CARTOGRAPHIC ANALYSIS OF U.S. TOPOGRAPHY FROM DIGITAL DATA

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ABSTRACT

We abstracted the surface-geometric character of U.S. physiographic subdivisions by image-processing 12 million digital elevations (grid spacing 0.8 km). Topographic homogeneity of the 82 Fenneman sections varies widely, elevation (e) having less dispersion than slope (s): estimates of this spread by the coefficient of variation range from a low 0.10 (e) and 0.62 (s) to a high 1.3 (e) and 3.5 (s). A large shaded-relief image of the conterminous 48 states was created by processing the log-transformed elevations through a photometric function. The 1:2,500,000-scale digital map has far more fidelity and detail than other synoptic portrayals of the nation's topography.

INTRODUCTION AND PHYSIOGRAPHIC TAXONOMY

Much of the geologic and tectonic information that lies encoded within topographic form can be deciphered by image-processing large files of digital elevations through fast computers. The three latter elements together have created unprecedented opportunities for automating the numerical and cartographic analysis of topography. Here we address two current needs. One, a regionally based characterization of U.S. terrain that can stand alone or combine with other data, is approached initially by comparing the existing physiographic subdivisions. The second need is for a large single-sheet portrayal of U.S. topography

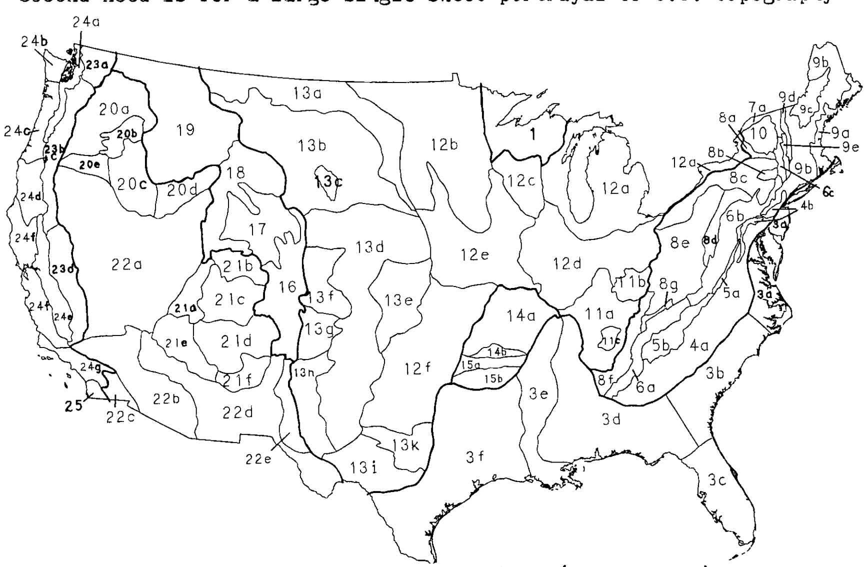

Figure 1. U.S. physiographic divisions (heavy lines), provinces (numbers), and sections (letters) on 1946 map in Fenneman (1931, reprinted 1946). Province 2, Continental Shelf, is not included. The names, omitted here for lack of space, are on the 1:7,000,000 -scale map Physical Divisions of the U.S., available from USGS.

that can be used to critique these units and also marks a significant increase in detail and accuracy over past, non-digital, graphics.

A physiographic unit is a distinctive area having common topography, rock types and structure, and geologic and geomorphic history. Such regions of contrasting surface character greatly assist the analysis of continents and large sea-floor tracts. The most widely accepted physiographic units of the U.S. are the eight division, 25 provinces, and 86 sections of Fenneman (1931, 1938). His hierarchical classification (Figure 1), first outlined in 1914, still is useful but both the taxonomy and its implications remain qualitative. The topographic uniqueness evident in most physiographic units has not been expressed numerically, and the presumed homogeneity of land form within them has never been measured or tested. The sole exception is a sampling of slope angle, length, and height within 24 provinces for a study of surface roughness (Wood et al., 1962).

