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Proof of Concept Test to Determine the Viability of Building an Extensive Database for Resolution of Far-Field Effects of the Acadian and Alleghanian Orogenies

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Abstract Several episodes of uplift have occurred along the Cincinnati arch. These periods of uplift are likely a result of several orogenic events although the exact timing of the uplift in relation to these orogenic events is not fully understood. One reason for this has been the lack of accessible structural data over this region. The southern end of the Cincinnati arch and the Nashville and Jessamine domes occur along the arch in Kentucky, Tennessee, and northern Alabama. These states have very different levels of data availability, but potentially enough to identify more subtle, second- and third-order folds and faults along and on the flanks of the arch. These structures may be the key to unraveling the pre-Devonian tectonic history of the two domes, and can be identified in structure contour maps with sufficient data. The goal of this study was to perform a preliminary assessment of the viability of constructing a complete series of structure contour maps of several geologic units across the region, using publicly available data. Thirty-two geologic quadrangle maps selected across the southern end of the Nashville dome in Tennessee were manually digitized utilizing ArcGIS™. The results from this initial study were then compared to the results produced using a less labor intensive method using basic GIS functions to generate data points. The results of this initial investigation seem promising, but methods of cross-verification to remove erroneous data points, the incorporation of subsurface data, and the incorporation of data sets from other states will be required to expand the coverage area. Automation of this process will need to be developed to allow further research to be performed.

Keywords: *structural Geology, GIS applications, Nashville dome, Cincinnati arch*

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1. Introduction

The Cincinnati arch is a regional structure that extends from northern Alabama to southern Ontario [1]. The Nashville and Jessamine domes make up the southern portion of this structure. Although there has been a great deal of research done on these structures, the tectonic history during the uplift of the Cincinnati arch and the formation of the Nashville and Jessamine domes along this feature are still poorly understood. One way of resolving the timing of these events is by constructing structure contour maps at important horizons along these structures, which can be performed either manually or automatically using GIS processing tools, if the appropriate data are available from published geologic maps. These maps could then potentially be used to identify 1:24,000 scale structural features related to tectonic events prior to the deposition of the Upper Devonian Chattanooga Shale (and equivalents) for the southern Cincinnati arch. The observed relationships between structural features and the timing of orogenic events may be used to tie these features to the Alleghanian or pre-Alleghanian orogenies.

To this end, this study serves as a preliminary assessment of the viability of using the available data from a subset of the total study area to construct accurate structure contour maps on top of several rock units within the study area. In addition, this study serves as a proof-of-concept test to evaluate the viability of automating parts of the process of constructing structure contour maps. The performance of this process was evaluated by comparing the resulting structure contour maps generated using both GIS tools and manual entry methods across a specific test area. The selected test area was located in south-central Tennessee, on the southern flank of the Nashville dome. Thirty-two of the available 7.5-minute 1:24,000 geologic quadrangle maps in the area were utilized to construct structure contour maps of specific geologic horizons (Figure 1). These selected horizons may provide critical geometries of pre- and post-Chattanooga unconformity deformation.

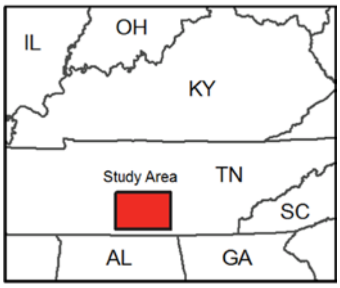

Figure 1. Location map showing the selected study area in southern Tennessee (indicated by the red square). This area consists of 32 geologic quadrangles across the southern end of the Nashville dome.

2. Methodology

In order to construct a structure contour map from a geologic map the elevation along the geologic contact must be determined. The typical method to accomplish this is to locate points on a geologic map where the geologic contact intersects a topographic contour. These points can then be contoured by hand or by using a GIS software package to interpolate between points. This will produce a structure contour map that depicts the structure of the surface of the geologic horizon.

