A STATISTICAL ANALYSIS OF TENNESSEE TOPOGRAPHY USING DIGITAL ELEVATION MODELS: A QUANTITATIVE EVALUATION OF PHYSIOGRAPHIC-PROVINCE BOUNDARIES

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ABSTRACT—A statistical analysis of Tennessee topography using digital elevation models was conducted and compared with existing physiographic-province maps. The 7.5-min quadrangle was used as the areal unit of analysis, and computed parameters included mean and maximum elevation, relief, mean and maximum slope, hypsometric integral, and the coefficient of variation of elevation and slope. More than 17 million point elevations were incorporated in the calculations. Drainage density, measured from paper maps, also was included in the analysis. Maps showing the areal distribution of values for each parameter produced some unexpected results. For example, the Central Basin has low values of the hypsometric integral, whereas the adjacent Western Highland Rim has high values. The Eastern Highland Rim, the northern part of the Western Highland Rim, and the northern Central Basin show low drainage density, presumably corresponding to the most karstic areas of the State. The southern parts of the Western Highland Rim and Central Basin have somewhat lower mean slopes than do the northern parts of these provinces. Existing physiographic maps are derived mainly from geology maps, based on the assumption that differential erosion produces distinct types of landforms on different formations and structures. Cluster analysis based on the computed parameters provides support for many of the established physiographic provinces but also suggests subdivisions. For example, the northern part of the Western Highland Rim is very different from the southern part, the eastern Cumberland Plateau differs substantially from its western part, and the northern Valley and Ridge differs from its southern part.

Safford (1869) divided Tennessee into eight "natural regions." From east to west, these were the Unaka Chain, the Valley of East Tennessee, the Cumberland Table-land, the Highland Rim, the Central Basin, the Western Valley of the Tennessee River, the Plateau or Slope of West Tennessee, and the Mississippi bottoms. By the early 20th century, the term "physiographic province" had come into use to denote such divisions (e.g., Fenneman, 1914), where a given province was understood to have some degree of unity with respect to topography, geology, and vegetation. Fenneman (1938: plate III) divided Tennessee into eight provinces: Blue Ridge; Ridge and Valley; Cumberland Mountains; Cumberland Plateau; Highland Rim; Nashville Basin; Coastal Plain; Mississippi Alluvial Plain.

By the late 20th century, the meaning of physiography had narrowed to that of broad-scale topography. Additional versions of Tennessee physiographic-province maps were provided by Miller (1974) and by W. M. Christie and M. Pyne (pers. comm.). The map by W. M. Christie and M. Pyne was used in the present study because it was available in a digitized and registered form. This map was derived directly from the State Geological Map of Tennessee and has 10 provinces (Fig. 1). Many physiographic maps in fact are derived in this manner, and this method generally works fairly well, given the strong control that rock type and structure exercise on erosional topography. However, this approach ignores other factors that may be important for landform development, such as the locations of major drainage systems, regional facies variations in geologic formations, and possible late Cenozoic crustal movement. We wanted to determine just how consistent topography is within physiographic provinces. We approached this problem by conducting statistical analyses of Tennessee topography, using standard morphometric parameters, and then determining how these parameters varied within and between provinces.

METHODS

As a basic unit of analysis, we chose the 1:24,000-scale 7.5-min quadrangle. This relatively large area does have the disadvantage that a substantial number of quadrangles include the boundaries between two or more physiographic provinces but has the advantage of containing a large enough sample of topography to reduce random fluctuation of values that often produce large differences between adjacent areal units. The quadrangle unit also has a pedagogical appeal, in that named quadrangles can be cited as illustrating certain types of morphometry.

