U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

TO ACCOMPANY MAP I–2206

LANDFORMS OF THE CONTERMINOUS UNITED STATES— A DIGITAL SHADED-RELIEF PORTRAYAL

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VISUALIZING THE LANDSCAPE

Realistic portrayal and mapping of topographic form is a centuries-old problem: to trick the eye into perceiving a two-dimensional graphic as a three-dimensional landscape. All traditional solutions, including those partly implemented by machine, have been artistic (Imhof, 1965; Horn, 1981). Among the cartographic devices invented by illustrators to supply the necessary visual depth cues are hachuring, hypsographic (elevation) tinting, contour density, parallel-profile density, pictorial relief, and shaded relief (Harrison, 1969; Alpha and Winter, 1971; Gilman, 1981). The latter two manual techniques have been particularly successful. Pictorial relief, which symbolizes topography by stylized morphologic types, was most fully developed in the 50 landform classes of Raisz (1931, 1939). Shaded relief, or hill shading, shows topography by the intensity of shadows cast by a light source (Imhof, 1965; Yoeli, 1965). First drafted by pencil, pen, or brush, shaded relief also has been executed by airbrush, dark-plate, and photography of raised-relief models. However, topographic detail is much too complex to be mapped both accurately and economically over large areas by any of these means.

Fast computers, analytical software, digital data, and graphic input/output devices have converged over the last three decades to largely mechanize the craft of mapmaking (for example, Burrough, 1987, p. 4–6). This digital revolution has, among its many accomplishments, also solved the problem of mapping topographic form. Machine visualization now frees terrain portrayal from longstanding limitations (Kennie and McLaren, 1988). Topography need no longer be mapped symbolically, by discrete hand-drawn morphologic types (Raisz, 1931), or subjectively, by manual shading (Imhof, 1965). Where the necessary information is available in digital format, the computer can represent landforms as they actually are—within limitations of the source data—and portray terrain in the infinite variety of form that constitutes the true landscape. No longer is it entirely correct that maps of landforms are "drawn by men and not turned out automatically by machines" (Wright, 1942).

Yet despite the digital revolution in cartography, much truth remains in Wright's (1942) admonition that map makers are humans, not machines. Design and production of landform maps will be increasingly automated and sophisticated (Kennie and McLaren, 1988; Weibel, 1989), but the conception of a map (Yoeli, 1965, 1967) is fundamentally an intellectual rather than a mechanical process. Moreover, the portrayal of topography using digital data only now is passing from an experimental to a production technique. The many steps to a machine-made map of landforms—from data formatting, editing and processing, through image generation and correction, to preparation of a reproducible master—may be streamlined, if not wholly automated, but the sequence can involve much nonroutine trial-and-error. Such maps of topography, however technical in execution, will continue to remain the constructs of human vision and judgment.

MACHINE IMAGES OF TOPOGRAPHY

Digital image-processing and computer graphics have mechanized much of the art of landform representation by combining the two most effective traditional techniques, pictorial relief and hill shading (Yoeli, 1967; Batson and others, 1975). The resulting image is a shaded pictorial-relief (physiographic) map in vertical perspective. Although automated shaded-relief maps can look deceptively like satellite pictures, they are not acquired directly by Earth-orbiting spacecraft, nor are the data from which they are made. The images are computed from a large array of closely spaced terrain heights, usually in grid-cell (raster) format, called a digital elevation (or terrain) model (DEM/DTM) (Miller and LaFlamme, 1958). Most DEMs still are made from conventional topographic maps (for details of a recent example see Hall and others, 1990).

Shaded relief is a complex derivative of terrain height (fig. 1). Digitally shaded maps of topography resemble cloud-free black-and-white aerial photographs taken at a low Sun angle, but actually they are large north-south/east-west arrays of minute gray squares (Yoeli, 1965). Each square, or picture element (pixel), represents a theoretical reflected-light intensity (brightness value) computed from a mathematical relation between ground slope, Sun position, and location of the observer (ground slope is estimated from the corresponding point and its neighbors in a DEM). The lightest and darkest tones in the image show the steepest areas; intermediate grey tones are gentle terrain. The visually most pleasing image is obtained by experimenting with location of the simulated Sun (conventionally from the northwest at

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Manuscript approved for publication April 17, 1991.

45° above the horizon) and illumination intensity. For more information, see the section entitled "Technical Details" at the end of the discussion.

Mechanization of the shaded-relief technique for DEMs, pioneered by Yoeli (1967), has been widely applied. Batson and others (1975) made the first synoptic shaded-relief images for parts of the western United States (at 1:500,000 scale), and Arvidson and others (1982) published the first image of the conterminous United States (albeit at 1:30,000,000). These were followed by small shaded-relief maps of Australia (Moore and Simpson, 1982) and South Africa (Lamb and others, 1987), the first shaded-relief map of the Earth (Heirtzler, 1985), and a large map of Sweden (Elvhage and Lidmar-Bergström, 1987). Among the latest synoptic images are those for the southwestern United States at 1:1,000,000 and 1:2,000,000 scale (Edwards and Batson, 1990a,b). Experimentation has further refined the technique (U.S. Geological Survey, 1986; Scholz and others, 1987; Ware, 1989), which has been equally effective in portraying gravity, aeromagnetic, geoid, and other geophysical data for interpretation (for example, Arvidson and others, 1982; Verhoef and others, 1989; Christou and others, 1989).

Computer-generated maps such as this offer several advantages for the visual study of topography. Above all, these images portray landforms accurately and disclose their true complexity (at a given resolution), two properties that often are lost in small-scale sketches, diagrams, or conventional maps. Perhaps equally important, surface features can be viewed in a broad regional context. Unlike aerial photographs, image extent is limited only by size of the DEM. Digital shaded-relief maps also lack the distortion inherent in photographs and radar images. They are free of the vegetation and cultural features that mask topographic form on images from Landsat, SPOT, and other satellites (for example, National Geographic Society, 1976; U.S. Geological Survey, 1990). Stereo pairs in shaded relief can be created digitally (Batson and others, 1975), and Sun position can be varied to obtain different views of the the same area (Moore and Simpson, 1982). Finally, shaded-relief images can be generated rapidly from digital files and do not require the time and artistic skill needed to prepare conventional relief maps.

APPLICATIONS OF DIGITAL LANDFORM MAPS

Computer maps of elevation derivatives have many uses. Applications of relief shading include, but by no means are limited to, resource evaluation (Burrough, 1987) and the interpretation of regional and structural geology (Moore and Simpson, 1982; Lamb and others, 1987), global tectonics (Verhoef and others, 1989), and geomorphology (Elvhage and Lidmar-Bergström, 1987). Surface features in shaded relief can be studied by conventional techniques, including aerial photointerpretation. Automated relief-shading also provides an excellent cartographic base for mapping cultural and Earth science information at any scale commensurate with resolution of the source data: local (Mark and Aitken, 1990), regional (Edwards and Batson, 1990a, b), and global (Simkin and others, 1989). Shaded relief may be combined with such nontopographic information by machine registration with another digital file, for example, a computer-coded version of King and Beikman's (1974) map of United States geology.

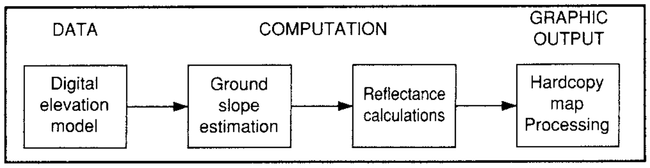


Figure 1. Basic steps in the generation of a shaded-relief map (modified from Brassel, 1974; Horn, 1981).

