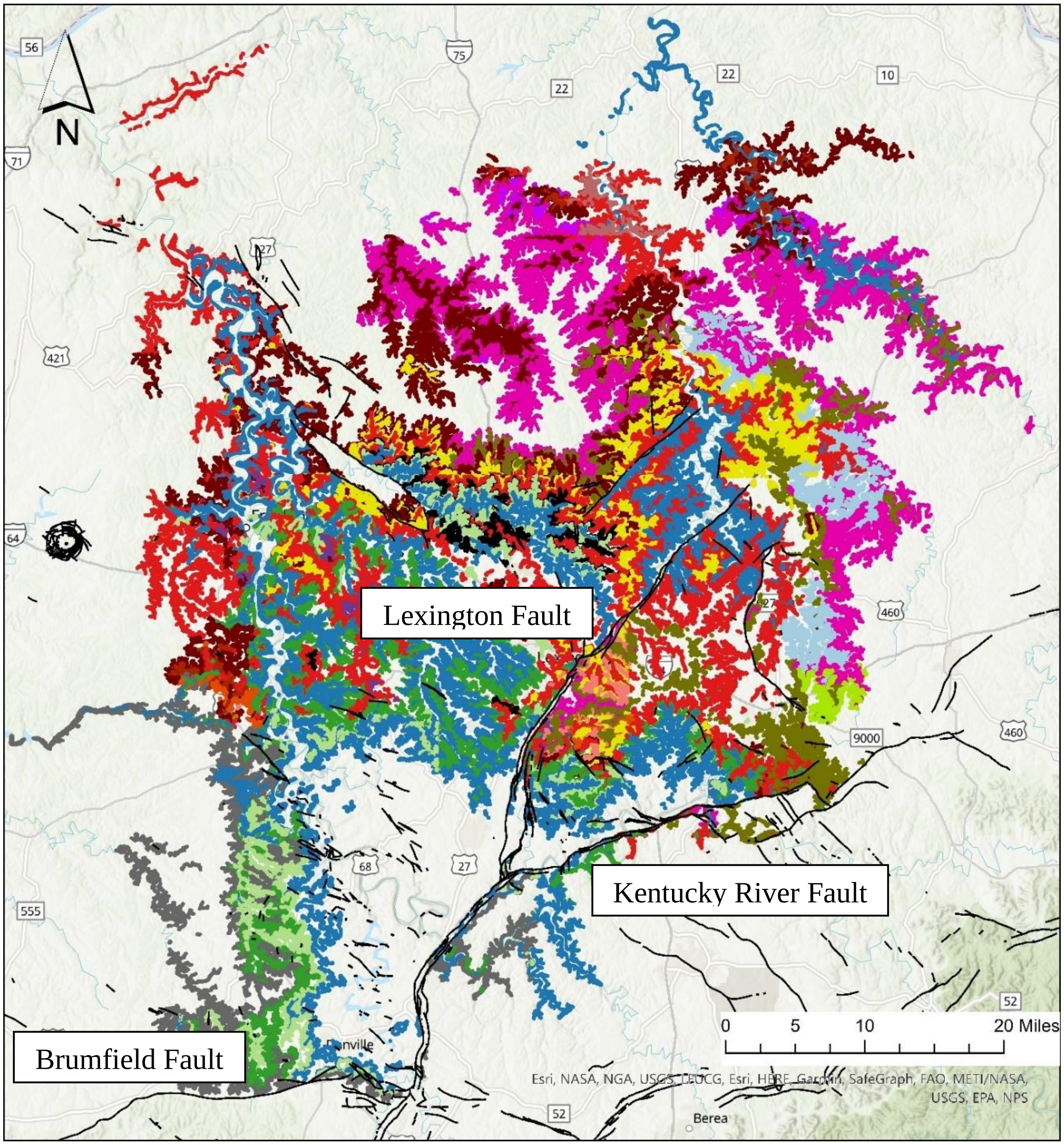


Figure 21. Figure 10 with the mapped surface faults expressed as solid black lines. The three major fault systems in the region are the Brumfield Fault, Lexington Fault, and Kentucky River Fault System. Several smaller surface faults are expressed as smaller black lines, many of which are hidden below the colors.

Member in the upper Lexington Limestone. The Kentucky River Fault system and the Lexington Fault system both intersect the Lexington Limestone (Figs. 5, 21).

3.2 Discussion of the Two-Dimensional Map

The lineament trends denoted in Figure 20 correlate in geographic proximity and cardinal direction with the mapped faults in Figure 21 (see Fig. 22). Lineaments A and B align with trends of the smaller, unnamed mapped surface faults in both cardinal direction and in general geographic proximity. These proximity and directional trends likely indicate that the geographic extent of members of the upper Lexington is locally controlled by basement fault systems that limited facies distribution, as inferred by Black (1986). Specifically, the surface expression of the Sulphur Well Member is bound in the south by the Brumfield Fault and is bound in the north by the series of smaller, unnamed faults. The Kentucky River Fault also acts as part of the northern boundary for eastern parts of the Sulphur Well Member. Hence, the distribution and formation of the Sulphur Well Member were largely controlled by the faults. This could also mean that these smaller surface faults and the Kentucky River Fault system reflect basement precursor fault systems that limited member distribution through growth faulting during deposition (Black, 1986).

The facies boundary between the Sulphur Well Member and other members of the upper Lexington Limestone apparently coincides with one side of the triangular-shaped Tanglewood buildup, suggesting fault control of unit deposition (Fig. 5) (Ettensohn, 1992). Figure 23 shows structural lineaments from Figure 5 superimposed onto Figure 21, which indicates that the margins of the Tanglewood buildup align with the previously mentioned facies boundaries. Several of these smaller faults, which align with the lineaments noted in Figure 20 and in Figure 23 are suggested to have been reactivated by basement faults (Ettensohn, 1992). Reactivation of these faults by subsurface growth is one possible explanation for the lateral constraints on distribution of the Sulphur Well and Devils Hollow members, despite no full thorough-going faults at the surface at the noted boundaries.

The Brannon Member is found both within the boundaries of the Tanglewood buildup and south of the buildup along with the Sulphur Well Member (Fig. 23).

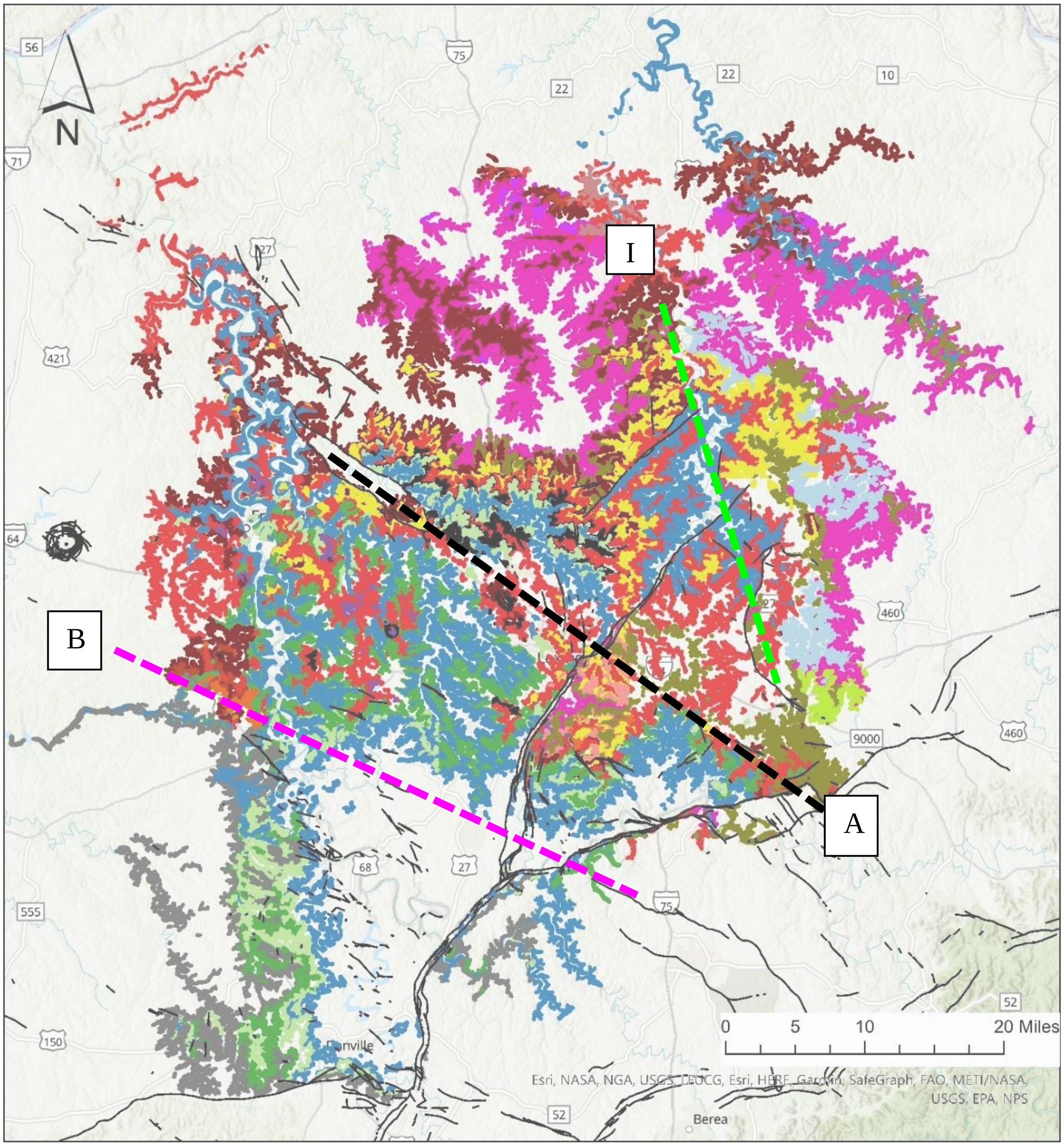


Figure 22. Structural lineaments from Figure 20 superimposed over Figure 21. Lineament B (pink) follows the same general northwest-southeast trend as several smaller surface faults that coincide with the northern limit of the Sulphur Well Member (grey), as well as with the northwest-southeast trend of several smaller surface faults near the labeled Interstate 75. Lineament A (black) follows the same general northwest-southeast trend of surface faults located at the northwest corner of lineament A and runs oblique to the Lexington Fault System and Kentucky River system. Lineament I (lime green) runs oblique to a small fault system and the Lexington Fault system, and overlays a smaller, unnamed, curved fault system.

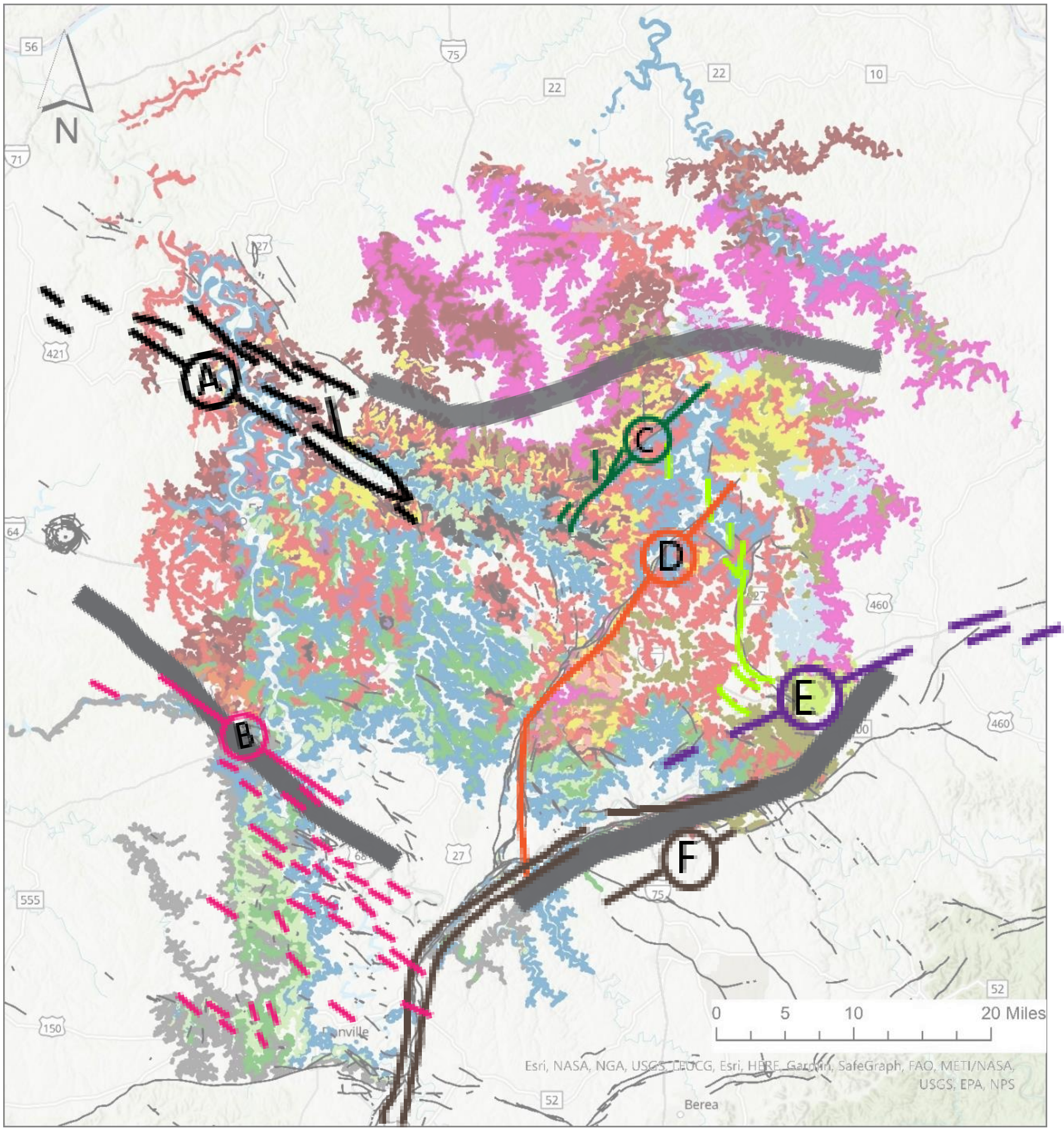


Figure 23. Surface-expressed faults that represent basement precursor faults from Figure 5 (Ettensohn, 1992) superimposed over Figure 22 with distinct colors for each group of basement faults. This highlights the correlation between the margins of the Tanglewood buildup and the extent of some members in the upper Lexington Limestone.