The manual method is obviously time consuming and even potentially a source of error due to the human component in manually reading contours and recording points. It is possible to automate this process using basic GIS tools, if the required data are available in digital format. Tennessee currently has no publicly available digital database of 7.5-minute geologic quadrangle maps. However, the majority of the quad maps that make up the area around the Nashville dome were manually digitized into ArcInfo™ coverage files as part of a USGS initiative in the mid 1990's to digitize the available 7.5-minute quadrangle maps from the original film scribecoats [2]. These scribecoats were scanned using a full scanner to minimize distortion. The maps were then vectorized using ArcInfo™ and transformed to state plane projection.

Unfortunately, despite the processes in place for checking the accuracy of the scanned maps, the digitized maps fail to register correctly with those in the printed quadrangle maps. The digitized data contain errors in location, due to problems with georeferencing, or possibly errors in the conversion process used to transform legacy coordinate systems for each map. These errors are somewhat different for each quadrangle, making any programmatic method of correction difficult. While the majority of the maps only contain minor errors in georeferencing, a few displayed significant errors resulting from the misplacement of the points used to align the corners of the maps in the initial setup. Consequently, this caused the geometry of the geologic contacts on the digital map to differ considerably after these points were used to transform between projections. These errors had to be corrected by manual spatial adjustment of the line and polygon data before the dataset could be used for the GIS tools method.

The manual data entry method utilized scanned images of the printed paper quadrangles which were then georeferenced to the corners of each 7.5 minute quadrangle area in the NAD 1927 Geographic Coordinate System and projected into UTM Zone 16N. Each map was then visually searched for the desired points where the geologic contact lines crossed the elevation contours for the base of Mfp and Olcy-Obc contacts. The values of the contour lines were read directly from the map and recorded as a point feature using the ArcGIS™ software suite, as each point was created within the database. The recorder was instructed to map enough points across each map to ensure a representative spatial distribution, because recording all points manually would be infeasible.

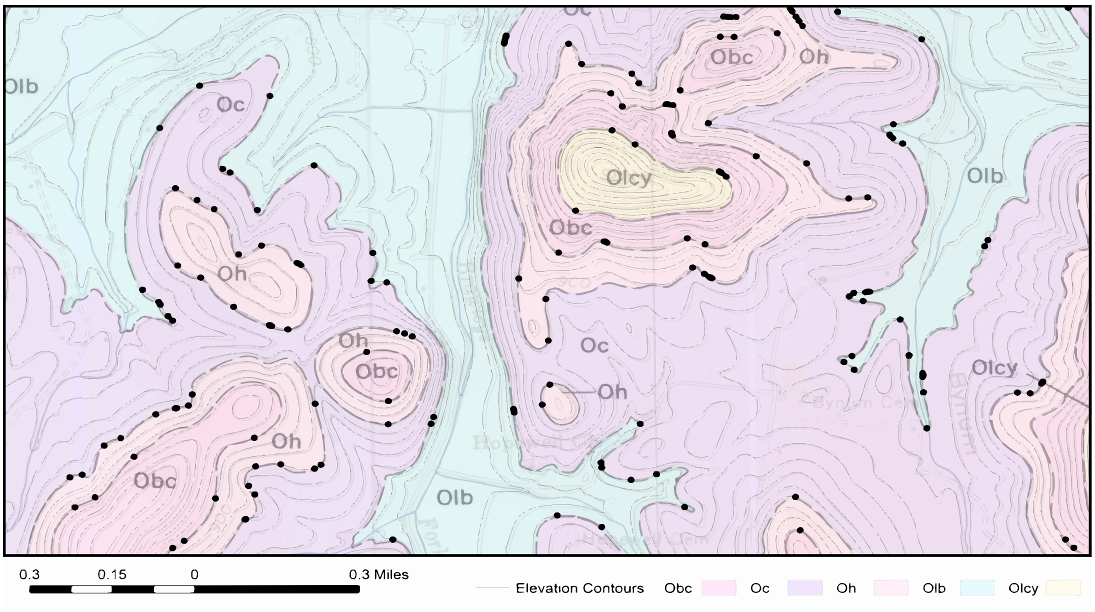

Figure 2. Geologic map from a central Tennessee quadrangle [3] showing the locations of the intersection points (black closed circles) of geologic boundaries and topographic contour lines generated using the GIS tools method. These points were generated for all surfaces using the GIS systematic method, but only two surfaces (base of Mfp and Olcy-Obc) using the manual data entry method.

