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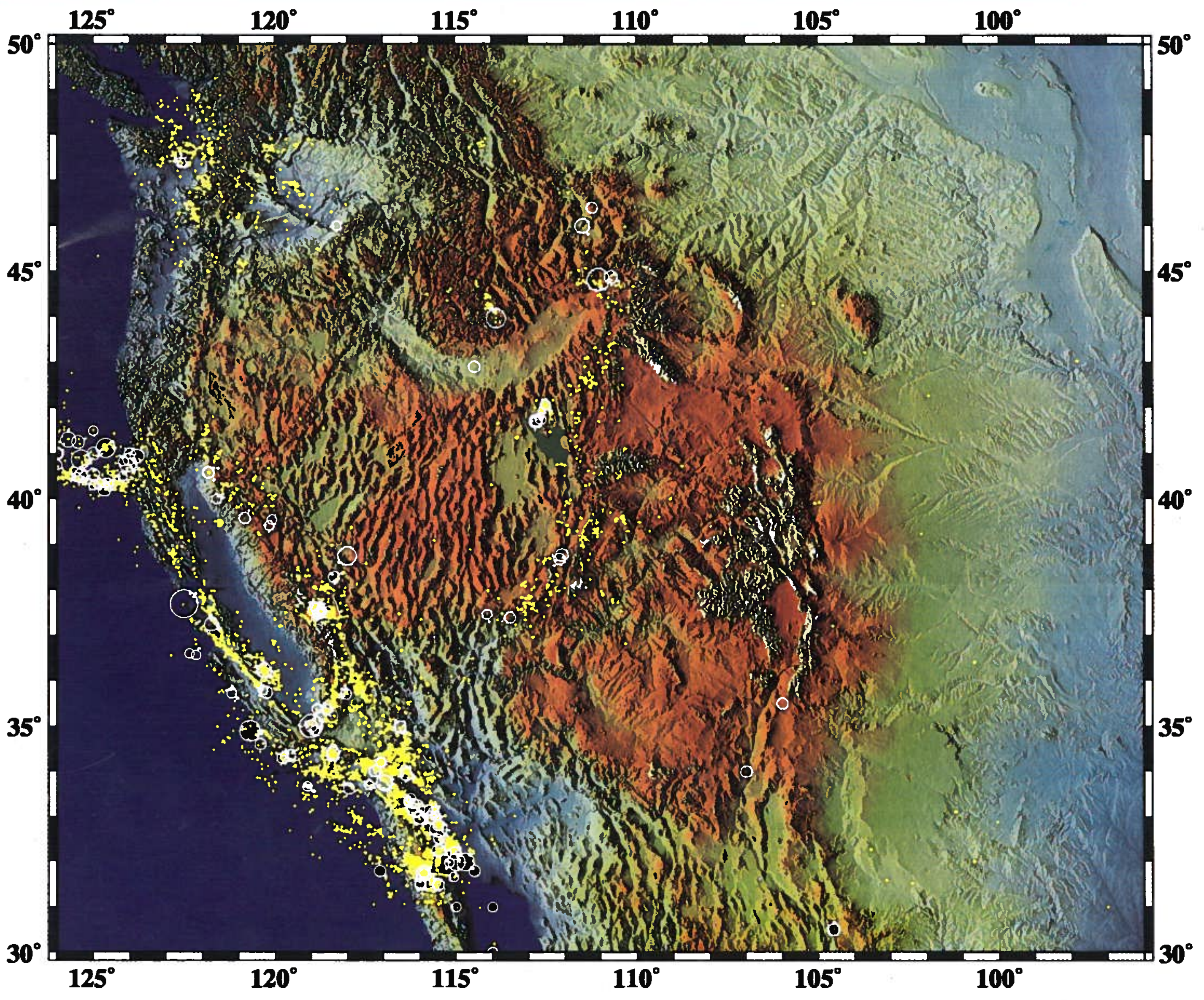

Figure 1. Topography and seismicity of the western United States. Shading mimics illumination from the west. Open white circles, with size scaled to magnitude, are 118 large earthquakes with magnitude greater than 6, 1900–1975. Yellow dots are 1807 earthquakes of magnitude greater than 2.5, 1970–1985. Epicentral data are from the Decade of North American Geology (DNAG) catalog of Engdahl and Rinehart (1989).

