IDENTIFICATION OF MAPPED ICE-MARGIN POSITIONS IN WESTERN NEW YORK FROM DIGITAL TERRAIN-ANALYSIS AND SOIL DATABASES

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Abstract: Geographic Information Systems (GIS) are rarely applied to problems associated with Wisconsinan ice-margins. This study identifies inconsistencies in ice extent in the Salamanca Re-entrant in western New York as mapped using soil properties and surficial geology. In essence, previous studies have revealed a zone of disagreement between those areas that were clearly glaciated and those that were not. This study uses a raster-based approach to extract the soil pH, silt, and clay contents from digital soil databases; and the morphometric parameters of elevation, slope, terrain ruggedness, and planform and profile curvature from mosaiced 10-m digital elevation models. Two-way ANOVA indicates a close correspondence between the zone of disagreement and the glaciated area when soil information is used; however on the basis of morphometry, the area of disagreement is analogous to the unglaciated terrain. These results highlight both previous difficulties and the source of the mapped differences, suggesting that a GIS analysis of former ice margins is a productive preliminary step to their precise delineation. [Key words: GIS, Salamanca Re-entrant, Wisconsinan ice margin, geomorphometry.]

INTRODUCTION

The Salamanca Re-entrant in western New York represents the only portion of the state that remained ice-free during the Wisconsinan glaciation (Fig. 1). The Re-entrant is part of the unglaciated foreland that extends southward into Pennsylvania, where the effects of seasonal freezing and possibly permafrost have been documented by Denny (1951, 1956). Subsequent soil and geomorphic studies support the paleoperiglacial hypothesis for the region (Pomeroy, 1983; Aguilar and Arnold, 1985; Waltman et al., 1990; Snyder and Bryant, 1992; Millar and Nelson, 2001). The delineation of the ice extent during glacial advances is, on the other hand, quite imprecise (Bryant, 1955; Muller, 1975) on the upland surfaces where no moraines are apparent. Muller (1975) identified three drift sheets representing glacial advances during the Wisconsinan stage. The Re-entrant is bounded on the east by the Olean moraine, likely of mid-Wisconsinan age (Calkin et al., 1982). The western Kent moraine probably correlates with the maximum ice advance beginning after 24,000 B.P. (Muller and Calkin, 1993).

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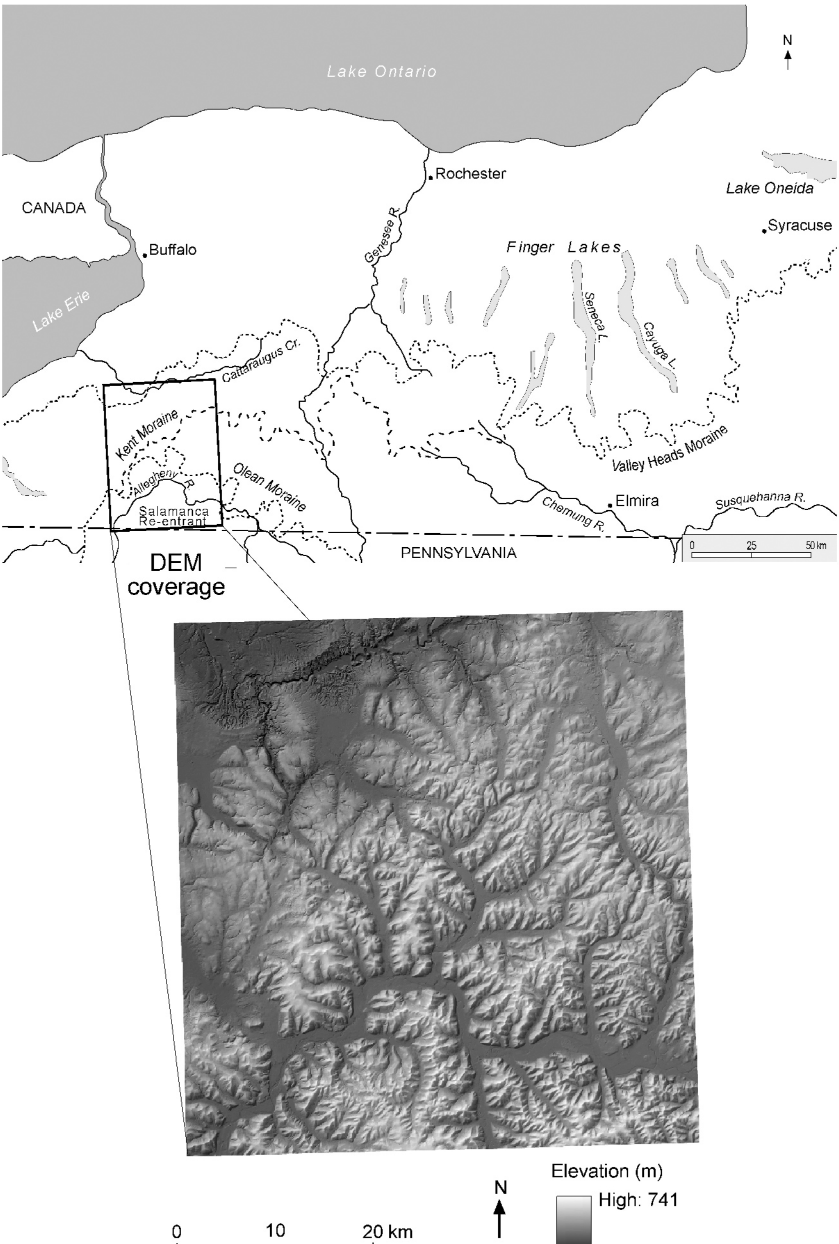