Figure 24 shows an isopach map of Brannon Member thickness, which shows that the Brannon is thickest is the middle of the Tanglewood buildup, and thins towards structural lineaments A and B. It also thins to less than two meters south of the Tanglewood buildup. These Brannon thickness trends relative to structural-lineament trends A and B, indicate likely structural influence on lateral distribution during deposition and is supported by distribution maps showing member restriction between the two structural lineaments (Figs. 20, 24).

3.3 Slope Analyses

The "Slope" tool in Esri ArcGIS Pro shows trends of percent rise in hillslope for the surface elevation of Lexington members, which were compared with previously mapped structure-contour lines available in the 1:24,000 Kentucky Geologic Map. This kind of analysis is useful in comparing the slopes of upper member contacts with structure-contours in order to search for the possible coincidence of high or low slopes with basement structural lineaments. Such analyses may also be useful in establishing possible trends in a stack of members, as well as in describing the nature of contact surfaces for comparison of shoal-complex contacts with those of deeper-water units. The mapped extent of the Sulphur Well and Devils Hollow members were not large enough to show conclusive results relative to structure-contour lines. However, the lower tongue of the Tanglewood (Fig. 25), Brannon (Fig. 26), the main body of the middle tongue of the Tanglewood (Fig. 27), the largest tongue of the Millersburg (Fig. 28), and the largest part of the upper tongue of the Tanglewood (Fig. 29) have extents large enough to analyze relative to structure-contour lines. All slope rasters reveal that the structure-contour lines directly overlay regions of each member that show changes in topographic slope, and especially regions of higher-percent change in topography. Surface faults were mapped overlaying the slope rasters of each member, respectively, (Figs. 30, 31, 32, 33, 34), which show that all areas of steepest percent-in-hillslope changes directly at or near surface faults.

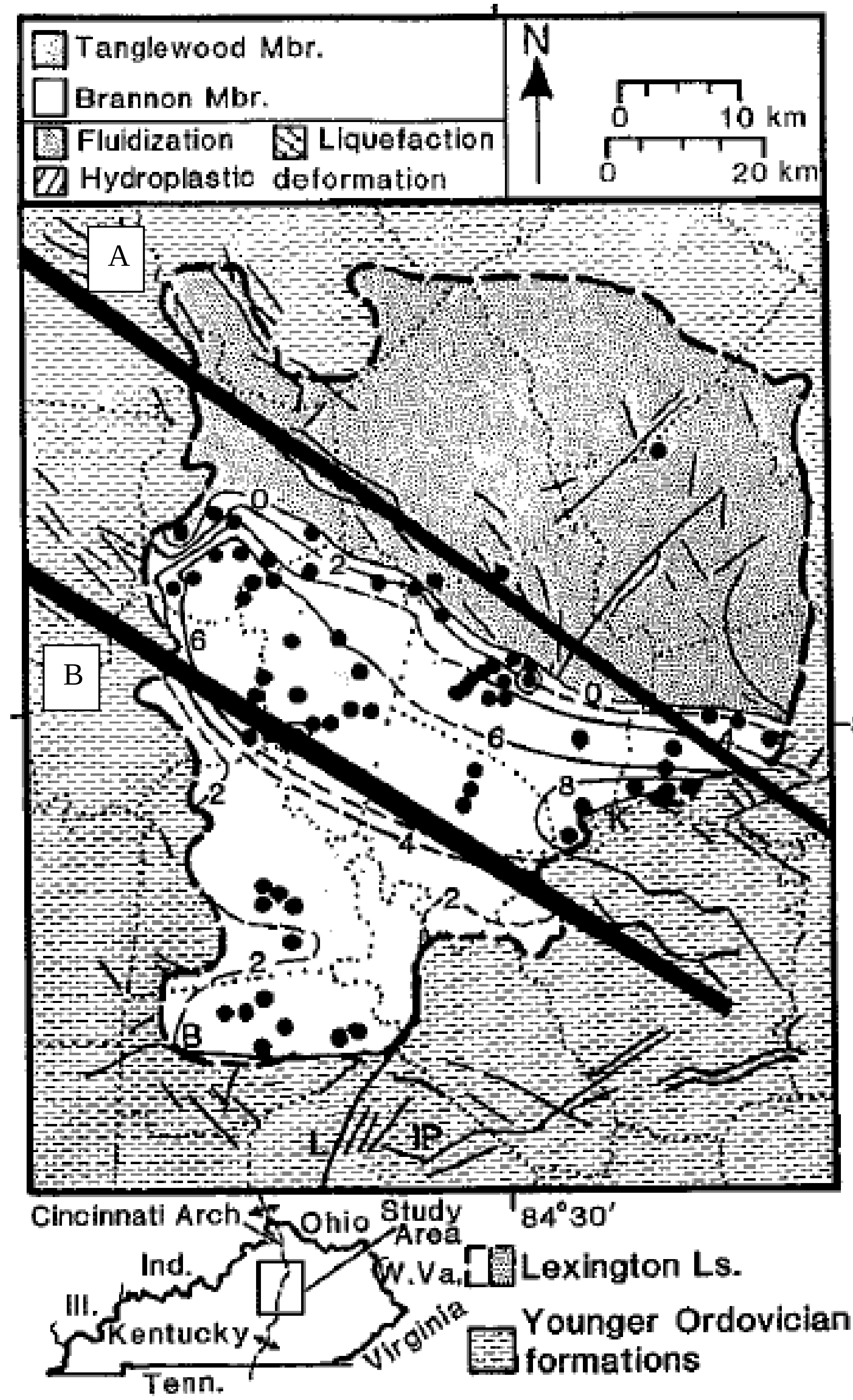
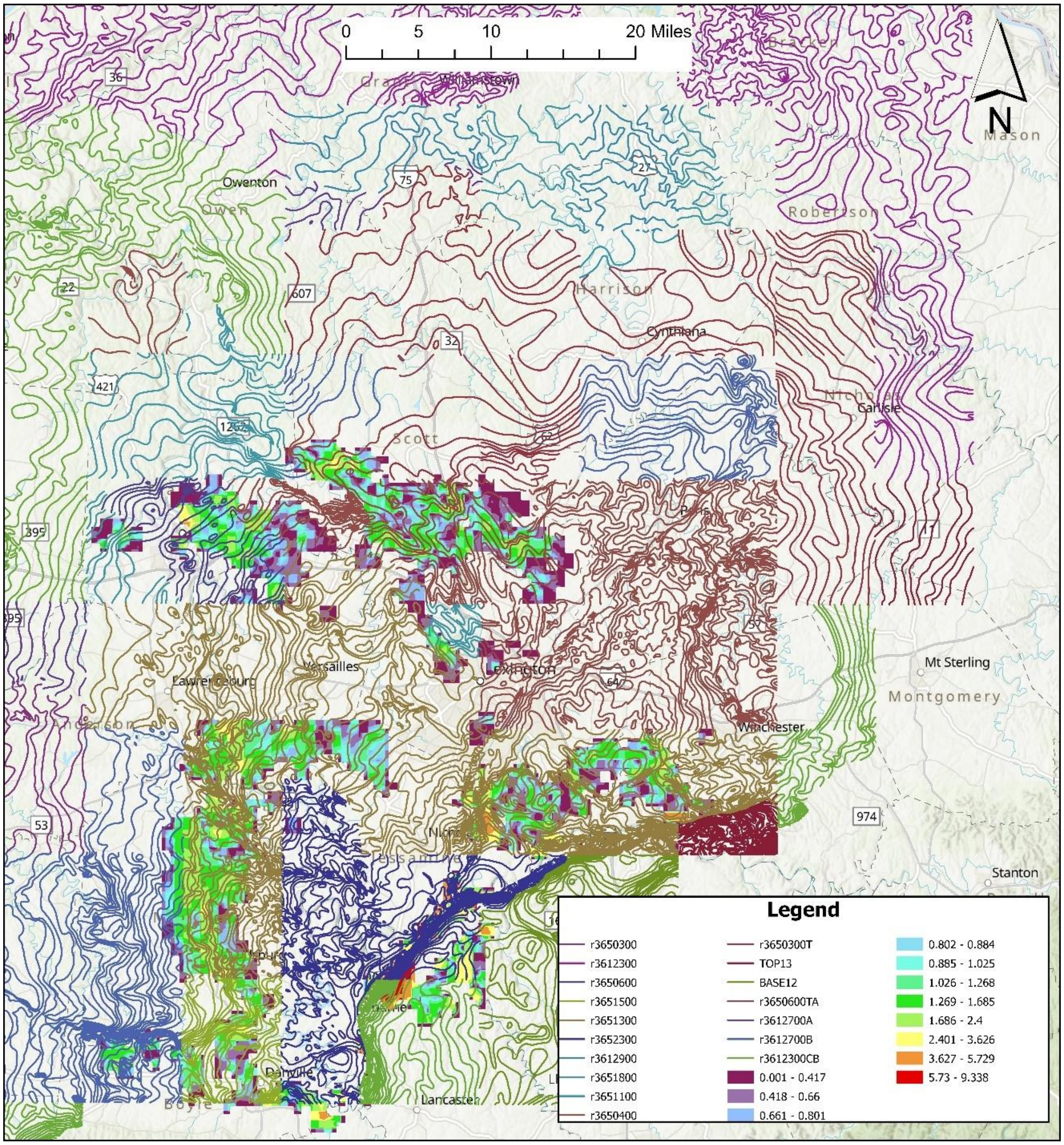


Figure 24. Isopach map (meters) of the Brannon Member showing bed thickness (adapted from Ettensohn et al., 2002b). Solid black lines A and B represent the structural lineaments in Figure 5 that acted as lateral constraints on the deposition of the Brannon Member.


0 5 10 20 Miles
N
Williamstown
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Cynthiana
Nicholas
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Scott
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Robertson
Versailles
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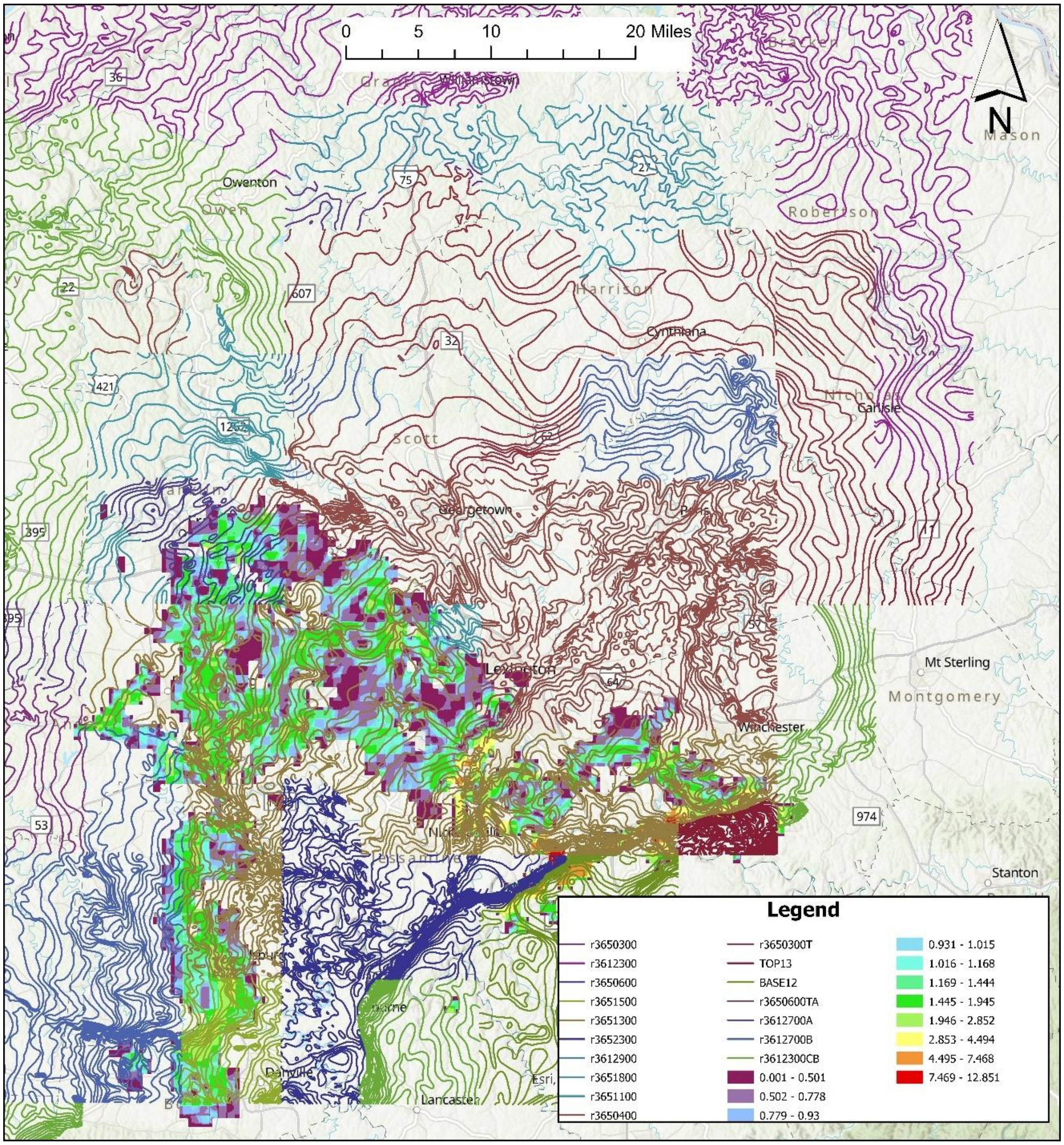
Lawrenceburg
Mt Sterling
Montgomery
Winchester
Stanton
Danville
Lancaster
Legend
r3650300
r3612300
r3650600
r3651500
r3651300
r3652300
r3612900
r3651800
r3651100
r3650400
r3650300T
TOP13
BASE12
r3650600TA
r3612700A
r3612700B
r3612300CB
0.001 - 0.417
0.418 - 0.66
0.661 - 0.801
0.802 - 0.884
0.885 - 1.025
1.026 - 1.268
1.269 - 1.685
1.686 - 2.4
2.401 - 3.626
3.627 - 5.729
5.73 - 9.338