Relief shading is only one of several ways to map topography by computer. Other derivatives of elevation include slope angle and aspect, slope curvature, local relief, and ridge and stream spacing and arrangement (Tobler, 1969; Evans, 1980; Dikau, 1989). Maps of these measures can be combined statistically to derive numerical fingerprints or signatures that characterize topography over large areas (Pike, 1988; Pike and Acevedo, 1988; Weibel, 1989). For example, the statistics of slope angle are contributing to the potential revision and elaboration of the Fenneman and Johnson (1946) physiographic units (fig. 2; Pike and Thelin, 1989). We expect that the regional geomorphology of the United States will be refined from these measures, as well as from the new shaded-relief map (for a Swedish example of such an analysis, see Elvhage and Lidmar-Bergström, 1987). Also, maps of slope and other derivatives of elevation can be combined digitally with maps of rock type, soils, vegetation, climate, and demography, using Geographic Information Systems (GIS) technology (Burrough, 1987), to address practical problems, particularly those of land use and the environment (McHarg, 1969). Such computer-intensive applications include mapping geologic hazards (Brabb, 1987; Pike, 1988), engineering geology (Wentworth and others, 1987), hydrologic analysis (Vieux, 1991), modeling air mass/terrain interactions for synoptic meteorology (Tesche and Bergstrom, 1978), and quantitative refinement of qualitative maps of the Nation's ecoregions (Gallant and others, 1989).

THE NEW DIGITAL SHADED-RELIEF MAP

This map is the largest single-sheet graphic of relief forms of the United States since the classic hand-drawn oblique map of the same area by Raisz (1939). In concept and execution it most closely resembles Harrison's (1969) vertical dark-plate map of United States shaded relief, but is intrinsically more detailed and accurate than either of the above maps. The new map clearly shows the regional terrain textures on which physiographic divisions of the United States were largely based (fig. 2; Fenneman and Johnson, 1946). It nicely complements Hammond's (1964) map depicting numerical classes of land-surface form and satellite-image color mosaics (National Geographic Society, 1976; U.S. Geological Survey, 1990), which emphasize vegetation and hydrography. The Raisz (1939) map, which is still available (from Raisz Landform Maps, P.O. Box 2254, Jamaica Plain, MA, 02130: 1–800–242–3199; in Massachusetts 1–617–868–3199), may be used to locate named surface features.

Greater detail is evident in the digital shaded-relief image than could, in all practicability, be included in synoptic portrayals of the Nation's terrain at this resolution by any manual technique. Much of the detail derives from the high density of the data set (and the computer's ability to rapidly process so many terrain heights), but much of it simply reflects the map's size, which is more than twice as large as its closest predecessor (Harrison, 1969). The 1:3,500,000 scale also is the largest scale consistent with visual merging of pixels into a continuous smooth surface (contrast with Bleed and Flowerday, 1990, p. 4). Data resolution on the map, the length of a pixel edge, is 0.23 mm (0.8 km on the ground), essentially the 0.25 mm/pixel maximum value proposed by Yoeli (1965) for shaded-relief portrayal by computer.

Resolution of the shaded-relief data is slightly too coarse to rid the map completely of evidence of its computer origin. Minute pixel-sized regularities (aliasing) still are evident in the fine sawtooth appearance of some narrow linear features. Other flaws in our map are discussed below under the section entitled "Source Data." All of these are minor compared to the information conveyed by the map and do not detract unduly from the portrayal.

SOME LANDFORMS OF INTEREST

The new map shows geomorphic and tectonic phenomena of the United States in vivid detail. These features, which are so numerous that only a small sampling is included here (figs. 2–4), fall into two overall groups: landforms that are obvious or familiar and those that are less so. Treatises on regional geomorphology of the United States (Graf, 1987, is the most recent example) and certain small-scale maps of the country (for example, U.S. Geological Survey, 1990) may be consulted for further study of these and innumerable other features evident on the map.

The most obvious surface forms portrayed on this map are of three main types: large physiographic subdivisions, major contrasts in style of topographic expression, and small but unique landforms.

All the general surface characteristics listed on the standard map of United States physiographic units (fig. 2; Fenneman and Johnson, 1946) are crisply rendered here in shaded relief. Examples of distinctive morphologies include structural control of topography in the folded Appalachian Mountains, the west-tilted Sierra Nevada fault block, and the domical Black Hills (fig. 4, Nos. 1–3, respectively). The Basin and Range physiographic province can be viewed in its entirety in detail previously unavailable at this scale. Both the great roughness and structural complexity of the Rocky Mountain system (fig. 2, Nos. 16–19) and Pacific Border province (No. 24) are portrayed convincingly by mechanized shaded relief.

Also conspicuous on the map are two important contrasts in overall geomorphic style. The more fundamental is that between the static eastern United States, a passive continental margin, and the active West, where the North American and Pacific crustal plates are colliding. These differing tectonic regimes also are reflected in the Country's coastline: the Atlantic and Gulf coasts, which developed on a gently sloping continental shelf, differ markedly in detail from the Pacific coast, where the offshore profile is steep. Glaciation of the continent during the Pleistocene imposed a second major distinction. The relief and fluvial texture of the Driftless section in southwestern Wisconsin (fig. 2, No. 12c and fig. 4, No. 4) contrast vividly on the new map with the muted drift-mantled terrain that surrounds it. This area exemplifies the many glacial/nonglacial differences in terrain across much of the northern United States (fig. 4, No. 5).

Only slightly less obvious on our map are certain small features, if familiar to the viewer or unique in morphology. Among those that can be located quickly are basalt ridges in the Connecticut River valley (fig. 4, No. 6), glacial moraines on Long Island and western Cape Cod (No. 7), two large caldera-forming volcanoes—Valles (No. 8) and Crater Lake (No. 9) and the approximate trace of the San Andreas fault zone (No. 10). Some small landforms of widespread interest, however, are found only if one knows the shape of the feature and just where to look. Most viewers seeking Mount St. Helens (No. 11), for example, will require a locational aid (such as Raisz, 1939, or a good atlas) to find it among the many other peaks in the Cascade Range.

A major strength of the new map is not so much its expression of the obvious, but rather its depiction of features that are subtler or less familiar. We have chosen examples from four main types: landforms of the central United States, low-relief landforms elsewhere, families of linear features that may have major significance, and minor linear trends.

The new image is unique in its clear portrayal of topography in the United States midcontinent. This large area contains landforms that are fully as interesting as the mountain chains to the east and west. Among these low-relief features are the broad extent and extraordinary flatness of the Mississippi Alluvial Plain (fig. 2, No. 3*e*) and the Llano Estacado (Staked Plains) of western Texas and eastern New Mexico (fig. 4, No. 12); the fine-grained hummocky texture of the Nebraska Sand Hills (No. 13)—the largest sand-dune area in the Western Hemisphere (Bleed and Flowerday, 1990); Crowleys Ridge (No. 14)—a late Pleistocene erosional remnant in the Mississippi River Embayment (near the epicenter of the 1811–12 New Madrid earthquakes); and the many occurrences of unusual drainage patterns arising from advance and retreat of the last ice cap (No. 15).