METHOD AND DATA

Raster image-processing, a digital technique developed primarily for handling images reassembled from spacecraft telemetry, has been successfully adapted for manipulating elevation matrices and their derivatives over large areas (Batson et al., 1975; Moore and Mark, 1986; Pike and Acevedo, 1988). Because one pixel = one elevation, the technique is an efficient spatial tool for landform study. The square-grid data structure enables quantitative measures that describe topography to be rapidly calculated, compared, and combined for display as shaded-relief (Figure 2) and other map images or as digital output for further analysis. Our results were generated by subroutines within the Interactive Digital Image Manipulation System* (IDIMS; ESL, 1983) installed on a DEC Inc. VAX 11/780* computer.

The data most suited to our objectives were gathered by the Defense Mapping Agency Topographic Center (DMATC). Contour lines, and later spot heights and stream and ridge lines, on the U.S. 1:250,000-scale topographic sheets were digitized and gridded semi-automatically at 0.01 inch map resolution (200 feet or three arc-seconds on the ground; Mays, 1966). Interpolation between digitized contours accounted for about 5/6 of the resulting data (Noma, 1966). The original DMATC set of over 2 billion elevations is available in $1^{o}x1^{o}$ blocks from the USGS. It has been sampled, regridded, thinned, and averaged (Godson, 1981) down to the more manageable file used here. The 12 million elevations (nearly twice that counting null-value background pixels in the 3750 X 6046 array) are spaced 0.805 km apart (30 arc-seconds on the ground, XY) within the conterminous 48 states.

Both data sets contain mistakes besides those inherent in the original maps. Most errors are systematic. They include flattened hills and inaccurate interpolation between widely spaced contours, the result of a fast but suboptimal algorithm dictated by the small computers of the time (Noma, 1966), and defective splices between data blocks. Less systematic errors include other flattened hilltops and random zero or unduly high elevations arising from unknown causes. Although first read or interpolated to the nearest foot, DMATC data were rounded to 10 m (map contour intervals were 100 feet or more) and may be accurate to no more than 30 m in smooth areas and 50 m in rough terrain.