Fig. 1. Location and digital shaded relief of study area.

Soil characteristics derived from drift or residuum have provided perhaps the most accurate method of delineation for the ice margin (Pearson et al., 1940; Bryant, 1955), although Bryant (1955, p. 121) does caution that updated soil-survey classification tends to minimize the importance of parent material, focusing instead on soil properties. Soil taxonomy, therefore, has limited value in identifying the glacial margin. Application of soil characteristics (e.g., Bryant, 1955) or surficial geology (Cadwell, 1988) has resulted in variations of several kilometers in the mapped position of the ice front. A regional scale assessment of geomorphometry across the margin, however, may shed light on patterns that are not observable from field examination, on the assumption that geomorphic and erosional histories north and south of the margin create distinct landforms. The purpose of this study, therefore, is to assess the value of digital terrain-analysis using a GIS, as a means to improve confidence in ice-margin delineation. Such information is valuable for paleoclimatic reconstruction and understanding ice dynamics in the region.

STUDY AREA

Southern Cattaraugus County, New York, is unique in the state by dint of escaping coverage by Wisconsinan ice sheets. The area is located at the northernmost part of the Allegheny Plateau and is underlain by interbedded conglomerate, sandstone and shale of Devonian and Pennsylvanian age, dipping gently to the southwest (Lytle, 1965). The accordance of summits, particularly in the nonglaciated southern portion, is attributed to outcrops of resistant sandstone and conglomerate members of the Pottsville, Pocono, and Conewango Groups (Muller, 1975). Elevations reach 741 m along the Pennsylvania border in the nonglaciated region. The unglaciated plateau is deeply dissected and shows evidence of intense periglacial mass wasting (Smith, 1949; Muller, 1975). Permafrost indicators have not been identified within the unglaciated areas of Cattaraugus County, but summit tors (Smith, 1953) and periglacial solifluction have been reported (Snyder and Bryant, 1992; Millar and Nelson, 2001). To the north, the glaciated terrain indicates modest lowering on abraded, rounded uplands (Muller, 1975). Valleys in the glaciated regions are generally broader, and deeply filled with lacustrine and alluvial sediments (Zarriello, 1987). Muller (1963) suggested that denudation in the glaciated region was less than 60 m. At this distant extent of the Wisconsinan ice mass, its ability to modify the landscape was relatively poor, and may explain the lack of moraines, particularly on the upland surfaces (MacClintock and Apfel, 1944; Muller and Calkin, 1993). Delineation of the ice margin on the upland surface has therefore, relied heavily on soil characteristics.