For our calculations we did not actually use the digital elevation models (grids of elevation points) for 7.5-min maps, which have a grid spacing of 30 m, but used digital elevation models for 1:250,000-scale maps, which have a grid spacing of 3 arc sec (i.e., spacing of ca. 75 m in the east-west direction and 92 m in the north-south direction, for Tennessee's latitude). These digital elevation models have the advantage that they can be downloaded free from a United States Geological Survey Internet site. Use of these digital elevation models undoubtedly produced different

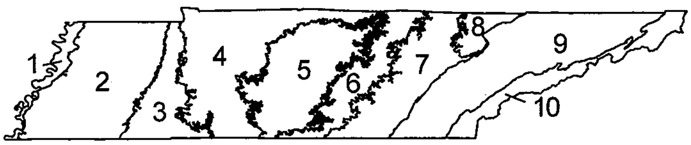

FIG. 1. Physiographic provinces of Tennessee (W. M. Christie and M. Pyne, pers. comm.): 1) Mississippi Alluvial Plain; 2) Coastal Plain, loess covered; 3) Coastal Plain, no loess; 4) Western Highland Rim; 5) Central Basin; 6) Eastern Highland Rim; 7) Cumberland Plateau; 8) Cumberland Mountains; 9) Valley and Ridge; 10) Blue Ridge Mountains.

absolute values than would be obtained from the 1:24,000 digital elevation models, but, because the real interest is in the relative differences between quadrangles, it seems unlikely that use of the 1:24,000 digital elevation models would significantly change the results of this study.

The 1:250,000 digital elevation models come in 1° by 1° blocks, so we divided each of these into 64 7.5-min blocks. Each of these smaller blocks corresponds to a named 1:24,000-scale quadrangle and consists of a grid of 150 rows by 150 columns, or 22,500 points. All quadrangles located wholly or partly within Tennessee were used, with the exception of a tier of quadrangles on the southern border of Tennessee that include only small slivers of Tennessee at their northern edges. Calculations were made for a total of 761 quadrangles, so that a total of >17,000,000 elevation grid points were used in the study. Parameters calculated from the digital elevation models included mean and maximum elevation, relief, mean and maximum slope, hypsometric integral, and the coefficients of variation (i.e., the ratio of the standard deviation to the mean, multiplied by 100) of elevation and slope. Slopes were calculated by using the slope-map option in the SURFACE program of the Idrisi Geographic Information System (Eastman, 1992:169). Before using this program, the digital elevation models were projected from latitude-longitude into the Tennessee State Plane coordinate system.

The hypsometric integral is simply an index derived from the area-altitude distribution (Strahler, 1952). Its value ranges from 0.0 to 1.0. Landscapes with most of their area at high elevations and little at low, such as a dissected plateau, have high values. Landscapes with most of their area at low elevations and little at high, such as plains surmounted by occasional hills, have low values. This parameter previously has been little used owing to the drudgery needed to calculate it. With computers and digital elevation models, however, it can be computed almost instantaneously.

In addition to the parameters calculated from the digital elevation models, drainage density was calculated for all Tennessee 7.5-min quadrangles by hand. Drainage density is the ratio of the total length of streams on a map to the area of the map. Because actually measuring the stream lengths would have been extremely time consuming, a proxy method was employed. The "intercept method" was used, in which the number of intersections between streams and lines drawn across the map is counted and converted into an estimated drainage density (Mark, 1975).

Besides compiling maps showing the distribution of the values of individual topographic parameters throughout the state, we wished to see how well the topography of particular areas could be distinguished by the simultaneous use of multiple parameters. To do this, we used cluster analysis, which is a statistical procedure for arranging a number of objects into homogeneous groups based on their similarities. Specifically, we used the SAS FASTCLUS procedure, which performs a disjoint cluster analysis on the basis of Euclidean distances computed for one or more quantitative variables (SAS Institute Inc., 1985). Because the results of classification may vary greatly according to the number of clusters specified and the particular variables used, we experimented by varying each of these factors and running more than a dozen analyses.

RESULTS

A correlation matrix (Table 1) shows that all variables related in some way to vertical position (elevation, relief, slope) correlate highly or fairly highly with one another and, thus, essentially represent only one topographic factor, which we refer to most generally as relief. On the other hand, note that drainage density and the hypsometric integral show only low correlations with each other and with the other variables. Hence, they represent factors separate from relief and, therefore, are particularly useful for classification purposes.

