Using LiDAR-derived DEM's to delineate and characterize landslides in Northern Kentucky and Hamilton County, Ohio

Jesse Amundsen[a,*], Sarah Johnson[a], Katie Rouse[a], Hongmei Wang[b]

[a] *Department of Physics and Geology, Northern Kentucky University, Highland Heights, KY 41015*
[b] *Department of Informatics, Northern Kentucky University, Highland Heights, KY 41015*

Abstract

Each year landslides cause measurable damage to homes, business, utilities, and roads in the Northern Kentucky and Cincinnati area. A traditional landslide inventory model typically involves aggregating known landslide locations from various public sources such as transportation cabinets and state mapping agencies and then painstakingly field checking them to confirm their existence and to assess their threat level. This study aims to assess the effectiveness of using topographic derivative maps generated from high resolution LiDAR-derived DEM's to characterize and delineate landslides within the region. Only recently has such high resolution data been made available. This new data provides previously unattainable detail of the topography of the region and facilitates the generation of derived data that can assist in locating and identifying both existing and previously unknown landslides. Data for Hamilton County was obtained from the Ohio Statewide Imagery Program (OSIP) while data for Kenton and Campbell counties was provided by the Northern Kentucky Area Planning Commission (NKAPC). The data was then processed within a geographic information system (GIS) to create slope, contour, curvature, and hillshade maps. Of these four derived data sets, slope and contour maps proved to be the most useful for locating and delineating landslides. Rotational landslides provide to be the easiest to identify of the three typical failure types found in the region. Of the five rotational failures examined by this study, three were newly discovered using the derived datasets processed using a GIS. Only one of two examined translational failures was able to be identified with confidence using the derived data, and the only block extrusion failure examined was difficult to delineate without the assistance of aerial photography. These results reflect the morphology of the landslide types with the steep arc-shaped head scarps of the rotational failures being easily identifiable on both slope and contour maps.

1. Background

Landslides are a costly natural hazard in the Cincinnati and Northern Kentucky area and the region has one of the highest cost per capita damage rates due to landslides in the country (Johnson R. L., 1996; Fleming R. a., 1980). The geology of the area creates optimal conditions for landslides due to the presence of unstable slopes, colluvium weathered from the Kope Fm., and lakebed clays. As the region continues to grow and develop, more construction is taking place in close proximity to landslide-prone slopes.

Cataloging existing landslides is the first step toward building a more comprehensive data set that could provide government agencies and private contractors with accurate information regarding these costly natural hazards. The second step is to discover previously unknown landslides which will increase the robustness of the data set. Traditionally, inventories of landslides were generated primarily using reports from transportation cabinets and other public sources. Increasingly, geographic information systems (GIS) are being utilized to more accurately locate reported landslides and to assist in the discovery of previously unknown landslides. The city of Seattle has employed a similar approach which was documented in Schulz et al. (2007) and Schulz (2004). The goal of this study is to apply similar techniques to the Cincinnati area to locate new landslides by using a GIS and high resolution LiDAR data.

Landslides vary in their morphology greatly. Major morphological characteristics of a landslide that could affect its visibility in DEM's include the scarp height, the maximum and average width, the maximum and average length, and the pattern on the affected surface. In the Northern Kentucky and Cincinnati region there are three primary landslide types that occur. Rotational slides have a curved failure surface that can often be deep-seated, a steep arc-shaped head scarp, and a flatter body followed by a bulging toe (Figure 1). They occur in colluvium weathered from steep slopes and can also be found in deposits of fill and lakebed clays. Translational landslides are characterized by a predominantly planar failure surface that is often shallow and a surface that is often hummocky (Figure 1). These most commonly occur on steep slopes with a failure plane that follows the contact between the unconsolidated materials on top

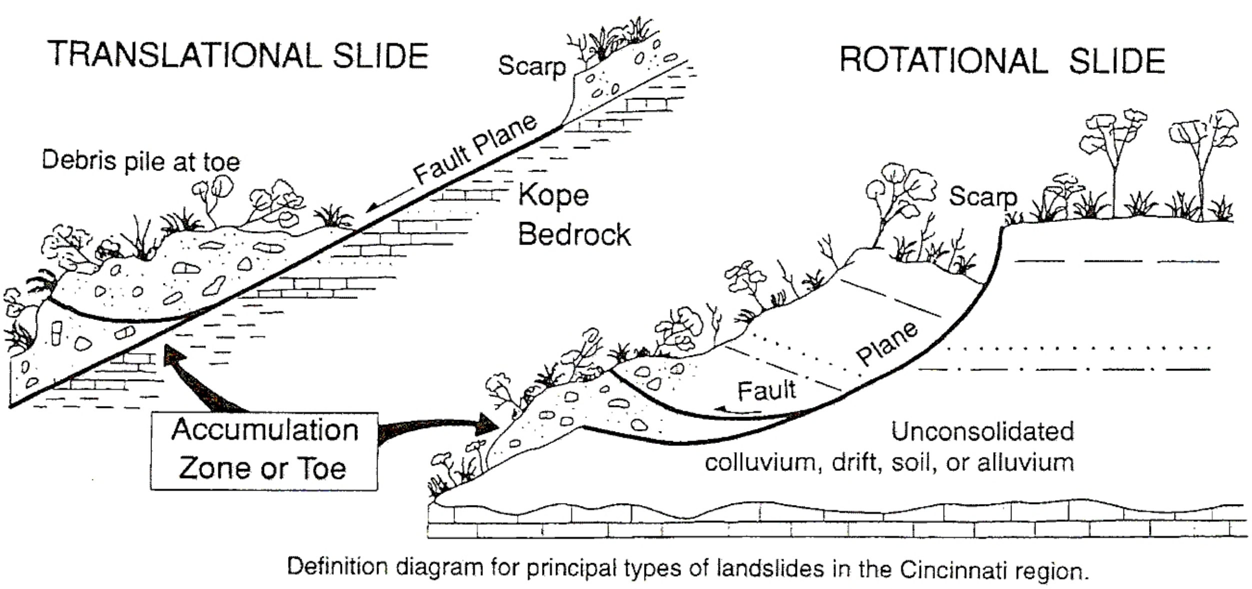

Figure 1: Illustration by Potter (2007) depicting the two most prevalent landslide types in the Cincinnati and Northern Kentucky area. Translational slides occur as material slips over a linear surface such as contact of material with bedrock (Kope Fm. Shown). Rotational landslides have a curved failure surface which often generates a more dramatic scarp.

and the bedrock on bottom. Block extrusion landslides can be found in locations where lakebed clays were deposited during the most recent glacial advances and appear as a succession of block failures as the clays are forced out of the slope.

Understanding the typical morphologies of the different landslide types provides information about which signatures may arise on topographic derivative maps. Due to their scarp height, rotational landslides are expected to be most visible on slope maps, or by using topographic contours. Translational landslides may become visible when viewing topographic contours, or by using derivative maps such as curvature that could potentially be indicators of the hummocky surface. Block extrusions exhibit a succession of steeper slopes and an irregular scarp shape that could potentially be visible in a number of derivative maps.

LiDAR (Light Detection and Ranging) is a remote sensing technique that uses pulses of light to gather information about the surface of the Earth below it. In this study, high-resolution digital elevation models (DEM) derived from aerial LiDAR surveys serve as the base data set for creating topographic derivative maps. LiDAR data typically provides higher resolutions than other remote sensing techniques and allows for the visualization of geologic features at a smaller scale than other remote sensing techniques (Lin, 2006; Dorsch, 2006). Higher resolution data could facilitate the discovery of new landslides and provide more information about existing landslides. Similar techniques were used by Ardizzone et al. (2007) to successfully conduct a landslide inventory in the Collazzone area of Italy. These derivative maps were visually inspected for indications of landslide activity. Successfully identifying a landslide often required the use of multiple derived data sets. Furthermore, it was demonstrated by Eeekhaut et al. (2007) that using LiDAR based surveys is an accurate method to map landslides that are obscured by vegetation which is important in the study region since many slopes are densely vegetated.

Only recently has such high resolution data become available for southwest Ohio and Northern Kentucky and, as a result, very little research has been undertaken utilizing the data which forms the basis of this project. Most prior work done in the Cincinnati area on landslides was done using traditional methods (Potter, 2007). Through collaboration with the Kentucky Geological Survey (KGS) the hope is that landslide-awareness and the availability of data relating to landslides will both increase.

2. Methods

2.1 Data Acquisition and Preparation

Data for Hamilton County was obtained from the Ohio Statewide Imagery Program (OSIP) which made LiDAR data flown in 2007-2008 publicly available in 2009. Pre-processed DEM's with a claimed horizontal resolution of 2.5ft were used for most of the analysis and supported by data from the raw LAS files that were processed independently using lastools or the data management toolbox within ArcGIS. The Northern Kentucky Area Planning Commission (NKAPC) provided the data for Kenton and Campbell County in Kentucky. LiDAR coverage is complete for both counties and was provided as a 10ft resolution DEM that covers both counties, two 5ft resolution DEM's that are split east-west, and eight 2ft resolution tiles. The Northern Kentucky data was flown in 2008 by Photo Science, a company based out of Lexington, KY.