Perhaps most striking of all midcontinent landforms shown on the map is the Coteau des Prairies (fig. 4, No. 16), "a flatiron-shaped plateau some 200 miles (300 km) long, pointing north" (Flint, 1955). The ice-scoured lowlands that flank the Coteau des Prairies in eastern South Dakota and neighboring States formerly were occupied by

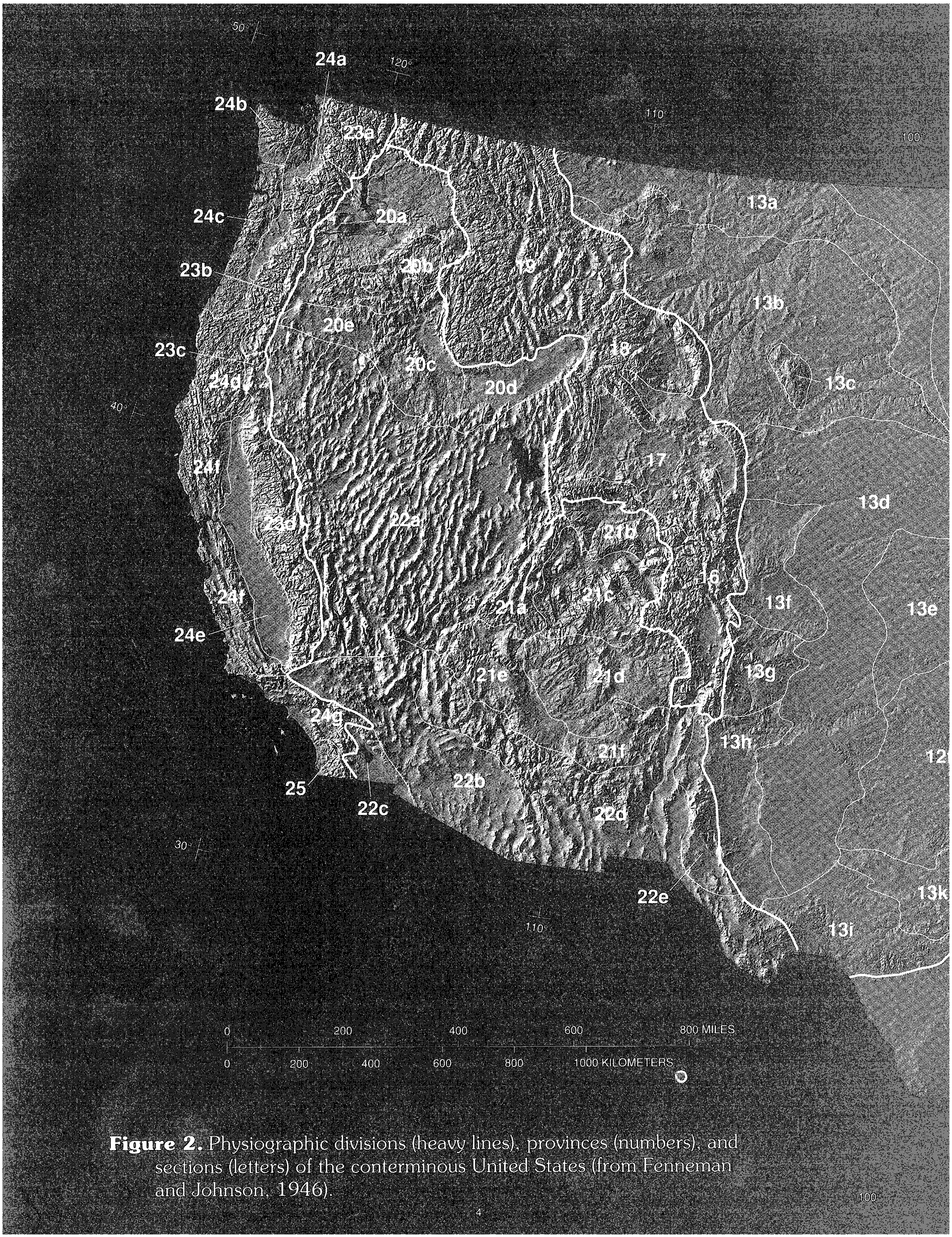
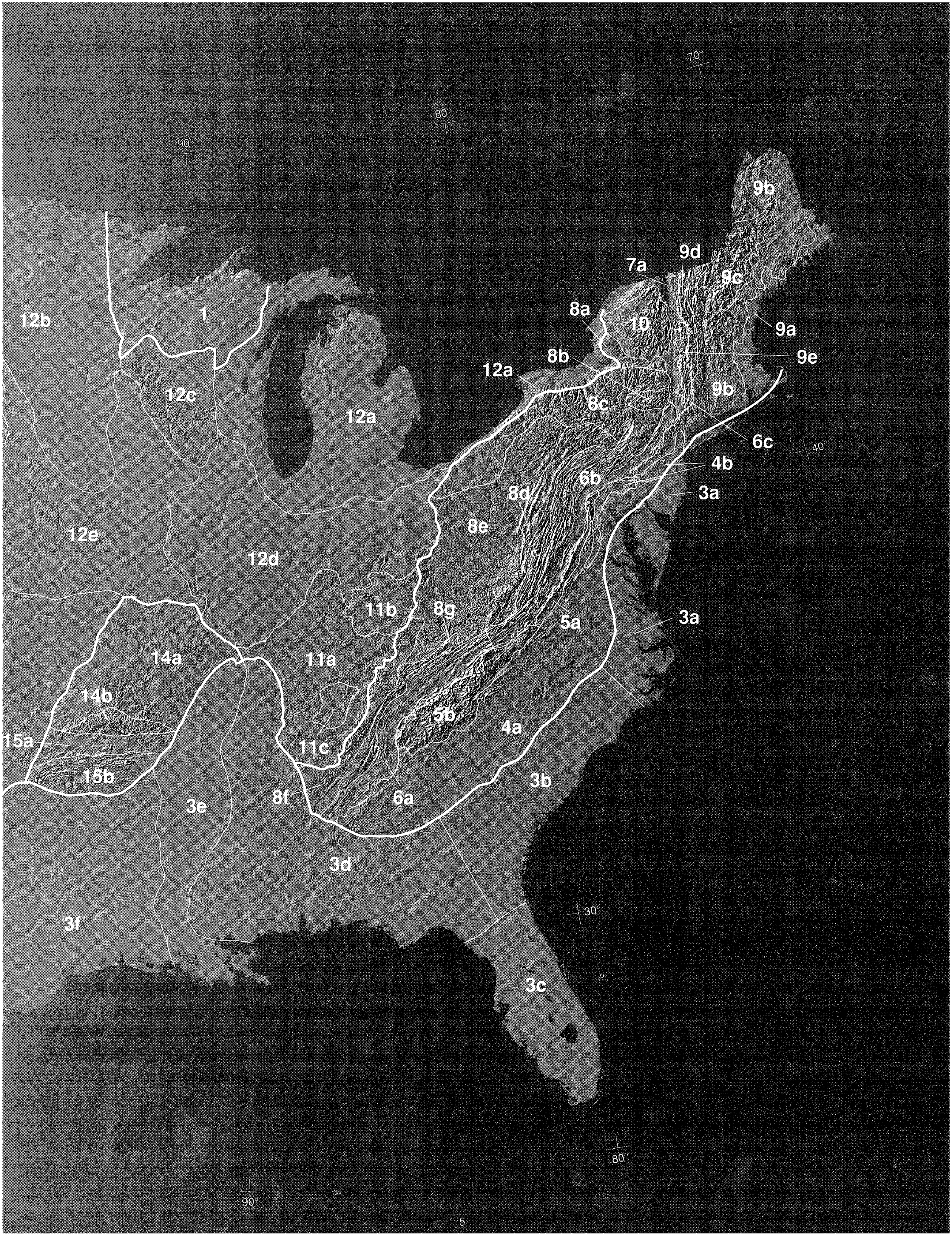


Figure 2. Physiographic divisions (heavy lines), provinces (numbers), and sections (letters) of the conterminous United States (from Fenneman and Johnson, 1946).



