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Neogene Uplift and Radial Collapse of the Colorado Plateau—Regional Implications of Gravity and Aeromagnetic Data

By H. Richard Blank, William C. Butler, *and* Richard W. Saltus

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ABSTRACT

Residual isostatic gravity and aeromagnetic total-intensity maps of a 5°x10° region centered on the northern Colorado Plateau reveal a first-order correlation of basement anomalies with structural (topographic) relief on the surface of Precambrian crystalline basement over the plateau's interior. Anomaly trends reflect a mosaic of generally northeast and northwest striking basement features. A pattern of arcuate structures peripheral to the plateau is interpreted as a manifestation of radial outward tectonic extension superposed on Laramide structures and the mainly westerly to southwesterly extension of neighboring provinces. The radial component may be attributable to gravitational collapse concomitant with mainly Neogene regional uplift. An earlier mid-Tertiary plateau uplift of lesser amount, accompanied by voluminous peripheral magmatism, was probably related to Laramide subduction, but Neogene activity is believed to be a consequence of the rise and lateral spreading of anomalously hot, low-density upper-mantle asthenosphere that is the source of long-wavelength topographic, geoidal, and Bouguer gravity anomalies of the U.S. western interior. This relatively stationary mantle feature, perhaps indirectly a product of several hundred million years of east-dipping subduction, is also the cause of the Yellowstone hotspot and the Alvarado Ridge of Colorado and New Mexico.

INTRODUCTION

Geophysical investigations of the Colorado Plateau and its margins have utilized data from seismic reflection and refraction profiles, earthquake traveltime studies, heat-flow measurements, paleomagnetic studies, in situ stress measurements, and regional stress analysis based on structural data, magnetotelluric soundings, and reconnaissance potential-field surveys. Results of most work prior to about 1978 have been discussed by Thompson and Zoback (1979), and comprehensive overviews of more recent work can be found in a series of papers on the geophysical framework of the conterminous United States (Pakiser and Mooney, 1989). In this report we consider mainly the residual isostatic gravity and aeromagnetic total-intensity anomaly fields plotted from data of the North American Data Set (available from the National Geophysical Data Center (NGDC), Boulder, Colo.) for the northern Colorado Plateau and parts of adjacent provinces in Colorado, Utah, Nevada, Arizona, and New Mexico (roughly an area bounded by long 105°–115° W. and lat 36°–41° N.). First we describe the residual fields and comment on some of the most prominent anomalies. We compare plateau basement anomalies with known structural (topographic) relief on the surface of the Precambrian (Butler, 1991), searching for indications of deep-seated influences on the disposition of Tertiary laccolithic centers. Next we examine anomaly trends both on the plateau and in surrounding regions. Finally, we remark on the possible significance of these trends with respect to the tectonic evolution of the region and mid- to late-Cenozoic magmatism.

For geologic interpretation of the potential-field data we used State geologic maps published at scales of 1:500,000 (Wilson and others, 1969; Stewart and Carlson, 1978; Tweto, 1979a; Hintze, 1980) and 1:1,000,000 (Hintze, 1975; Stewart and Carlson, 1977; New Mexico Geological Society, 1982; Tweto, 1987; Reynolds, 1988; Western Geographics/Colorado Geological Survey, 1991; Western Geographics/Geological Survey of Wyoming, 1991), as well as regional geophysical maps at these scales (Sauck and Sumner, 1970a, b; Zietz and Kirby, 1972a, b; Aiken, 1975; Zietz and others, 1976, 1977; Cordell and others, 1982; Cordell, 1984; Keller and Cordell, 1984; Saltus, 1988; Hildenbrand and Kucks, 1988; Cook and others, 1989; Abrams, 1993). These included maps of the Bouguer and isostatic gravity anomalies, aeromagnetic total-intensity anomaly, aeromagnetic anomaly reduced to pole, and selected derivatives of these parameters. Smaller scale maps that were used include (1) wavelength filtered gravity maps of Hildenbrand and others (1982) and Kane and Godson (1989); (2) a wavelength terrain map of Kane and Godson (1989); and (3) basement and tectonic compilations of Bayley and Muehlberger (1968), Bayer (1983), Muehlberger (1992), and Reed (1993). Reed's (1993) basement compilation is also overprinted on isostatic residual gravity and magnetic anomaly maps of the conterminous United States (Jachens and others, 1993, and Committee for the Magnetic Anomaly Map of North America, 1993, respectively).

ACKNOWLEDGMENTS

We are indebted to Viki Bankey, Tien Grauch, and Gerda Abrams for providing preliminary copies of their current regional compilations, and to Viki Bankey, Curtis Huffman, Peter Rowley, and Dwight Schmidt for provocative reviews that encouraged us to look beyond immediate sources of anomalies and investigate more fully their tectonic and magmatic implications. An editorial review by Peter L. Martin considerably improved the manuscript.