Tectonics and Topography of the Western United States—An Application of Digital Mapping

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ABSTRACT

The most evident expression of the tectonic processes that have shaped Earth is the topography of its surface. From global divisions between continents and oceans to regional divisions between mountains and plains to subtle offsets in landscape that reflect fault motion, topographic data are rich in geological information. Maps created from digital topographic data can be manipulated to maximize the geologic information inherent in such data. Such maps can be used for tectonic interpretations over a range of scales. Features stand out or are subdued depending upon their orientation with respect to the illumination direction in digitally produced relief maps. At a regional scale, the topography of individual provinces of the western United States reflects their tectonic histories, such as the extensional faulting of the Basin and Range province or the limits of Mesozoic thrusting. At a more local scale, the topography of the northeastern Basin and Range province shows a close correlation with patterns of historic faulting. Finally, digital topographic analysis can be used to assess tectonics on the scale of individual mountain ranges, such as the Wasatch Range of central Utah.

INTRODUCTION

The ancient art of map making is being revolutionized by the increasing variety and quality of digital data describing Earth's surface and by the availability of computer software and hardware capable of handling the resulting large volumes of high-resolution data. All of the traditional components of maps—topography, outlines of lakes and rivers, locations of cities, roads, and other cultural features—are becoming available in digital form. Various geological and geophysical data are also being converted into digital form from existing maps or are being collected by digital means. The advent of Earth-looking satellites such as Landsat and SPOT, weather satellites, and special missions of the Space Shuttle are providing new synoptic views of Earth. Taken alone, these new data are fundamentally valuable, but combined with the ease of manipulation of digital data on computers and with the ability to incorporate data from diverse sources to create new maps, they become revolutionary. From the higher density and accuracy of digital data, new perspectives can be obtained. Our study of the topography of the western United States demonstrates these capabilities.

The amount of detail that a topographic map can portray depends on the density of the measurements available. Global elevation coverage is available in 5 minute (approximately 10 km) averages of topography and bathymetry from the National Oceanic and Atmospheric Administration's (NOAA) DBDB5 data set. Complete coverage of the United States (derived from the contour information on existing 1:250,000 topographic maps) is available at point spacing of 30 arc seconds (approximately 1 km). The U.S. Geological Survey National Cartographic Information Service currently provides detailed coverage, at point spacing of 30 m, for selected areas and plans to cover the entire United States at this resolution.

The shaded relief maps of Pike and Thelin (1989), Thelin and Pike (1991), and Pike (1991) spectacularly demonstrate that moderate-scale topographic data can resolve continental scale variations in topographic fabric. Here we present a color version of a similar map for the western United States (Fig. 1) and show how the topographic data can be combined with other types of data in tectonic studies.

Map Preparation

We have selected digital elevation data from the Geophysics of North America CD-ROM compilation, distributed by NOAA. The processing of the data is a simplified version of that carried out by Pike and Thelin (1989). The original data, equally spaced in latitude and longitude, are re-sampled on a rectangular grid with the east-west direction compressed by the cosine of the average map latitude. This produces a map projection similar to Mercator, but considerably simpler to execute. The shaded relief effect is produced by determining the west-to-east gradient in the topography using a simple difference operator. The elevation and gradient information are combined using color to represent absolute elevation and intensity to represent the gradient. The color scheme designates blue at sea level, ranges up to green and orange, and finally attains white at the highest elevation. Each primary component of color (red, green, and blue) for each point is then multiplied by a value corresponding to the gradient at that

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Editor's Note:

In March 1991, we published a science article that was a first report of the results of the Magellan Venus orbiter, which has been sending back images of Earth's neighbor since September 1990. At this time, Magellan is on its third complete coverage of the Venusian surface. As a result of this successful and exciting space mission, we have a comprehensive view of almost the entire surface of Venus. Paradoxically, therefore, we have a much better view of Venus's solid surface than we do of Earth's. There are two reasons for this state of affairs: One is that most of Earth's surface is covered by water, which is even harder to see through than the clouds that surround Venus. The other is that the amount of money spent on the Magellan mission vastly exceeds the amount ever spent on imaging, high or low tech, Earth's surface. Efforts are underway, however, to provide remote sensing images of Earth's surface that compare in quality and coverage with those of the Magellan radar images of Venus. The article by Richard Pike in November 1991 *GSA Today* was an example of this kind of approach, using digital topography (in that case of the conterminous United States). The article in this issue, by Simpson and Anders, is a complementary approach to the use of such imaging for geologic analysis of a specific region. We will publish others in the future.

—*Eldridge Moores*

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point. We use a full 24-bit representation of the color to produce a smooth modulation with height and gradient. Points (earthquake epicenters), vectors (faults), and annotation are laid over the topographic raster, using the techniques described by Wessel and Smith (1991) and Davis (1990) and additional software developed at Lamont-Doherty Geological Observatory. The final figures are printed on a high-resolution (300 dot per inch, 24-bit color) ink-jet plotter (IRIS Graphics Model 3024).