The entirety of the data provided for Northern Kentucky was loaded into a file geodatabase (fGDB) that allowed for rapid access to the large amount of data stored in the DEM's. For Ohio, individual tiles covering areas of interest were downloaded using the provided online tile viewer from OSIP and subsequently loaded into the fGDB. During the preliminary research period for the project, GRASS (Geographic Resource Analysis and Support System) was used as the primary GIS, but was largely replaced by ArcGIS 10 for the final project with the exception of some comparison calculations for consistency verification.

Locations of known landslides were inventoried from a variety of sources including the Kentucky Department of Transportation (KDOT), the KGS, geologic quadrangles, and professional publications by Johnson (1994, 1996). Other sources include landslide experts in the area and directly reported slides by the public. All of the landslide locations were aggregated into a single table which then became the basis for a feature class within the GIS that indicated the locations of landslides and certain properties of each slide.

It is worth noting that the general appearance of the data and derived maps for the OSIP provided data differs from that of the data provided by the NKAPC. Data obtained from OSIP for Ohio was processed by generating a triangulated irregular network (TIN) which was then rasterized to create the resulting DEM's that are provided on the download interface. The affects of the TIN can be seen readily on slope and aspect maps. This is in contrast to the data obtained from the NKAPC where the DEM's were processed using a smoothing method that interpolated between known data points.

2.1 Processing and Analysis

Unique landslides were chosen for preliminary analysis in the GIS using raster analysis techniques that focused on topographic derivative maps generated from the high-resolution DEM's. The extents surrounding landslide locations identified as being particularly interesting or unique were analyzed using slope, curvature, hillshade and contour maps.

The preliminary analysis served two purposes, the first of which was to more confidently delineate and identify existing landslides that had been previously studied or observed. In addition to providing more strongly defined landslide extents, it provided a method for observing how certain landslide types appeared in topographic derivative maps. In order to successfully locate and delineate a previously unidentified slope failure it would require that observers be familiar with how they would appear in the data.

Two primary approaches were employed when searching for previously undiscovered landslides. The first approach involved a brute force attempt at locating landslides by selecting an extent and generating a topographic derivative map of the entire area and searching for signs of slope failures. The second method involved focusing on areas that were believed to possess a high propensity for landslides. The primary criteria that were used to identify high-risk areas were average slope angle and the known landslide density. The criteria for searching for landslides involved identifying arc-like features with high immediate slope angles that may be head scarps, other breaks in a normal slope pattern, anomalies in the curvature of the terrain, and arc-like clusters of contours which may indicate the head scarp of a rotational failure.

Both new and existing landslides were verified in the field to confirm that our delineations or characterizations were correct. Indicators of slope failures include an obvious scarp, bent trees, bulge-toes, or cracks in brittle materials such as pavement used for driveways and sidewalks. This step was particularly important for previously undocumented landslides where there was no record of the extent of the landslide or any photographic evidence of its existence.

An illustration of the data analysis and processing flow is depicted in Figure 2.

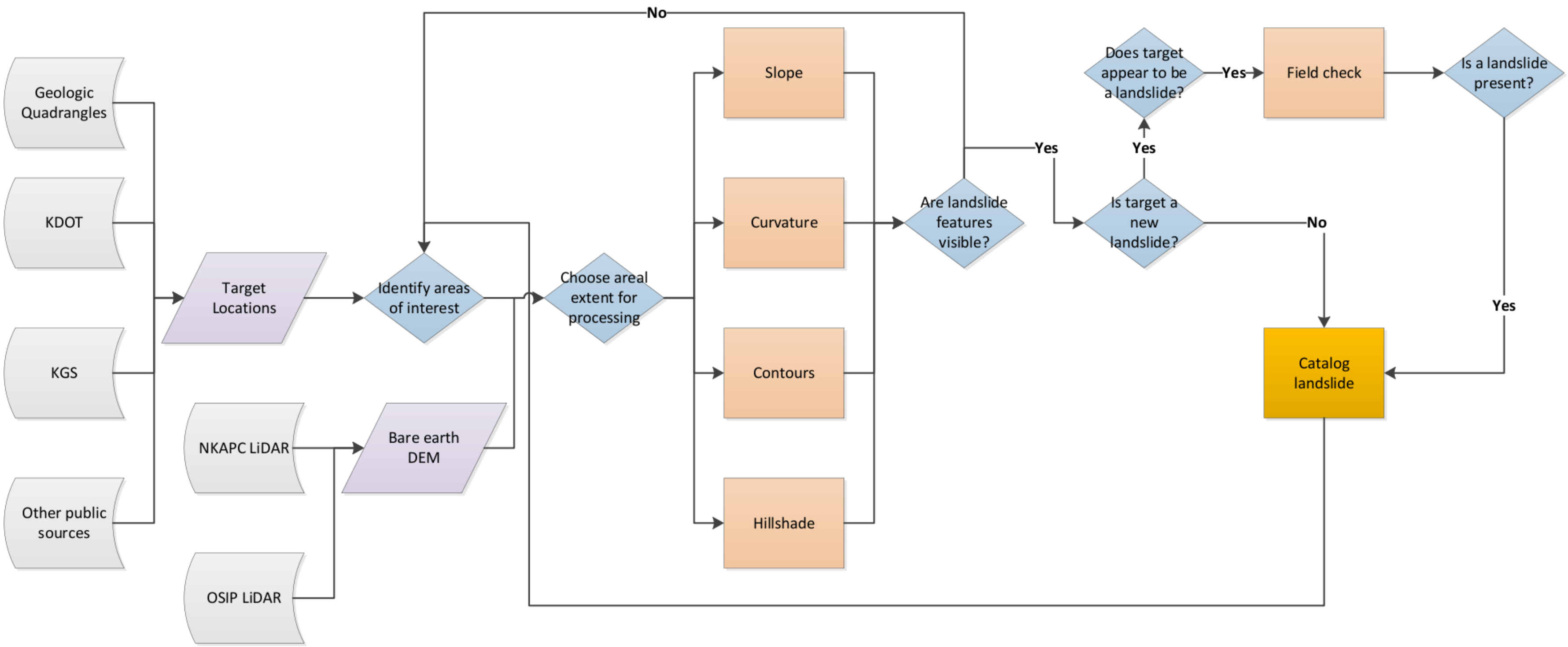

Figure 2: Flow chart illustrating the data analysis and processing flow used to identify landslides.

3. Results

3.1 Rotational Failures

Five rotational failures were examined for this study, three of which were previously undiscovered landslides. These types of landslides can be identified on topographic derivative maps by their steep arc-shaped head scarps which show up most clearly on slope and contour maps. The River Rd. and Delhi Pk. landslides represent two known landslides that possess a characteristic rotational morphology but occur in two different material types with the River Rd. slide predominantly occurring within a deposit of fill and the Delhi Pk. Landslide forming within native material from the Kope Fm. Of the three newly discovered landslides, West KY-8 and Dry Creek formed in slopes covered in colluvium weathered from the Kope and Fairview Fms. while the Lawyers Pt. landslide formed within glacial lake clays.

3.1.1 River Rd. (KY-445)

Found off of River Rd. in Ft. Thomas, Kentucky is an active landslide that developed after the construction of the I-275 beltway that resides directly behind the slope that the landslide is affecting. The landslide is primarily occurring in a thick layer of fill deposited during construction of the expressway, but appears to be propagating through the bedrock which lies beneath River Rd. Few landslides in the region are as well-defined as the River Rd. landslide due to its sizable head scarp and characteristic bulge. From the surface, the landslide is easily observed as a rotational landslide (Figure 3).

Figure 3: The River Rd. landslide as viewed from the northwest (Photo by Sarah Johnson).

Due to the unusual height of the head scarp, the River Rd. landslide is readily visible on slope and contour maps (Figure 4A; Figure 4D). The slope angle of the head scarp is considerably higher than the slope itself with local values up to 40-45°. In the slope map these appear as the warmer colors of yellow, orange, and red while in the contour map the scarp is identified by a clustering of elevation contours.

The head scarp and the flanks of the landslide were moderately visible when viewing the curvature map (Figure 4C). Both features exhibited a pattern of higher curvature values transitioning to lower values which was unique to area surrounding the landslide in each direction for approximately 250m. Most curious is the linear region of high slope values that is visible to the southwest side of River Rd. While this feature appears to be landslide-related in the data, field work led to the discovery that it was a deep ditch that had been dug next to the road. The ditch has been dug into the toe of the slide causing the entire toe to be elevated on the south side of the road. An approximation of the area affected the landslide is provided in Figure 4C.

3.1.2 Delhi Pike

The second existing rotational landslide to be examined was an older slide located off of Delhi Pike in Cincinnati, OH. Unlike the River Rd. landslide, the Delhi Pike slide is obscured by thick vegetation and trees. Another marked difference between the two slides is that the Delhi Pike slide is occurring entirely in native materials (colluvium weathered from the Kope Fm.) whereas the River Rd. slide developed within fill. The head scarp of the slide is evident on both the slope and contour maps (Figure 5A; Figure 5D). The curvature map appears to give a meaningful approximation of the area affected by the landslide where the pattern of high to low curvature values becomes much tighter on top of the slide (Figure 5C).

3.1.3 Lawyers Pt.

After analyzing the River Rd. and Delhi Pike slides, work began on combing through areas that we identified as having a high propensity for developing landslides. The primary criteria were high slopes, weathered colluvium or large deposits of fill, and valleys that were known to have lakebed clay deposits (Johnson R. L., 1996). There were multiple reported landslides near Anderson, OH that prompted us to begin processing that region. While searching through a slope map of a tile near Anderson a sequence of features were found that appeared to have characteristics of rotational landslides. They were found in a valley surrounded by residential housing near Lawyers Pt.