In contrast, the GIS-tools-method utilized the digitized geologic contact lines after manual correction. The digital geologic contacts were converted from their original ArcInfo™ coverage files into feature classes and stored in a file geodatabase. The converted files consist of a polygon feature class containing fields for the name of the geologic unit, and a line feature class that contain fields that define the type of line (outcrop, fault, and map edge boundary). Two point feature classes containing the corner “tic-mark” locations (originally used to transform the maps between projections), and label location for each geologic unit, were also imported but not used for this study. The geologic unit polygons were converted to line features in such a way that the resulting line feature contains the name of the geologic unit on both sides of the line. This information was used to define the contact between each geologic formation. Finally, the Arc Map™ "intersect" tool was used to create a point at each intersection of the geologic contact and topographic contour line (Figure 2). This process recorded intersection points for all geologic contacts across the area and incorporated the elevation and the formation name information. These data were then integrated into a single database, which could then be queried to display all points for a specified contact.

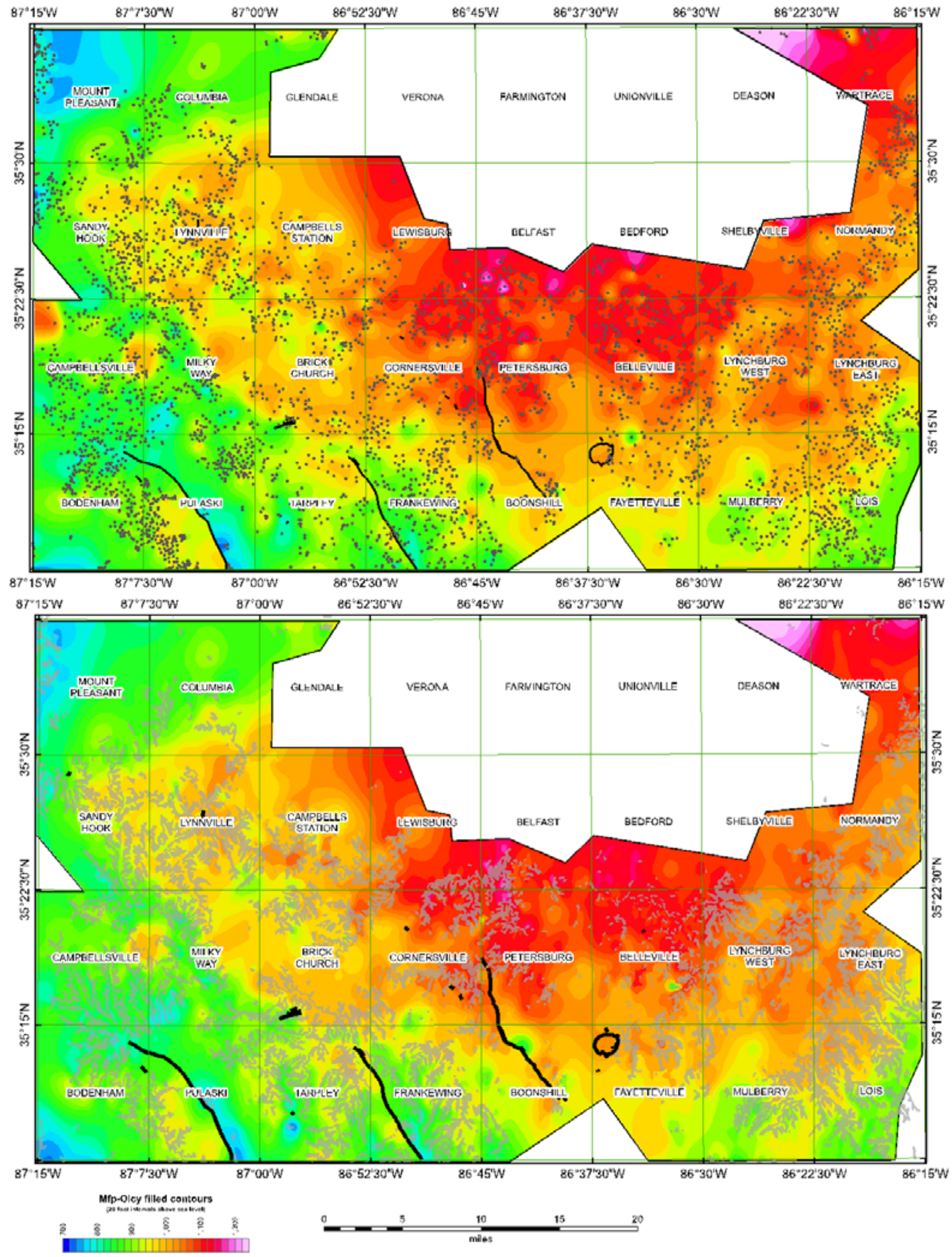

Figure 3. Comparison of the structure contour maps on the base of the Mfp generated using two methods of data collection for the area in the southern Nashville dome. These maps were constructed using identical parameters with the exception of the data collection methods across an area of 32 quadrangles [6-37]): (a) was constructed by manually picking ~4,000 data points (gray circles) and (b) was generated from ~82,000 auto-picked points (gray dots that appear as a dendritic pattern along outcrop surfaces, the density of points were too high to display correctly at this resolution) using the methods developed during this study. These maps appear very similar regionally, but many more sub-quadrangle-scale features are visible in the higher-resolution auto-picked map that are not present in the lower-resolution manually picked map. The white areas indicate areas where no outcrops for this contact occur.

The resulting data points generated by each method were then used to create structure contour maps of the study area. A spline-with-barriers function was used to interpolate between data points. This function generates a continuous interpolated surface using a minimum-curvature method that minimizes the integral of the squared curvature over the surface [4,5]. A database fault locations was used to define the barriers, which created discontinuities in the interpolated surface in order to preserve the differences in the surface elevation across each fault. The settings for this function remained static for each method so that the resulting interpolated surfaces could be compared.