As pointed out by Pike (1991), the gradient calculation (or sun angle illumination) accentuates features with a strong grain transverse to the direction of the gradient and subdues those parallel to it. This can distort the significance of directional features and must be chosen carefully. In Figure 2, we show gradient maps whose illumination directions vary by 45°. Broad areas with strong structural grain and high relative relief, such as the Basin and Range province, retain the same general appearance under all illuminations. Narrow linear features, such as the San Andreas fault system, stand out clearly in transverse illumination, but are much less obvious when the illumination is along strike. In areas of moderate relief with less obvious lineation (the Snake River Plain, Columbia Plateau, northwestern Basin and Range province, and eastern Montana), texture and the apparent orientation of grain can substantially change with illumination direction.

The earthquake data used in Figures 1 and 4 are from the compilation of Engdahl and Rinehart (1989) prepared for the Geological Society of America's Decade of North American Geology. For this compilation, epicenters from a variety of historical and instrumental catalogs were combined to provide relatively uniform coverage over the United States. Larger earthquakes from historical and recent catalogs indicate areas of major seismicity, whereas lower magnitude seismicity, from regional networks operating over the past 15 years, shows more clearly the details of spatial trends in activity.

The color map (Fig. 1) provides the absolute elevation information missing in gray-shade digital relief maps or satellite images. It also provides a basis for comparing elevation of widely separated regions—for example, the relative elevations of the Sierra Nevada and the Rockies or the Great Plains. Subtle regional changes in elevation such as the gradual eastward increase in elevation in the eastern Snake River Plain can also be easily discerned. Moreover, regional elevation patterns of tectonic origin become evident, such as the dramatic steplike drop in elevation from the northern Basin and Range province to the region between the Colorado Plateau and the southern Sierra Nevada (including the region labeled "Mojave Desert" in Fig. 2) which then drops in mean elevation to the southern Basin and Range south of lat 34° N.

All of the above topographic features are observable on conventional topographic maps, but detailed digital maps provide a clarity that previously was available only on satellite images; at the same time, they provide important relative elevation information. Furthermore, these topographic features can be quantitatively compared by generating digital elevation profiles across any of these regions, as is shown in Figure 3. Average elevation of one of these regions or average elevation along a strip can be determined in order to compare one region to another.

Topography and the Tectonic History of the Western United States

The western United States is part of an orogenic belt that has undergone significant tectonism from the latest Proterozoic through the Phanerozoic. During the late Proterozoic and Early Cambrian the western margin of North America underwent continental-scale rifting associated with development of a passive margin (Stewart, 1972; Bond and Kominz, 1984; Levy and Christie-Blick, 1991). From the middle Paleozoic to the Eocene, the western United States underwent a series of tectonic shortening events that increased both its areal extent and its thickness (Burchfiel and Davis, 1975; Oldow et al., 1989; Levy and Christie-Blick, 1989). Continental landmass was increased by the addition of exotic terranes (Coney et al., 1980), and regional crust was thickened by the emplacement of east-directed thrust sheets. Following the cessation of shortening in the Eocene, extensional tectonism has dominated in the central and southern parts of the western United States, and strike-slip tectonism has dominated along the southwestern margin of the continent. Throughout the Phanerozoic, magmatism has contributed significant volumes of material to large areas of the western United States. Magmatism has varied in composition and in temporal and spatial patterns of emplacement. The tectonic history of shortening, extension, and magmatism has left an indelible mark that can be easily identified by their physiographic expressions.

A notable aspect of the physiography of this orogenic belt is the close correspondence between high mean elevation and the limits of thrusting. This correspondence is best illustrated in the northeast part of Figure 1 by the sharp drop in elevation along the eastern boundary of the Rocky Mountains, where the elevated rocks of the Idaho-Montana thrust belt form a precipitous contact with the unfaulted lower-lying sediments of the western Great Plains. Although the mean elevation of the western United States was most certainly increased during the shortening event, the subsequent extension has reduced the elevation. Currently, broad patterns in mean topography are supported by buoyancy forces, which vary from one region to another, depending on the relative thickness of the lithosphere (Eaton et al., 1978; Eaton, 1982). The relative heights of many of the highest mountain ranges (white in Fig. 1) are caused by a complex interaction between changes in lithospheric buoyancy, erosion, magmatism, and lithospheric rigidity.