What appeared to be head scarps were identified on hillshade, slope, and contour maps (Figure 6A; Figure 6B; Figure 6D). The ground strike density of the surrounding area caused the curvature map to be unhelpful, though a weak pattern of clustering of high to low values is seen on the affected area much like for the Delhi Pike landslide in Ohio (Figure 6C). Field observation confirmed that the features were landslides, though they appeared inactive at present and trees were observed growing on them that were at least 45 to 50 years in age (Figure 7). It is unclear why the slides developed on a relatively low slope. The housing development had likely not begun when the slope initially failed which ruled out loading from development. While exploring the stream adjacent to the property lakebed clays were discovered in the channel (Figure 8). It is likely that movement of the plastic lakebed clays out of the slope led to the development of the landslides.

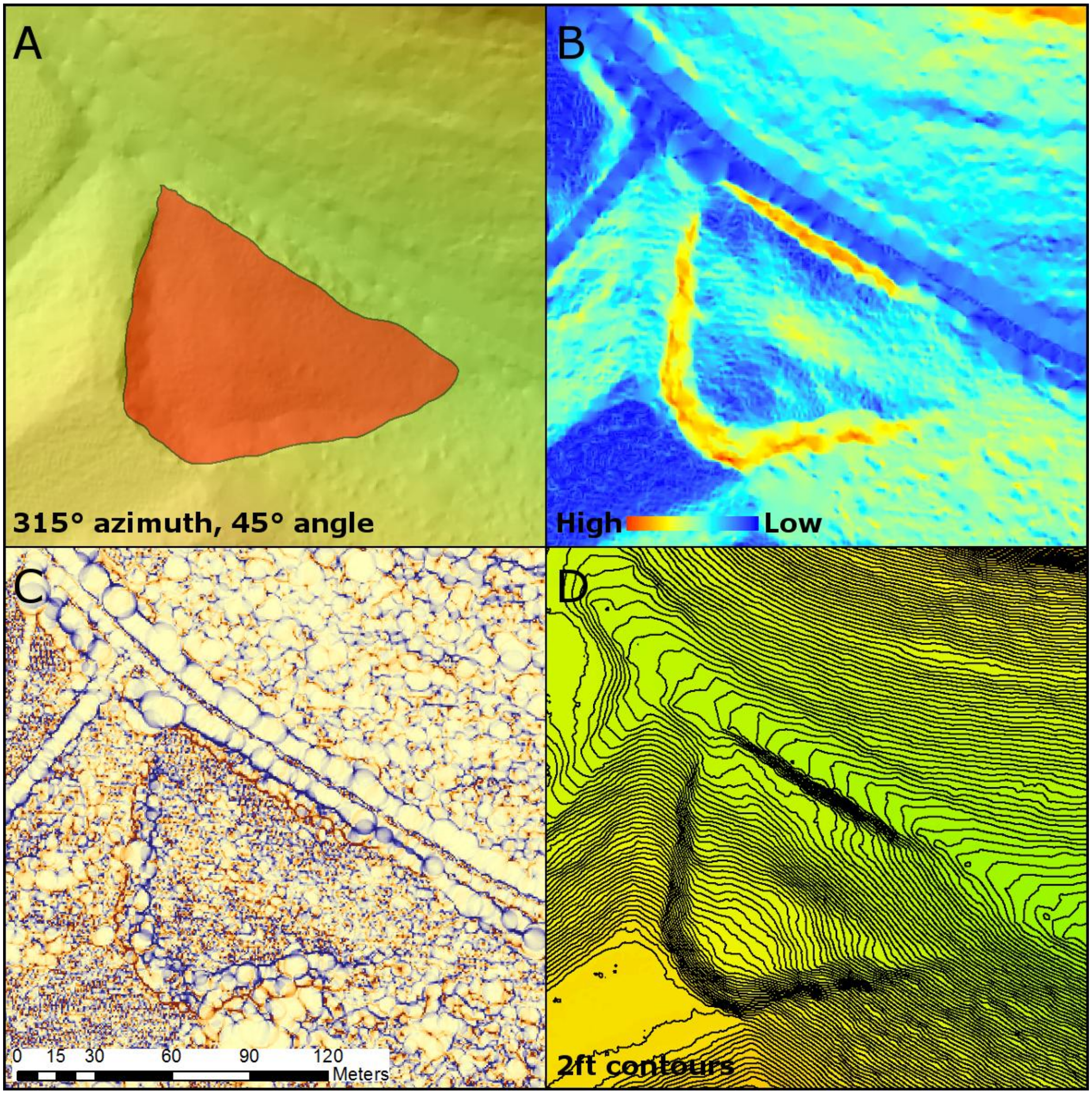

Figure 4: Composite display of four different topographic derivative maps of the River Rd. landslide in Ft. Thomas, KY. This slide is a classic example of a rotational landslide and is characterized by a high head scarp, flanks that form a pattern in the shape of a 'V', and a slight bulge near its center. It initially formed within a large pile of fill but has propagated underneath the road through bedrock as it continues to slide. (A) Hillshade map generated with an azimuth of 315° and a sun angle of 45° draped over a bare earth DEM. The estimated extent of the landslide is highlighted in red. (B) Slope map showing areas of high slope angle in warmer colors (reds, oranges, yellows) and areas of low slope angle in cooler colors (greens, blues). The head scarp of the landslide is clearly evident to the southwest corner of the image due to its high slope angle. The linear feature paralleling the road showing high slope values is a ditch. (C) Curvature map showing areas of high curvature in warmer colors (reds, oranges) and areas of low curvature in cooler colors (blues). The scarp of the landslide appears to be characterized by a transition from high to low curvature. (D) Contour map generated with a 2ft contour spacing.

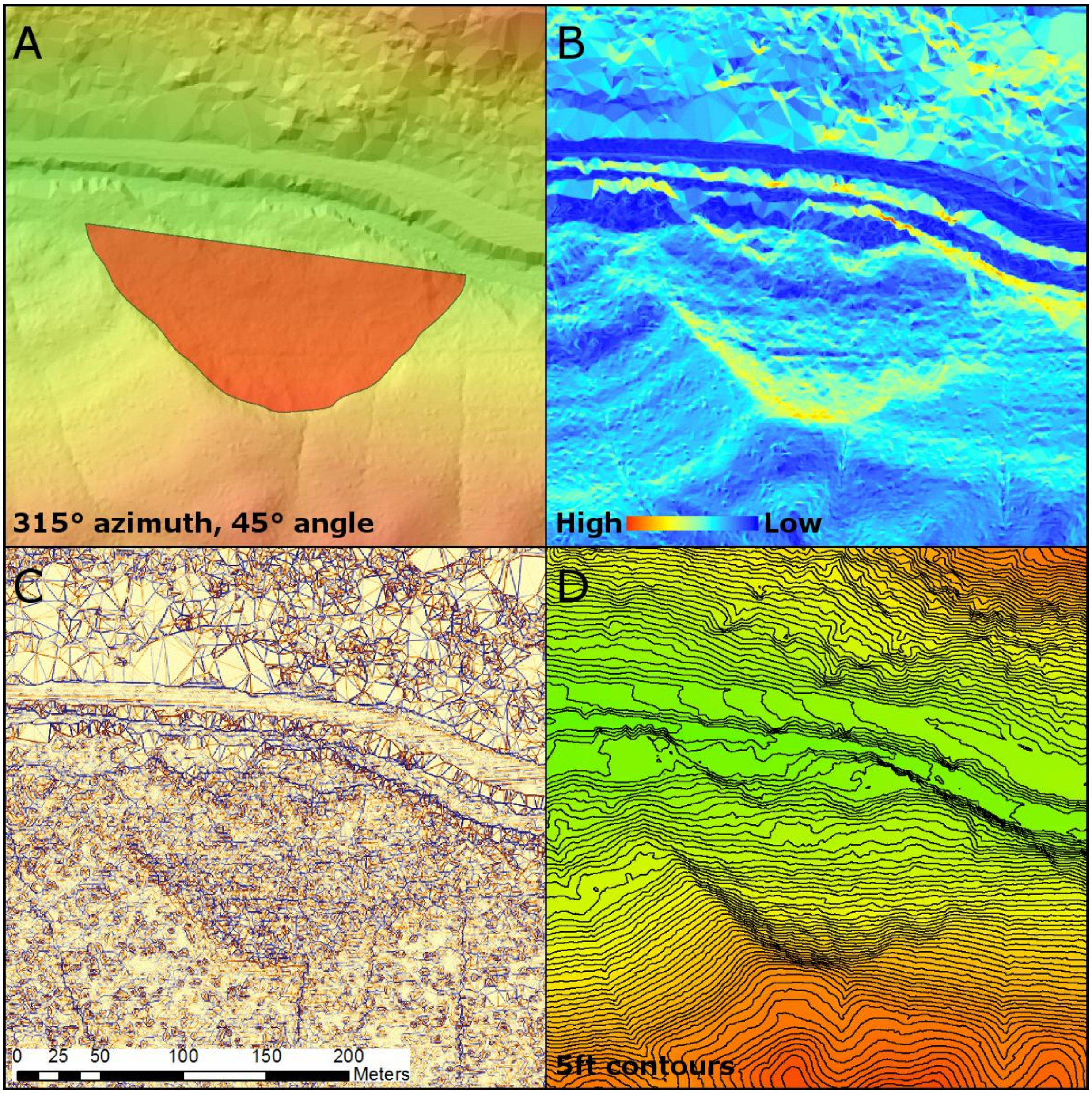

Figure 5: Composite display of four different topographic derivative maps of the Delhi Pike landslide in Cincinnati, OH. This is a rotational slide that has occurred in colluviums that weathered from the Kope Fm. (A) Hillshade map generated with an azimuth of 315° and a sun angle of 45° draped over a bare earth DEM. The estimated extent of the landslide is highlighted in red. (B) Slope map showing areas of high slope angle in warmer colors (reds, oranges, yellows) and areas of low slope angle in cooler colors (greens, blues). Though not as large as the River Rd. landslide, the head scarp of this slide is still clearly evident. (C) Curvature map showing areas of high curvature in warmer colors (reds, oranges) and areas of low curvature in cooler colors (blues). It appears that the extent of the landslide can be roughly approximated by observing where the clustering of high to low contour values becomes more concentrated. (D) Contour map generated with a 5ft contour spacing.