Although many regard soil characteristics in the county as the most valuable means for identifying the glacial margin, several factors constrain their application in this area. First, intense periglacial weathering and debris removal from summit areas have reset the clock for soil formation (Muller, 1975; Snyder and Bryant, 1992). Soils in the nonglaciated uplands often have no more well-developed or mature soil profiles than those in the glaciated terrain. Second, criteria emphasized in the original soil survey classification of Cattaraugus County have changed in subsequent surveys. Parent material is no longer a key criterion, but rather properties such as soil drainage, profile description, and delineation of great soil groups are emphasized, thus reducing the need to define the glacial margin precisely (Bryant, 1955). As an example, the DeKalb soils, formerly a series associated with nonglaciated upland, has been reclassified into Lordstown, Mardin, or Bath soils. Because Lordstown soils are generally associated with glacial drift, the distinction between nonglacial and glacial has been lost through this change. Finally, the relatively weak glacial influence in Cattaraugus County limited development of distinct geomorphic clues on upland areas. Higher plateau surfaces undoubtedly retarded ice flow, leading to the local complexity of the margin. The transition from drift parent material to residuum supports a gradational rather than distinct change in soil characteristics. Key characteristics that generally aid in distinguishing such parent materials are color and subsurface texture (Bryant, 1955).

The lack of geomorphic evidence and the difficulties that have emerged using soil characteristics to define the ice margin mean that a degree of uncertainty still exists. In this study, I examine differences in geomorphometry across the margin to determine if the boundary is discernible. Although minor, glacial erosion north of the margin should have created a landscape with more rounded topography and lower relief than the unglaciated fluvially dissected terrain to the south. In this assessment, applying digital terrain-analysis to the problem, morphometry was compared in areas that were glaciated, not glaciated and those where disagreement exists. This study provides the first quantitative mapping and identification of the area, in order to address the main objective: whether the area of disagreement can be identified as glacial or nonglacial on the basis of morphometry.

METHODS

Geomorphometry and Digital Terrain-Analysis

Digital terrain-analysis provides a tool for examining landscape geomorphometry across regions. Geomorphometry is a means of quantifying landscape elements, such as slope and profile curvature, founded on the notion that particular morphologies are representative of a particular suite of processes (Pike, 2000). Although descriptive, terrain parameters are helpful for understanding process-response systems in terms of their spatial and topologic attributes (Schmidt and Dikau, 1999; Pike, 2000; Etzelmuller et al., 2001; Bartsch et al., 2002). Such information can aid in interpretations of landscape history and landscape evolution. In geomorphology, the concept of equifinality of landscape elements must be carefully considered. In the study area, because of its distal position relative to the ice center, postglacial modification of the landscape is likely to produce a suite of landforms reminiscent of the periglacial regime to the south, and therefore exhibit the steep, rectilinear slopes of the fluvially dissected terrain. On the basis of earlier work in the region, however, there is evidence that the general form of the landscape differs between the glacial and nonglacial areas (Muller, 1975). These differences suggest that an approach using morphometry is a fruitful way to differentiate between these formative geomorphic environments.

Digital terrain-analysis typically uses digital elevation models (DEMs) as data sources for the calculation of morphometric parameters. Raster-based DEMs are easily manipulated in a Geographic Information System to calculate slope angle, aspect of steepest slope, slope planform and slope profile curvature, and indices representing land-surface texture. The results are stored in new raster data sets at the same resolution as the input DEM. In this study, I have used ArcGIS v8.3 (Environmental Systems Research Institute, 2002), and its integrated ArcInfo workstation, to run the analyses.

Data Acquisition and Preparation

The majority of the data was available in digital form. DEMs at a 10 m × 10 m resolution are available from the U.S. Geological Survey. Digital soil maps for Cattaraugus County were acquired as ArcInfo coverages from the Natural Resources Conservation Service (NRCS) State Soil Survey Geographic (SSURGO) Database (U.S. Department of Agriculture, 2003), and the NRCS State Soil Geographic (STATSGO) Database (U.S. Department of Agriculture, 1994). Relational database files with detailed soil descriptions were also retrieved from the NRCS online resource. Bedrock and surficial geology maps are available from the New York State Museum in arc interchange format. The Olean glacial margin as delineated by soil characteristics by Bryant (1955) was originally drawn on a paper version of the Soil Survey of Cattaraugus County (Pearson et al., 1940). This was scanned on a large format drum scanner, georeferenced to the study area with a first-order polynomial transformation (RMSE = 83.615), and digitized using heads-up digitizing.