The Basin and Range province provides one of the best examples of the effects of a complex tectonic history on topography. Within this province there are many north-trending fault blocks that are bounded by Tertiary high-angle normal faults, many of which have been active during the Quaternary. Generally, the pattern of magmatism and extension began in the Eocene in the south-central Canadian Rockies, western Montana, and central Idaho and migrated down the central region of the northern Basin and Range now defined by the topographic high between lows once occupied by Pleistocene Lakes Lahonton and Bonneville (Cross and Pilger, 1978; Wernicke, 1992). From the Oligocene to the present, within the northern Basin and Range there has been an outward migration of magmatism and extension whose limit is

Tectonics *continued on p. 120*

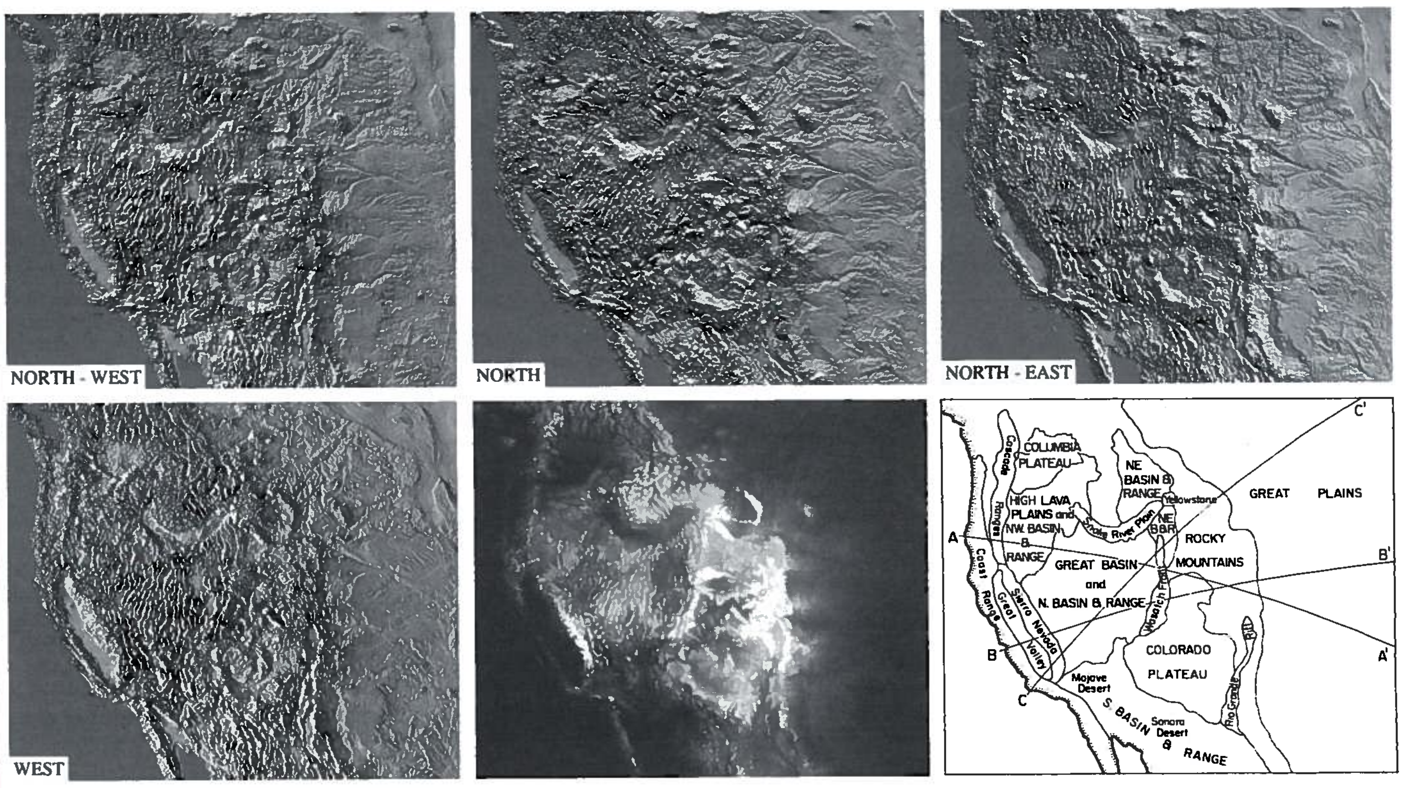

Figure 2. Gradient maps for the western United States, with illumination from different compass directions (lower left panel and top left, center, and right panels). Gray-scale map of the topography of the western United States (lower center panel). Figure 1 was created by combining a colored version of this map with the gradient map in the lower left panel. Major physiographic features of the western United States are shown in lower right panel. Lines A-A', B-B', and C-C' indicate the profiles used for the cross sections of topography shown in Figure 3.