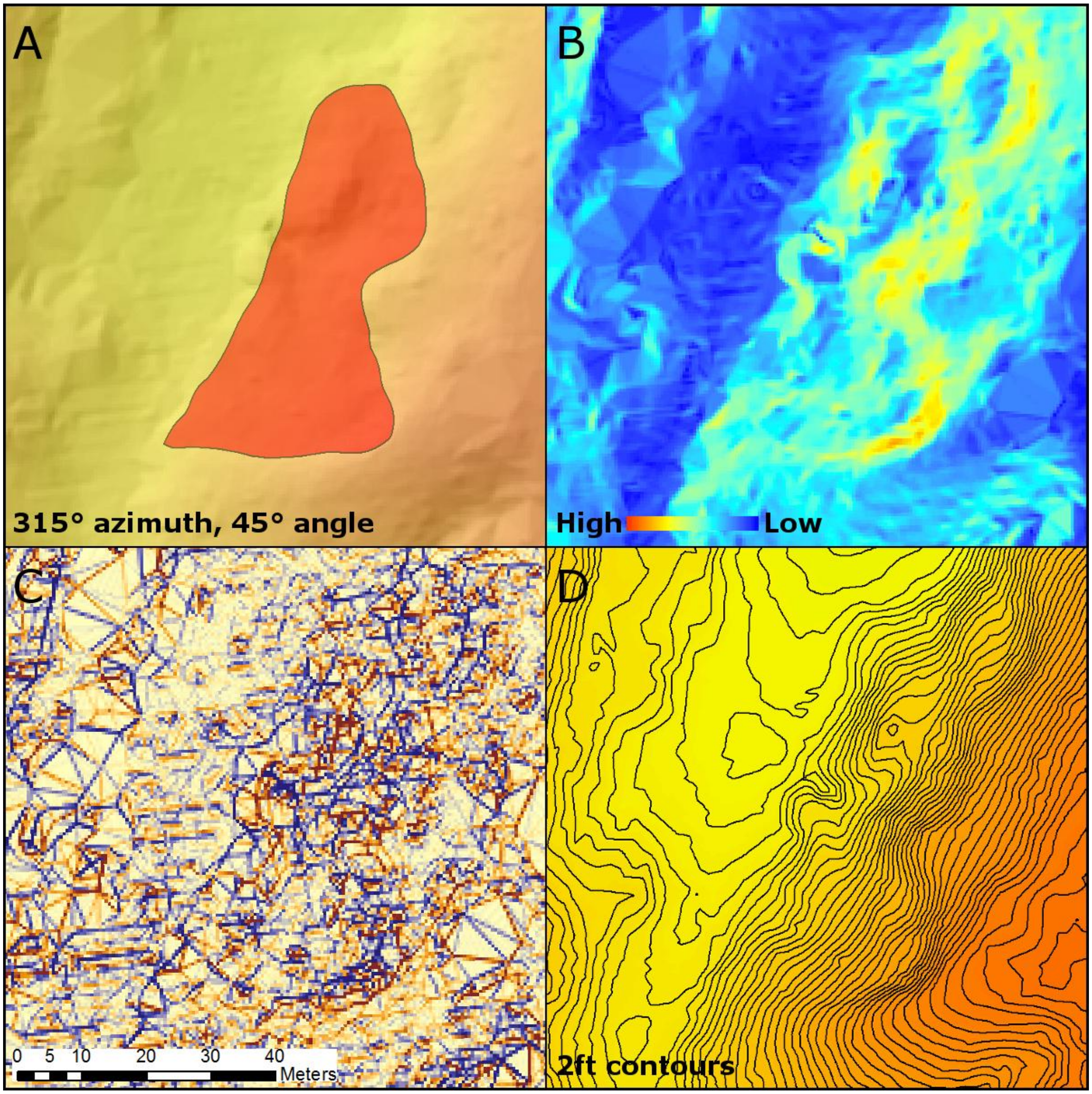

Figure 6: Composite display of four different topographic derivative maps of a newly discovered rotational landslide off of Lawyers Pt. in Anderson, OH that is believed to have occurred in lakebed clays. (A) Hillshade map generated with an azimuth of 315° and a sun angle of 45° draped over a bare earth DEM. The estimated extent of the landslide is highlighted in red. (B) Slope map showing areas of high slope angle in warmer colors (reds, oranges, yellows) and areas of low slope angle in cooler colors (greens, blues). There are a series of three features that appear to resemble head scarps of rotational landslides. Two of these features were confirmed in the field, but the third may have been caused by the unsmoothed TIN. (C) Curvature map showing areas of high curvature in warmer colors (reds, oranges) and areas of low curvature in cooler colors (blues). There is a weak but observable correlation between a clustering of low curvature values where the landslide toes are located. (D) Contour map generated with a 2ft contour spacing.

Figure 7: Trees growing vertically on top of the Lawyers Pt. landslide suggest that it is an older slide (Photo by Sarah Johnson).

Figure 8: On the opposite side of the valley where the Lawyers Pt. landslide occurred was a stream that had exposed lakebed clays seen here in their dark grey and blue (Photo by Sarah Johnson).

3.1.4 West River Rd (KY-8)

KY-8 (also known as River Rd.) is well-known for its numerous landslides and the road is frequently closed for repairs. Most of these slides are cataloged by the KDOT if they require repairs to the road. However, slides that do not warrant road repair often go unnoticed and undocumented. Locating new landslides along the large cliffs that overlook the Ohio River valley was considerably easy due to their frequency and size.

An area near the northwest corner of the extent for the Northern Kentucky data was selected for analysis. Slides appeared to be very numerous so a smaller scale was chosen for analysis. Results were similar to both the River Rd. and Delhi Pike landslides and a majority of the failures were identified as rotational based on the morphology of their head scarps as seen in Figure 12B and Figure 12D. Most interesting was the continued pattern of a higher variation of curvature values on top of landslides. The western facing slope on the southwest corner of the map exhibits a much lower variation of curvature values than the north facing landslide-covered slopes (Figure 12C). This complicated landslide complex poses challenges for area estimations without an extensive field study and for this reason the affected area was approximated as being a majority of the hillside (Figure 12A).

Field work confirmed the presence of multiple slides. Rather than a series of large consecutive landslides, the slope appeared to contain many smaller rotational slump failures. The presence of trees growing both at an angle and straight upwards suggests that these small rotational failures are separated by at last 30 years (Figure 9). Many of the slides continue through the road and have caused it to deform and crack (Figure 10).

Figure 9: Trees located on the north-facing slope that parallels KY-8 near the Kenton and Boone county borders. The presence of both tilted and straight trees suggests that the numerous small rotational failures vary in age by at least 30 years (Photo by Sarah Johnson).

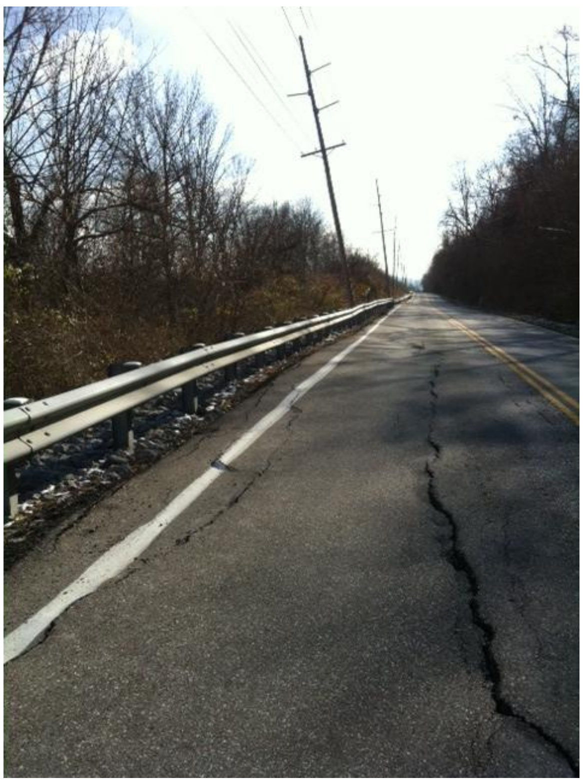

Figure 10: Many of the landslides on the steep slope on the south side of KY-8 have affected the road. These affects can be seen as cracks in the pavement, rolling or bumpy sections of road, and tilted utility poles (Photo by Sarah Johnson).