70°
80°
90
9b
7a
9d
9c
12b
1
8a
10
9a
8b
9e
12a
12c
12a
8c
9b
6c
40°
4b
6b
8d
3a
12e
8e
12d
11b
8g
5a
3a
14a
11a
14b
5b
4a
15a
11c
15b
8f
6a
3b
3e
3d
30°
3f
3c
80°
90°

the James and Des Moines lobes of the last ice sheet. These lowlands, which drained melting ice and various ice-dammed lakes during deglaciation of the region, bear a remarkable resemblance to outflow channels (usually interpreted as fluvial features) observed on spacecraft images of the planet Mars (Kehew and Lord, 1986).

Subtle or only locally important landforms elsewhere in the Country also are well shown on the new map. These include the enigmatic Sutter Buttes volcano (fig. 4, No. 17) in California's Sacramento Valley, the many low volcanic shields on the Snake River plain (No. 18), Trail Ridge (No. 19, an important domestic source of the minerals ilmenite and zircon) and other long north-trending sandy ridges in Florida, the inactive Clinton-Newbury (or Essex) fault zone (No. 20) and its extensions in eastern Massachusetts and Connecticut (a minor crustal suture), and the overall north-northeast-trending texture of the Appalachian Mountains in northern New England (No. 21).

EXPLANATION

LAURENTIAN UPLAND

1. Superior Upland

ATLANTIC PLAIN

2. Continental Shelf (not on map)
3. Coastal Plain
    - a. Embayed section
    - b. Sea Island section
    - c. Floridian section
    - d. East Gulf Coastal Plain
    - e. Mississippi Alluvial Plain
    - f. West Gulf Coastal Plain

APPALACHIAN HIGHLANDS

4. Piedmont province
    - a. Piedmont Upland
    - b. Piedmont Lowlands
5. Blue Ridge province
    - a. Northern section
    - b. Southern section
6. Valley and Ridge province
    - a. Tennessee section
    - b. Middle section
    - c. Hudson Valley
7. St. Lawrence Valley
    - a. Champlain section
    - b. Northern section (not on map)
8. Appalachian Plateaus
    - a. Mohawk section
    - b. Catskill section
    - c. Southern New York section
    - d. Allegheny Mountain section
    - e. Kanawha section
    - f. Cumberland Plateau section
    - g. Cumberland Mountain section
9. New England Province
    - a. Seaboard Lowland section
    - b. New England Upland section
    - c. White Mountain section
    - d. Green Mountain section
    - e. Taconic section
10. Adirondack province

INTERIOR PLAINS

11. Interior Low Plateaus
    - a. Highland Rim section
    - b. Lexington Plain
    - c. Nashville Basin
12. Central Lowland
    - a. Eastern Lake section
    - b. Western Lake section
    - c. Wisconsin Driftless section
    - d. Till Plains
    - e. Dissected Till Plains
    - f. Osage Plains
13. Great Plains province
    - a. Missouri Plateau, glaciated
    - b. Missouri Plateau, unglaciated
    - c. Black Hills
    - d. High Plains
    - e. Plains Border
    - f. Colorado Piedmont
    - g. Raton section
    - h. Pecos Valley
    - i. Edwards Plateau
    - k. Central Texas section

INTERIOR HIGHLANDS

14. Ozark Plateaus
    - a. Springfield-Salem plateaus
    - b. Boston "Mountains"
15. Ouachita province
    - a. Arkansas Valley
    - b. Ouachita Mountains

ROCKY MOUNTAIN SYSTEM

16. Southern Rocky Mountains
17. Wyoming Basin
18. Middle Rocky Mountains
19. Northern Rocky Mountains

INTERMONTANE PLATEAUS

20. Columbia Plateau
    - a. Walla Walla Plateau
    - b. Blue Mountain section
    - c. Payette section
    - d. Snake River Plain
    - e. Harney section

21. Colorado Plateaus
    - a. High Plateaus of Utah
    - b. Uinta Basin
    - c. Canyon Lands
    - d. Navajo section
    - e. Grand Canyon section
    - f. Datil section
22. Basin and Range province
    - a. Great Basin
    - b. Sonoran Desert
    - c. Salton Trough
    - d. Mexican Highland
    - e. Sacramento section

PACIFIC MOUNTAIN SYSTEM

23. Cascade-Sierra Mountains
    - a. Northern Cascade Mountains
    - b. Middle Cascade Mountains
    - c. Southern Cascade Mountains
    - d. Sierra Nevada
24. Pacific Border province
    - a. Puget Trough
    - b. Olympic Mountains
    - c. Oregon Coast Range
    - d. Klamath Mountains
    - e. California Trough
    - f. California Coast Ranges
    - g. Los Angeles Ranges
25. Lower Californian province

Figure 2.—Continued

Groups of throughgoing linear features, which may mark significant events in the tectonic evolution of the North American continent, are among the most remarkable patterns on this map. Some of them, such as the west-trending lineament in the Rocky Mountains (fig. 4, No. 22), the east-northeast trend that aligns with the Garlock fault zone (No. 23), and an east-northeast trend (No. 24) that includes parts of the Gila and Salt Rivers (Arizona) and the Canada River (Texas), are perhaps seen clearly for the first time here. The latter two trends parallel the Murray fracture zone and other inactive transform faults (not shown) of the eastern Pacific plate. Major elongate features that are more familiar from previous study include the Olympic-Wallowa lineament (No. 25) and the many, possibly related, subparallel northwest trends in the Rocky Mountains (No. 26) to the southeast of it. Some of the large lineaments on this map may include currently active faults.

Minor trends in some parts of the map also may reflect neotectonic activity. However, interpreting such trends requires restraint, as it does for aerial photographs and radar images in certain types of topography (Howard and Larsen, 1972; Yamaguchi, 1985). On this map, the 300° lighting slightly exaggerates 325°-striking ridges and valleys, especially those that produce the remarkable north-northwest grain on the Great Plains (fig. 4, No. 27), which seems to be real nonetheless (unidirectional lighting at a low elevation angle may artificially enhance small linear features in preferential directions, typically 20° to 35° from that of the light source, while suppressing them in others, parallel to the light source). The north-northwest trend may mark a regional fracture pattern imprinted on the middle one-third of the Country that reflects its coupling a mobile West to a more stable East. It suggests indeed "that the effect of plate collisions may extend across vast distances upon the surface of a continental plate" (Beckinsale and Beckinsale, 1989).