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marked by the Quaternary volcanism as well as by the pattern of historic seismicity (Fig. 1) on its eastern and western margins (Armstrong et al., 1969; Christiansen and McKee, 1978). Coeval with the southward migration in the northern Basin and Range, magmatism and extension in the southern Basin and Range province migrated north. Both trends converged in what is called the central Basin and Range province (between lat 37° and 34°N) in the middle Miocene (Axen, 1991; Wernicke, 1992). From the late Miocene to the present, extension in many parts of the Basin and Range province has been accommodated on high-angle faults and the concomitant tilted blocks that form a pattern on topographic maps resembling "snakes slithering south." This northerly trend reflects a shift to a roughly east-west extension direction in the middle Miocene from the previous southwest-northeast extension direction (Eaton et al., 1978; Wernicke, 1992), although local variability in extension direction existed throughout the Basin and Range province during the Cenozoic.

Tectonic Analyses Using Digital Maps: Northeastern Basin and Range Province

The northeastern Basin and Range province underwent significant northeast-directed thrusting from the Jurassic to the early Eocene. Subsequently, it has experienced several extension events. These include extension directed east-west to northwest-southeast from the early Eocene to the Oligocene in its western part (Hait, 1984; Wust, 1986; Janecke, 1991). Overprinting some of the earlier events are the Miocene-to-present high-angle normal faults that include areas to the east unaffected by the earlier Tertiary events. These younger faults are clearly seen as the north- to northwest-trending mountain ranges in Figure 4.

Prominent in Figure 1 is a northeast-trending topographic depression oriented perpendicular to the mountain ranges within the northeastern Basin and Range. This feature, the eastern Snake River Plain, is underlain by several kilometres of rhyolitic volcanic rocks interbedded by sediments that are capped by 1–3 km of basalt. Intruded within the crust are another 5–10 km of basaltic material. As discussed by Armstrong et al. (1975), a succession of rhyolitic volcanic eruptions followed by basaltic eruptions has migrated to the northeast across the entire length of the eastern Snake River Plain during the past 17 m.y. Morgan (1972), Smith and Sbar (1974), and Suppe et al. (1975) have suggested that the Snake River Plain is the track of a hotspot that lies beneath the Yellowstone Plateau (the region northeast of the Snake River Plain that is dominated by earthquake epicenters in Figs. 1 and 4). Seismicity in the circum-eastern Snake River Plain forms a pattern that is symmetric about the track of the migrating Yellowstone hotspot. This shape has variously been defined as an "arc" (Myers and Hamilton; 1964), a "V" (Scott et al., 1985; Smith et al., 1985), and a "parabola" (Anders et al., 1989). Although surrounded by intense seismic activity, the eastern Snake River Plain, as well as some of the mountainous areas adjacent to the plain, is a region of tectonic quiescence called a "collapse shadow" (Anders and Geissman, 1983). The quiescence has been attributed to mechanical strengthening by magmatic intrusion (Anders et al., 1989) and/or by overpressuring from magmatic intrusion (Parsons and Thompson, 1991).

Figure 4 shows the pattern of historic seismicity and major late Cenozoic normal faults superimposed upon the relief map of the northeastern Basin and Range province. It can be clearly seen that the distribution of historic and latest Quaternary faulting mimics the symmetric pattern of seismicity about the axis of the eastern Snake River Plain. Furthermore, there is a close correlation between high peaks and historic and latest Quaternary faulting (red and purple). This close correspondence between elevation and the age of faulting suggests a mechanistic link between normal faulting and topography. As we discuss below, elevation patterns can provide important clues about the growth and development of normal faults like the ones found in the northeastern Basin and Range province.

Tectonic Analyses Using Digital Topographic Data: Normal-Fault Segmentation

Many of the higher mountain ranges within and bordering the Basin and Range province are associated with high-angle normal faults. As first discussed by Vening Meinesz (1950), normal faulting results in isostatic-elastic footwall uplift. Mountain-building associated with normal faulting produces a distinctive topographic pattern that is easily identified. Faulting-induced uplift results in a characteristic wedge-shaped profile evidenced in the physiography of several mountain ranges in the western United States (Figs. 1 and 3). Good examples of this type of topographic expression are the Sierra Nevada along the western boundary of the Basin and Range province and the Wasatch Range along the eastern boundary. The Sierra Nevada is bounded on the east by a steep escarpment formed by displacement on the Owens Valley fault and on the west by a gently dipping slope that grades into the Great Valley of California. The shape of the Sierra Nevada and the close timing between the start of faulting (3–6 Ma; Bacon et al., 1982) and the start of the bulk of uplift (about 5 Ma; Unruh, 1991) suggest isostatic-elastic uplift; however, this interpretation is controversial. Others have suggested that uplift is caused by low-angle normal faulting (Jones, 1987), by tectonic release of a suppressed buoyant root (Chase and Wallace, 1988), or sinking of the upper mantle via a mantle "drip" (Humphreys, 1987).