Figures 2 and 3 show the areal variation of parameter values, classified into quantiles for display. In Fig. 2, the map of mean elevation shows, as expected, that the lowest elevations occur on the Mississippi Alluvial Plain and western Coastal Plain, and highest elevations on the Cumberland Plateau, Cumberland Mountains, and Blue Ridge Province. Other, less obvious trends also are shown, however, such as the increasing elevations to the south in the Western Highland Rim and Central Rim and to the northeast in the Valley and Ridge. Maximum elevation (Fig. 2) shows a generally similar pattern. The coefficient of variation for elevation indicates the variation within each quadrangle. As Fig. 2 shows, this parameter appears to reflect degree of dissection. For example, the flat undissected parts of the Eastern Highland Rim and Cumberland Plateau stand out because of their low coefficients. The central part of the Valley and Ridge also shows low variability. In the Western Highland Rim and the Central Basin, higher variability is associated with the major drainage lines, especially the Cumberland, Stones, and Tennessee rivers.

Mean slope shows a gross correlation with elevation, but some details are of interest (Fig. 2). For example, note the contrast between relatively high slopes on the Western Highland Rim and low slopes in the central part of the Central Basin. The northeast-southwest decrease in slope is somewhat less pronounced than is the decline in elevation. The distribution of maximum slope shows a few differences from mean slope. For example, the difference between the Western Highland Rim and the inner Central Basin now greatly decreases. The northeast part of the Cumberland Plateau shows lower values than the southwest part, due to the presence of the deep Sequatchie Valley in the latter. The coefficient of variation for slope (Fig. 2) shows a relation to mean slope that is the converse of that shown by elevation. In this case, quadrangles with low slopes show somewhat higher variability than those with high slopes. Some details of interest are the high values of the Mississippi Alluvial Plain and the high values in the inner Central Basin.

The distribution of relief (Fig. 3) shows a great similarity to that of mean elevation. One difference is that in the Western Highland Rim and Central Basin there is little north-south difference in relief, unlike the case for elevation. Also, note the northwest-southeast contrast in the Cumberland Plateau and in the Eastern Highland Rim.

Drainage density and hypsometric integral show quite different areal distributions than do the previously described variables (Fig. 3). The most striking feature of the drainage-density distribution is the low values of the northeastern Western Highland Rim, northern Central Basin, and the Eastern Highland Rim. These areas are the most karstic parts of the state, characterized by sinking streams and underground drainage, so that the low drainage density is to be expected. This area is in striking contrast to the main part of the Western Highland Rim, which has some of the highest drainage densities in the state. The hypsometric integral shows a clear difference between the northwestern and southeastern parts of the Cumberland Plateau, presumably because the northwestern part more closely resembles a tableland dissected by gorges, a setting that yields high values of the integral. The most striking result, however, is the precision with which the Central Basin is delineated from the surrounding Rim, and the contrast between the low values in this province and the high values of the Western Highland Rim. This difference suggests that the Central Basin consists mainly of lowlands surmounted by isolated hills, whereas the Western Highland Rim is more like a tableland dissected by gorges.

Selected results of cluster analysis are presented in the bottom three maps of Fig. 3. The maps indicate, for each quadrangle, the cluster that its topographic parameters most closely resemble. Because, as the maps show, different numbers of clusters and combinations of variables give different groupings, there is no one analysis which gives "the" solution. Instead, the most meaningful way of evaluating the findings is to look for consistency of grouping from analysis to analysis. An area of quadrangles consistently grouped together by many (but not necessarily all) of the analyses, in other words, probably signifies an area that possesses a relatively homogeneous topography. Experimentation showed that a choice of six to 10 clusters usually gave classification results that could be most clearly related to the physiographic provinces.