FUTURE PROSPECTS

Our shaded-relief image of the United States is not static. Like any reconnaissance geologic map, or for that matter a good scientific hypothesis, it is an ongoing experiment (Yoeli, 1965). Because this map reflects a still-evolving technology, various improvements are under consideration. Foremost among these are restoration of digital elevations for southern Canada and northern Mexico (see following section entitled "Technical Details"; Arvidson and others, 1982), inclusion of Alaska and Hawaii, eliminating or reducing errors in the dataset through further editing and edge-matching of data blocks, and more hydrography. The visual perception of elevation could be enhanced through the use of color (Harrison, 1969; Lamb and others, 1987).

Changes in the shaded-relief calculation might address some remaining shortcomings of the map, particularly tonal imbalance between steep and gentle terrain. Detail in very mountainous areas is obscured because the steepest slopes are too dark or too light. We have found that the desired balance in tone cannot be achieved simply by transforming all elevation or slope values to logarithms or square roots, and then computing brightnesses from the transformed values (U.S. Geological Survey, 1986). The solution is likely to be more complex and may require incorporating special algorithms, called local operators, within the computer software to tailor reflectance values to specific conditions of elevation and slope (Brassel, 1974).

Lastly, the map could be best improved simply by increasing scale, data density, and image resolution (for example, Edwards and Batson, 1990a,b). Such a map would provide the detail needed for a more effective relief portrait in many parts of the United States (for example, Bleed and Flowerday, 1990, p. 4). An improved map of the entire Country, probably at 1:1,000,000 scale and necessarily in several sheets, would require a cleaned-up file of all the original digitized elevations and an image resolution of about 0.1 mm/pixel (130 m on the ground). Multiple editions of this map at several Sun azimuth and elevation settings (Moore and Simpson, 1982) would further exploit the research potential of digital shaded-relief by accentuating terrain features that follow all the different trends in the Country's landscape.

TECHNICAL DETAILS

IMAGE PROCESSING AND HILL SHADING

Our map was made by digital image-processing, a technical specialty related to the broader fields of computer graphics and machine vision (Dawson, 1987; Kennie and McLaren, 1988). The technology includes the many spatially based operations first brought together and developed systematically to manipulate Ranger, Mariner, Landsat, and other images that are reassembled from spacecraft telemetry in a raster or scan-line arrangement of square-grid elements (Nathan, 1966; Castleman, 1979; Sheldon, 1987). These computer procedures have been successfully transferred to landform analysis from remote-sensing applications by substituting terrain heights or sea-floor depths for the customary values of electromagnetic radiation obtained from satellites and stored in digital arrays of pixels (Batson and others, 1975).

It is the 1 pixel=1 elevation equivalence that enables image-processing technology to so efficiently map elevation matrices and their derivatives over large areas. Recent examples are given by Arvidson and others (1982), Simpson and others (1986), and Verhoef and others (1989). Slope angle and other quantitative measures of surface form can be rapidly calculated, compared, and combined for display as shaded-relief and color images or stored as digital files for further study of topography and registration with nontopographic data sets (Batson and others, 1975; Moore and Mark, 1986; Pike and Acevedo, 1988; Pike and Thelin, 1989).

The image-processing tool applied here, relief shading, is more formally termed analytical hill shading. Although well known as an artistic and manual technique (Imhof, 1965), it was impractical for large areas until Yoeli (1965) developed a modern analytical version for square-

Figure 3. Boundaries of the conterminous United States.


70°
80°
90°
40°
30°
80°
90°

Figure 4. Topographic features cited in discussion of shaded-relief map of the conterminous United States.


70°
80°
90°
21
21
6
15
20
4
6
7
4
5
7
4
40°
1
15
1
5
1
14
1
19
30°
80°
90°

grid matrices of terrain elevations and then automated it for the computer (Yoeli, 1967). Analytical hill shading maps topographic form through variations in mathematically determined intensity of reflected light (I) at each elevation/pixel located on the ground (fig. 5). This relation, known as the photometric function, has many variants (Brassel, 1974; Batson and others, 1975; Horn, 1981; Christou and others, 1989). The simplest case is the cosine law of Lambert

$$I=k_d\cos(i) \qquad (1)$$

where i is the angle between the incident light (the Sun) and a vector normal to the sloping ground, and k_d is a coefficient describing reflectivity of the surface material (here, a perfect diffuser of incident light; Greenberg, 1989). Position of the viewer is directly overhead. Ground slope may be estimated from a DEM in several ways, using three to nine adjacent height values (Ware, 1989; Mark and Aitken, 1990). Repetition of these calculations pixel-by-pixel over a large DEM yields a reflectance map, a continuous X,Y array of brightness values (Horn, 1981).

EXPLANATION

1 Folded Appalachian Mountains
2 Sierra Nevada
3 Black Hills
4 Driftless area
5 Southern limit of Pleistocene continental glacial deposits
6 Basalt ridges in the Connecticut River valley
7 Terminal moraines on Long Island and western Cape Cod
8 Valles caldera
9 Crater Lake caldera
10 San Andreas fault zone
11 Mount St. Helens
12 Llano Estacado (Staked Plains)
13 Nebraska Sand Hills
14 Crowleys Ridge
15 Unusual drainage patterns emplaced during Pleistocene
16 Coteau des Prairies
17 Sutter Buttes
18 Low volcanic shields on Snake River plain
19 Trail Ridge
20 Clinton-Newbury (Essex) fault zone
21 Linear texture in northern New England
22 West-trending lineament in Rocky Mountains
23 Alignment with Garlock fault zone
24 Linear trend following Gila, Salt, and Canada Rivers
25 Olympic-Wallowa lineament
26 Northwest trends in Rocky Mountains
27 North-northwest grain on Great Plains

Figure 4.—Continued

Many refinements to the basic approach itself can improve relief shading without having to add data from other sources (such as Landsat). Besides direct illumination, reflectance maps generally include some ambient light, which strikes and reflects from a surface equally in all directions, to improve appearance of the final image (Greenberg, 1989; Christou and others, 1989). Shadows cast by steep terrain also can be incorporated into the calculation (Ware, 1989), and even atmospheric effects can be simulated (Brassel, 1974). Finally, advanced techniques of computer graphics used in some industries to digitally depict virtually any object with photorealistic quality (Whitted, 1982; Greenberg, 1989) conceivably could be adapted to take shaded-relief portrayal to even higher levels of realism (Kennie and McLaren, 1988).

SOURCE DATA

The terrain heights from which our map was made do not owe their origin to remote sensing by Landsat or other spacecraft. Rather, the data result from the machine sampling—initially by contour-tracing, later by drum-scanning—of available contour maps, some of which were first compiled as early as 1947. These measurements have a complex history that spans a quarter of a century, starting with the Defense Mapping Agency Topographic Center's (DMATC) creation of a nationwide set of gridded elevations in 1964 to 1972.