Figure 25. The slope raster for the lower tongue of the Tanglewood Member with structure-contours overlaying the slope raster. The colors within the legend for the slope raster represent percent rise in slope for the surface topography, with a flat surface represented by 0 percent, and a 45-degree surface represented by 100 percent. The “r” number series represents codes in the 1:24,000 Kentucky Geologic Map for structure-contours drawn on top of different units. r3650300 was drawn on the top of the Lexington Limestone. r3612300 was drawn on the base of the Fairview Formation above the Lexington. r3650600 was drawn on the base of the Devils Hollow Member. r3651500 was drawn on the top of the Perryville Member of the lower Lexington. r3651300 was drawn on the base of the Brannon Member. r3652300 was drawn on the top of the Tyrone Formation below the Lexington Limestone. r3612900 was drawn on the Point Pleasant tongue of the Clays Ferry Formation above the Lexington Limestone. r3651800 was drawn on the top of the Lexington Limestone. r3651100 was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). r3650400 was drawn on the base of the Millersburg Member. r3650300T was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). TOP13 was drawn on the top of the Garrard Sandstone above the Lexington. BASE12 was drawn on the base of the Garrard Sandstone above the Lexington. r3650600TA was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). r3612700A was drawn on the top of the Clays Ferry Formation above the Lexington. r3612700B was drawn on the base of the Clays Ferry Formation above the Lexington Limestone. r3612300CB was drawn on the Calloway Creek Formation above the Lexington Limestone.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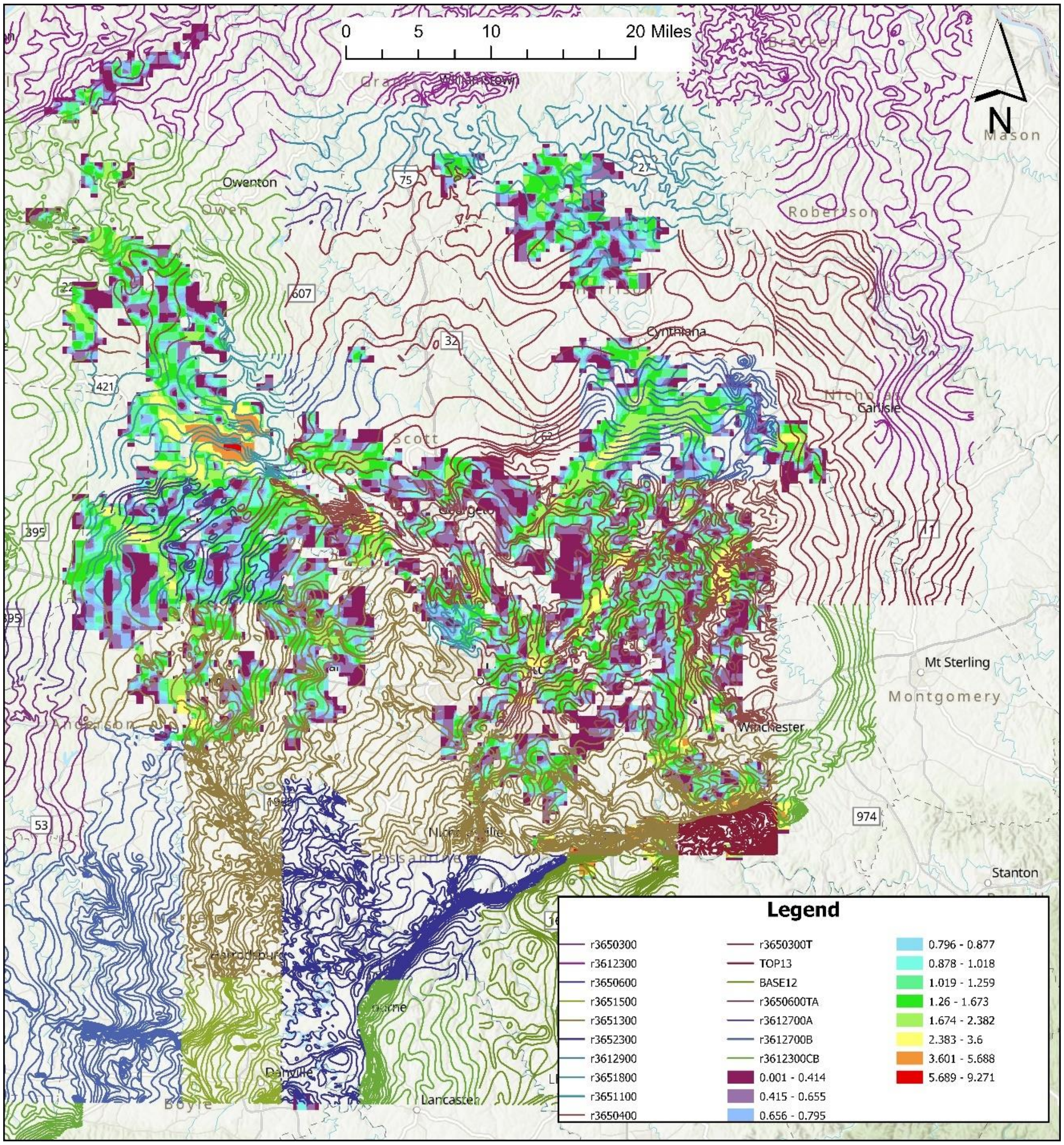
r3650400
r3650300T
TOP13
BASE12
r3650600TA
r3612700A
r3612700B
r3612300CB
0.001 - 0.501
0.502 - 0.778
0.779 - 0.93
0.931 - 1.015
1.016 - 1.168
1.169 - 1.444
1.445 - 1.945
1.946 - 2.852
2.853 - 4.494
4.495 - 7.468
7.469 - 12.851
Owenton
Harrison
Cynthiana
Scott
Georgetown
Lexington
Winchester
Mt Sterling
Montgomery
Stanton
Danville
Lancaster
Mason
Carlisle

Figure 26. The slope raster for the Brannon Member with structure-contours overlaying the slope raster. The colors within the legend for the slope raster represent percent rise in slope for the surface topography, with a flat surface represented by 0 percent, and a 45-degree surface represented by 100 percent. The “r” number series represents codes in the 1:24,000 Kentucky Geologic Map for structure-contours drawn on top of different units. r3650300 was drawn on the top of the Lexington Limestone. r3612300 was drawn on the base of the Fairview Formation above the Lexington. r3650600 was drawn on the base of the Devils Hollow Member. r3651500 was drawn on the top of the Perryville Member of the lower Lexington. r3651300 was drawn on the base of the Brannon Member. r3652300 was drawn on the top of the Tyrone Formation below the Lexington Limestone. r3612900 was drawn on the Point Pleasant tongue of the Clays Ferry Formation above the Lexington Limestone. r3651800 was drawn on the top of the Lexington Limestone. r3651100 was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). r3650400 was drawn on the base of the Millersburg Member. r3650300T was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). TOP13 was drawn on the top of the Garrard Sandstone above the Lexington. BASE12 was drawn on the base of the Garrard Sandstone above the Lexington. r3650600TA was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). r3612700A was drawn on the top of the Clays Ferry Formation above the Lexington. r3612700B was drawn on the base of the Clays Ferry Formation above the Lexington Limestone. r3612300CB was drawn on the Calloway Creek Formation above the Lexington Limestone.


0 5 10 20 Miles
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Cynthiana
Carlisle
Mt Sterling
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Winchester
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Robertson
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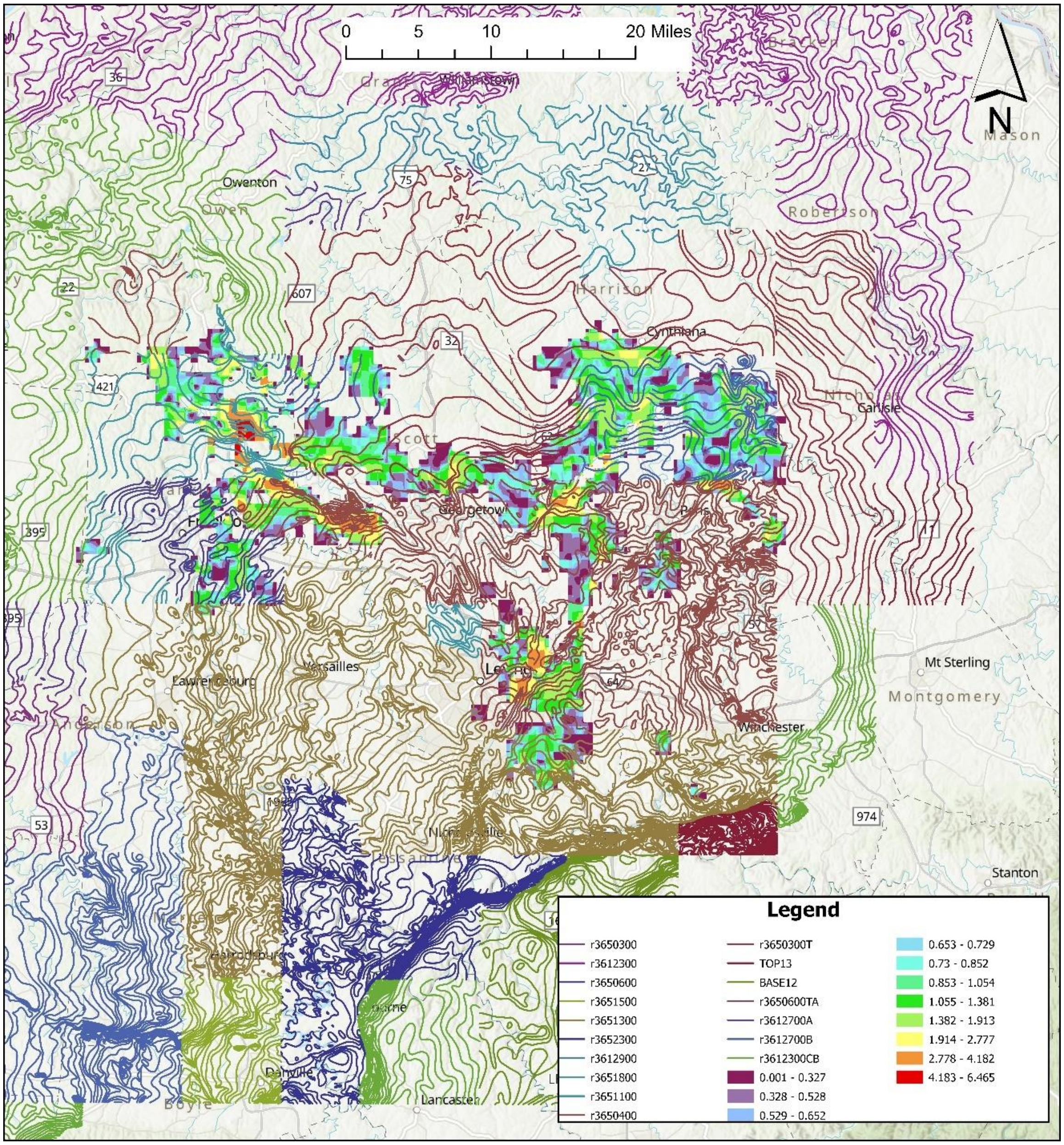
r3612300
r3650600
r3651500
r3651300
r3652300
r3612900
r3651800
r3651100
r3650400
r3650300T
TOP13
BASE12
r3650600TA
r3612700A
r3612700B
r3612300CB
0.001 - 0.414
0.415 - 0.655
0.656 - 0.795
0.796 - 0.877
0.878 - 1.018
1.019 - 1.259
1.26 - 1.673
1.674 - 2.382
2.383 - 3.6
3.601 - 5.688
5.689 - 9.271

Figure 27. The slope raster for the middle tongue of the Tanglewood Member with structure-contours overlaying the slope raster. The colors within the legend for the slope raster represent percent rise in slope for the surface topography, with a flat surface represented by 0 percent, and a 45-degree surface represented by 100 percent. The “r” number series represents codes in the 1:24,000 Kentucky Geologic Map for structure-contours drawn on top of different units. r3650300 was drawn on the top of the Lexington Limestone. r3612300 was drawn on the base of the Fairview Formation above the Lexington. r3650600 was drawn on the base of the Devils Hollow Member. r3651500 was drawn on the top of the Perryville Member of the lower Lexington. r3651300 was drawn on the base of the Brannon Member. r3652300 was drawn on the top of the Tyrone Formation below the Lexington Limestone. r3612900 was drawn on the Point Pleasant tongue of the Clays Ferry Formation above the Lexington Limestone. r3651800 was drawn on the top of the Lexington Limestone. r3651100 was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). r3650400 was drawn on the base of the Millersburg Member. r3650300T was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). TOP13 was drawn on the top of the Garrard Sandstone above the Lexington. BASE12 was drawn on the base of the Garrard Sandstone above the Lexington. r3650600TA was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). r3612700A was drawn on the top of the Clays Ferry Formation above the Lexington. r3612700B was drawn on the base of the Clays Ferry Formation above the Lexington Limestone. r3612300CB was drawn on the Calloway Creek Formation above the Lexington Limestone.