For many analyses, we found that there is one large cluster that includes the large majority of quadrangles in several physiographic provinces, often including provinces that are considered to be somewhat different. For example, in the seven-cluster analysis (Fig. 3), note that the cluster indicated by an open circle occurs extensively in both Coastal Plain provinces, the Central Basin, and the Valley and Ridge. This tendency, however, should not detract from the more important finding that many areas do indeed show consistency in quadrangle classification. For example, the previously mentioned map clearly differentiates the Central Basin from the Rim. Also note that the Western Highland Rim is clearly broken into a northern and southern section, the northern one more closely resembling the Eastern Highland Rim. The Cumberland Mountains are clearly distinguished from adjacent provinces, as is the Valley and Ridge. The northeastern part of the latter province is shown to differ from its southwestern part.

The nine-cluster, five-variable analysis (Fig. 3) again shows a clear difference between the northern and southern parts of the Western Highland Rim. Unlike the first analysis, this one shows a clear difference between the northwestern and southeastern parts of the Cumberland Plateau. The Cumberland Mountains are again distinct, and the Valley and Ridge is again divided into a northeastern and southwestern part. The Blue Ridge Mountains are clearly distinguished from the Valley and Ridge, although being composed of several small clusters. The nine-cluster, three-variable analysis resembles the first analysis in that the northern and southern Western Highland Rim and the Central Basin are

TABLE 1. Pearson correlation coefficients for topographic variables (n = 761).

Variable	Mean elevation	Maximum elevation	Minimum elevation	Coefficient of variation of elevation	Mean slope	Maximum slope	Coefficient of variation of slope	Relief	Drainage density	Hypsometric integral
Mean elevation	1.00	0.95	0.94	0.37	0.84	0.80	−0.48	0.88	0.20	−0.05
Maximum elevation	0.95	1.00	0.89	0.54	0.87	0.84	−0.49	0.97	0.23	−0.24
Minimum elevation	0.94	0.89	1.00	0.23	0.72	0.72	−0.42	0.76	0.21	−0.17
Coefficient of variation of elevation	0.37	0.54	0.23	1.00	0.63	0.65	0.34	0.64	0.15	−0.31
Mean slope	0.84	0.87	0.72	0.63	1.00	0.86	−0.67	0.88	0.22	−0.15
Maximum slope	0.80	0.84	0.72	0.65	0.86	1.00	−0.43	0.83	0.20	−0.21
Coefficient of variation of slope	−0.48	−0.49	−0.42	−0.34	−0.67	−0.43	1.00	−0.48	−0.24	−0.02
Relief	0.88	0.97	0.76	0.64	0.88	0.83	−0.48	1.00	0.23	−0.25
Drainage density	0.20	0.23	0.21	0.15	0.22	0.20	−0.24	0.23	1.00	−0.09
Hypsometric integral	−0.05	−0.24	−0.17	−0.31	−0.15	−0.21	−0.02	−0.25	−0.09	1.00