The pattern of footwall uplift is more clearly demonstrated on fault blocks having a shorter flexural wave length than that of the Sierra Nevada. The Wasatch Range, which bounds the eastern side of the northern Basin and Range province along a steep 300-km-long west-dipping fault escarpment, exemplifies such a shorter wavelength wedge-shaped feature. The eastern slope dips gently to the east, merging with the Colorado Plateau, and the western slope dips steeply westward and is bounded by the Wasatch fault. As suggested by Zandt and Owens (1980), the topographic profile of the Wasatch Range is consistent with isostatic-elastic footwall uplift.

If isostatic-elastic uplift is proportional to fault displacement, as suggested by Vening Meinesz (1950), then the displacement history of a normal fault can be read by the elevation patterns of the adjacent mountain ranges. Of course, removal of material by erosion degrades the profile, thus making the technique more useful for estimating fault displacement for geologically recent uplifts. Older footwall uplifts, like those associated with the Triassic border faults of the Atlantic margin, are not as useful in assessing displacement, because they have been significantly eroded. Many younger normal faults, typically less than 10–15 m.y., that bound mountain ranges within the Basin and Range province are pristine enough to be used to estimate the fault displacement history. Examples of relatively young uplifts are the Sierra Nevada, postdating about 5 Ma, and the Wasatch Range, younger than about

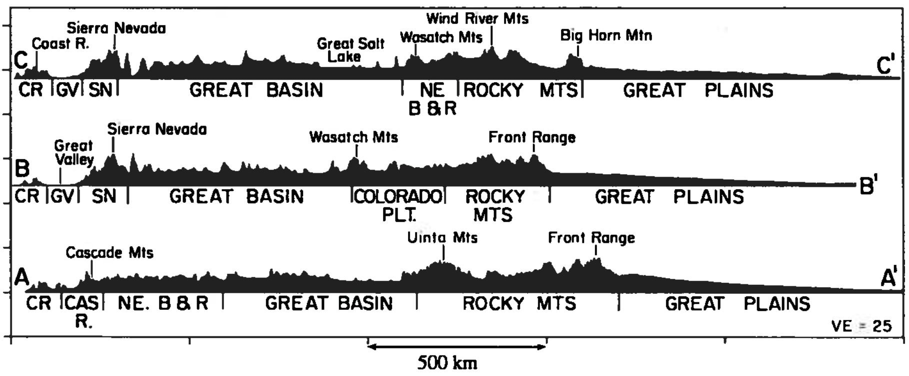

Figure 3. Cross sections of topography for the profiles shown in Figure 2 lower right panel. Major physiographic provinces are indicated. Profiles are plotted with a vertical exaggeration of 25:1.