Overlay Analysis

The surficial geology map was reclassified using SQL statements and the field calculator to define two zones: *glacial* or *nonglacial*. Kames, kame moraines, till and till moraines were classified as glacial; colluvium was reclassified nonglacial. The polygon coverage created from digitizing the Olean glacial margin (Bryant, 1955) was also classified into *glacial* and *nonglacial*. The intersection of the two maps identified areas with mismatched classification; representing glacial terrain according to Bryant (1955), but nonglacial according to surficial geology. A database field was used to identify three zones: *glacial*, *nonglacial*, and *difference*. The last category represents the area of mismatch between soil mapping and surficial geological mapping (Fig. 2A).

The STATSGO soil and bedrock geology maps were overlain with the three-zone map of *glacial*, *nonglacial*, and *difference* classes. Of particular interest were the soil and bedrock associated with the area of disagreement, the *difference* in the analysis. Two bedrock formations underlie this area: the Oswayo and Ellicott. Similarly, only two soil groups were associated with the area of difference: the Mardin-Lordstown-Volusia and the Rayne-Kinzua-Ernest Variant. The extent of the intersection of these four classes was used to delimit the area of interest for all further analyses in an attempt to control for morphometric variation associated with bedrock type or soil classes (Table 1). The SSURGO data tables were joined to the clipped area of interest, so that the distribution of soil orders and variations in silt and clay content and pH could be assessed and compared in the three zones (Figs. 2A and 2B).

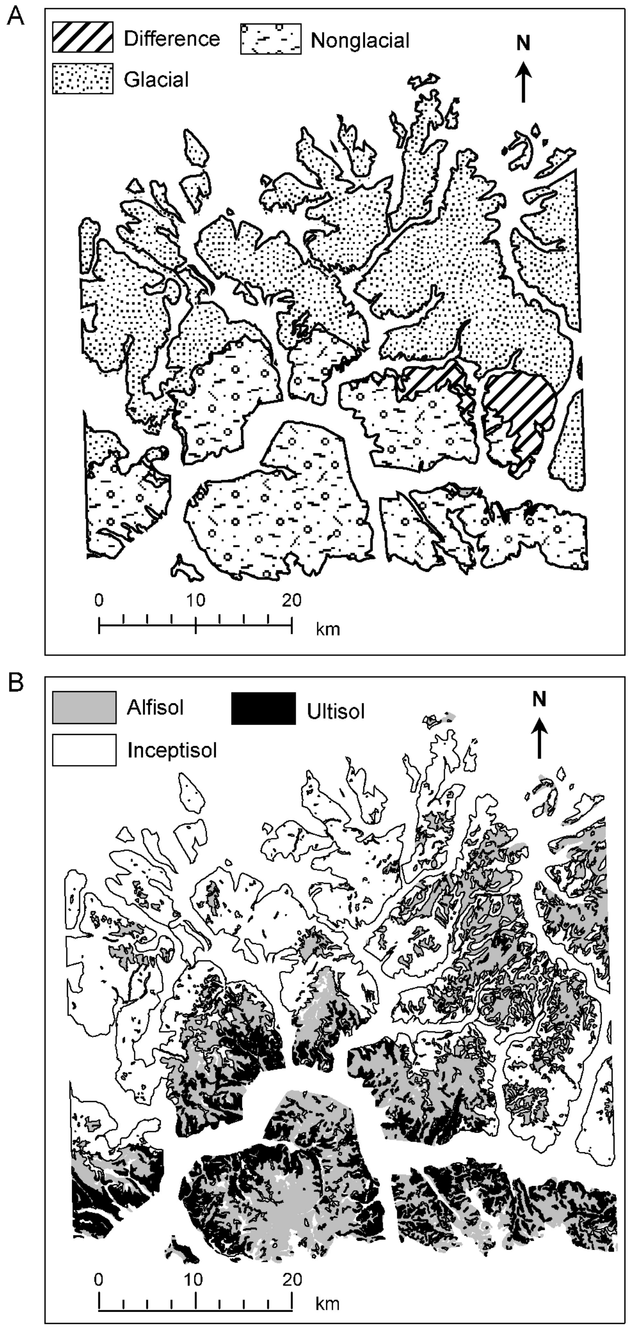

Fig. 2. Area of analysis showing (A) distribution of zone classes and (B) distribution of soil orders.