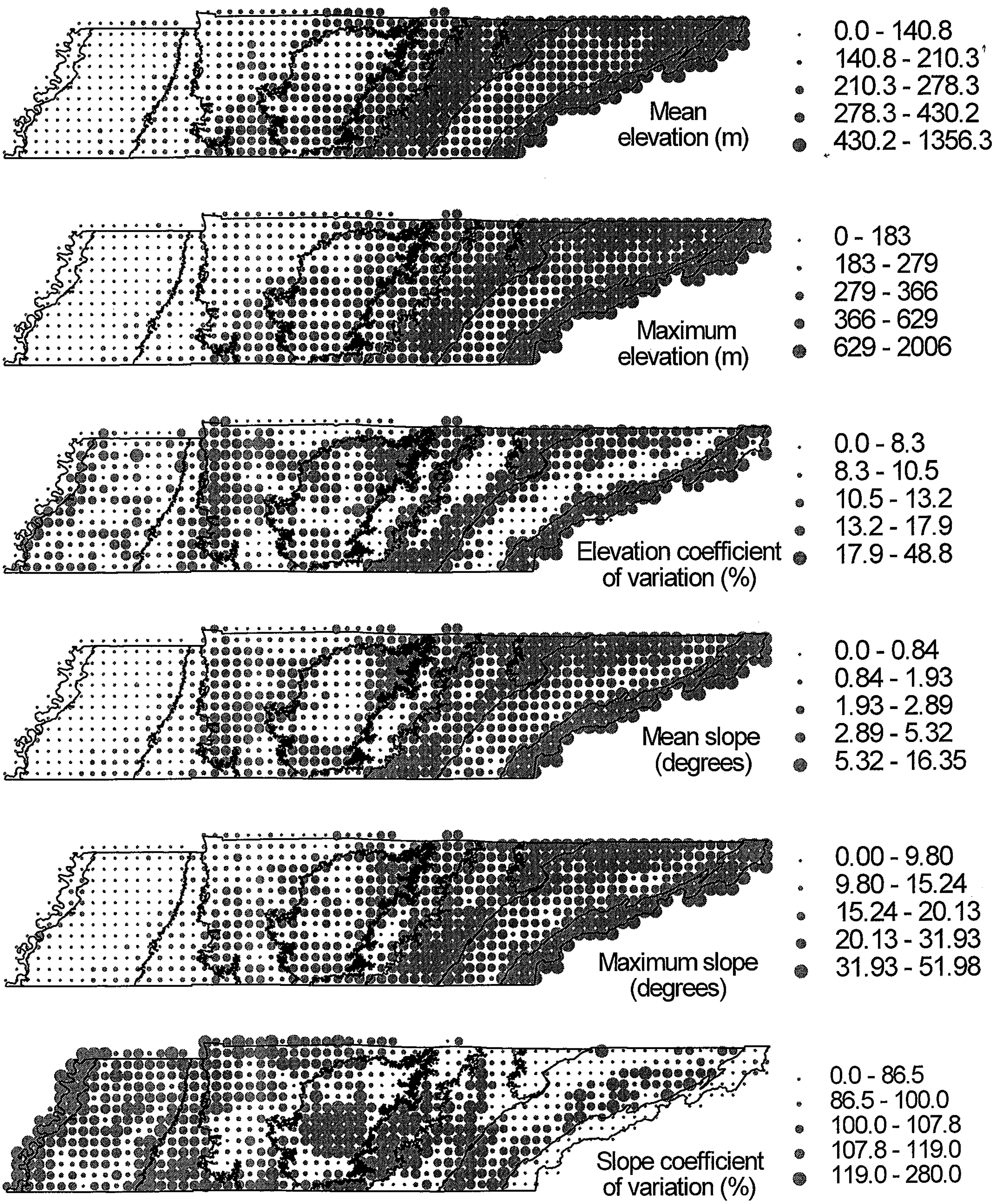

FIG. 2. Maps showing distribution of topographic-parameter values, where values are subdivided by quantiles (i.e., lowest 20% of values, 20–40% of values, etc.).