0 5 10 20 Miles
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Williamstown
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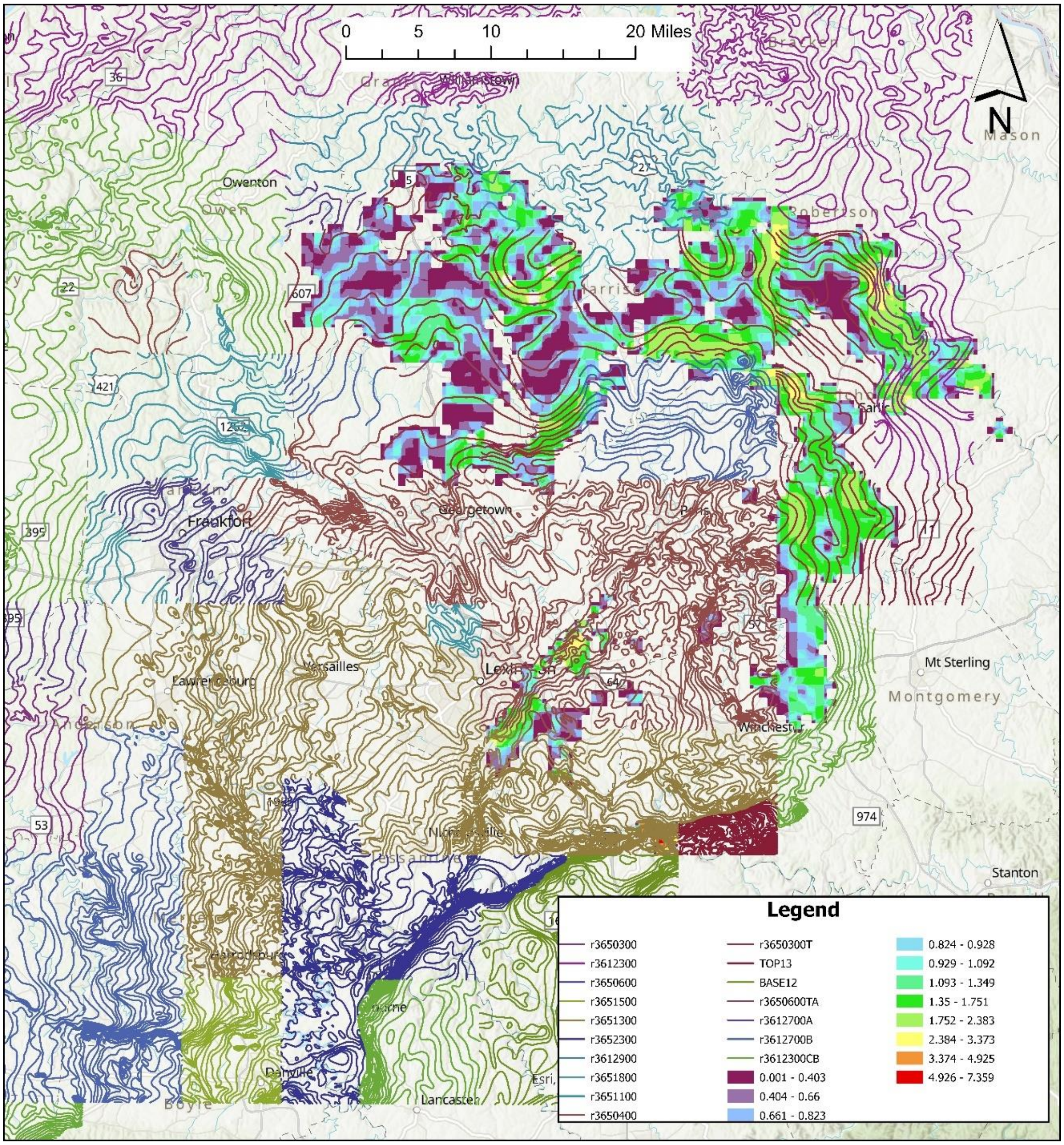
Harrison
Cynthiana
Carlisle
Mason
Georgetown
Versailles
Lawrenceburg
Winchester
Mt Sterling
Montgomery
Stanton
Danville
Lancaster
Legend
r3650300
r3612300
r3650600
r3651500
r3651300
r3652300
r3612900
r3651800
r3651100
r3650400
r3650300T
TOP13
BASE12
r3650600TA
r3612700A
r3612700B
r3612300CB
0.001 - 0.327
0.328 - 0.528
0.529 - 0.652
0.653 - 0.729
0.73 - 0.852
0.853 - 1.054
1.055 - 1.381
1.382 - 1.913
1.914 - 2.777
2.778 - 4.182
4.183 - 6.465

Figure 28. The slope raster for the largest tongue of the Millersburg Member with structure-contours overlaying the slope raster. The colors within the legend for the slope raster represent percent rise in slope for the surface topography, with a flat surface represented by 0 percent, and a 45-degree surface represented by 100 percent. The "r" number series represents codes in the 1:24,000 Kentucky Geologic Map for structure-contours drawn on top of different units. r3650300 was drawn on the top of the Lexington Limestone. r3612300 was drawn on the base of the Fairview Formation above the Lexington. r3650600 was drawn on the base of the Devils Hollow Member. r3651500 was drawn on the top of the Perryville Member of the lower Lexington. r3651300 was drawn on the base of the Brannon Member. r3652300 was drawn on the top of the Tyrone Formation below the Lexington Limestone. r3612900 was drawn on the Point Pleasant tongue of the Clays Ferry Formation above the Lexington Limestone. r3651800 was drawn on the top of the Lexington Limestone. r3651100 was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). r3650400 was drawn on the base of the Millersburg Member. r3650300T was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). TOP13 was drawn on the top of the Garrard Sandstone above the Lexington. BASE12 was drawn on the base of the Garrard Sandstone above the Lexington. r3650600TA was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). r3612700A was drawn on the top of the Clays Ferry Formation above the Lexington. r3612700B was drawn on the base of the Clays Ferry Formation above the Lexington Limestone. r3612300CB was drawn on the Calloway Creek Formation above the Lexington Limestone.



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Mt Sterling
Montgomery
Versailles
Lawrenceburg
Lexington
Winchester
Stanton
Nicholasville
Harrodsburg
Danville
Lancaster
Legend
r3650300
r3612300
r3650600
r3651500
r3651300
r3652300
r3612900
r3651800
r3651100
r3650400
r3650300T
TOP13
BASE12
r3650600TA
r3612700A
r3612700B
r3612300CB
0.001 - 0.403
0.404 - 0.66
0.661 - 0.823
0.824 - 0.928
0.929 - 1.092
1.093 - 1.349
1.35 - 1.751
1.752 - 2.383
2.384 - 3.373
3.374 - 4.925
4.926 - 7.359

Figure 29. The slope raster for the upper tongue of the Tanglewood Member with structure-contours overlaying the slope raster. The colors within the legend for the slope raster represent percent rise in slope for the surface topography, with a flat surface represented by 0 percent, and a 45-degree surface represented by 100 percent. The “r” number series represents codes in the 1:24,000 Kentucky Geologic Map for structure-contours drawn on top of different units. r3650300 was drawn on the top of the Lexington Limestone. r3612300 was drawn on the base of the Fairview Formation above the Lexington. r3650600 was drawn on the base of the Devils Hollow Member. r3651500 was drawn on the top of the Perryville Member of the lower Lexington. r3651300 was drawn on the base of the Brannon Member. r3652300 was drawn on the top of the Tyrone Formation below the Lexington Limestone. r3612900 was drawn on the Point Pleasant tongue of the Clays Ferry Formation above the Lexington Limestone. r3651800 was drawn on the top of the Lexington Limestone. r3651100 was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). r3650400 was drawn on the base of the Millersburg Member. r3650300T was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). TOP13 was drawn on the top of the Garrard Sandstone above the Lexington. BASE12 was drawn on the base of the Garrard Sandstone above the Lexington. r3650600TA was drawn on the top of a tongue of the Tanglewood Member (tongue not noted). r3612700A was drawn on the top of the Clays Ferry Formation above the Lexington. r3612700B was drawn on the base of the Clays Ferry Formation above the Lexington Limestone. r3612300CB was drawn on the Calloway Creek Formation above the Lexington Limestone.

3.4 Discussion of the Slope Analyses

The direct overlap of the structure-contours with the locations of changes in the slope of the topography of the members strongly supports the influence of post-depositional structural control on the topography of these members. However, the overlap of the contours with slope changes does not indicate any structural control or influence on the distribution or formation of these members. The structure-contour lines may indicate the locations of member deformation in response to tectonic and structural influences that occurred during the formation of these. However, the results are inconclusive for determining the likelihood of structural influence on member distribution. Moreover, the fact that many of the structural contours were drawn on formations or members outside of the Lexington Limestone decreases the likelihood that they would reflect structures and structural influences within the Lexington Limestone.

The maps of slope rasters with overlain surface faults (Figs. 30, 31, 32, 33, 34) all indicate that the highest percent change in hillslope for the members occurred along or near mapped surface faults. These slope changes likely suggests that the steepest changes in surface topography in the members were caused by the post-depositional movement of these faults. The location of surface faults along the northern extent of the Brannon Member (Fig. 31) further suggest that these surface faults align with a basement-fault lineament (Black, 1986) that was active during the deposition of the Brannon, and hence limited the extent of the member.

3.5 Three-Dimensional Map

The three-dimensional map of the surface expression of the upper Lexington Limestone (Supplemental Video 1) viewed from above (Fig. 35) shows the same trends that are present within the 2-D map (Fig. 20). The Sulphur Well Member is still bounded by lineament B; the Devils Hollow Member occurs between lineaments A and B; the Brannon Member by lineament A; and the Strodes Creek Member is bounded by lineament I. The superposition of members atop one another in Figure 35, similar to that of a stratigraphic column, shows that several members reflect similar trends in lateral distribution. For example, the yellow tongue of the Millersburg Member appears to

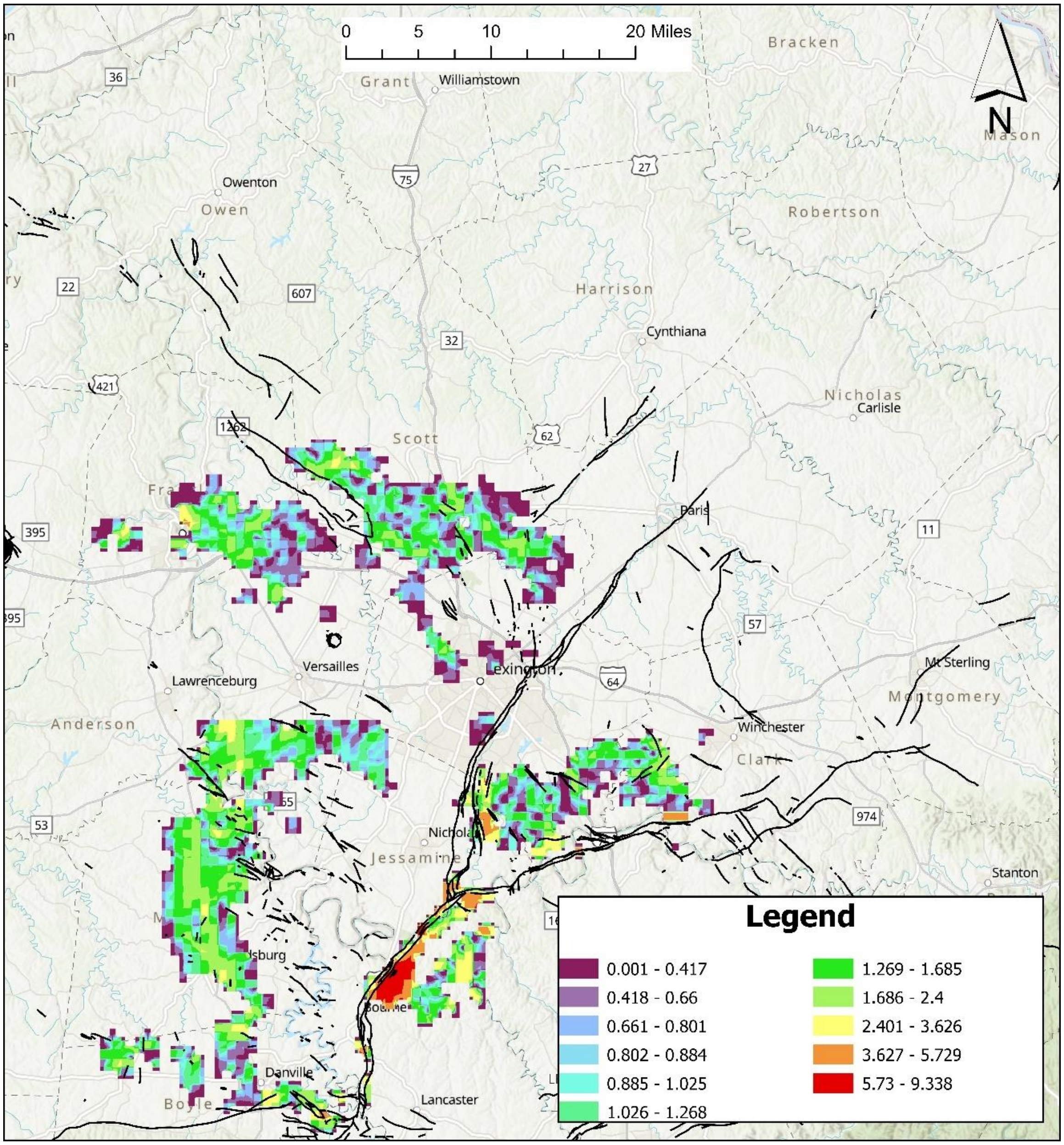

Figure 30. The slope raster for the lower tongue of the Tanglewood Member with surface faults overlaying the slope raster. The colors within the legend for the slope raster represent percent rise in slope for the surface topography, with a flat surface represented by 0 percent, and a 45-degree surface represented by 100 percent. Areas of highest values of percent hillslope correspond with the presence of surface faults.