Table 1. Percent Area of Bedrock Geology in Three Zones

Formation	Difference	Glacial	Nonglacial
Ellicott	89	95	45
Oswayo	11	5	55
Total	100	100	100

Table 2. Cross-Tabs of Row Percents of Soil Orders and Zone Class

Zone	Alfisol	Inceptisol	Ultisol	Other	Total	*N*
Difference	19.684	78.258	1.989	0.069	100	1,458
Glacial	23.373	75.549	0.347	0.731	100	15,860
Nonglacial	59.336	11.433	23.578	5.654	100	11,231
Total	37.332	50.464	9.570	2.634	100	28,549
N	10,658	14,407	2,732	752	2,732	28,549

Morphometry and Comparative Analysis

The ArcInfo GRID command CURVATURE was used to calculate the slope, aspect, planform curvature and profile curvature for the DEM mosaic (Fig. 1). Two more grids were created to represent terrain roughness: the standard deviation and range of elevation were calculated in a 5 × 5 moving window operation using the neighborhood statistics of the spatial analyst tool in ArcMap. The map of the three zones was rasterized for use as a mask grid so that the SAMPLE function could be used to extract morphometric parameters into an ascii file for importing into a statistical analysis program for ANOVA.

RESULTS AND DISCUSSION

Analysis of variance tests were run on morphometric and soil characteristics sampled on a cell-by-cell basis in ArcInfo GRID in order to compare differences across the glaciated and nonglaciated areas, and the area of disagreement, and across different soil orders. Cross-tabulation of soil order and zone class indicates that soil orders do not match terrain classification, although general patterns do exist (Table 2). The glaciated terrain is dominated by inceptisols and the nonglacial terrain by alfisols. The area of disagreement most closely resembles the glacial terrain in terms of the relative coverage of soil order.

Two-way ANOVA was run in SYSTAT (1998). Assumptions of normality and equal variance were upheld by standardizing elevation, and using a log transformation of silt content, standard deviation and range of elevation, and transformation of clay content to a proportion. The two-way ANOVA model calculates the total sums of squares as the sum of those across each factor and the error term. The F-ratio is the mean-square for each factor divided by the mean square for error. A comparison of F-ratios, therefore, provides a method for examining the contribution of soil

Table 3. Two-Way Analysis of Variance of Soil Properties and Morphometric Parameters across Each Zone and Soil Order

Property	Mean	Variance	Soil type *F*-ratio	Zone *F*-ratio	Soil-*F*/ zone-*F*	R^2
pH	6.284	0.204	79.861	228.312	0.350	.277
Silt	72.954	0.004[a]	143.115	9.202	15.553	.064
Clay	27.965	0.004[b]	298.459	77.701	3.841	.183
Elevation	572.000	1.000[c]	162.575	16.467	9.873	.144
Slope	9.885	0.376[a]	14.676	45.890	0.320	.047
SD elevation	2.490	0.076[a]	18.423	145.060	0.127	.112
Elevation range	8.858	0.086[a]	18.737	142.000	0.132	.108
Planform curvature	0.002	0.506	n.s.	n.s.	n.s.	n.s.
Profile curvature	0.007	0.706	n.s.	n.s.	n.s.	n.s.

[a] Log_{10} transformation.
[b] *N*/100 transformation.
[c] *Z*-score transformation.

properties and morphometric factors to the total variance (Zar, 1998; Park and Burt, 2002). The structure of this test allows for comparison of means across the three zones, and enables assessment of the relative importance of soil or morphometric properties for explaining those differences. Results of the test are shown in Table 3.