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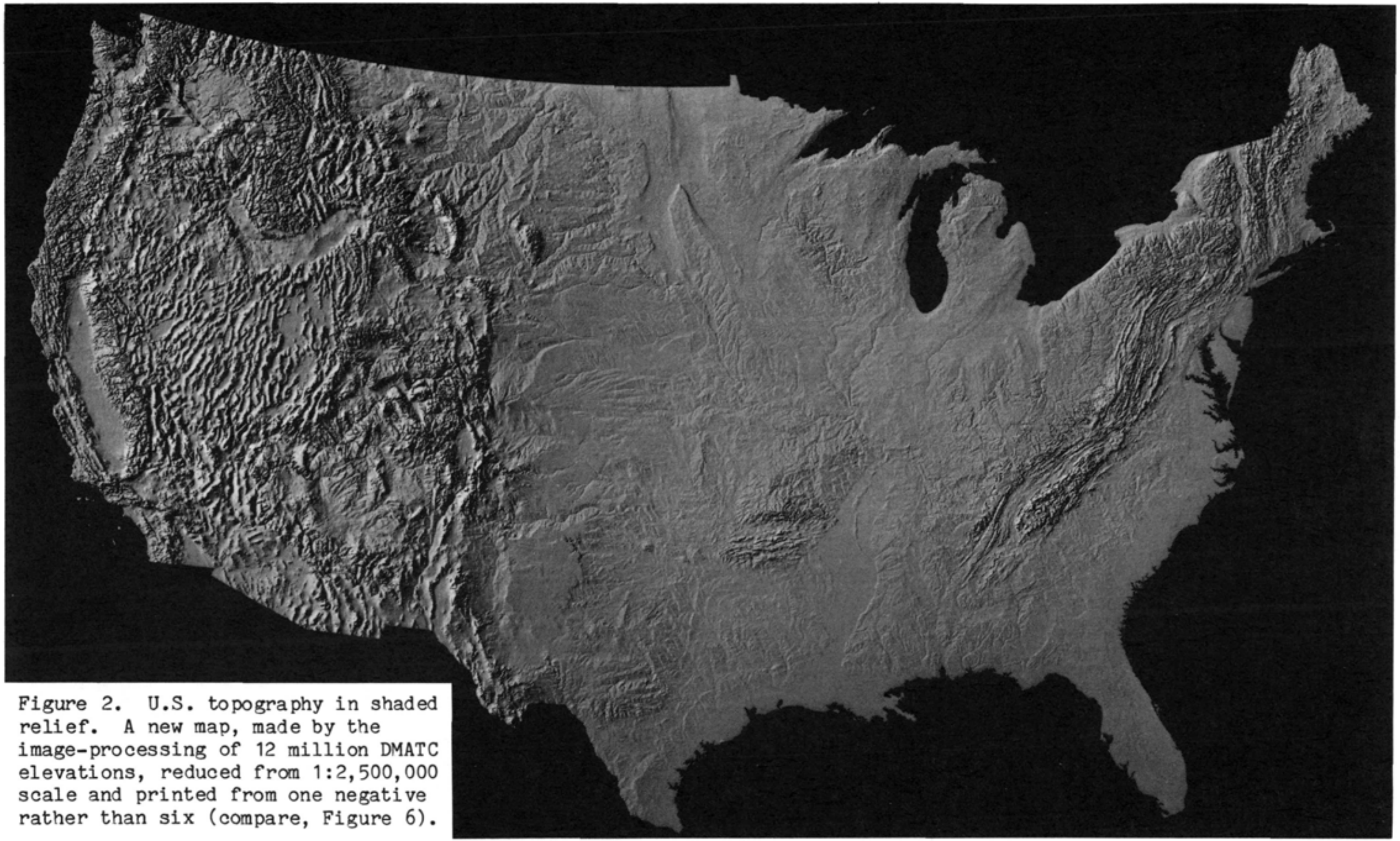

Figure 2. U.S. topography in shaded relief. A new map, made by the image-processing of 12 million DMATC elevations, reduced from 1:2,500,000 scale and printed from one negative rather than six (compare, Figure 6).

THE NEW WORK

We have begun a long-term study of the quantitative properties of regional topography within the U.S. The objective is to translate such verbal descriptions of terrain as gentle, rolling, hilly, steep, subparallel, blocky, and fine-textured into numerical terms that can not be interpreted in more than one way and are easily communicated. The first results are statistical generalizations on elevation and slope angle for 82 of the 86 physiographic sections (no data for sections 2, 7b, 11d; 23b and c were inadvertently combined). These are early steps toward a multivariate parametric characterization, or geometric signature (Pike, 1988), that uniquely expresses topographic form in each unit. We have already begun to synthesize our own units from such signatures (Pike and Acevedo, 1988; cf., Hammond, 1964).

Of the many elements of landform geometry (Hammond, 1964; Mark, 1975; Pike, 1988) elevation and slope are perhaps best suited for the first experiments. Estimates of these, the most straightfoward properties, were the very criteria by which Fenneman and other field observers first recognized and summarized the topographic character of the physiographic units. Indeed, many of the Fenneman map boundaries can be reproduced on the basis of whether juxtaposed topography is high or low, rough or smooth (compare Figures 1 and 2).

We generated histograms of elevation (50-foot and 250-foot bins) and slope angle (1° bins) for each physiographic section and computed (to 0.01 units) four measures of central-tendency and dispersion: mean, minimum, maximum, and variance. The calculations were made for the 48-state area by processing all 12 million terrain elevations through IDIMS. First we digitized physiographic section boundaries from the Fenneman map, using Arc/Info* geographic information system software installed on a Prime 9955-II* computer. Upon transferring this vector file to a VAX 11/780 computer, we generated a digital raster image of the boundaries within IDIMS. From the elevation file we created a digital image of topographic slope by means of the TOPOG* algorithm, a polynomial fit to 3x3 neighborhoods of elevations, moved through the data one pixel at a time. Lastly, we calculated statistics for the 82 physiographic sections from the slope and elevation images, using the POLYSTAT* algorithm and the digital image of Fenneman's map lines.