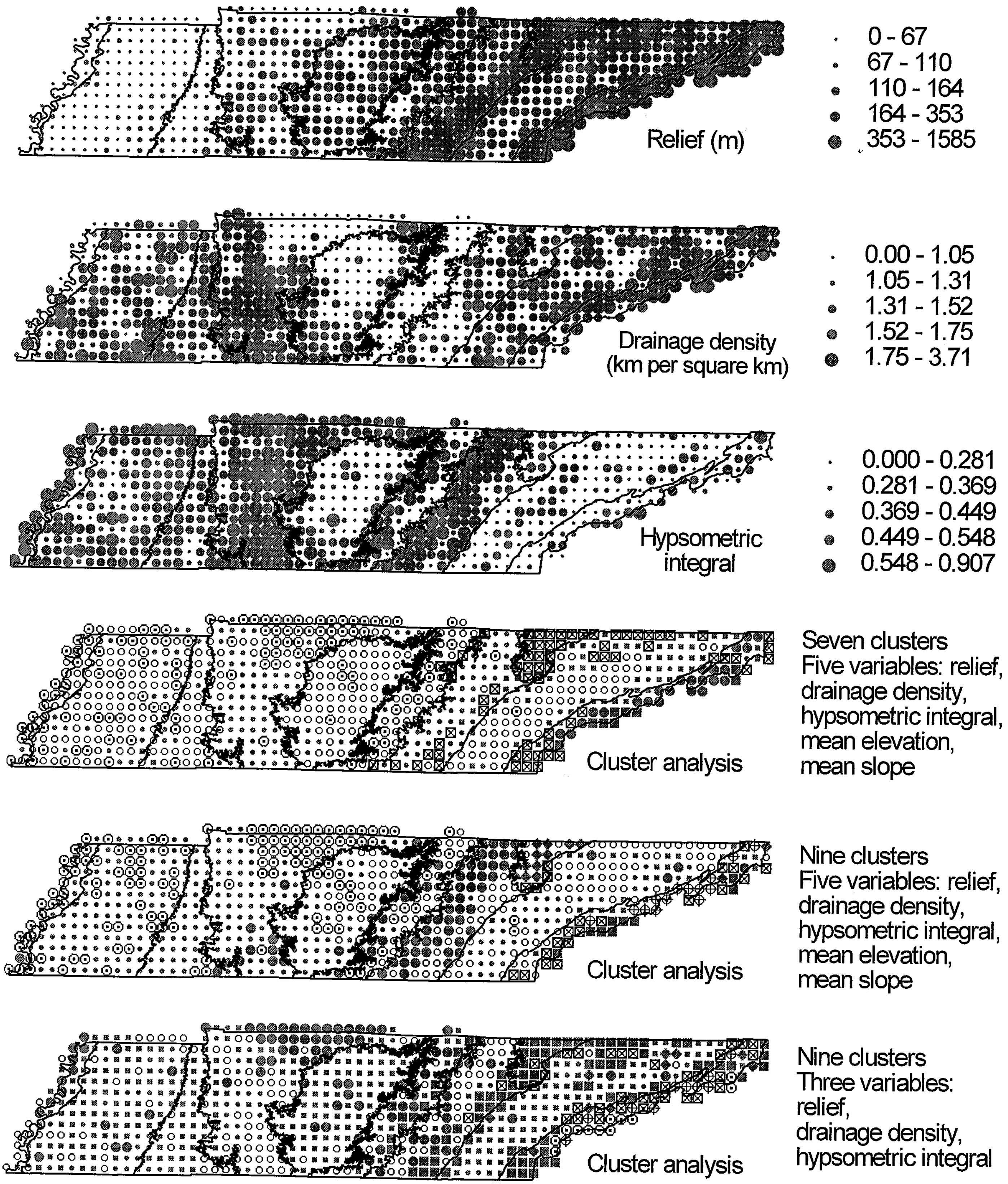

FIG. 3. Maps showing distribution of topographic-parameter values, where values are subdivided by quantiles (top three maps), and results of cluster analyses (bottom three maps). For the cluster-analysis maps, each symbol corresponds to a particular cluster. Each quadrangle, thus, has been classified into the cluster that its topography statistically most resembles.

all differentiated from one another. Like the second analysis, the northwestern and southeastern parts of the Cumberland Plateau are distinguished. The Cumberland Mountains are not as clearly distinguished from adjacent provinces as in the first two analyses, although the Valley and Ridge is shown as more homogeneous. The Blue Ridge Mountains, as in both previous maps, are clearly separated from the Valley and Ridge, although again consisting of several small clusters.

CONCLUSIONS

The results show that statistical analysis supports many of the traditional physiographic-province divisions. There are some disparities, however. First, the eastern and western part of the Coastal Plain show little difference based on the parameters we used. Second, the northern and southern Western Highland Rim are as different as many of the traditional provinces and should be made into separate provinces. Some other provinces show parts that differ substantially enough to warrant division into subprovinces, albeit not separate provinces. For example, the northern and southern Valley and Ridge fall into this category, as do the western and eastern Cumberland Plateau.

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