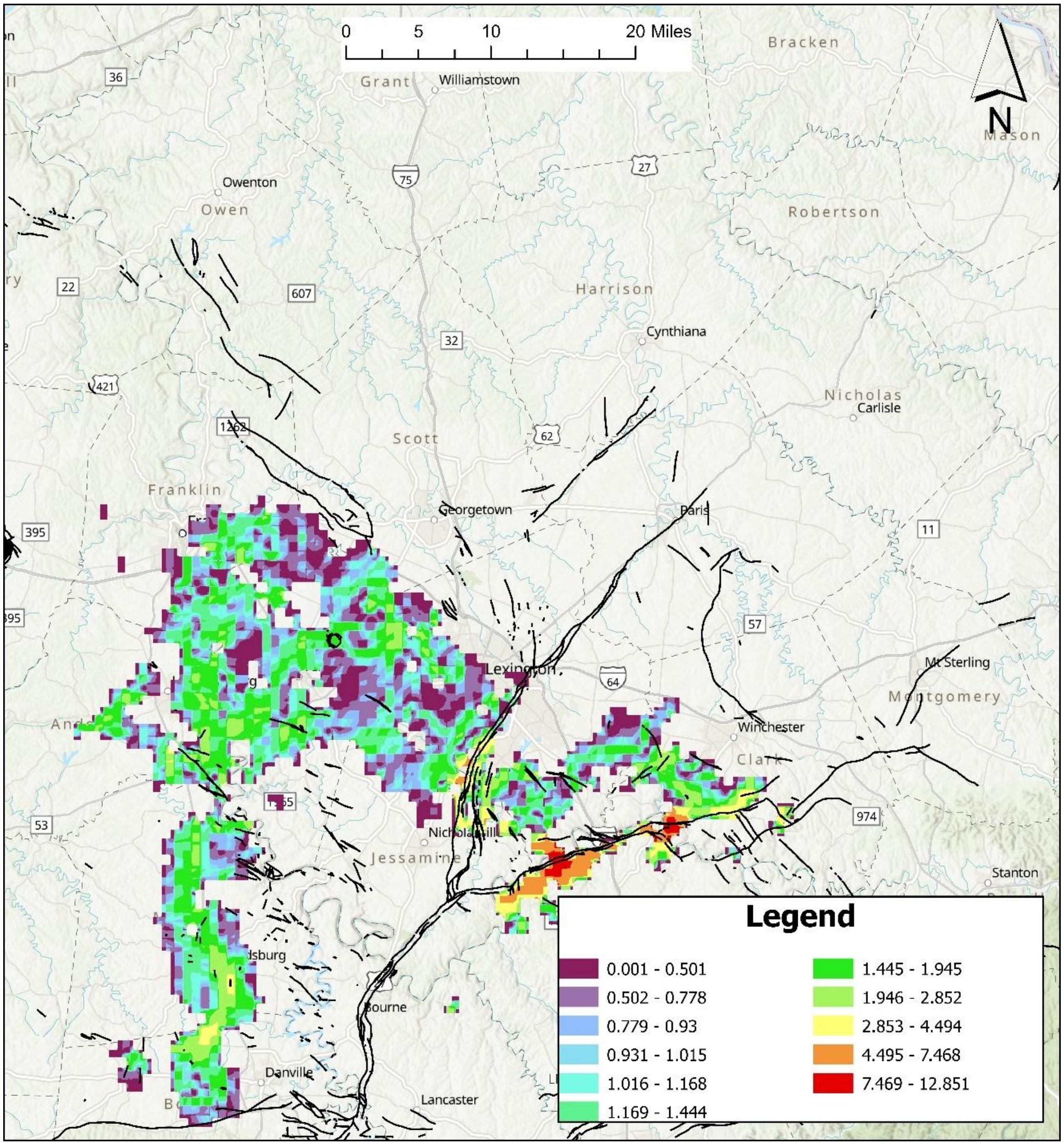

Figure 31. The slope raster for the Brannon Member with surface faults overlaying the slope raster. The colors within the legend for the slope raster represent percent rise in slope for the surface topography, with a flat surface represented by 0 percent, and a 45-degree surface represented by 100 percent. Areas of highest values of percent hillslope correspond with the presence of surface faults.

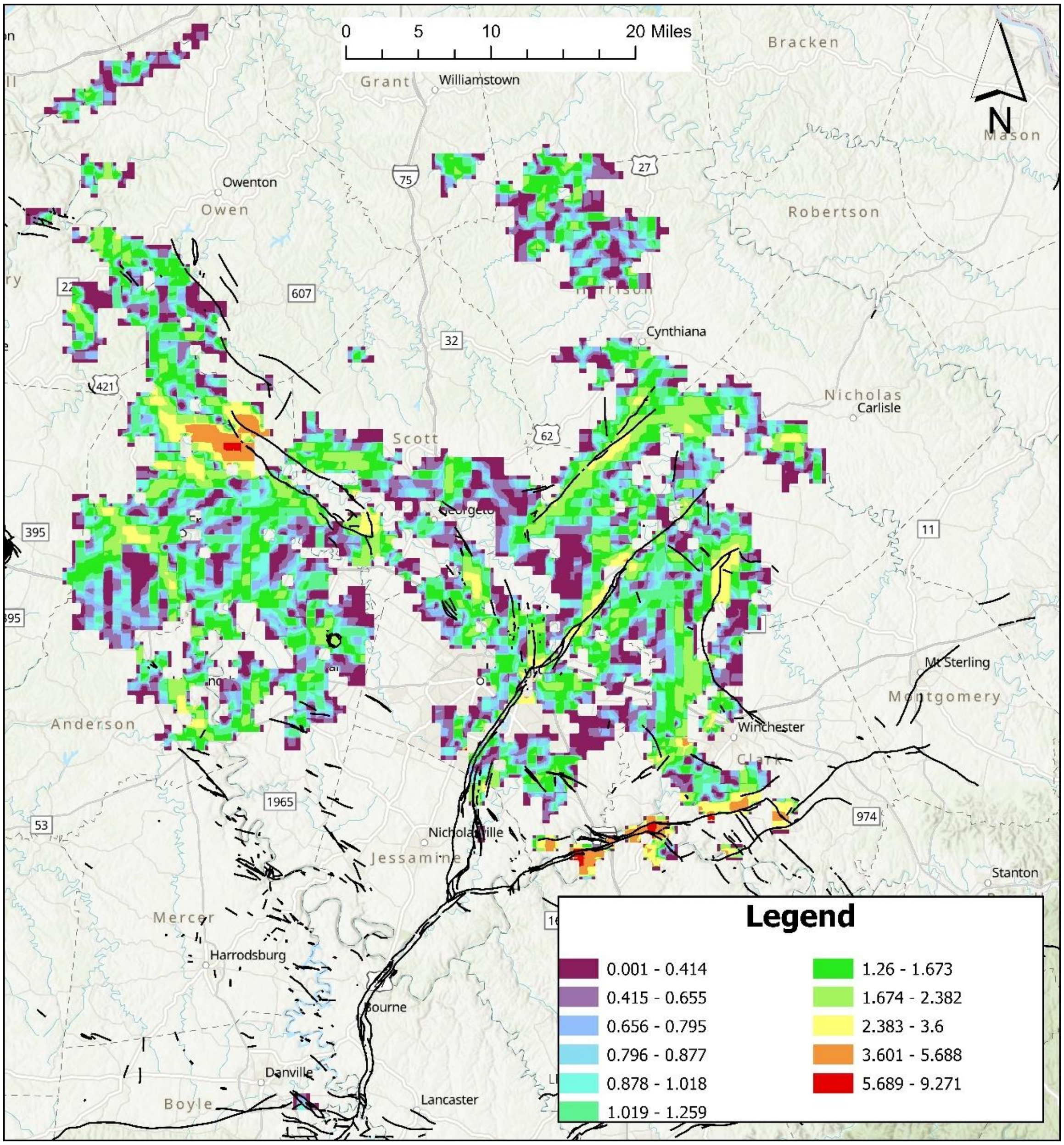

Figure 32. The slope raster for the middle tongue of the Tanglewood Member with surface faults overlaying the slope raster. The colors within the legend for the slope raster represent percent rise in slope for the surface topography, with a flat surface represented by 0 percent, and a 45-degree surface represented by 100 percent. Areas of highest values of percent hillslope correspond with the presence of surface faults.

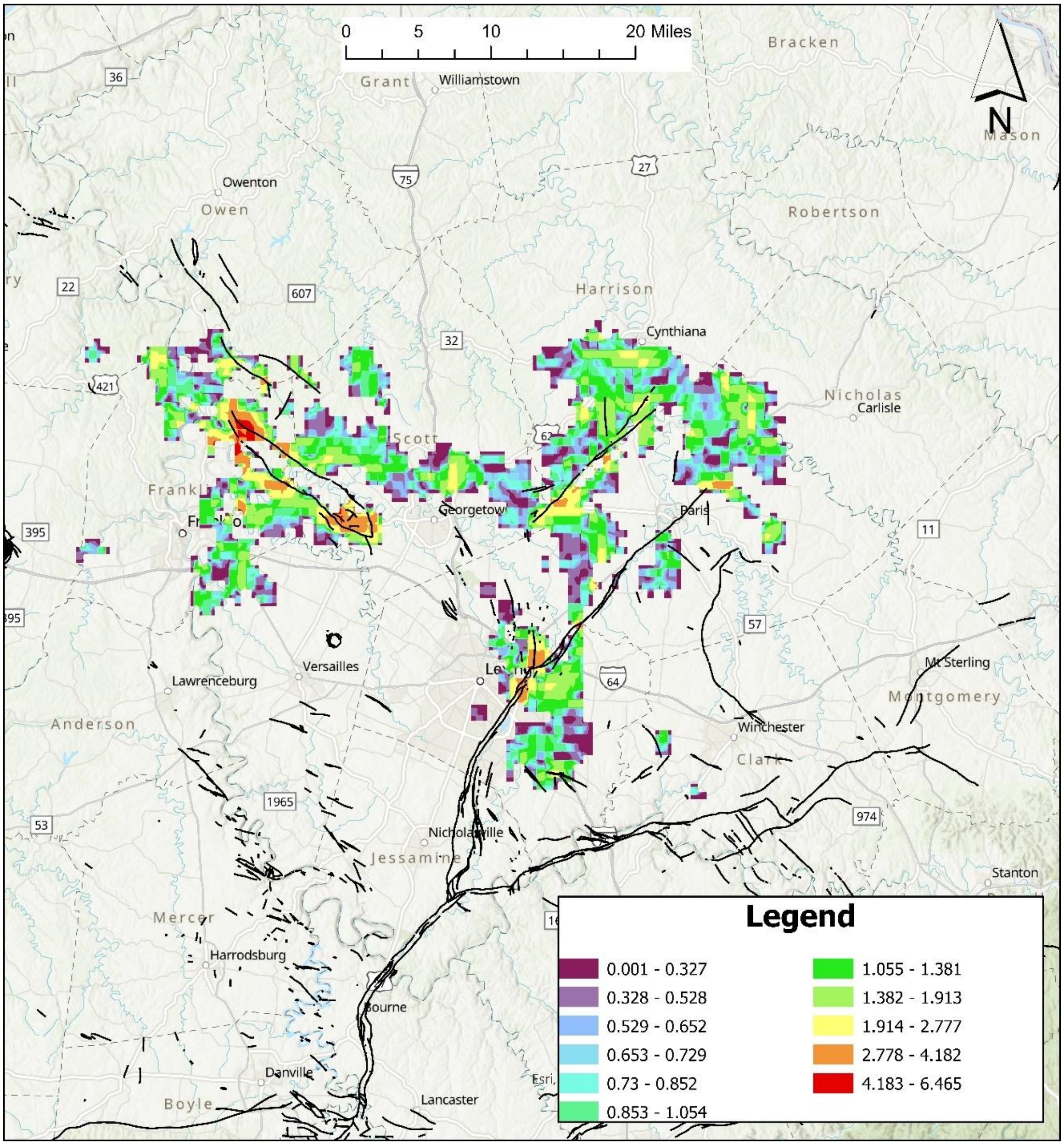

Figure 33. The slope raster for the largest tongue of the Millersburg Member with surface faults overlaying the slope raster. The colors within the legend for the slope raster represent percent rise in slope for the surface topography, with a flat surface represented by 0 percent, and a 45-degree surface represented by 100 percent. Areas of highest values of percent hillslope correspond with the presence of surface faults.