3.1.5 Dry Creek

While investigating a potential landslide in a large valley occupied by the Dry Creek Wastewater Treatment Plant in Villa Hills, KY, a large feature downstream was discovered that had an appearance that resembled a rotational landslide. This was on the opposite side of the valley where the original landslide was reported and was thus labeled as a newly discovered failure.

Both the slope and contour maps display the scarp of the landslide (Figure 13B; Figure 13D) as having a considerably higher slope angle than the surrounding terrain. The classic pattern of an arc-shaped, high scarp strongly suggests that the failure is rotational. As has been previously observed, there appears to be a dramatic change from high to low curvature values within the upper head scarp of the slide (Figure 13C). Field work also provided strong support for the claim that a landslide was present. There were numerous older trees that were growing at an angle, while younger trees were growing straight upwards (Figure 11). This, much like at the KY-8 site nearby, suggests that the slide is old and may no longer be active.

Figure 11: There were tilted trees growing alongside younger straight trees below the scarp-like feature found at Dry Creek. These could be indications that movement has ceased and the landslide is no longer active (Photo by Jesse Amundsen).

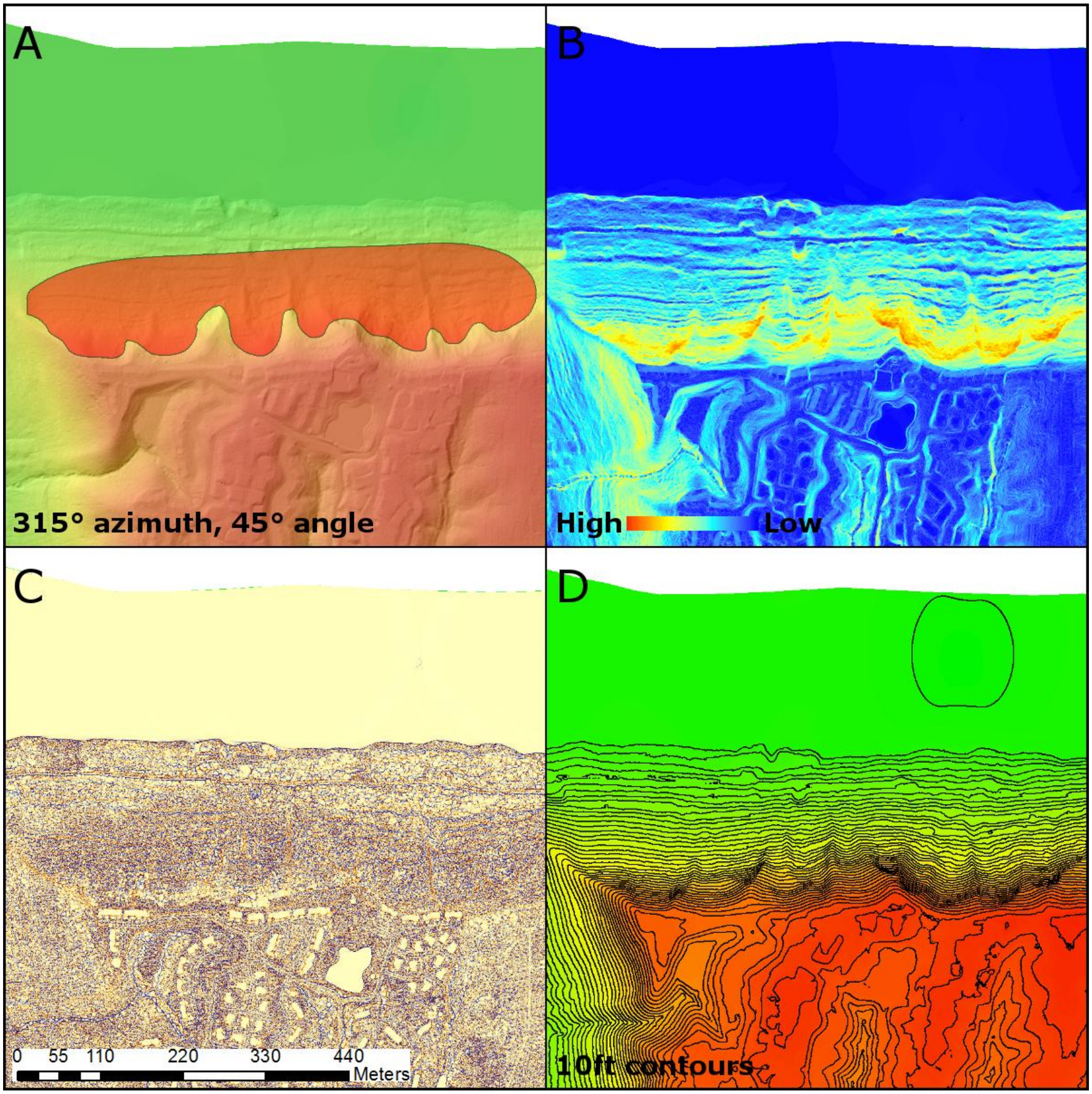

Figure 12: Composite display of four different topographic derivative maps of a landslide complex near the far northwestern corner of Kenton County along a section of KY-8. (A) Hillshade map generated with an azimuth of 315° and a sun angle of 45° draped over a bare earth DEM. The estimated extent of the landslide is highlighted in red. (B) Slope map showing areas of high slope angle in warmer colors (reds, oranges, yellows) and areas of low slope angle in cooler colors (greens, blues). Numerous northward-facing scarps are visible along with a undulating pattern of high and low slope values often observed on landslide-affected hillsides. (C) Curvature map showing areas of high curvature in warmer colors (reds, oranges) and areas of low curvature in cooler colors (blues). It appears that the undisturbed slope to the west has a lower variance of curvature values. (D) Contour map generated with a 10ft contour spacing.

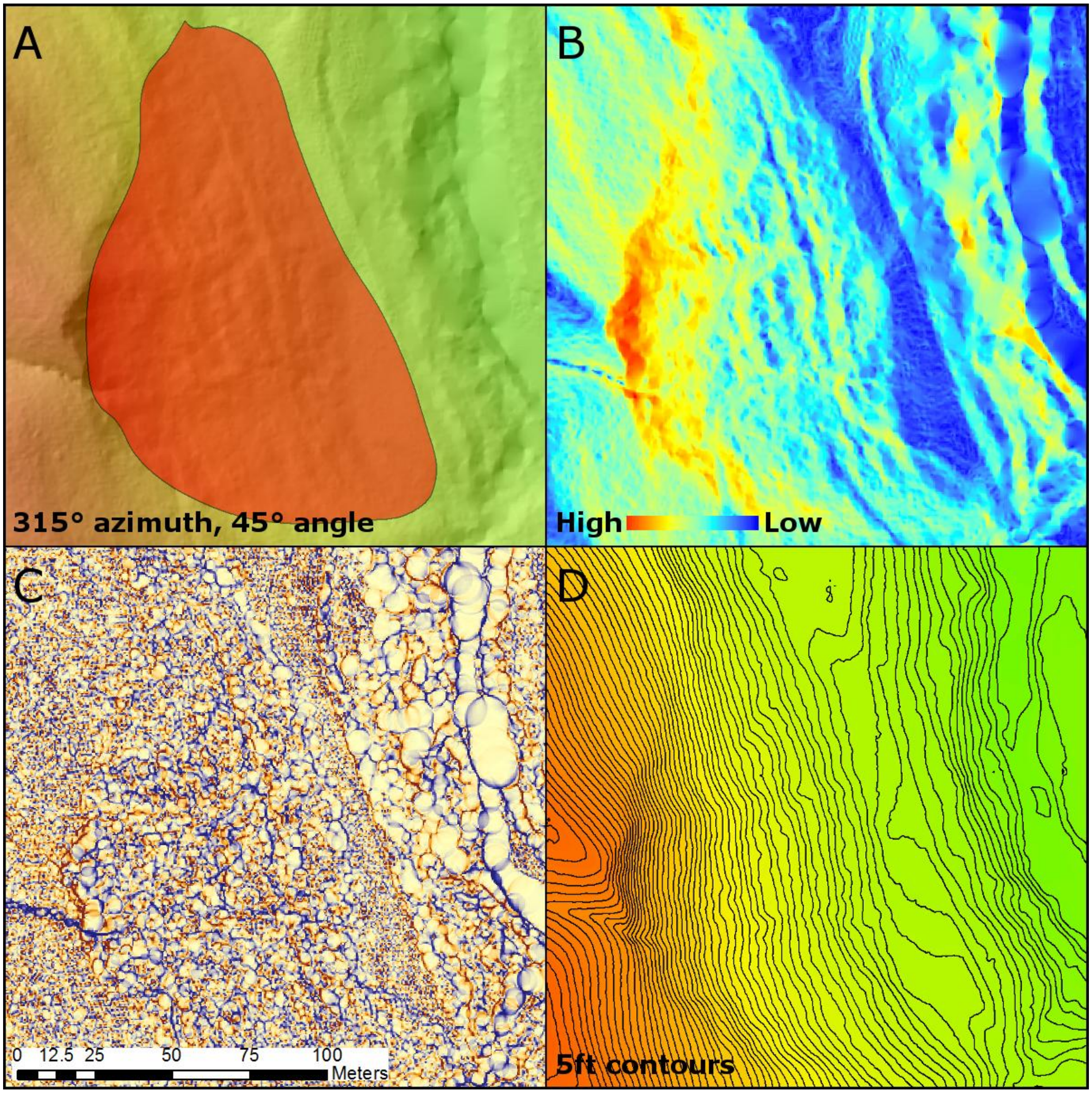

Figure 13: Composite display of four different topographic derivative maps of a landslide behind the Toyota Boshoku offices located off of Dolwick Rd. in Kenton County, KY. (A) Hillshade map generated with an azimuth of 315° and a sun angle of 45° draped over a bare earth DEM. The estimated extent of the landslide is highlighted in red. (B) Slope map showing areas of high slope angle in warmer colors (reds, oranges, yellows) and areas of low slope angle in cooler colors (greens, blues). There appears to be a head scarp of a rotational landslide identified by the dark red colors. (C) Curvature map showing areas of high curvature in warmer colors (reds, oranges) and areas of low curvature in cooler colors (blues). Much like has been observed in other rotational landslides there exists a pattern of high to low curvature values near the scarp. (D) Contour map generated with a 5ft contour spacing.