DMATC digitized and labeled contour lines, and later spot heights and stream and ridge lines, on hundreds of 1:250,000-scale (1° by 2°) topographic sheets covering the United States and parts of Canada and Mexico. Digitizing these maps by semi-automated methods at 0.01 in. (0.25 mm) resolution, 3 arc-seconds or about 200 ft (63 m) on

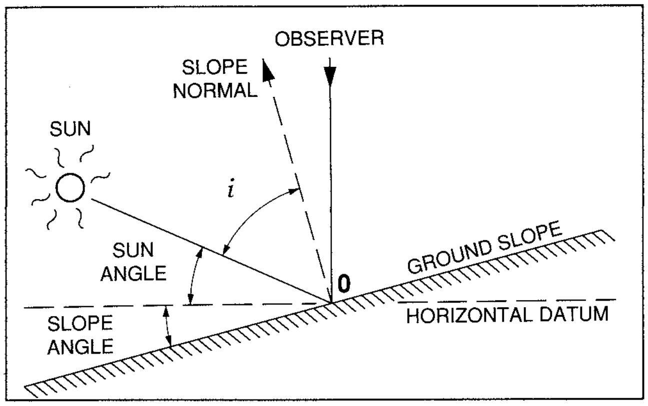


Figure 5. Geometric relation between ground slope and Sun position that is basic to reflected-intensity (brightness) calculations for shaded-relief mapping (modified from Batson and others, 1975). i, angle between incident light (the Sun) and a vector normal to the sloping ground; see equations (1) and (2) in text. Point 0 is center terrain height in five-point sample of the digital elevation model (see fig. 6).

the ground, accounted for 1/6 of the elevations (Mays, 1966). The remaining 5/6 of the data were interpolated between digitized contours by computer (Noma, 1966). The entire DEM, containing more than 2 billion elevations arrayed in a square grid of 3-arc-second resolution, has been available since 1974 in over 900 1° by 1° blocks from the U.S. Geological Survey (USGS), currently the Earth Science Information Center (Rm. 1C107, 507 USGS National Center, Reston VA 22092: 1-800-860-6045).

The original DMATC data were later resampled (thinned) and averaged down (see Godson, 1981, for some details) to the more manageable file used here and by Godson (1981) and by Arvidson and others (1982). The resulting 12 million elevations are spaced 30 arc-seconds apart, nominally 0.805 km on the ground, north-south and east-west. The actual array (6,046 by 3,750) processed to make our map includes null (black) background values lying between the national boundary and the map border and thus is much larger. Although the initial DMATC data were read or interpolated to the nearest foot (Mays, 1966), the elevations were later rounded to 10 m (map contour intervals were coarse: 100 ft or more). Accordingly, vertical accuracy of the data for this image may be no more than 30 m in smooth areas and 50 m in rough terrain. The 30-arc-second DEM is available from the National Oceanic and Atmospheric Administration's National Geophysical Data Center (Code E/GC1, 325 Broadway, Boulder CO 80303: 1-303-497-6128).

Errors in both the 3-arc-second and the 30-arc-second data sets, in addition to those inherent in the source maps, account for visible flaws in the map (Batson and others, 1975). Most of these errors are systematic. The flattened hills and the fine-scale rectilinear and stair-step textures on the map arise from round-off error and also from inaccurate interpolation between widely spaced contours, the result of too large a contour interval and a fast but suboptimal algorithm dictated by the slow computers available 25 years ago (Noma, 1966). Faint, widely spaced north-south and east-west lines mark defective splices between 1° data blocks. Less systematic errors include additional flattened hilltops, unexplained textures, and randomly located zero or unduly high elevations arising from unknown causes.

COMPUTATION AND PRODUCTION

We created this map by processing all of the 30-arc-second height data through proprietary software, the Interactive Digital Image Manipulation System (IDIMS; Electromagnetic Systems Laboratory, Inc., 1983), installed on a DEC VAX 11/780 computer. After registering the location of each of the 12 million elevations to an Albers Equal-Area Conic projection (standard parallels at 29.5° N. and 45.5° N.; central meridian at 96.0° W., and latitude of projection's origin at 23.0° N.), we produced a new grid of 0.805-km-resolution pixels from bilinear resampling. Topography beyond the national boundary, in two strips across southern Canada and northern Mexico, was excluded from the dataset by a 1:2,000,000-scale United States outline obtained from a USGS digital line graph.

The SUNSHADE routine within IDIMS computed strike and dip angles of terrain slope, by algebraic manipulation of the four elevations immediately north, south, east, and west of each sample point in the DEM (fig. 6), and from them assigned brightness values ranging from 0 (deeply shadowed areas) to 255 (fully illuminated surfaces) to all 12 million pixels (these calculations took about 17 minutes on the VAX 11/780). The algorithm (Electromagnetic Systems Laboratory, Inc., 1983) is built around a much-modified Lambertian photometric function (Horn, 1981) that uses diffuse scattering to simulate the effects of solar illumination,

$$I=k_d[L\cos(i)]+A \qquad (2)$$

where L is a scaling factor for the intensity of illumination, and A is an additive ambient light factor (the remaining terms are defined for equation 1, above). The calculation does not provide for cast shadows (Ware, 1989). Various parameters to the SUNSHADE routine control image contrast and thus final appearance of the shaded relief. We found that the following values gave the most crisp and visually appealing portrayal overall: vertical exaggeration, 2x; Sun azimuth, 300°; Sun elevation, 25°; scaling factor for the intensity transformation, 1.2 units; ambient-light factor, 0.7 units.

Errors in the DEM were located from both statistical analysis of the elevations (Pike and Thelin, 1989) and visual identification of aberrant patterns in the image. We repaired some of the most visible artifacts by editing flawed portions of the map and changing brightness values on a pixel-by-pixel basis, using a Hewlett-Packard 9000 Series-360 Turbo workstation. To retain maximum local detail in the map, we

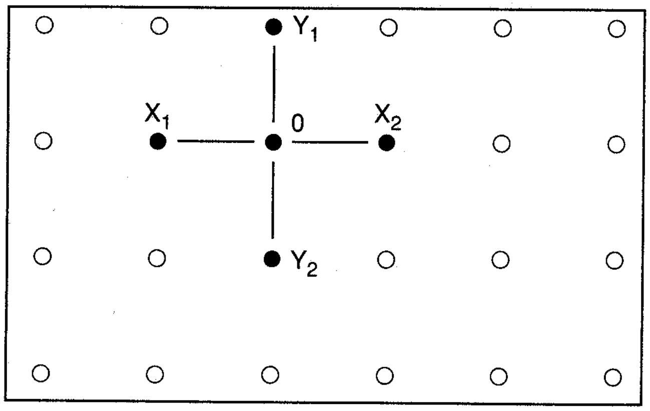


Figure 6. Obtaining values of strike and dip for local terrain slope within a square-grid digital elevation model (subset of 24 heights shown here by circles) from a five-point sample design (filled circles). Calculation for center terrain height, 0 (see fig. 5), averages east-west and north-south slope values defined by neighboring heights X_1 and X_2 and Y_1 and Y_2, respectively (Electromagnetic Systems Laboratory, Inc., 1983). Sample point 0 is relocated at each height value throughout the DEM and the calculation repeated. Resulting values of strike and dip are used to compute the slope normal and then angle i (fig. 5) for text equations (1) and (2).

did not attempt to correct or change any of the erroneous elevations globally, by applying a digital filter to the entire DEM.

Preparation of the final image required several steps. To increase tonal contrast in smooth topography and diminish it in areas of high relief, we remapped the intensity values output from SUNSHADE, using a piecewise linear transformation, to new values based on breakpoints that we defined in the original shaded-relief image from a histogram of its brightnesses. Over 70 of the largest (more than 20 mi^2 in area) natural lakes—plus the coastline and national boundary—were obtained from an analog 1:2,500,000-scale United States map and used to mask the shaded-relief file photomechanically, as a nondigital overlay (shown in black on the map).