RESULTS

The 82 elevation histograms computed by IDIMS in a single pass (e.g., Figure 3) provide the simplest numerical comparison of the terrain units in Figure 1. Many of the distributions are skewed. Asymmetry of elevation is a basic descriptive property of topography; it should not be removed or adjusted (by transforming the raw data), save for purposes of graphic presentation. Distributions often are bi- or multi-modal, and accordant summits and dominant elevations can be identified readily on many of them. Mean heights of the 82 sections range from 40 feet (Embayed Atlantic Plain, 3a) to 8973 feet (Southern Rocky Mountains, 16); the median for all section means is 1550 feet.

The histograms and statistics of elevation have proved essential for detecting errors and evaluating the accuracy of boundaries of many physiographic sections. Nonsystematic errors are easily recognized as unexpected maxima and minima and as isolated values on histogram tails for regions where such values are clearly impossible. Most of these errors correspond to equally aberrant values in histograms of slope angle, each bad elevation resulting in several bad slopes.

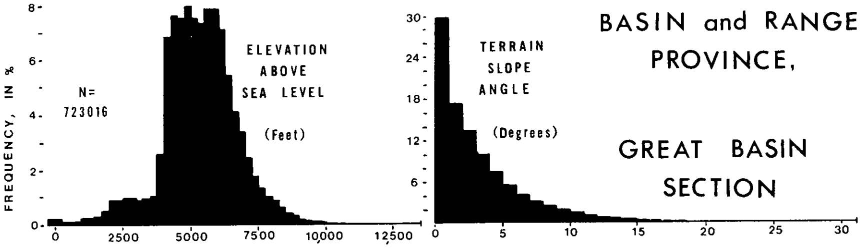

Figure 3. Histograms of height (L) and slope (R) for one of 82 Fenneman sections (22a). Elevations at 1% frequency are lower (southern) basin floors at 2000-3500 feet; those at 7-8% are higher (northern) basins at 4000-6000 feet. Slopes on some mountain ranges exceed 30^o, but low values prevail overall.

Many other high elevations, evident in the histograms as unusually long tails, are not incorrect but rather belong to neighboring physiographic units that differ strongly in height. We checked several of these suspect sections (California Trough 24e, Salton Trough 22c, St. Lawrence Valley 7a, and Puget Trough 24a), by overlaying the Fenneman map on a topographic map of the U.S. We observed in every case that boundaries as currently drawn occasionally intersect mountain ridges that protrude into the section from a neighboring unit, rather than skirting them as they should.

Slope-frequency distributions, which are smoother than those of elevation for the Fenneman sections, are never multimodal, even in the dichotomous terrain of the Basin and Range province (Figure 3). All histograms of slope are highly and positively skewed. Mean slope angle as calculated currently (we have not yet transformed the data to improve statistical validity) on the 1.6-km slope samples ranges from 0.004^o (Florida 3c) to 10.6^o (northern Cascades 23a). This 1000X difference nicely summarizes, quantitatively, results from the most disparate slope-forming processes within the conterminous 48 states. Median slope for the 82 regions is about 1.35^o.

Groupings of map units in slope/elevation space (Figure 4) affirm most of the Fenneman hierarchy. Sections (dots in Figure 4) within the same province link to form polygons. Not only are most polygons quite compact, but the provinces overlap remarkably little. Four sections lie abnormally far from other province constituents: New England Seaboard Lowland (9a), California Trough (24e), Wisconsin Driftless area (12c), and Salton Trough (22c). The two Ozarks sections (14a,b) differ markedly. Fenneman's eight divisions (Figure 1) also are evident in Figure 4 as fairly distinct clusters of slope/elevation polygons. Only the Laurentian Upland (Superior Upland, province 1) resembles another division, the Interior Plains (prov. 11-13).