3.2 Translational failures

Two translational failures were examined using topographic derivative maps. The failure off of Montague Rd. proved difficult to delineate with confidence and had been remediated which made field work impossible. The larger Licking Pike landslide was visible on the LiDAR data, but appeared to more closely resemble a rotational slide than a translational slide. The effectiveness of the slope and contour maps was minimized by the lack of well-defined steep head scarps that most rotational slides possess. This study was unable to locate any previously undiscovered translational landslides.

3.2.1 Montague Rd.

Montague Rd. passes through Devou Park which is an area recognizable by its high hills and steep slopes. At one location these conditions contributed to the development of a mid-sized translational landslide. The landslide was repaired in late 2009 after it began to rapidly advance which led to the blocking of the driveway of a home nearby (Figure 14). The LiDAR for Northern Kentucky was flown in 2008 before repair work had begun.

Analysis using topographic derivative maps revealed minimal indications about the extent of the landslide or of its existence. The feature that appears to resemble a small scarp seen on the slope and contour maps (Figure 17B; Figure 17D) is a cut made in the side of the hill to provide level ground to provide a foundation for the construction of a residential housing unit. It is known that the area around the home and leading down to the driveway was affected by the landslide. Neither the hillshade or curvature maps provided any convincing indication of a landslide (Figure 17A; Figure 17C).

Figure 14: Photograph from 2005 of debris blocking the driveway off of Montague Rd. caused by a translational landslide. The slide was repaired after debris continually blocked the road (Photo by Sarah Johnson).

3.2.2 Licking Pike

Identified on the Alexandria quadrangle as "landslide deposits"(Gibbons, 1971) the landslide off of Licking Pike (KY-915) is a large failure located on private property with limited access. It is located at the end of a small ridge and has an orientation that shows it progressing toward a stream that parallels Licking Pike.

The scarp appears to resemble that of a small rotational slide, but closer examination of both the slope and contour map shows that there are no flanks on the north or south side of the slide (Figure 19B; Figure 19D). While it is possible that this landslide has both translational and rotational components, it is being identified as a translational slide by this study due to its appearance in the topographic derivative data. There is a clear curvature disturbance for the scarp of the slide and on the first major step when heading east from the scarp (Figure 19C).

3.3 Block Extrusions

One existing block extrusion failure located off of Huffman Ct. in Cincinnati, OH was examined in the study to provide a more encompassing look at the varying types of slope failures found in the study region. Unlike rotational and translational slides, the movement in a block extrusion failure more closely resembles the effects of subsidence. They typically lack well-defined head scarps and were not sought out as targets in this project.

3.3.1 Huffman Ct.

In order to build a new subdivision on the north end of Cincinnati, development began as early as 1961 near Huffman Ct. off of Compton Rd but was abandoned until the early 1970's when development was reinitiated in order to build a small subdivision of 26 low cost housing units. Up to four housing units have been damaged to some degree by a landslide that developed on the northwest side of the neighborhood. Numerous studies have been conducted on the landslide that conclude that glacial lakebed clays were present and overlaying glacial till with the landslide occurring within them (Fleming R. W., 1981). Despite the fact that the landslide has persisted and continued to affect homes on Huffman Ct. (Figure 15), it has yet to have been properly remediated.

Figure 15: Photograph from 2005 of the backyard of one of the four homes directly affected by the large block extrusion failure at Huffman Ct. in Cincinnati, OH. The deck is shown slipping downwards away from the home indicating substantial movement (Photo by Sarah Johnson).

There are different interpretations of the sliding process at the Huffman Ct. landslide that involve both rotational and block extrusion mechanisms. Due to the presence of lakebed clays and a non-rotational movement profile it was treated as a block extrusion failure. The slide lacks a well-defined scarp and toe that is typically present in slope and contour maps (Figure 18B; Figure 18D) which also suggests that the failure process may involve movement more typically associated with block extrusions. Lakebed clays were identified in the stream bed channel. The data had a particularly low ground strike return density in the area and there appears to be far less returns on the head and toe of the slide than in the body. This can be seen readily on the curvature map (Figure 18C). Field work discovered that honeysuckle was present in these areas with low ground strike densities. While the landslide presents challenges for identification in the topographic derivative maps, it is easily delineated when using a recent aerial photograph due to its affects on the sidewalk and homes nearby (Figure 16).

Figure 16: Aerial photograph obtained from the OSIP aerial imagery archive of the landslide located off of Huffman Ct. north of Cincinnati, OH. The top of the slide can be seen affecting the sidewalk on the northeast side of the turn in the road. The gray feature near the bottom of the slide is an access road which is moving with the slide.

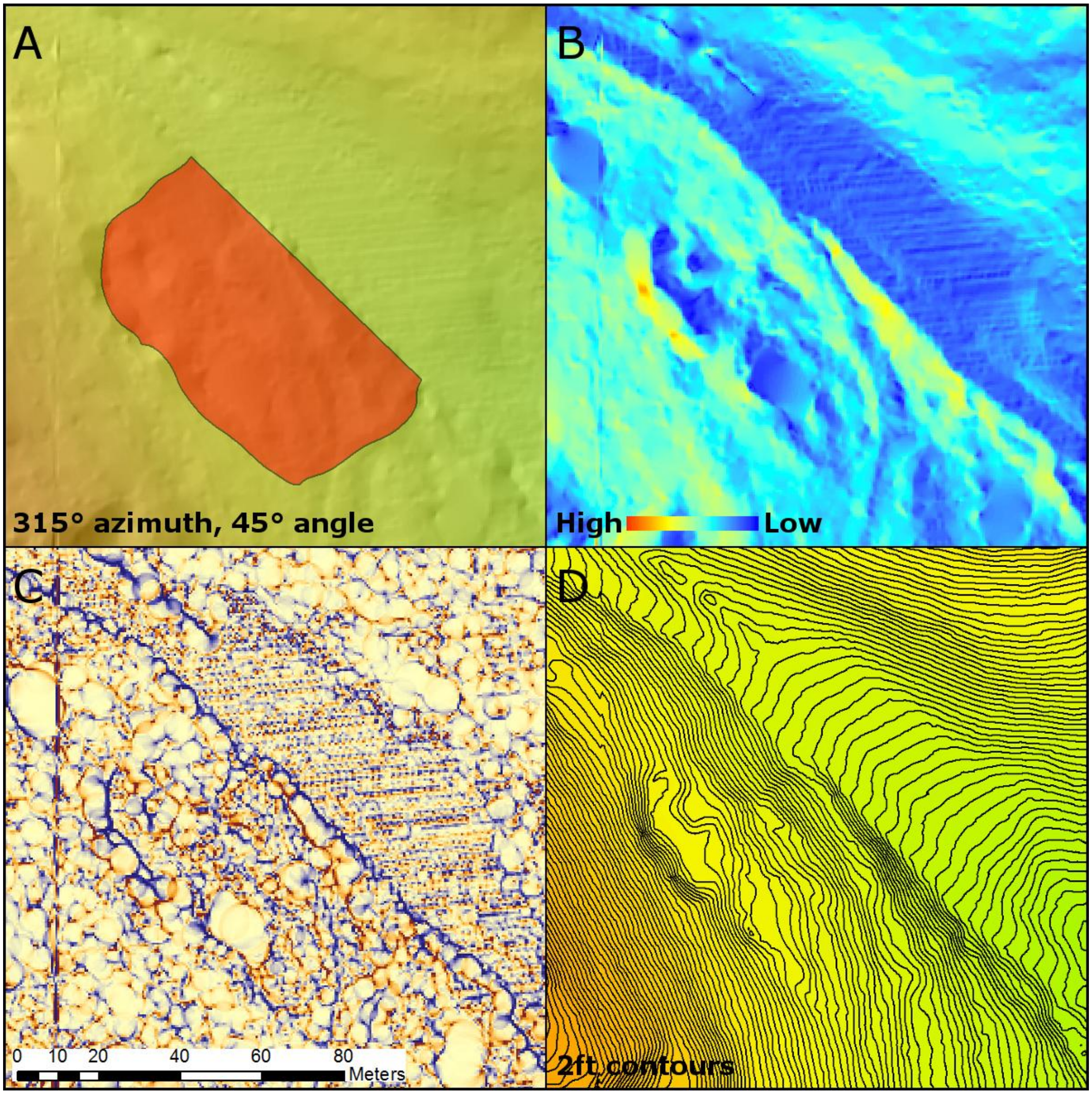

Figure 17: Composite display of four different topographic derivative maps of a translational landslide affecting the south side of Montague Rd. in Covington, KY. (A) Hillshade map generated with an azimuth of 315° and a sun angle of 45° draped over a bare earth DEM. The estimated extent of the landslide is highlighted in red. (B) Slope map showing areas of high slope angle in warmer colors (reds, oranges, yellows) and areas of low slope angle in cooler colors (greens, blues). The scarp-like feature to the middle of the west side of the map is a cut-out of the hillside that was removed to build a residential home on the property. With no distinguishing scarp, it is difficult to locate this translational slide. (C) Curvature map showing areas of high curvature in warmer colors (reds, oranges) and areas of low curvature in cooler colors (blues). (D) Contour map generated with a 2ft contour spacing.