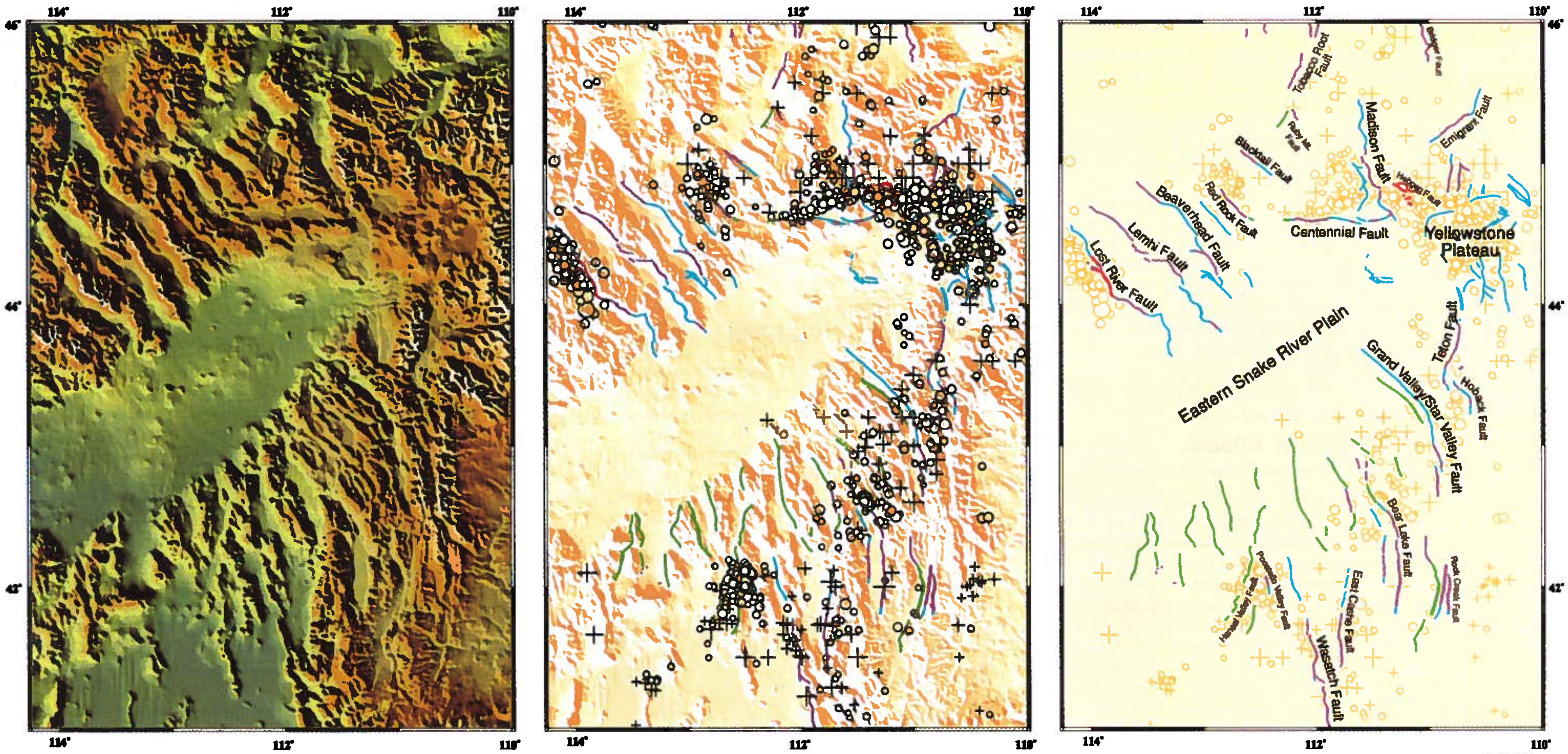

Figure 4. Left: Topographic map of the northeastern Basin and Range province. Center: Seismicity and faulting in the northeastern Basin and Range province, superimposed on a map of the topographic gradient. Right: Earthquake epicenters for historical earthquakes are shown as crosses, recent earthquakes as circles. Earthquake data are from the DNAG compilation, most of the recent seismicity in this area being reported by the University of Utah seismographic network. Faults are color-coded by age: red for historical ruptures, purple for latest Quaternary (<15 ka), light blue for Quaternary, and green for late Cenozoic (roughly later than middle Miocene).

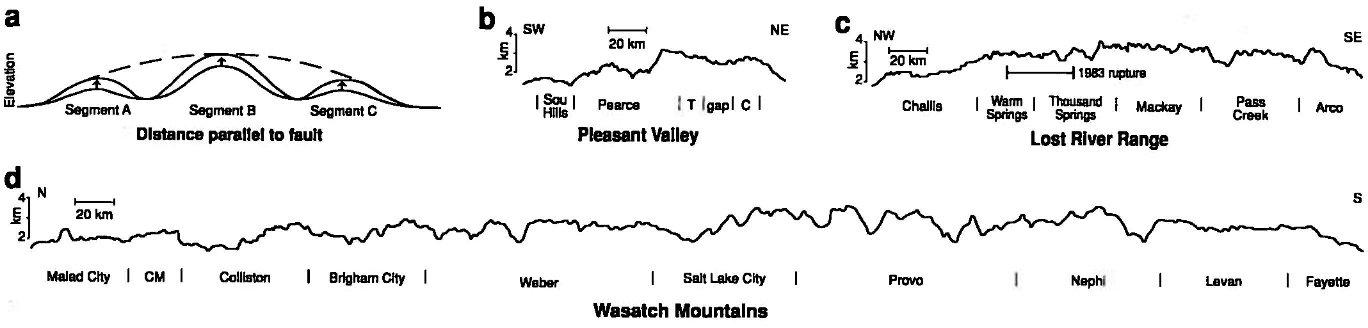

Figure 5. Four normal-fault footwall elevation profiles. a: Hypothetical elevation profiles show a single-humped profile (dashed line) and multi-humped elevation profiles assuming the rupturing is pinned at segment boundaries. b, c, and d: Profiles of the highest elevation across a 5 km swath parallel to their respective faults. Vertical lines are segment boundaries separating named rupture segments (Wallace, 1984; Haller, 1990; Machette et al., 1991). Vertical exaggeration is 5:1.