Mean slope in the U.S. is a weak log-log function of elevation (Figure 4). Although such covariance has long been suspected, the nature of the relation and its anomalies now can be determined exactly. For example, the Western Lakes (12b) and three Great Plains sections (13d-f) lie at a much higher elevation than is normal for such smooth terrains. Three Pacific Border sections (24a-c) are much rougher than would be expected for such low-lying areas. These atypical values contribute to unique characterizations, or signatures, for the sections and pose intriguing problems for geologic interpretation.

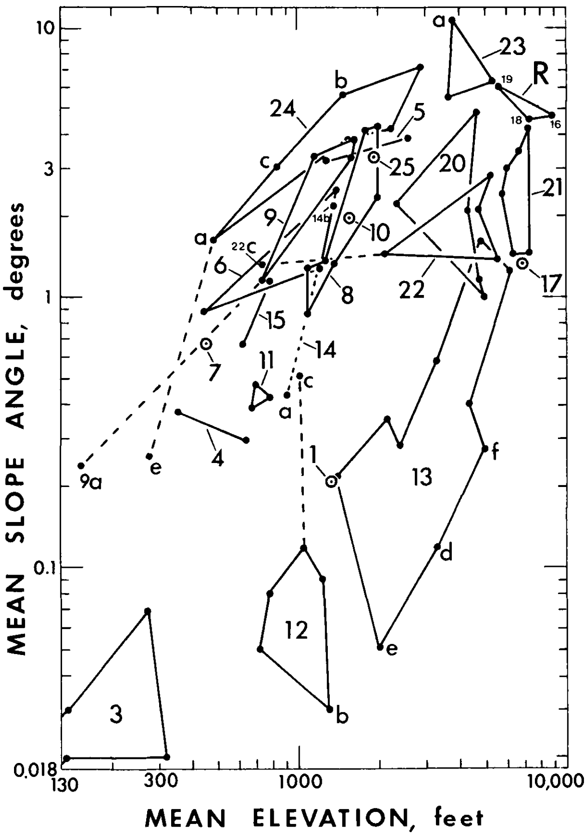

Figure 4. Groupings of physiographic divisions in the conterminous U.S., according to average steepness and height above sea level, computed from 12,000,000 digitized DMATC elevations. The 82 Fenneman sections (dots, small letters) form compact polygons (numbered provinces). Dashes join atypical sections to provinces. R is Rocky Mountain system. Province 3 extends to lower values (2 sections: Florida, Mississippi Alluvial Plain).

The topographic homogeneity of U.S. physiographic subdivisions varies widely (Figure 5). Our estimates, from a statistic of relative dispersion -- the coefficient of variation (C_v, standard deviation/mean), are provisional. Software limits excluded the 13 smoothest sections and the skewed slope distributions have not been transformed. Values of C_v available for slope range from 0.6 (Pacific Border, 24, and Cascades, 23) to over 3.0 (California Trough, 24e); those for elevation vary from 0.10 (Harney section, Columbia Plateau, 20e) to 1.3 (Salton Trough, 22c).

Slope dispersion may be a very weak, inverse, log-log function of elevation dispersion (Figure 5). The C_v relation only vaguely resembles that for slope/elevation. Although sections cluster by province and provinces by division, as in Figure 4, the resulting polygons overlap more. Median C_vs are about 0.33 (elevation) and 1.26 (slope), values of relative dispersion that best typify the