3. Results

The results of each method of data collection were compared both visually and in terms of their spatial and frequency distribution. The base of the Ft. Payne Formation and Chattanooga Shale was chosen as the basis of comparison between the two methods because of its lateral extent across the area and its potential utility as a means of differentiating between structures resulting from orogenic events before and following its deposition. The resulting structure contour maps produced using the manually picked and auto-picked methods can be seen in Figure 3.

The two maps appear generally visually similar, with only minor differences visible at the current scale. Both methods produced maps that clearly show the change in elevation of the base Mfp contact from ~700 ft in the southwestern most corner, to over 1200 ft approaching the crest of the dome. Although most areas are fairly consistent, the subset of data points was picked up using the auto-picked method in areas where no points were initially identified through manual picking, specifically in the Wartrace and Normandy quadrangles [35,36]. These locations are indicated by where the gray dots occur within the white spaces on the auto-picked map (Figure 3b) but were excluded from the final map in order to maintain consistency between the two maps for comparison purposes. The data point density of the auto-picked map was much greater than the manually picked map. The data point elevation values used to construct each map for each data collection process for the base Mfp contact are summarized in Table 1.

Table 1. Summary of data points collected for the Mfp-Olcy contact using each method

Method	Number of Points (n)	Mean (μ)	Standard Deviation (σ)
Manual Entry	4044	959.58 ft	84.64 ft
GIS tools	82,524	959.01 ft	74.41 ft

A total of 4044 intersection points were recorded for the manually picked Mfp-Olcy surface. The values of elevations determined by the topographic contour at each point were divided across a set of 47 discrete values. These values ranged from 720 ft to 1230 ft, with an average of μ = 959.58 ft, and a standard deviation of σ = 84.64 ft. The total number of points collected using the GIS tools method (n = 82,524), is an order of magnitude greater than those collected by the manually picked method. The elevations at these points had almost the same range as the handpicked points (720 ft to 1240 ft) across 47 total possible discrete values which were l argely similar (though not identical) to those collected using the manual method. Despite this, the manually picked points and had an almost identical mean of μ = 959.01ft. The standard deviation of this set was slightly lower σ = 74.41ft, indicating the distribution of points collected using the auto picking method have a slightly different distribution.