The map image was created from three separate negatives made on a Scitex Response-300 computerized cartographic system. To obtain the desired tonal contrast and balance, each negative emphasizes a different range of brightness. The full range of light intensities in each negative was computed for the 12 million pixels to generate a printing screen of 175 lines/inch (an image resolution of 0.15 mm) on the Scitex system's laser drum plotter. The final map was printed in black ink, from five lithographic plates—three made from the shaded-relief negatives and two made from the nondigital overlay to ensure a deep black for the background.

ACKNOWLEDGMENTS

Gail P. Thelin compiled the map in 1989–90. We thank William Acevedo, C.M. Wentworth, T.R. Alpha, and R.W. Simpson (all USGS) for comments on drafts of this report. We are grateful to the many exhibit attendees, starting with those at the 1988 Geological Society of America Centennial meeting in Denver, Colo. for insights and observations on surface features shown by our map. This report was edited by S.M. Stone. C.P. Stevens, V.N. Badal, and Stuart Allan (Allan Cartography) helped in the production of the map. J.F. Vigil and L.M. Larsen produced the pamphlet.

REFERENCES CITED

Alpha, T.R., and Winter, R.E., 1971, Quantitative physiographic method of landform portrayal: Canadian Cartographer, v. 8, no. 2, p. 126–136.

Arvidson, R.E., Guinness, E.A., Strebeck, J.W., Davies, G.F., and Schulz, K.J., 1982, Image-processing applied to gravity and topography data covering the continental U.S.: Eos (American Geophysical Union Transactions), v. 63, no. 18, p. 257, 261–265.

Batson, R.M., Edwards, Kathleen, and Eliason, E.M., 1975, Computer-generated shaded-relief images: U.S. Geological Survey Journal of Research, v. 3, no. 4, p. 401–408.

Beckinsale, R.P., and Beckinsale, R.D., 1989, Eustasy to plate tectonics: unifying ideas on the evolution of the major features of the Earth's surface, *in* Tinkler, K.J., ed., History of geomorphology: Boston, Unwin Hyman, p. 205–221.

Bleed, Ann, and Flowerday, Charles, eds., 1990, An atlas of the Sand Hills: University of Nebraska, Conservation and Survey Division, Institute of Agriculture and Natural Resources, Resource Atlas No. 5, 265 p.

Brabb, E.E., 1987, Analyzing and portraying geologic and cartographic information for land-use planning, emergency response, and decision making in San Mateo County, California, *in* v. 1 *of* GIS '87–San Francisco, International Conference, Exhibits, and Workshops on Geographic Information Systems, 2d, San Francisco, October 26–30, 1987, Proceedings: American Society for Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping, p. 362–374.

Brassel, Kurt, 1974, A model for automatic hill-shading: American Cartographer, v. 1, no. 1, p. 15–27.

Burrough, P.A., 1987, Principles of geographical information systems for land resources assessment (corrected reprinting): Oxford, Clarendon Press, 193 p.

Castleman, K.R., 1979, Digital image processing: Englewood Cliffs, N.J., Prentice-Hall, 429 p.

Christou, Nikolaos, Vaníček, Petr, and Ware, Colin, 1989, Geoid and density anomalies: Eos (American Geophysical Union Transactions), v. 70, no. 22, p. 625 and 631.

Dawson, B. M., 1987, Introduction to image processing algorithms: BYTE, v. 12, no. 3, p. 169–186.

Dikau, Richard, 1989, The application of a digital relief model to landform analysis in geomorphology, *in* Raper, Jonathan, ed., Three dimensional applications in geographical information systems: London, Taylor and Francis, p. 51–77.

Edwards, Kathleen, and Batson, R.M., 1990a, Experimental digital shaded-relief map of California: U.S. Geological Survey Miscellaneous Investigations Series Map I–1848, 2 sheets, scale 1:1,000,000. [Similar maps of Arizona, Nevada, Utah, and Wyoming are published in the same series.]

———1990b, Experimental digital shaded-relief map of Southwestern United States: U.S. Geological Survey Miscellaneous Investigations Series Map I–1850, 2 sheets, scale 1:2,000,000.

Electromagnetic Systems Laboratory, Inc., 1983, Interactive digital image manipulation system, User's Guide, v. 1: Sunnyvale, Calif., variously paged.

Elvhage, Christian, and Lidmar-Bergström, Karna, 1987, Some working hypotheses on the geomorphology of Sweden in the light of a new relief map: Geografiska Annaler, v. 69, ser. A, p. 343–358.

Evans, I.S., 1980, An integrated system of terrain analysis and slope mapping: Zeitschrift für Geomorphologie Supplementband 36, p. 274–295.

Fenneman, N.M., and Johnson, D.W., 1946, Physical divisions of the United States: U.S. Geological Survey, scale 1:7,000,000.

Flint, R.F., 1955, Pleistocene geology of eastern South Dakota: U.S. Geological Survey Professional Paper 262, 173 p.

Gallant, A.L., Whittier, T.R., Larsen, D.P., Omernik, J.M., and Hughes, R.M., 1989, Regionalization as a tool for managing environmental resources: Corvallis, Oreg., U.S. Environmental Protection Agency document EPA/600/3–89/060, 152 p.

Gilman, C.R., 1981, The manual/photomechanical and other methods for relief shading: American Cartographer, v. 8, no. 1, p. 41–53.

Godson, R.H., 1981, Digital terrain map of the United States: U.S. Geological Survey Miscellaneous Investigations Series Map I–1318, scale 1:7,500,000.

Graf, W.L., ed., 1987, Geomorphic systems of North America: Geological Society of America, Centennial Special Volume 2, 643 p.

Greenberg, D.P., 1989, Light reflection models for computer graphics: Science, v. 244, no. 4901, p. 166–173.

Hall, J.K., Schwartz, Eric, and Cleave, R.L.W., 1990, The Israeli DTM (digital terrain map) project, *in* Hanley, J.T., and Merriam, D.F., eds., Microcomputer applications in geology, II: Oxford, Pergamon Press, p. 111–118, plates 1A–1D.

Hammond, E.H., 1964, Classes of land surface form in the forty eight states, U.S.A.: Annals of the Association of American Geographers, v. 54, no. 1, Map Supplement Series no. 4, scale 1:5,000,000. [Adapted version published as Hammond, E.H., 1969, Classes of land-surface form, *in* The National Atlas of the United States of America: U.S. Geological Survey, scale 1:7,500,000, p. 62–63.]

Harrison, R.E., 1969, Shaded relief, *in* The National Atlas of the United States of America: U.S. Geological Survey, scale 1:7,500,000, p. 56–57.

Heirtzler, J.R., ed., 1985, Relief of the surface of the Earth, computer generated shaded relief: Boulder, Colo., U.S. National Oceanic and Atmospheric Administration National Geophysical Data Center Report MGG–2, scale 1:39,000,000.

Horn, B.K.P., 1981, Hill shading and the reflectance map: Proceedings of the Institute of Electrical and Electronics Engineers, v. 69, no. 1, p. 14–47. [Reprinted in Geo-processing, v. 2, no. 1, p. 65–146.]

Howard, K.A., and Larsen, B.R., 1972, Lineaments that are artifacts of lighting, *in* Apollo 15 preliminary science report: Washington, U.S. National Aeronautics and Space Administration Special Publication 289, p. 25–58 to 25–62.