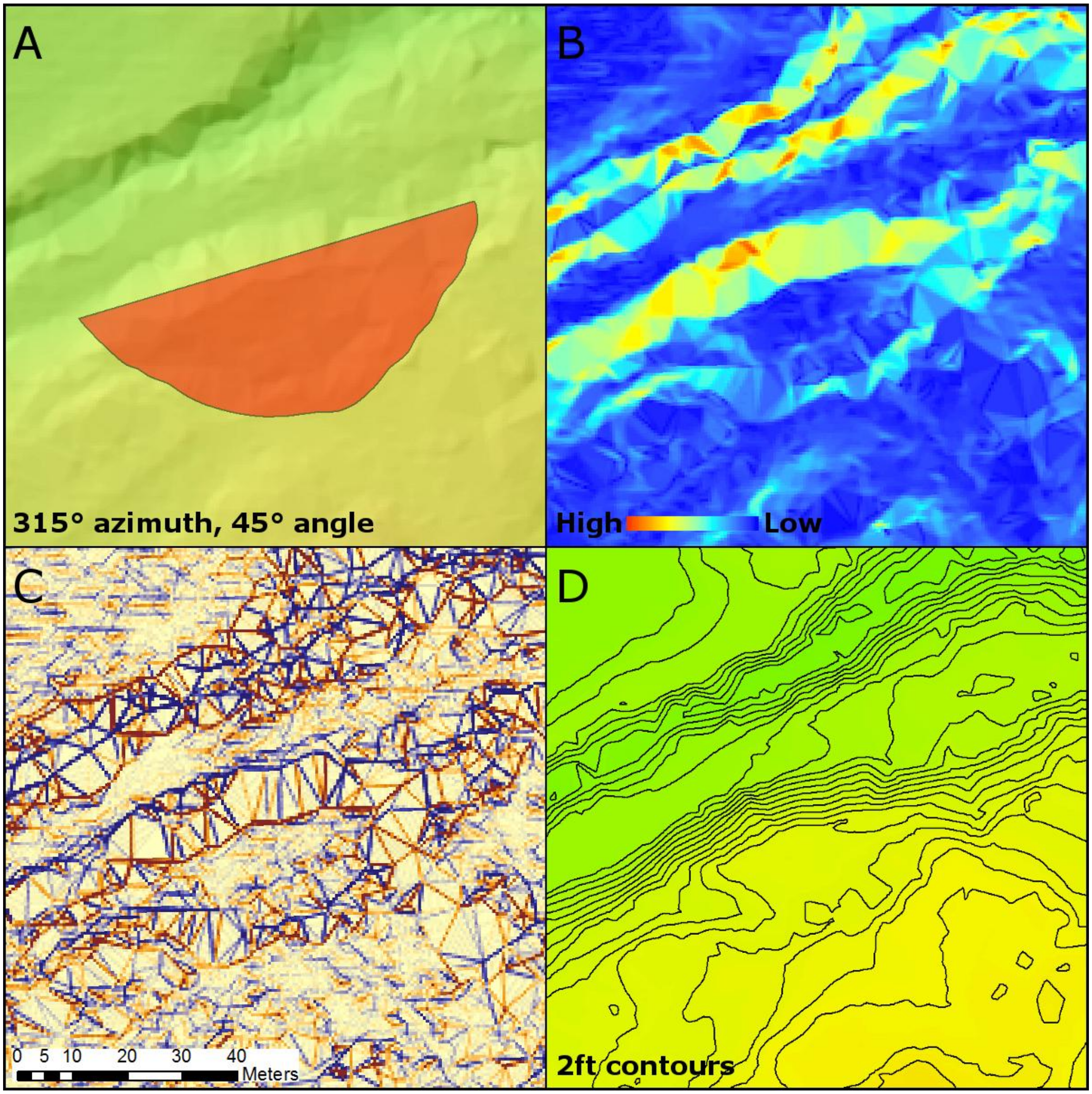

Figure 18: Composite display of four different topographic derivative maps of the large landslide located off of Huffman Ct. in Cincinnati, OH. This slide developed within lakebed clays and glacial till and is believed to be a block extrusion failure. (A) Hillshade map generated with an azimuth of 315° and a sun angle of 45° draped over a bare earth DEM. The estimated extent of the landslide is highlighted in red. (B) Slope map showing areas of high slope angle in warmer colors (reds, oranges, yellows) and areas of low slope angle in cooler colors (greens, blues). Since this area has been graded numerous times the natural slope angles are not preserved. The top of the landslide is actually the lighter blue line toward the southeast of the middle of the map. (C) Curvature map showing areas of high curvature in warmer colors (reds, oranges) and areas of low curvature in cooler colors (blues). There appear to be poor ground strike returns at both the head and the toe blocks. (D) Contour map generated with a 2ft contour spacing.

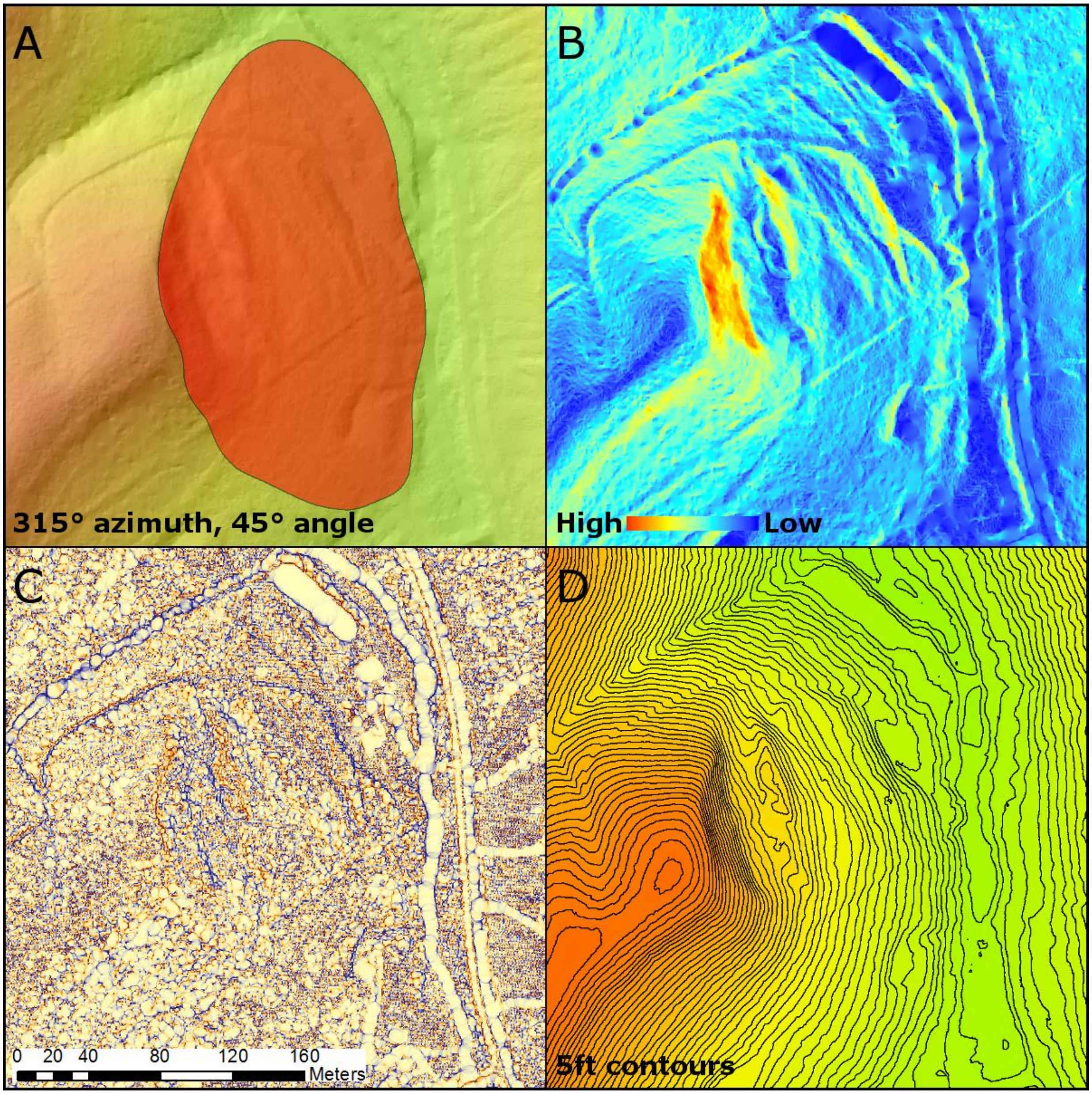

Figure 19: Composite display of four different topographic derivative maps of a landslide located off of Licking Pk. (KY-915) in Campbell County, KY. (A) Hillshade map generated with an azimuth of 315° and a sun angle of 45° draped over a bare earth DEM. The estimated extent of the landslide is highlighted in red. (B) Slope map showing areas of high slope angle in warmer colors (reds, oranges, yellows) and areas of low slope angle in cooler colors (greens, blues). There appears to be what looks like a scarp followed by an undulating pattern down the hillside to the east. (C) Curvature map showing areas of high curvature in warmer colors (reds, oranges) and areas of low curvature in cooler colors (blues). (D) Contour map generated with a 5ft contour spacing.