The histograms in Figure 4 show the frequency of the point elevations for each method and the differences in the distribution of the sampled points. The contour line intervals are typically 20ft and, as a result, most of the point elevations are multiples of 20 although a few maps contain different contour intervals (e.g. 10 ft) and as a result, possible elevation values are not restricted to multiples of 20.

Different distributions between the two collection methods may result from visual bias when identifying and manually recording a point (some points may be more apparent or easier to see than others). The small difference in the two methods indicates that manual picking can still achieve a representative distribution, but requires a much larger time investment.

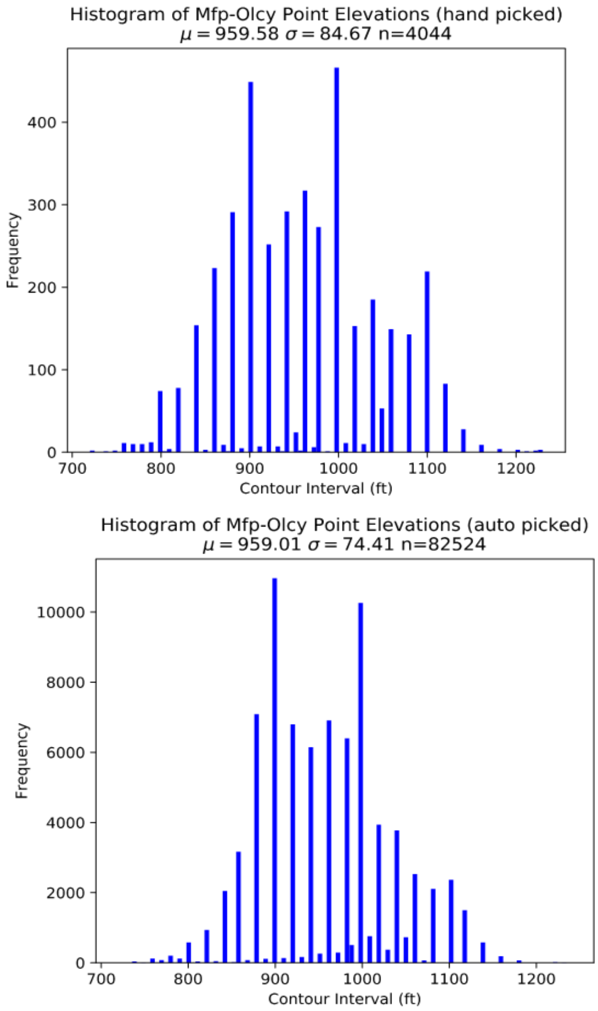

Figure 4. Histograms showing the distribution of point elevations for both methods. The distribution of elevations are slightly different between collection methods.