17 Ma. Within the northeastern Basin and Range province prior to 4 Ma the Teton and Centennial Ranges (Fig. 4) had little or no relief and have since been tilted 10° to 15°, forming a topographic profile as predicted by isostatic-elastic footwall uplift. As insightfully noted by G. K. Gilbert (1884), long-term normal-fault rupture patterns should be reflected by the elevation patterns of the associated range fronts. Using footwall elevation data along the Wasatch Range, Schwartz and Coppersmith (1984) have suggested that rupture segments pinned at end-points over several earthquake cycles will produce multi-humped range-front elevation patterns (Fig. 5a solid lines; exaggerated for emphasis). If, on the other hand, segment boundaries are not pinned, but rather are transitory features, then the overall elevation pattern will reflect a single hump, as first suggested by Vening Meinesz for uplift associated with the east African rift valleys.

Cowie and Scholz (1992) have suggested that fault growth is controlled by the fracture strength of rocks at the leading edges or ends of the fault, causing faults to have a characteristic aspect ratio of length to displacement for a given tectonic environment. Their fault-growth model predicts a single-humped footwall elevation profile caused by outward growth of a fault from a single nucleation point. The ability to construct digital topographic profiles and to average elevation along these profiles permits one to test the single-hump vs. the multi-humped model of footwall growth (see Fig. 5a). Parts b, c, and d in Figure 5 show elevation profiles of several range fronts that bound active normal faults in the Basin and Range province. By qualitative inspection, these segment boundaries (vertical lines in Fig. 5), defined by neotectonic studies, show little or no correlation with expected range-front elevation lows. Using digital topography, we can perform a more quantitative test between multi-humped and single-humped fault-bounded range fronts. The test of multi-humped vs. single-humped elevation profiles assumes a downward slope between segment mid-points and segment ends for multi-humped profiles and assumes that the segment mid-points to end-points slope will most commonly be upward for a single-hump profile. This test was performed on 25 segment boundaries on faults in Utah, Idaho, and Nevada. The results (Fig. 6) show a positive regression slope with 65% of elevation intercepts being positive, which suggests a gross single-humped architecture. Since a positive slope indicates a single-humped profile, segment boundaries are not likely to be fixed features over a long enough geologic time to establish differential range-front uplift. The length of time necessary to cause observable differential uplift is not known well, but at present coseismic rates of offset of active faults in the Basin and Range province (about 1 mm/yr), this could be on the order of 1 to 2 m.y., assuming there is half a kilometre sensitivity in differential elevation. Resolution below 1 m.y. is lost in the significant scatter in the data in Figure 6. The scatter is likely due to erosion and the effects of normalizing short (<10 km) fault segments.

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Note: Full-resolution copies of the maps and profiles in Figures 1, 2, 3, and 4 are available for purchase through the Office of the Director, Lamont-Doherty Geological Observatory, Palisades, NY 10964.

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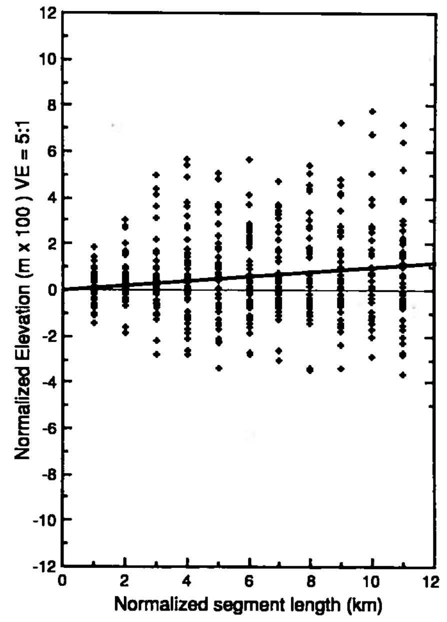

Figure 6. A compilation of normalized elevations between segment ends and midpoints. Slope data to the right of midpoints are inverted so that the sign of respective segments is the same. The regression is fixed at the origin and has a slope of 9.2×10^{-2}.

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