4. Discussion and Conclusions

The processing of LiDAR data into a DEM can greatly affect the usefulness and accuracy of the output data. Data for the Northern Kentucky region that was processed using an interpolating smoothing method had a markedly different appearance than data obtained from OSIP for Hamilton County, OH which was processed by generating a triangulated irregular network (TIN) and then rasterizing the result. The level of “TINning” (as it came to be called) reflects the point return density of the original raw LiDAR data which is both valuable information and a visual distraction. It is important for an observer to be aware of the quality of the data used to generate a modeled surface, but it can be very distracting when searching for features on that same surface when they are largely obscured by triangles. At times, the quality of the data for Hamilton County was poor enough to obscure known landslides. An example of this is the south side of the Delhi Pk. landslide which has numerous other smaller landslides present.

Of the four topographic derivative map types used to investigate landslides, the two that proved most useful were slope and contour maps. The curvature and hillshade maps varied in their effectiveness and were difficult to interpret with confidence. Slope and contour maps provide visual indicators of a slope pattern in a given extent and landslides often have changes in slope associated with their various morphologies. Curvature maps presented data with such variance that it was typically difficult to distinguish a change across a surface, though the overall pattern of curvature in a given area was often a moderately effective indicator of the extent of the area affected by landslides. Hillshade maps can provide a very powerful visual aid when looking for landslides, but their usefulness depends on the sun angle and the azimuth with which the derivative map was processed using. To utilize hillshade maps effectively would require the generation of multiple hillshade maps that varied both the modeled sun angle and azimuth for the source light since not all features share a similar aspect. Features in particularly rugged areas could also be cloaked in the shadow of a larger feature such as a large hill or mountain.

Rotational landslides were the easiest to locate and delineate using topographic derivative maps generated from high resolution LiDAR data. Translational landslides and block extrusion failures were difficult to identify and presented considerable challenges for processing and mapping. Rotational failures are typically associated with large head scarps while both translational and block extrusion failures often lack such features. Both the slope and contour maps (and to some extent the hillshade maps) show how slope changes over an area, and the head scarps of rotational landslides were clearly visible in both derived maps. There were no new translational or block extrusion failures found during the course of this study.

It became apparent during this study that many landslides are more complex than they appear on aerial photos and in DEM’s and their associated derivative maps. At the west KY-8, Dry Creek, and Delhi Pk. locations there were numerous smaller failures either within or nearby the primary landslide being targeted. One other aspect that all three of these locations share is that the contact between the Kope and Fairview Fm. was often present on the hillside. In the case of the west KY-8 landslides and the Dry Creek slide, the contact between these two units was right above the head scarp. This pattern may be a result of the relative compositions of these two formations with the Kope Fm. being composed of 80% mudstone and 20% limestone whereas the Fairview Fm. has a roughly equal distribution of 50% mudstone and 50% limestone. Under typical conditions, the mudstone would more readily form unstable slopes since it is more easily weathered.

Careful examination of the curvature, contour, and slope maps from the west KY-8 landslide area reveals an interesting pattern with notable differences between the north and west facing slopes (Figure 12). The reason for this pattern is unclear since the same geology is present on both the north and west slopes. One currently unpublished theory was put forth by Dr. Bill Haneberg from the Department of Geology at the University of Cincinnati during a seminar at Northern Kentucky University which postulates that there may be some structural control on the orientation and development of unstable slopes in the region.

5. Future Research

This project involved the collaboration of four different people stationed in three different places which presented measurable difficulties when attempting to synchronize data and information both in the laboratory and in the field. Preliminary work was done to build a landslide database that could potentially act as a standardized storage model for landslide information. The KGS has expressed repeated interest in having such a supporting system for their landslide inventory initiative and it is possible that the work that was begun for this project could provide the base for a future project focused on the storage of information pertaining to landslides in the commonwealth of Kentucky.

To supplement the database and provide a method for demonstration, a rudimentary web-based interface for adding and querying landslide data was written. This interface could prove to be a useful asset to government agencies since it has the potential to provide a user-friendly portal for querying information about existing landslides and the threat of slope failures developing in a particular region.

It is evident that new research techniques and analysis methods will be required to more readily locate and delineate translational landslides. Future research using the same LiDAR data could focus more specifically on translational landslides and newer topographic derivative maps such as those using Eigenvalue ratios which were demonstrated as successful landslide indicators by Roering et al. (2004), other roughness calculations, and more direct techniques related to the processing of raw point cloud data.

Throughout the project there were frequent observations of low ground strike densities at locations where honeysuckle was present. This hampered the search for landslides especially in many regions in Ohio. Further research into the affects of honeysuckle on point returns from LiDAR surveys could provide a powerful tool for environmental scientists looking to locate patches of honeysuckle or map regional extents of its current distribution.

6. Acknowledgments

This project would not have been possible without the generosity of the NKAPC who provided the LiDAR data for Kenton and Campbell County. My thanks and gratitude goes out to Sarah Johnson, who worked on this project for over a year, Hongmei Wang for fostering and supporting my interest in GIS, and Katie Rouse for assisting with field work. I would like to thank Matt Crawford from the KGS who shared data and collaborated with me throughout the second half of this project.

7. References

Dorsch, N. F. (2006). Analysis of LiDAR-derived topographic information for characterizing and differentiating landslide morphology and activity. *Geomorphology , 73*, 131 - 148.

F. Ardizzone, M. C. (2007). Identification and mapping of recent rainfall-induced landslides using elevation data collected by airborne Lidar. *Natural Hazard and Earth System Science , 7*, 637 - 650.

Fleming, R. a. (1980). Estimating the costs of landslide damage in the United States. *U.S. Geological Survey Circular , 832*, 21.

Fleming, R. W. (1981). *Engineering Geology of the Cincinnati Area* (Vols. Volume 3: Geomorphology, hydrogeology, geoarcheaology, engineering geology). (T. G. Roberts, Ed.) Cincinnati: Geological Society of America.

Gibbons, A. (1971). Geologic map of the Alexandria quadrangle, Campbell and Kenton Counties, Kentucky. Lexington, KY: Kentucky Geological Survey.

Johnson, R. L. (1996). Overview of Landslide Problems, Research, and Mitigation, Cincinnati, Ohio Area. *USGS Bulletin , 2059*, 33.

Johnson, R. W. (1994). Landslides in Colluvium. *U.S. Geological Survey Bulletin , 2059B*, 1-24.

Lin, R.-F. C.-J.-C.-T.-L. (2006). Topographical changes revealed by high-resolution airborne LiDAR data: The 1999 Tsaoling landslide induced by the Chi-Chi earthquake. *Engineering Geology , 88*, 160 - 172.

M. Van Den Eeckhaut, J. P. (2007). Use of LIDAR-derived images for mapping old landslides under forest. *Earth Surface Processes and Landforms , 32*, 754 - 769.

Potter, P. E. (2007). *Exploring the Geology of the Cincinnati/Northern Kentucky Region*. Lexington: Kentucky Geological Survey.

Roering, J. M. (2004). Objective landslide detection and surface morphology mapping using high-resolution airborne laser altimetry. *Geomorphology , 57*, 331 - 351.

Schulz, W. H. (2007). Landslide susceptibility revealed by LIDAR imagery and historical records, Seattle, Washington. *Engineering Geology , 89*, 67 - 87.

Schulz, W. H. (2004). *Landslides mapped using LIDAR imagery, Seattle, Washington*. Seattle: United States Geological Survey.

8. Appendix

8.1 Table of Referenced Landslides

Latitude	Longitude	PrimaryRoute	Materials	FailureType	Repaired	VisibleOnLidar	VisibleOnAerial	AreaSqM
39.055988	-84.441194	River Road	Fill, Kope/Fairview	Rotational	N	Y	Y	9,274.59
39.069681	-84.611685	KY-8	Colluvium from Kope/Fairview	Rotational	N	Y	Y	190,507.58
38.953042	-84.415017	KY-915		Translational	N	Y	Y	53,905.83
39.050207	-84.607968	Dry Creek	Colluvium from Kope/Fairview	Rotational	N	Y	Y	23,216.39
39.098866	-84.657	Delhi Pike	Colluvium from Kope/Fairview	Rotational	N	Y	Y	26,677.00
39.233742	-84.52	Huffman Ct	Lakebed clays	Block Extrusion	N	Y	Y	2,948.69
39.077614	-84.528557	Montague	Colluvium from Kope	Translational	Y	N	Y	4,686.53
39.10581	-84.348115	Lawyers Point Dr	Lakebed clays	Rotational	N	Y	N	2,910.39