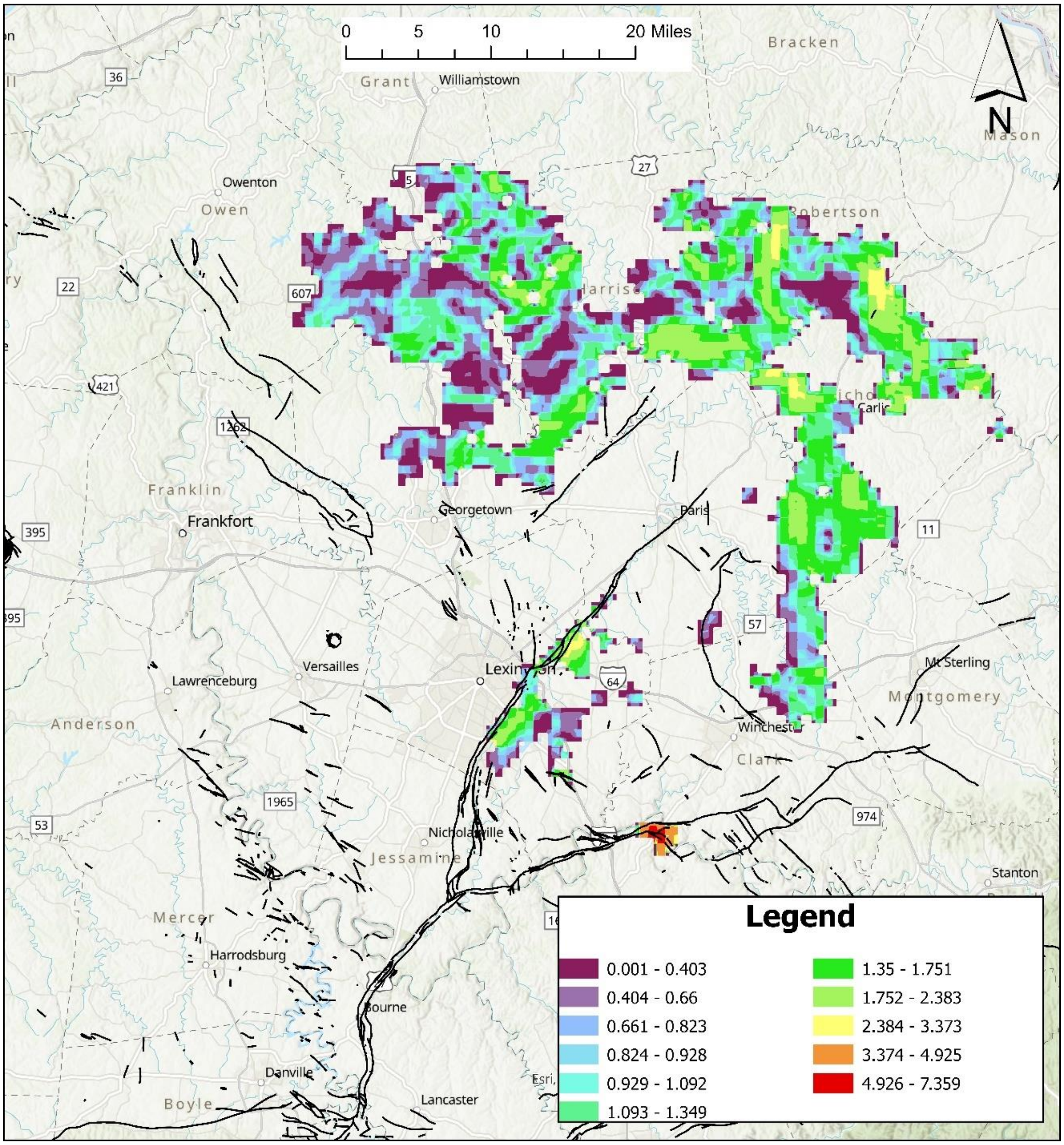

Figure 34. The slope raster for the upper tongue of the Tanglewood Member with surface faults overlaying the slope raster. The colors within the legend for the slope raster represent percent rise in slope for the surface topography, with a flat surface represented by 0 percent, and a 45-degree surface represented by 100 percent. Areas of highest values of percent hillslope correspond with the presence of surface faults.

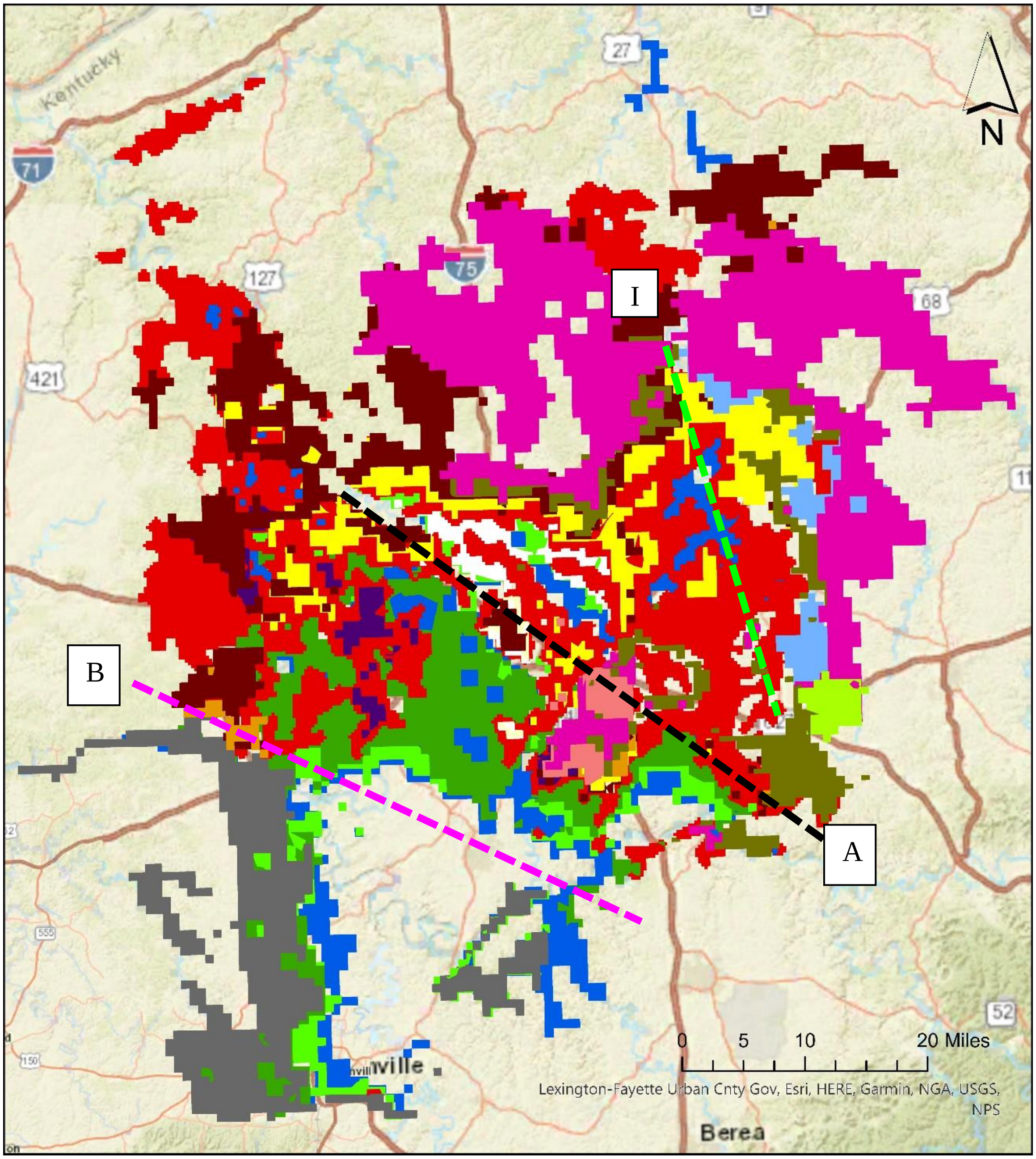

Figure 35. View from above of the 3-D map for members of the upper Lexington Limestone with structural lineaments (colored dashed lines) from Figure 20 superimposed on top of the Lexington Limestone. Lineament B (pink) denotes the northward limit of the Sulphur Well Member (grey), which only occurs south of the line and does not occur elsewhere within the Lexington Limestone. However, no other members of the upper Lexington occur south of lineament B. Lineament B (black) marks the northward geographic lateral extent of the Brannon Member (dark green), which does not occur north of the line within the Lexington. The Devils Hollow Member (purple) only occurs geographically between lineaments A and B. Lineament I (lime green) denotes the lateral extent of the Strodes Creek Member (light blue), where the member is only present east of Lineament I.

terminate where the fuchsia upper tongue of the Tanglewood Member begins in the northeastern region of the map (Fig. 35). On the other hand, the yellow tongue of the Millersburg Member appears to terminate at its southern margin where the green Brannon Member begins (Fig. 35).

The 3-D nature of the map allows for the rotation of the map along the x, y, and z axes to view the members from any vantage point. The rotation of the map to view in east-west profile and with a northward-pointing vantage point shows member positions based upon their mapped elevations (Fig. 36). Figure 36 shows that the Lexington Limestone has a gentle westward dip on the western flank of the Jessamine Dome. In the foreground of Figure 36, there appears to be a declivity along which several members show a drastic decrease in elevation (Fig. 37). The Brannon, Grier, and tongues of the Tanglewood member are continuous across this declivity boundary and show that they are sloping downward (Fig. 37) (Supplemental Video 1). Structural lineaments A and B in Figure 35 are also related to localized elevational changes (Figs. 38, 39). Structural lineament B represents the northern extent of the Sulphur Well Member and the line along which members of the upper Lexington Limestone begin to increase in elevation toward the north (Fig. 38). Structural lineament A represents the northern limit of the Brannon and Devils Hollow members and is accompanied by a "v"-shaped depression in the elevations and slopes of all members present in this region (Fig. 39).

The inclusion of the 3-D faults in this 3-D map (Fig. 40) (Supplemental Video 2) shows trends similar to those noted in the 2-D map and in the 2-D faults (Fig. 21). The three major fault systems present in the region (Brumfield, Lexington, Kentucky River) are mapped in Figure 40, but several of the smaller surface faults were not included due to computer-hardware processing limitations. The Brumfield Fault acts as a southern limit, terminating the Sulphur Well and all members present in this location, such that no Lexington members appear south of this boundary at the surface. The Lexington Fault and the surrounding smaller faults act as limits for the lateral distribution of the Strodes Creek Member (light blue) and constrain the upper tongue of the Tanglewood Member (fuchsia).

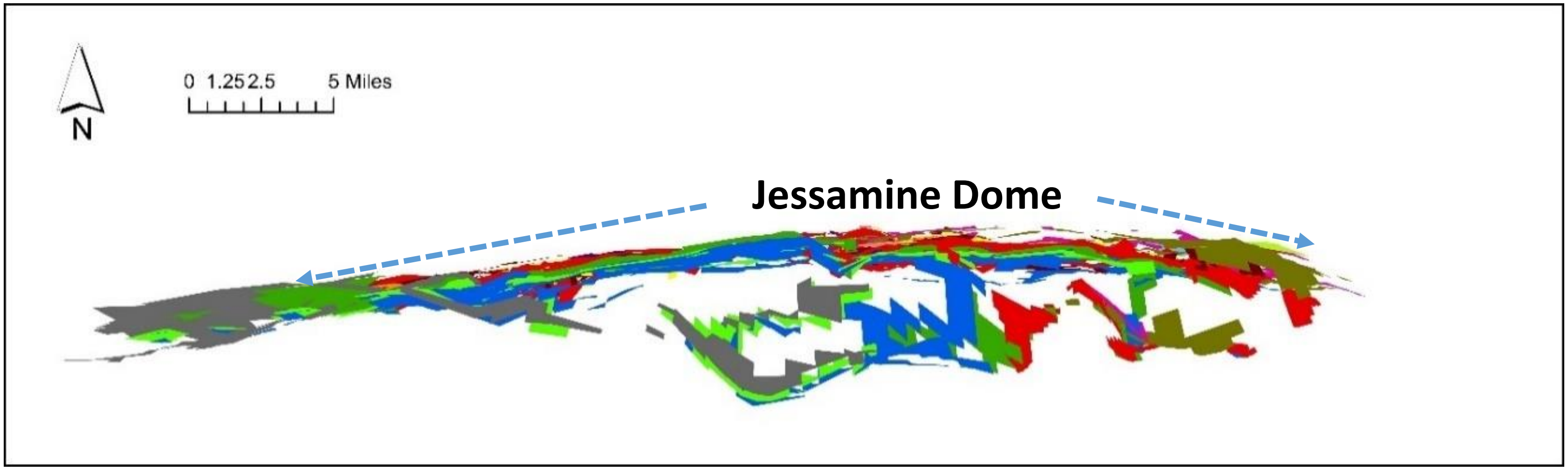

Figure 36. 3-D-profile view of the upper Lexington Limestone looking north. The profile view expresses the shape of the Jessamine Dome present in the study area. Members are mapped superpositionally based upon mapped elevations, creating a stacked effect. A drastic sloping of members and decrease in elevation is present in the bottom middle of the figure along the Kentucky River Fault System.

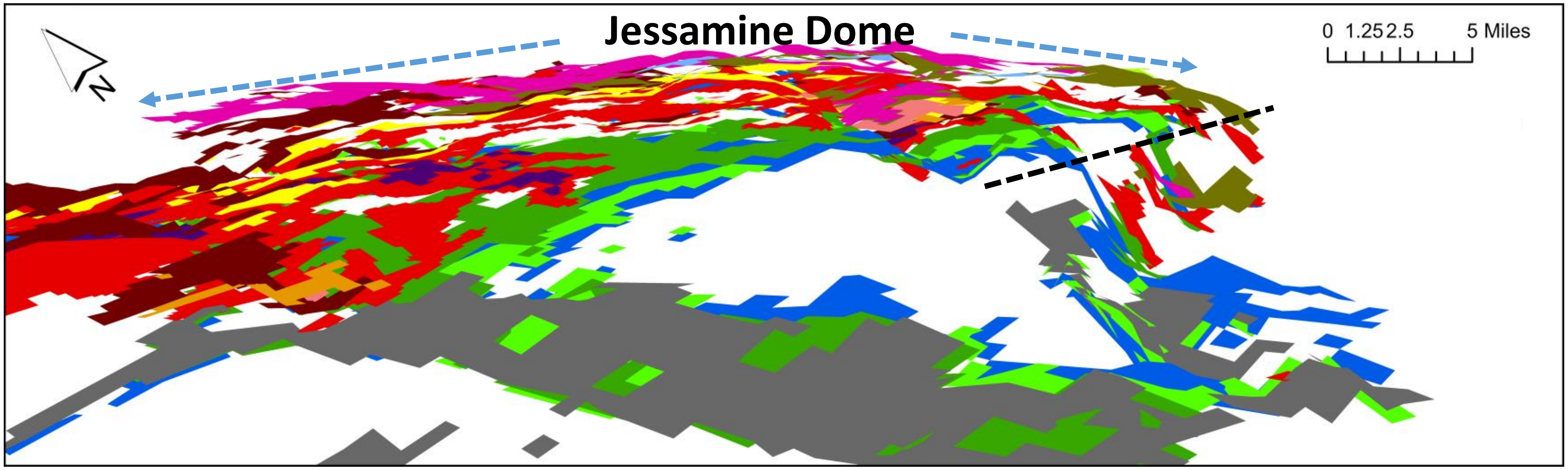

Figure 37. 3-D-profile view of the upper Lexington Limestone looking northeast. The profile view demonstrates the shape of the Jessamine Dome in the study area. Members are mapped superpositionally based upon elevations, creating a stacked effect. The black dashed line denotes the location of a major declivity that represents the Kentucky River Fault system. The Grier (blue), Brannon (dark green), and tongues of the Tanglewood (red, fuchsia) are continuous in their slope downward along the declivity.