Variation Associated with Soil Orders

Variation in silt and clay content is associated with soil order rather than morphometry. Bryant (1955, p. 52) suggested that texture can help delineate the ice margin although differences are more apparent at depth: soils in residuum are generally finer than those in glacial till. As a diagnostic for the position of the glacial margin, the analysis here suggests that surface soil texture has limited use. Variation in elevation is also associated with soil order rather than zone class. Based on the premise that glacial scour has lowered the terrain to the north of the margin, this result is somewhat unexpected. A comparison of least squares means across the zone classes and grouped by soil order is worthy of note (Fig. 3). Alfisols are associated with the highest terrain in all zones; inceptisols are at lower, intermediate elevations. This relation is most likely associated with better drainage conditions and therefore soil development on the upland surfaces, allowing for argillic horizon formation. In the nonglaciated area and area of difference, ultisols are located at the lowest elevations; in the glaciated terrain ultisols are at a higher elevation, comparable to the position of alfisols. Ultisols in Cattaraugus County exhibit deep weathering profiles, and are usually associated with pre-Wisconsinan surfaces (Snyder and Bryant, 1992). Their presence in the glaciated terrain at high elevation suggests that the ice sheet was either punctuated by nunataks or had such little power that

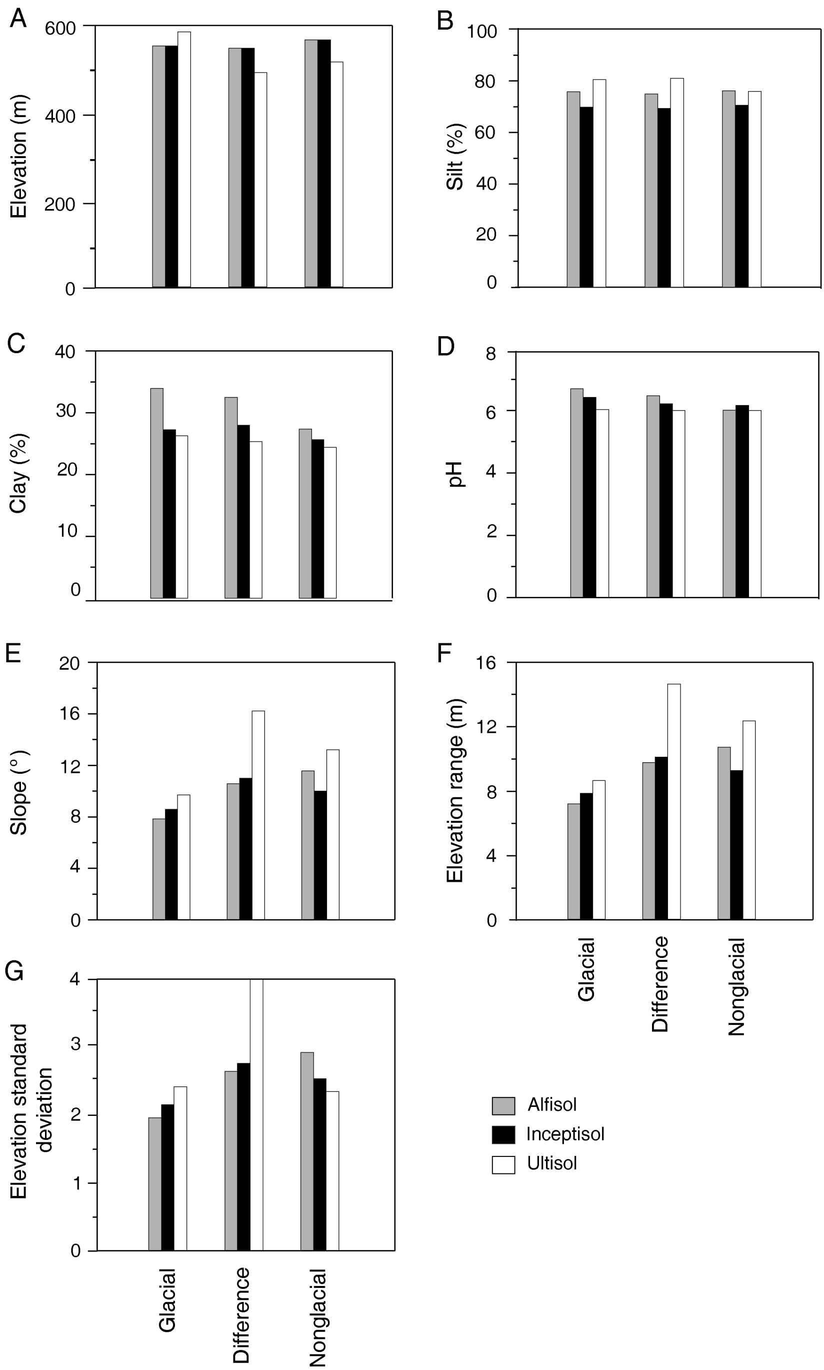

Fig. 3. Comparison of mean values in each soil order across glacial and nonglacial areas, and the area of difference of (A) elevation, (B) silt content, (C) clay content, (D) pH, (E) slope angle, (F) standard deviation of elevation in a 5 × 5 neighborhood, and (G) elevation range in a 5 × 5 neighborhood.

underlying substrate was not eroded (Rea et al., 1996; Kleman and Stroeven, 1997; Stroeven et al., 2002). A large area of ultisols is located to the northeast of the Re-entrant where Olean ice advanced over the terrain during the mid Wisconsinan, possibly between 30,000 and 40,000 B.P. (Muller and Calkin, 1993). The isolated patch of ultisols lies on prominent summits that were likely nunataks emergent above an incomplete ice cover, thus allowing for continued soil development in these areas (Dixon et al., 1984).

Variation Associated with Zone Class

Slope angle varies across the three zones; steeper slopes are present in nonglaciated terrain and the area of difference. The dominance of fluvial dissection south of the margin is apparent. However, the zone of difference was modified either minimally or not at all by glacial processes. The glaciated area has gentler slopes overall, suggestive of ice scour. Terrain parameters representing terrain ruggedness, the standard deviation of elevation and elevation range, calculated in a 5 × 5 neighborhood, paint a similar picture. The glaciated area exhibits the most subdued terrain, whereas the nonglaciated area and the area of difference show comparable and more rugged terrain. The area of difference, on the basis of these morphometric criteria, is more analogous to the nonglaciated terrain than glaciated. Since bedrock influence on elevation was eliminated by focusing the analysis on the two dominant formations in the area, the morphometric differences due to geomorphic history rather than geology between the glaciated and nonglaciated terrain are considered robust.