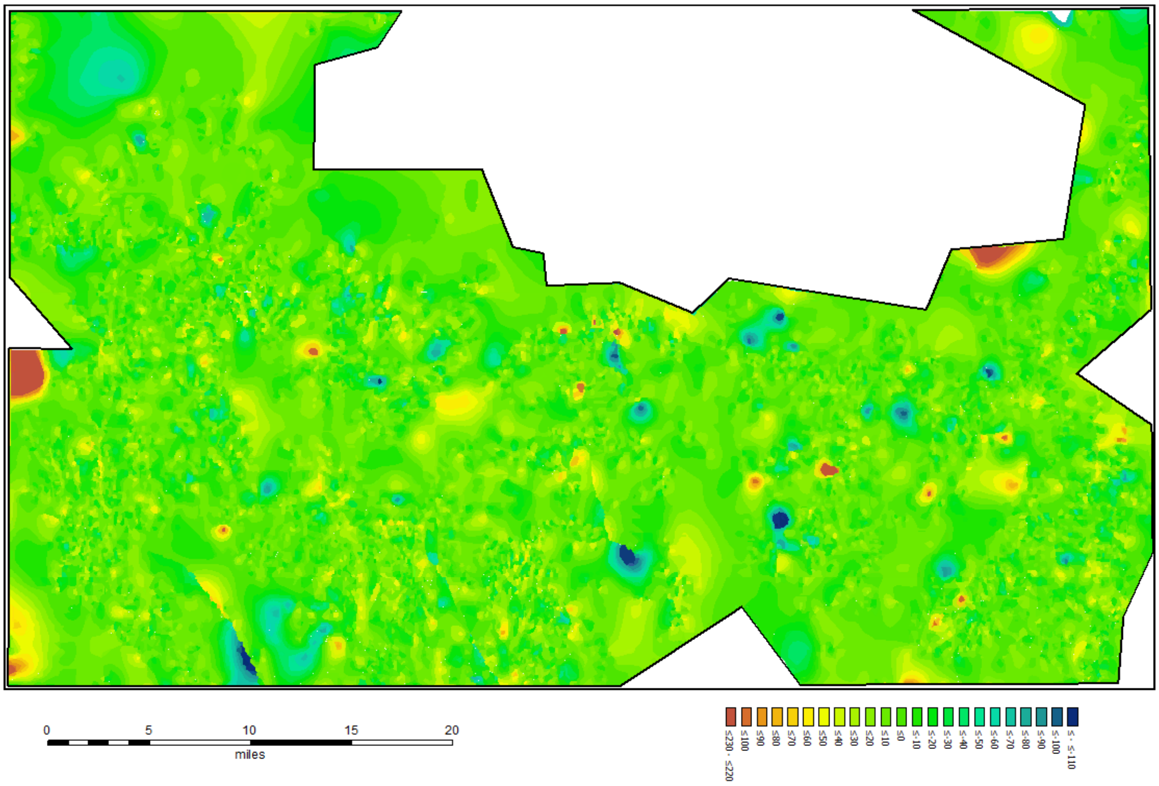

Figure 5. Differential map of the study area. The colder colors indicate where the surface produced by contouring the points using each method differs from each other. Blue areas indicate where the handpicked surface is lower in elevation than the auto-picked method, red areas indicate the hand-picked surface is higher in elevation than the auto-picked method; Green areas indicate where the surfaces are roughly equal in elevation.

The differential map (Figure 5) was constructed in order to better visualize the spatial distribution of locations where the results differ from each method. The map was generated by simply subtracting the elevation values at each pixel of the raster surface of the automated map from the hand-picked map. The result highlights locations where the two maps differ by a significant degree. The majority of the area displays only minor differences between the results of each collection method, however some isolated locations display a higher differential. These locations are most likely a result of a misplaced, or erroneously entered elevation value at that location on the manually picked map, or an incorrectly labeled point (e.g. a point labeled as Mfp-Olcy that should be labeled as Olcy-Obc due to a polygon that was mislabeled during the initial digitization of the geologic map), though only one instance of this was identified.

4. Conclusions

1) The volume of digital data available for this region is sufficient to allow the process of construction of structure contour maps to be automated, so long as the errors in georeferencing are corrected.

2) The method of picking points automatically using geologic contacts and elevation contours produces similar results to those picked by manual entry (so long as the digital geologic contact lines are equivalent).

3) The manually picked points have a slightly different distribution, the are still a representative sample.

4) The manual correction of the geologic contact lines was necessary, however it saved more time compared to manual picking.

5) An automated approach to this problem can yield results on a much shorter timescale, allowing larger-scale studies to be performed.

6) The resulting structure contour maps display many subtle features along outcrop belts and in areas with high well density. These maps also identify potential faults where none are shown on existing detailed geologic maps.

7) The structure contour maps generated using the GIS automated method are a higher resolution than handpicked maps and can be used to identify small-scale structures that can be used to infer information about the tectonic uplift history of the Cincinnati arch.

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