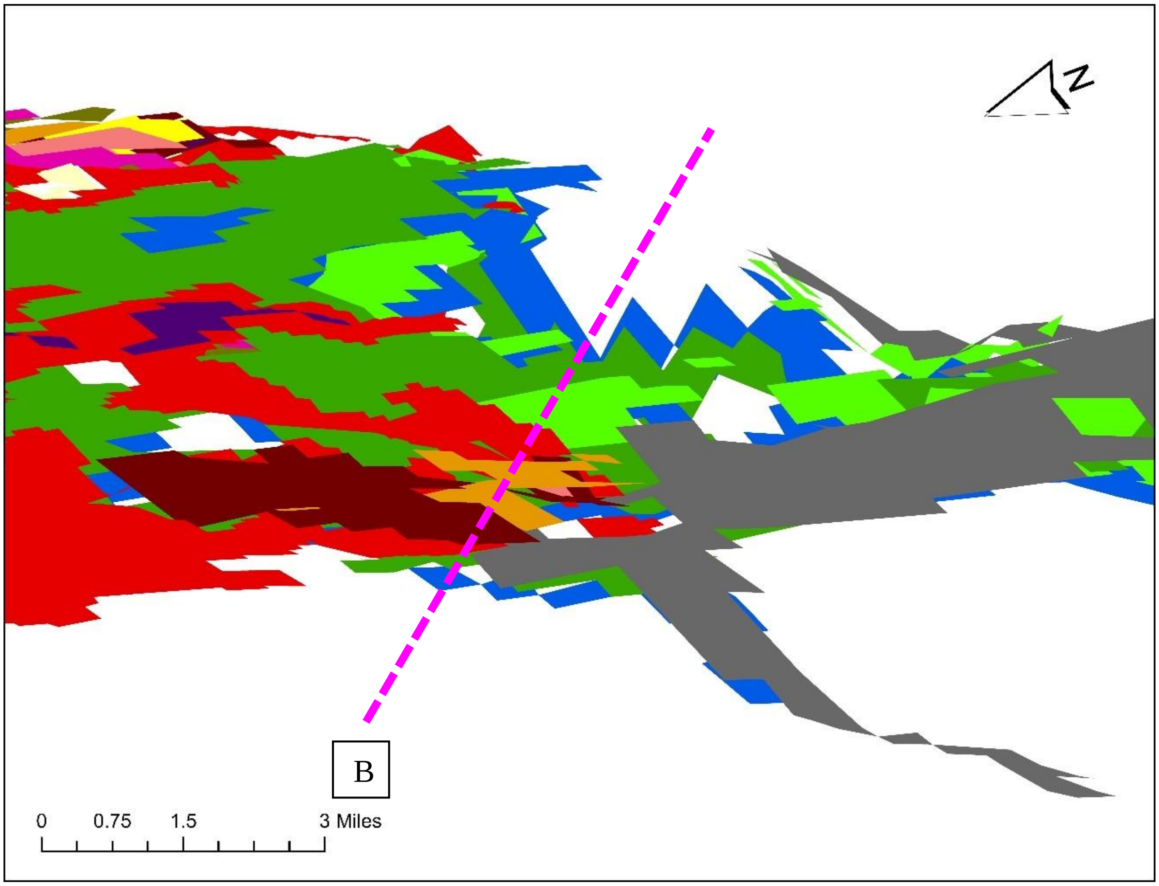

Figure 38. 3-D visualization of the pink dashed structural lineament B from Figure 20, looking southeastward along the structural lineament. North (left) of the structural lineament, the members of the upper Lexington Limestone begin to rise in elevation, whereas the Sulphur Well Member (grey) and other lower Lexington members drop in elevation.

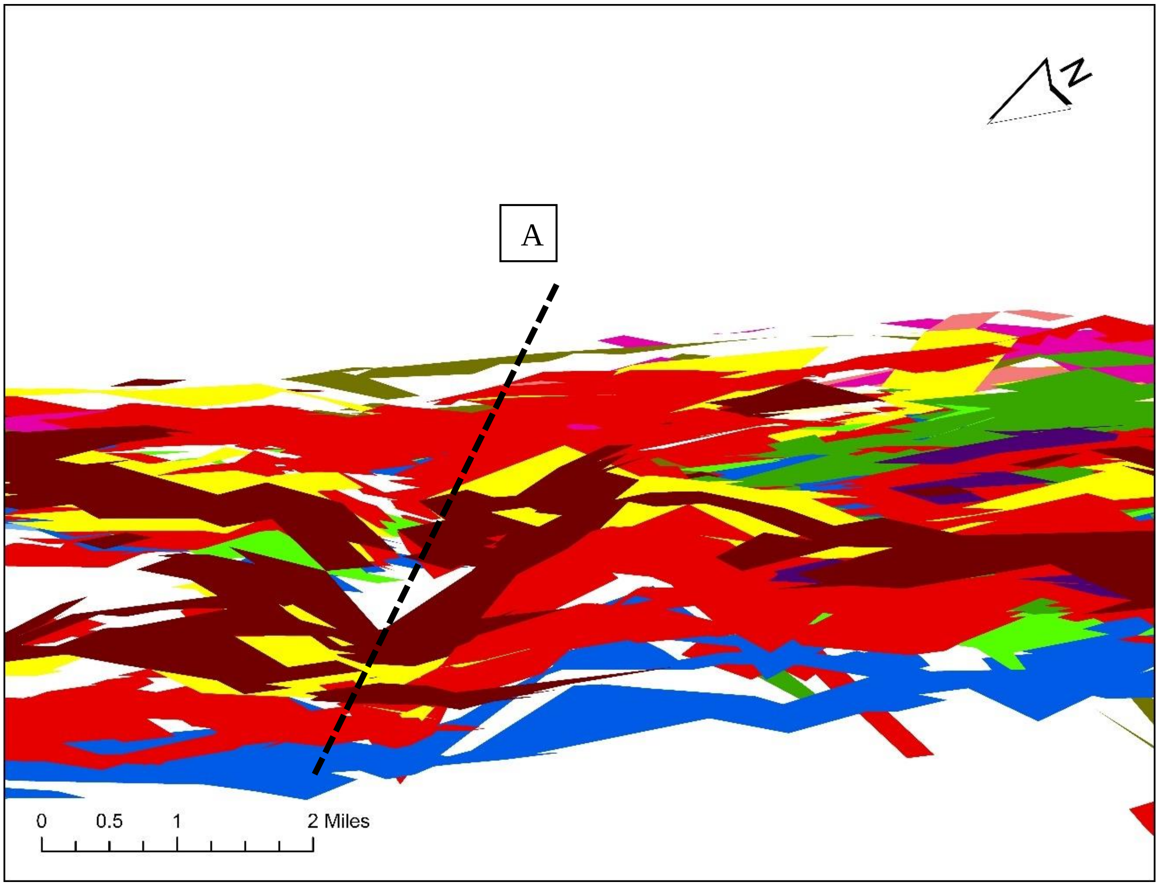

Figure 39. 3-D visualization of the black dashed structural lineament A from Figure 20, looking southeastward along the structural lineament. The structural lineament occurs in an elevational low throughout the region, in which all the members are bisected by a "v"-shaped low in elevation along the structural lineament (black dashed line). This line delineates the northern lateral extent of the Devils Hollow Member (purple) and the Brannon Member (dark green).

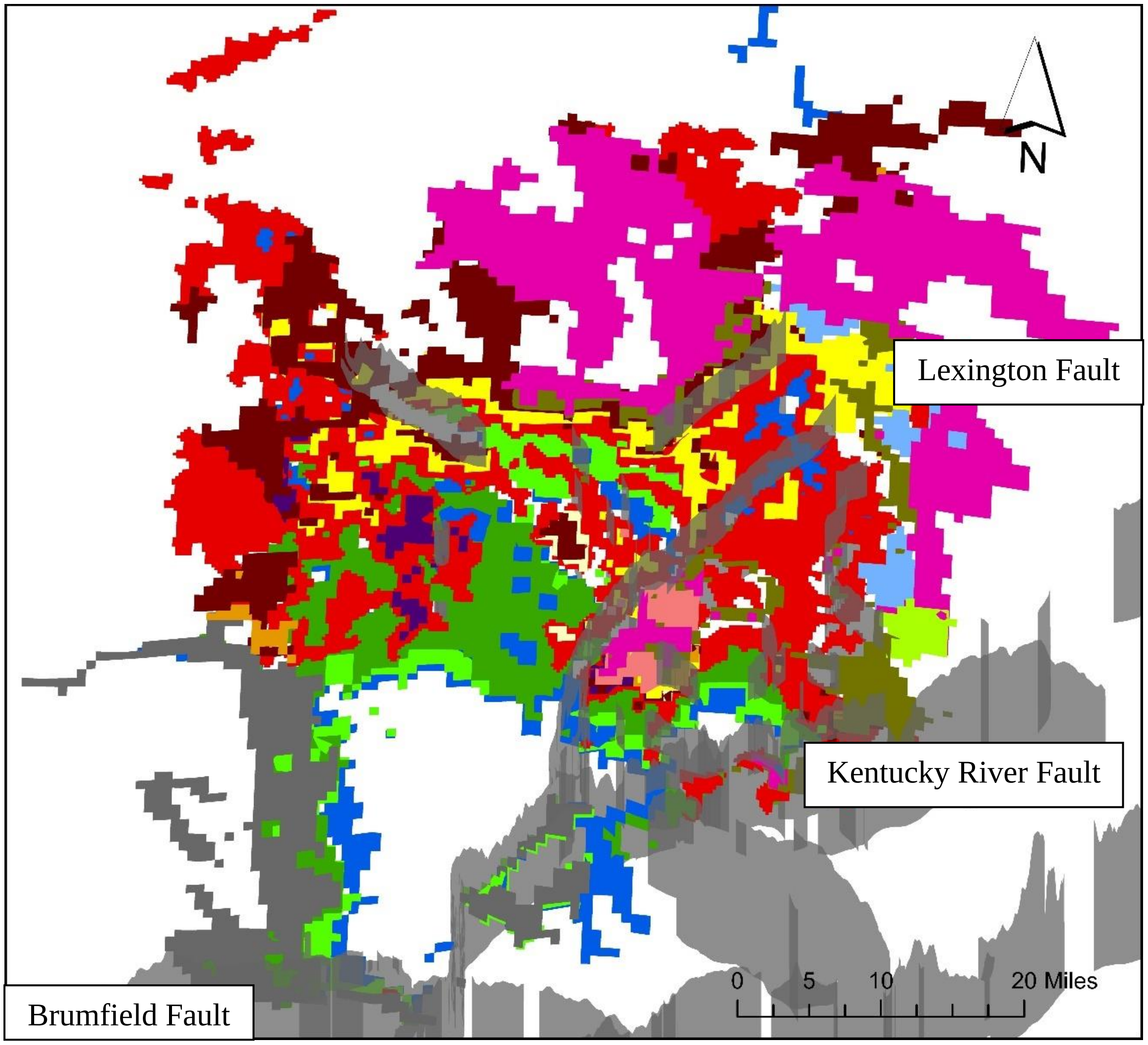

Figure 40. View from above of the 3-D map for members of the upper Lexington with 3-D surface faults expressed as translucent grey “walls”. The three major fault systems (Brumfield, Lexington, and Kentucky River) from Figure 21 are mapped, but several of the smaller surface faults define structural lineaments, which are not shown due to computer-hardware limitations.

of this boundary at the surface. The Lexington Fault and the surrounding smaller faults act as limits for the lateral distribution of the Strodes Creek Member (light blue) and constrain the upper tongue of the Tanglewood Member (fuchsia).

3.6 Discussion of the Three-Dimensional Map

Similar to the 2-D map, the distribution of the members within the 3-D map coincides with the suggested triangular shape of the Tanglewood buildup (Fig. 5) (Ettensohn, 1992). One of the most important examples is the northern extent of the Sulphur Well Member (Supplemental Video 3), where the members of the upper Lexington that occur north of this boundary rise in elevation, so that the Brannon Member is higher in elevation than the Sulphur Well Member (Fig. 38) despite being lower in the stratigraphic column (Fig. 1). This stratigraphic inversion suggests that the distribution of the Sulphur Well Member reflects downdrop and growth faulting along structural lineament B, some of which resulted in erosion of the Brannon during generation of the sub-Sulphur Well unconformity (Ettensohn et al., 2002a). Later post-depositional movement (probably Alleghanian) enhanced this inversion relationship.

The declivity over which some of the members in the southern region of the Lexington Limestone are draped (Figs. 36, 37) represents movement along the Kentucky River Fault (Fig. 40). This same fault system acts as one boundary of the Tanglewood buildup and constrains the distribution of tongues of the Tanglewood and Millersburg members in the southeastern region; however, it does not limit distribution of the lower Lexington members. The Grier and Brannon members are continuous across the sloping declivity (Figs. 36, 37), which means that this the uplift which defines this declivity occurred after the deposition of these members because the top-of-member contacts are not equal in elevation. If the deformation had occurred during or prior to deposition of the members, then the members would be consistent in elevation at the top of the contacts across the declivity with an increase in thickness of member beds, but this does not occur at this location. The timing of this deformation may indicate that further post-depositional deformation occurred, possibly during the later Alleghanian orogeny.

The extent of the upper tongue of the Millersburg (yellow-brown), and two surfaces within the upper tongue of the Tanglewood (dark red, fuchsia) spatially correlate with the northern extent of the lower, largest tongue of the Millersburg (yellow) (Figs. 35, 40) (Supplemental Video 4). The northern extent of the largest tongue of the Millersburg also aligns with the northern extent of the triangular shape of the Tanglewood buildup (Fig. 23). This may potentially mean that the Lexington Fault activated during later stages of deposition of the Lexington, acting as a facies limit for Later, upper tongues of the Tanglewood and Millersburg members. One possible explanation for this is that suggested basement faults C and I (Fig. 23), which were active at the time of the deposition of the largest tongue of the Millersburg, were silent during deposition the upper tongues of the Tanglewood and Millersburg. The lineaments represented by current surface faults then constrained deposition of the upper tongues, acting as a control on the distribution of these member tongues, and thus, creating the large difference in elevation between the stratigraphic tops of these tongues (Supplemental Video 4).