Imhof, Eduard, 1965, Kartographische Geländedarstellung: Berlin, Walter de Gruyter, 425 p. [English translation published as Steward, H.J., ed., 1982, Eduard Imhof, Cartographic relief representation: New York, Walter de Gruyter, 389 p.]

Kehew, A.E., and Lord, M.L., 1986, Origin and large-scale erosional features of glacial-lake spillways in the northern Great Plains: Geological Society of America Bulletin, v. 97, no. 2, p. 162–177.

Kennie, T.J.M., and McLaren, R.A., 1988, Modelling for digital terrain and landscape visualization: Photogrammetric Record, v. 12, no. 72, p. 711–745.

King, P.B., and Beikman, H.M., 1974, Explanatory text to accompany the geologic map of the United States: U.S. Geological Survey Professional Paper 901, 40 p.

Lamb, A.D., Malan, O.G., and Merry, C.L., 1987, Application of image processing techniques to digital elevation models of southern Africa: South African Journal of Science, v. 83, no. 1, p. 43–47.

Mark, R.K., and Aitken, D.S., 1990, Shaded-relief topographic map of San Mateo County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I–1257–K, scale 1:62,500.

Mays, R.R., 1966, Production of numerical maps, *in* Conference—Numerical topographic data and other new map products, Fort Belvoir, Va., May 3–5, 1966, Proceedings: Washington, Department of the Army, Office of the Chief of Engineers, p. 38–41K.

McHarg, I.L., 1969, Design with nature: Garden City, N.Y., Natural History Press, 198 p.

Miller, C.L., and LaFlamme, R.A., 1958, The digital terrain model—theory and application: Photogrammetric Engineering, v. 24, no. 3, p. 433–442.

Moore, J.G., and Mark, R.K., 1986, World slope map: Eos (American Geophysical Union Transactions), v. 67, no. 48, p. 1353, 1360–1362.

Moore, R.F., and Simpson, C.J., 1982, Computer manipulation of a digital terrain model (DTM) of Australia: BMR Journal of Australian Geology and Geophysics, v. 7, no. 3, p. 63–67.

Nathan, Robert, 1966, Digital video-data handling: Pasadena, Calif., Jet Propulsion Laboratory Technical Report no. 32–877. [Also published as Nathan, Robert, 1968, Picture enhancement for the Moon, Mars, and man, *in* Cheng, G.C., Ledley, R.S., Pollock, D.K., and Rosenfeld, Azriel, eds., Pictorial pattern recognition: Washington, Thompson Book Co., p. 239–266.]

National Geographic Society, 1976, Portrait U.S.A. the first color (Landsat) photomosaic of the 48 contiguous United States: Washington, scale 1:4,560,000.

Noma, A.A., 1966, Current AMS computer processing of numerical topo data, *in* Conference—Numerical topographic data and other new map products, Fort Belvoir, Va., May 3–5, 1966, Proceedings: Washington, Department of the Army, Office of the Chief of Engineers, p. 42–48.

Pike, R.J., 1988, The geometric signature: quantifying landslide-terrain types from digital elevation models: Mathematical Geology, v. 20, no. 5, p. 491–511.

Pike, R.J., and Acevedo, William, 1988, Image-processed maps of southern New England topography: Geological Society of America Abstracts with Programs, v. 20, no. 1, p. 62.

Pike, R.J., and Thelin, G.P., 1989, Cartographic analysis of U.S. topography from digital data, *in* Auto-Carto 9, International Symposium on Computer-Assisted Cartography, 9th, Baltimore, April 2–7, 1989, Proceedings: American Society of Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping, p. 631–640.

Raisz, Erwin, 1931, The physiographic method of representing scenery on maps: Geographical Review, v. 21, no. 2, p. 297–304.

———1939, Landforms of the United States, *in* Atwood, W.W., 1940, The physiographic provinces of North America: New York, Blaisdell, scale about 1:4,500,000.

Scholz, D.K., Doescher, S.W., and Hoover, R.A., 1987, Automated generation of shaded relief in aeronautical charts, *in* Cartography: American Society of Photogrammetry and Remote Sensing and American Congress of Surveying and Mapping, Annual Convention, Baltimore, March 29–April 3, 1987, Technical Papers, v. 4, p. 212–219.

Sheldon, Ken, 1987, Probing space by camera, the development of image processing at NASA's Jet Propulsion Laboratory: BYTE, v. 12, no. 3, p. 143–148.

Simkin, Tom, Tilling, R.I., Taggart, J.N., Jones, W.J., and Spall, Henry, 1989, This dynamic planet, world map of volcanoes, earthquakes, and plate tectonics: U.S. Geological Survey, scale 1:30,000,000.

Simpson, R.W., Jachens, R.C., Blakely, R.J., and Saltus, R.W., 1986, A new isostatic residual gravity map of the conterminous United States with a discussion on the significance of isostatic residual anomalies: Journal of Geophysical Research, v. 91, no. B8, p. 8348–8372.

Tesche, T.W., and Bergstrom, R.W., 1978, Use of digital terrain data in meteorological and air quality modeling: Photogrammetric Engineering and Remote Sensing, v. 44, no. 12, p. 1549–1559.

Tobler, W.R., 1969, An analysis of a digitalized surface, *in* Davis, C.M., A study of the land type: Ann Arbor, University of Michigan Department of Geography, Final Report on Contract No. DA–31–124–ARO–D–456 to U.S. Army Research Office, Durham, N.C., p. 59–83.

U.S. Geological Survey, 1986, Production of shaded-relief products: U.S. Geological Survey Yearbook 1986, p. 37–38.

———1990, U.S. satellite view: The National Atlas of the United States of America (separate sheet), scale 1:7,500,000.

Verhoef, J., Roest, W.R., and Srivastava, S.P., 1989, Plate reconstructions and gridded data: Eos (American Geophysical Union Transactions), v. 70, no. 21, p. 609 and 618.

Vieux, B.E., 1991, Geographic information systems and non-point source water quality and quantity modelling, *in* Moore, Ian, ed., Digital terrain modelling in hydrology: Hydrological Processes, v. 5, no. 1, p. 101–113.

Ware, Colin, 1989, Fast hill shading with cast shadows: Computers and Geosciences, v. 15, no. 8, p. 1327–1334.

Weibel, Robert, ed., 1989, Contributions to digital terrain modeling and display: University of Zürich, Department of Geography, Geoprocessing Series, v. 12, 100 p.

Wentworth, C.M., Ellen, S.D., and Mark, R.K., 1987, Improved analysis of regional engineering geology using geographic information systems, *in* v. 2 *of* GIS '87–San Francisco, International Conference, Exhibits, and Workshops on Geographic Information Systems, 2d, San Francisco, October 26–30, 1987, Proceedings: American Society for Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping, p. 636–649.

Whitted, Turner, 1982, Some recent advances in computer graphics: Science, v. 215, no. 4534, p. 767–774.

Wright, J.K., 1942, Map makers are human: comments on the subjective in maps: Geographical Review, v. 32, no. 4, p. 527–544.

Yamaguchi, Yasushi, 1985, Image-scale and look-direction effects on the detectability of lineaments in radar images: Remote Sensing of Environment, v. 17, no. 2, p. 117–127.

Yoeli, Pinhas, 1965, Analytical hill shading (A cartographic experiment): Surveying and Mapping, v. 25, no. 4, p. 573–579.

———1967, The mechanisation of analytical hill shading: Cartographic Journal, v. 4, no. 2, p. 82–88.