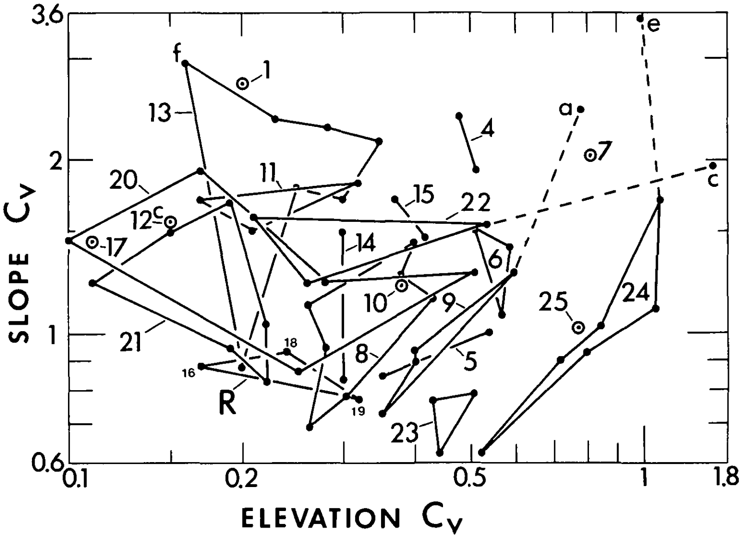

Figure 5. Varying topographic homogeneity of physiographic units in the conterminous U.S. Relative dispersion of slope, C_V, as a function of elevation dispersion, C_V, for 69 Fenneman sections (same label conventions as in Figure 4). C_V, the coefficient of variation -- standard deviation / mean, is dimensionless.

Adirondacks (10), the Appalachian Plateaus (8), and some sections of the Columbia Plateau (20). Most Pacific Border (24) sections and the Salton Trough (22c) are far above average in heterogeneity of elevation. Slopes in the Superior Upland (1) and St. Lawrence Valley (7) provinces, plus Colorado Piedmont (13f), New England Seaboard Lowland (9a), and California Trough (24e) sections, are more heterogeneous than average. Some of these anomalies may diminish upon revision of the Fenneman taxonomy and refinement of section borders.

A NEW MAP OF SHADED RELIEF

Analytical hill-shading, the portrayal of topographic form by mechanical techniques (Brassel, 1974; Horn, 1981), was adapted for computer automation and elevation data in raster format by Yoeli (1967). Batson et al. (1975) made the first shaded-relief images of regional extent, from the DMATC terrain data tapes, and Arvidson et al. (1982) published the first image of the continental U.S., albeit at 1:30,000,000 scale, from the 30-arc-second data. Broad-scale shaded-relief maps of South Africa and Australia followed (Moore and Simpson, 1982; Lamb et al., 1987), while in the U.S. experiments continued to improve the technique (USGS, 1986; Scholz et al., 1987).

We made a wall-sized shaded relief image of the conterminous 48 states by processing the entire file of 30-arc-second elevations through IDIMS. After creating two files on the VAX 11/780 (data were supplied in eastern and western U.S. halves), we registered each on Albers equal-area projection, using bilinear interpolation, to yield 0.805-km pixels. Once the two files were mosaicked into one DEM, we masked it with a U.S. national boundary to separate terrain from background pixels and data in Canada and Mexico. To increase tonal contrast in smooth topography and diminish it in areas of high relief, we reduced skewness of the elevation frequency distribution, by transforming all 12 million elevations to their logarithms (see also USGS, 1986).

The SUNSHADE* routine (ESL, 1983; Scholz et al., 1987), which computed the angles of terrain slope and aspect (azimuth) and assigned to them brightness values and the corresponding 256 shades of grey, employs a modified Lambertian, or diffuse-scattering, photometric function. The following parameters were used: vertical exaggeration 2X, sun azimuth 300°, sun elevation 25°, image intensity 1.2 units, image ambience 0.7 units. We examined the histogram of resulting brightness values and redistributed the range to truncate its tails, and thus further reduce tonal imbalance between steep and gentle terrain. From an output tape of stretched brightnesses, we made six negatives on an Optronics* C-4500 Color Scanner and Film Recorder*. Lastly, we enlarged the negatives to prints of the same scale as the standard geologic map of the U.S. and mosaicked them to yield the 1:2,500,000-scale wall map.