The “v”-shape declivity (Fig. 39) along structural lineament A (Fig. 35) represents limits that define the northern extent of the Brannon and Devils Hollow members (Fig. 39) (Supplemental Video 5). However, lower Lexington members, such as the Grier and the lower tongue of the Tanglewood, are not bound by this lineament, but do experience a drop in elevation near the fault lineament. The “v”-shape nature of the surface topography continues with a reduced exaggeration along the structural lineament for the Grier, Millersburg, and lower and middle tongues of the Tanglewood until the line meets the Lexington Fault system (Supplemental Video 5). This would suggest that lineaments represented by the smaller faults were active during the deposition of these members, experiencing control on the distribution of the aforementioned members. Later, this fault zone then reactivated again after deposition, resulting in the sloping declivity seen in other members of the Lexington Limestone at this lineament.

3.7 Discussion of Structure

The suggested structural lineaments that define the Tanglewood buildup are present in both the 2-D and 3-D maps, with the southeastern and southwestern extents of the buildup strongly correlating with the locations of the basement fault lineament B from Figure 5 and with the Kentucky River Fault System (Figs. 22, 23, 40) (Black, 1986; Ettensohn, 1992), suggesting depositional control by fault reactivation. The outline of the Tanglewood buildup approximately coincides with the Jessamine Dome, and members outside of the buildup, such as the Sulphur Well, do not contribute the shape of the Jessamine Dome (Figs. 36, 37, 38). The Sulphur Well Member does exhibit a sloping surface topography, but this surface does not match the same slope and slope angle shown by the members within the Tanglewood buildup (Figs. 36, 37, 38) (Supplemental Video 3). This situation implies that precursor basement faults limited the extent of the Tanglewood buildup, effectively separating it from the Sulphur Well Member.

The slight dips shown across the Jessamine Dome likely indicate that there was broad, large-scale, post-depositional deformation across the region. The nature of the Jessamine Dome is shown in profile view of the Lexington Limestone (Figs. 36, 37), showing that the members present within the structure are all deformed in the same fashion, gently dipping on the westward flanks, and more steeply dipping along the eastward flank. The difference in slopes along the Jessamine Dome suggests that the Lexington Fault acted as the axis along which the dome formed (Supplemental Video 2). If the Jessamine Dome were present during the formation and deposition of the members of the upper Lexington, then member distribution would have been terminated at the apex of the Jessamine Dome, and potentially continue on the other side of the structure. Post-depositional deformation is also indicated by the sloping declivity in the southern region of the Lexington Limestone along the Kentucky River Fault system (Figs. 36, 37, 40) (Supplemental Video 1). While lower members maintain thicknesses across the declivity, elevations drop significantly (Figs. 36, 37). If the declivity had been present during deposition, thicknesses of Lexington members would have varied substantially across the structure. The fact that they do not vary reflects the post-depositional nature of this deformation.

Were the controls on deposition and deformation of the upper Lexington caused by eustacy, facies would be expected to have been more tabular in nature like those of the lower Lexington. The boundaries between facies might appear as more transitional and gradational instead of the sharp, stark facies boundaries present within the upper Lexington facies mosaic. Based on facies boundaries present in the produced 2-D and 3-D maps, it is most likely that the deformation and distributions of members of the upper Lexington Limestone were largely controlled by growth faulting on suggested basement faults (Black, 1986) that were activated and reactivated by far-field tectonic forces. Many of the members of the upper Lexington, including the Brannon, Devils Hollow, Sulphur Well, tongues of the Millersburg, and tongues of the Tanglewood, all exhibit distributions that were apparently limited along basement precursor structural lineaments, which were later reactivated to produce the current surficial faulting (Figs. 31, 32). Hence, this facies distribution suggests that at the large scale, facies within the upper Lexington were structurally controlled during their deposition by syndepositional fault movement at depth. However, deformation of other members, like those shown at the declivity (Figs. 36, 37) suggests that post-depositional forces were also present, most likely due to Alleghanian far-field forces. Overall, it is not likely that eustacy was a dominant influence in the complex facies mosaic within the upper Lexington.

CHAPTER 4. CONCLUSIONS

The upper Lexington Limestone does exhibit the potential for likely structural control in the deposition and distribution of members, creating a complex facies mosaic. The deposition of the upper Lexington coincided with the Taconic tectophase of the Taconian orogeny, creating far-field forces that apparently reactivated suggested precursor basement structures (Black, 1986) to control the distribution of members within the upper Lexington in both vertical and lateral extent. Previous two-dimensional mapping efforts have suggested this structural control, but new technological advances in geographic information systems (GIS) have allowed for a three-dimensional-compatible geoframework to be created to better understand the presence and potential influence of structural control on the upper Lexington Limestone. The method utilized in this study of deconstructing previous 2-D maps to generate 3-D compatible maps demonstrates that 3-D mapping techniques can be used to determine the likelihood of structural control on member distributions, specifically within the Lexington Limestone.

The generated 3-D maps indicate that the distribution of upper Lexington members is closely constrained by the basement precursor faults within the region. The lateral distribution and limits of the Brannon, Devils Hollow, Sulphur Well, Strodes Creek, and tongues of the Millersburg and Tanglewood members all significantly align with known basement faults, many of which have present-day surface expressions. This alignment indicates that broad-scale, syndepositional, structural control influenced the deposition of the upper Lexington Limestone. These structural features align with previously suggested 2-D mapped features such as the triangular Tanglewood buildup and Jessamine Dome.

The 3-D maps further indicate that structural features such as the Jessamine Dome and the fault-related declivity in the southern region of the Lexington Limestone are suggestive of post-depositional deformation across the entire region. These features do not represent typical syndepositional deformation because unit thicknesses and facies remain unaltered across these structural features. These deformational features suggest late-stage deformation across the entire area, likely due to Alleghanian far-field forces. Clearly, 3-D mapping from 2-D maps has the potential to help clarify the nature of such stratigraphic complexities, but obviously, more work and better GIS resolution will be required.

APPENDICES

APPENDIX 1. Glossary of Geographic Information System (GIS) Terms

All definitions for these terms are from the Esri Support GIS Dictionary

Buffer – A specified zone around a map feature or features, measured in units of distance or time.

Coordinate System – A reference framework consisting of a set of points, lines, and/or surfaces, and a set of rules, used to define the positions of points in space in either two or three dimensions. [The coordinate system utilized within this project is the NAD 1983 StatePlane Kentucky North FIPS 1601 (Meters)].

Digital elevation model (DEM) – he representation of continuous elevation values over a topographic surface by a regular array of z-values, referenced to a common vertical datum. DEMs are typically used to represent the bare-earth terrain, void of vegetation and manmade features.

Feature class – In ArcGIS, a collection of geographic features with the same geometry type (such as point, line, or polygon), the same attributes, and the same spatial reference. Feature classes can be stored in geodatabases, shapefiles, coverages, or other data formats. Feature classes allow homogeneous features to be grouped into a single unit for data storage purposes.

Point cloud – A (typically) large collection of x, y, z coordinates in three-dimensional space representing the real-world surface dimensions of objects.

Polygon – On a map, a closed shape defined by a connected sequence of x, y coordinate pairs, where the first and last coordinate pair are the same and all other pairs are unique.

Polylines – In ArcGIS software, a shape defined by one or more paths, in which a path is a series of connected segments.

Raster – In imagery and elevation, a spatial data model organized into a matrix of equally sized cells, or pixels, and arranged in rows and columns, composed of single or multiple bands. Each cell contains a numeric value representing information such as temperature at a particular height or depth, elevation, or image brightness value. The scale can be nominal, ordinal, interval, or ratio. Unlike a vector structure, which stores coordinates explicitly, raster coordinates are contained in the ordering of the matrix. Groups of cells that share the same coordinate value represent the same geographic feature.

Scene map – In 3D Analyst, a document containing 3D data that can be viewed in perspective.

Symbology – The set of conventions, rules, or encoding systems that define how geographic features are represented with symbols on a map. A characteristic of a map feature may influence the size, color, and shape of the symbol used.

Three-dimensional compatible data – data that has z-values, allowing data to be represented in all three dimensions.

Triangulated irregular network (TIN) – A vector data structure that partitions geographic space into contiguous, nonoverlapping triangles. The vertices of each triangle are sample data points with x-, y-, and z-values. These sample points are connected by lines to form Delaunay triangles. TINs are used to store and display surface models.

APPENDIX 2. Digital Mapping Methods

The following steps were completed to generate the resultant 2-D and 3-D maps for this project. All parameters for the tools within Esri ArcGIS Pro were used as their default unless otherwise stated.

1. Create a new project within Esri ArcGIS Pro, changing the coordinate system to NAD 1983 StatePlane Kentucky North FIPS 1601 (Meters). The reasoning for this coordinate system is that StatePlane systems are more geographically accurate when working at smaller geographic scales, and the study region is located in the northern half of the state, providing the most accurate coordinates possible for the project.
2. Import the 1:24,000 Kentucky Geologic Map package from the KGS website to gain access to all published geologic maps for the state of Kentucky required for this project (Cressman and Noger, 1981).
3. Use the “Select By Attributes” tool, “New selection” to select the “US-KY_KGS_24K_Contacts” layer and search for “formation_code” contains “365”. This will select all stratigraphic contacts in the map that represent the Lexington Limestone (state formation code for Upper Ordovician strata: 365). Members that are included in the lower Lexington were excluded from the selection process using the same tool and sorting process, based on individual member codes.
4. The selection of all upper Lexington contacts generated a new layer using the “Make layer from the selection” tool.
5. The symbology of the contacts in this layer were changed to the colors in Table 1, using the formation codes to check for consistency in codes across the Lexington. The codes in Table 1 were assigned to all contacts for the following step.
6. Each member and tongue of the upper Lexington was individually selected using the “Select By Attributes” tool, the “New selection” tool, and the code from step 5 and Table 1. Each member and tongue were formed into a new layer following step 4. Layer formation allows each member or tongue to be viewed independently and for the following steps to be individually completed for each member and tongue.

7. For all member or tongue contacts, the “Generate Points Along Lines” tool was used to generate discrete data points along the contact horizon. For this tool, a distance of 1,000 feet was selected, with 2,000 feet used for the Grier Member. The Grier Member was geographically large enough that it created files too large to process in the following steps (over one million data points).
8. The layer created from step 7 was loaded into the “Add Surface Information” tool, and the 10 Meter DEM from the KGS website was used for the input surface. The output property chosen was “Z”.
9. The layer with surface information from step 8 was used in the “Topo to Raster” tool to generate a 3-D compatible continuous layer for each contact. The output of the surface raster was chosen to match the geographic extent of each individual contact layer. For parameters, do not enforce drainage, tolerance 1 is 1, and Tolerance 2 is 100. The primary type of input data is spot.
10. The raster generated from step 9 was used in the “Buffer” tool, choosing a distance of one-half-mile. Dissolve type is “dissolve all features into a single output feature”. This will create one continuous polygon of a buffer zone to be used in the following step. The buffer zone generated is important to constrain elevation data within a relatively close distance to the contact lines. This ensures high confidence in the data generated that they are truly representative of the contacts within the formation.
11. Each raster file was processed by the “Clip Raster” tool with the output extent the buffer zone generated in step 10. The “Use Input Features for Clipping Geometry” box was checked, which constrains the raster file to the output extent of the buffer zone from step 10.
12. “Create local scene” within the project generates a 3-D-view compatible map in the localized region of the study area.
13. Import the clipped rasters from step 11 into the new local scene.
14. Within the local scene, use the imported clipped rasters in the “Raster Domain” tool with the polygon option for the “Output Feature Class Type”.
15. Use the imported clipped rasters in the “Raster to TIN” tool with a “Z tolerance” of 25. This is a typical tolerance, and this step constrains the maximum difference in

height for data to 25 feet (because this is the unit used for this project) between the raster and TIN files.

16. The polygon generated from step 14 was used in the "Interpolate Polygon to Multipatch" tool, which generates a 3-D surface that represents the elevation of the mapped member or tongue contact that can be rotated and viewed in three dimensions.
17. For this study area, the members are relatively flat and thin, so the vertical exaggeration of each member or tongue contact was increased from one to twenty.
18. The mapped 3-D faults were obtained from KGS and imported into the project as a shapefile into the local scene (Kentucky Geological Survey, 2023). The vertical exaggeration of the faults was increased to fifty so that the faults would act as barriers cutting through the formation.
19. The "Slope" tool was used in the 2-D map on the clipped raster files from step 11. Output measurement was changed to "percent rise". The symbology for the slope raster was changed to "Classify" and "Geometric Interval", which regroups the visualized data into groups of equal sizes based on the data present.
20. The "Create Features" tool was used to create feature classes to draw trends along the slope rasters in order to analyze any trends that may occur across different member or tongue contacts.

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VITA

Education

B.S., Earth Science Education, Miami University, 2018

Professional Experience

Graduate Research Assistant, Department of Earth and Environmental Sciences, University of Kentucky, Lexington, KY: August 2022 – August 2023

Teaching Assistant, Department of Earth and Environmental Sciences, University of Kentucky, Lexington, KY: August 2021 – August 2022

Geology Teacher, Fairfield High School, Fairfield City Schools, Fairfield, OH: August 2018 – August 2021

Undergraduate Research Assistant, Department of Geology and Environmental Earth Science, Miami University, Oxford, OH: August 2016 – May 2017

Scholastic and Professional Honors

Outstanding Teaching Assistant – 2023

USGS EDMAP Grant - 2022

Professional Publications:

Davis, S., Ettensohn, F. R., Andrews, W. M. and Martins, G. 2023. Using 3-D mapping to understand an Upper Ordovician buildup and facies complex in the upper Lexington Limestone, central Kentucky, USA. Estonian Journal of Earth Sciences, 72(1), 14–17 (https://doi.org/10.3176/earth.2023.81).

Sean Davis