Bryant (1955) noted that soils in the glaciated terrain had a higher base saturation than in the nonglaciated terrain. The degree of variation in pH is associated more with zone class than with soil order; the glacial area has the highest pH and the nonglacial terrain the lowest. The area of difference is intermediate between the two, although ultisols in this area exhibit the lowest pH recorded in the study area. In terms of pH then, the zone of difference represents a transition between glaciated and nonglaciated terrain.

CONCLUSION

This regional assessment of soil and landscape morphometry illustrates the problems that have plagued attempts to delineate a precise glacial margin in the Salamanca Re-entrant. Although general spatial associations of soil orders with zone class exist, the distribution of soil orders does not provide evidence of a clear-cut ice margin. Soil properties vary more strongly with soil order than landform, suggesting that they provide a measure of the time of soil formation rather than the influence of parent material. The presence of ultisols in glaciated terrain indicates a landscape position allowing for preservation of a pre-Wisconsinan soil profile, most likely above a thin, ineffective or incomplete ice cover. The gradational increase in base saturation from south to north further supports the contention that glacial impacts in this area were minor, and probably short-lived.

On the basis of morphometric parameters, the area of difference is more closely analogous to the nonglacial terrain. This finding certainly supports the delineation of the margin using geomorphic evidence (Cadwell, 1988); however, it does not answer the question as to whether the area of disagreement was covered by Wisconsinan ice. The ruggedness may simply be a function of the incapacity of the ice in the area to establish a glacial imprint. Or, the ruggedness may be the result of a complete lack of ice cover because of the barrier to ice flow that it presented.

The analysis discussed here, using digital terrain-analysis in concert with digital soil data, provides further insight into the problems facing those trying to delineate the Wisconsinan ice-sheet margin in the Salamanca Re-entrant. Depending on the technique used, the ice-margin position has been variously mapped. This study was designed to determine whether the area of difference was more likely to have been ice-free or glaciated. Application of a GIS provides an ideal tool for mapping such areas of contentious interpretation, although in this case no conclusive results have emerged. In future analyses of former ice margins, such a GIS-based approach should prove a useful preliminary step for identifying specific locations worthy of closer field inspection.

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