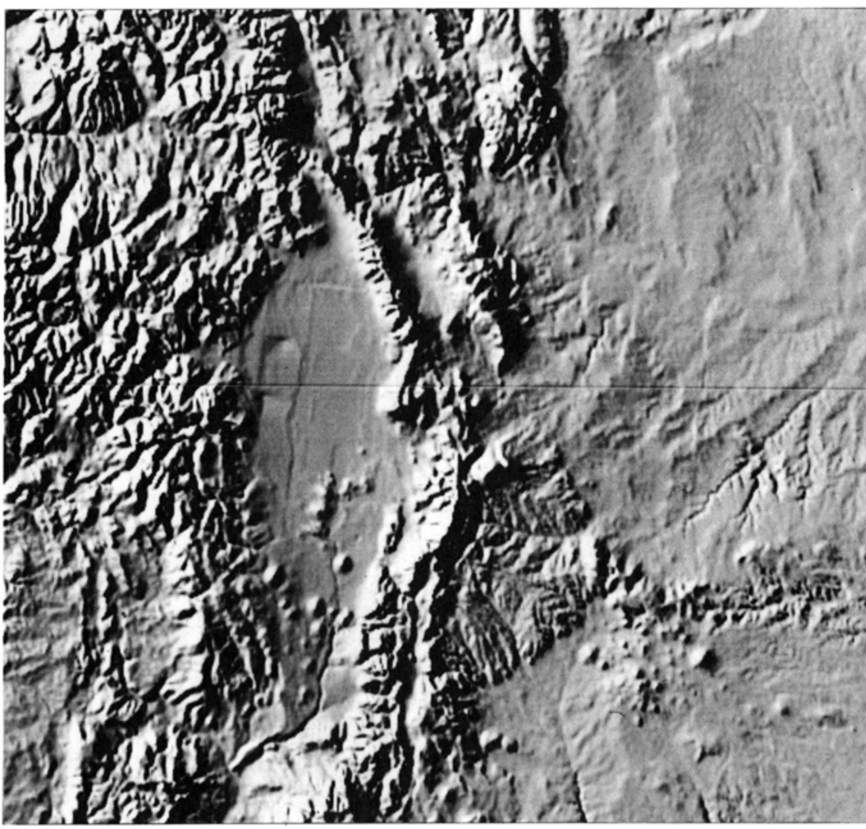

Figure 6. Detail from the 1:2,500,000-scale U.S. shaded-relief map, centered on the San Luis Valley and Sangre de Cristo Range, Colorado, including parts of Southern Rocky Mountains (Province 16) and the Raton (13g) and Colorado Piedmont (13f) sections of the Great Plains province. Horizontal line is mosaic seam. Area shown is 192 km across.

The resulting image (Figures 2, 6) is the first one-sheet graphic of U.S. landforms larger than Raisz's (1939) hand-drawn map. Fidelity and detail are far greater than that evident on Raisz's and other synoptic portrayals of terrain by pictorial relief, airbrush, or dark-plate (Harrison, 1969). The new map shows regional geomorphic and tectonic features not readily viewed by other means. It complements Hammond's (1964) map depicting numerical classes of land-surface form, and will aid in analyzing the Fenneman map units and adjusting their boundaries. The map also has revealed the worst errors in the data, which are being corrected before its publication at 1:2,500,000.

The new image can be improved, by employing local operators within SUNSHADE (Brassel, 1974), by experimenting with other advanced techniques of image processing (Whitted, 1982), and by adding color (Lamb et al., 1987). Maps at several sun angle and azimuth settings (e.g., Moore & Simpson, 1982) will be required to accentuate terrain features that follow different trends in the U.S. landscape.

CONCLUSIONS

Statistics of elevation and slope for 82 physiographic sections provide the first quantitative basis on which to summarize and compare topographic properties of the conterminous U.S. from so many map units. The results, derived wholly by image-processing a large file of terrain heights, both reveal that the Fenneman subdivisions vary widely in topographic homogeneity and yield criteria for refining the taxonomy. The accompanying wall map of U.S. topography in shaded relief, also from digital image-processing, is the best single-sheet graphic yet produced of the nation's landforms. Its accuracy and detail are unprecedented. Both the map and the geometric signatures extracted from elevation derivatives are new tools for addressing problems of regional extent in geology and geography.

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