GRAVITY FIELD

Residual isostatic gravity anomalies for the study area are shown on the color-contour map of figure 1A. This map is based on an Airy-Heiskanen isostatic model that uses a crustal thickness of 35 km, a topographic load density of 2.67 g/cm^3, and a density contrast across the isostatic root of 0.35 g/cm^3 (Simpson and others, 1986), computed at a grid interval of 4 km. This figure for crustal thickness is probably low, considering the average thickness of 40–45 km determined from long-range seismic refraction profiles (Prodehl and Lipman, 1989) and the 50- to 52-km average derived from COCORP deep reflection data (Hauser and Lundy, 1989). However, the residual anomalies over the plateau are only weakly model-dependent, so as a matter of expediency we did not recompute using the larger figure. On the other hand, the data supplied at 4-km grid spacing were regridded at 2 km to improve the visual effect of the contoured product. The map projection used for this and for figures 1*B*, 2*A*, and 2*B* is Albers Conical Equal Area, with standard parallels of 29.5° N. and 45.5° N.

The anomaly field as rendered in figure 1*A*, with a color interval of 5 mGal, emphasizes only the most strongly positive (yellow and red) and most strongly negative (dark blue and purple) areas; anomalies with amplitudes in the range –25 to about +10 mGal are much less conspicuous, although perhaps no less significant.

Figure 1*B* shows loci of maximum horizontal anomaly gradients computed from data of figure 1*A*, using software developed by Blakely and Simpson (1986). The gradient maxima approximately coincide with surface projections of steep upper-crustal density discontinuities. Notably strong gradients are distinguished in the figure by hachures on the side of lower anomaly values. This figure also provides selected geologic and geographic information, as explained in table 1. The thick dashed line on the figure is the outline of the northern plateau according to Bayer (1983).

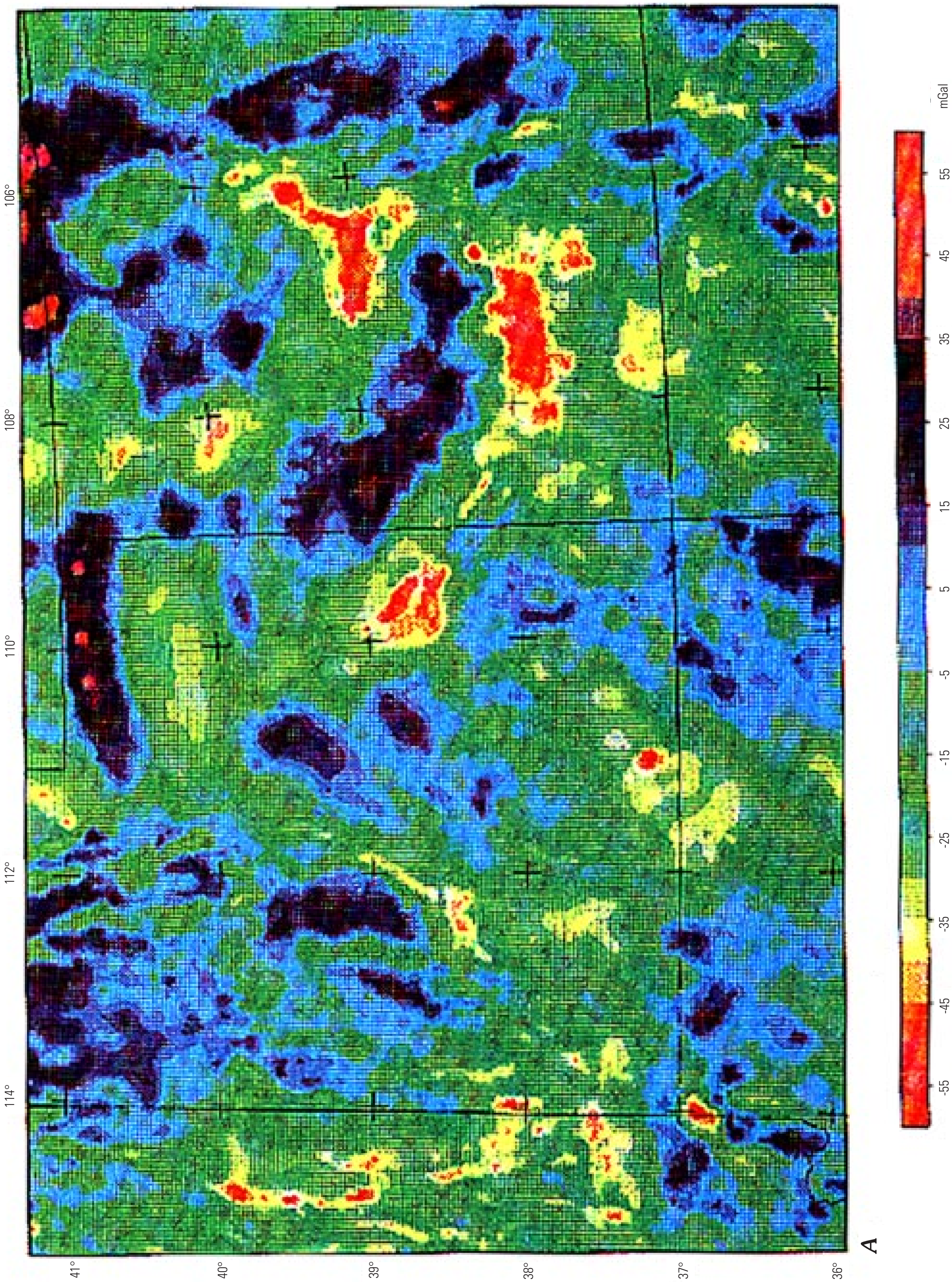
As expected, broad anomaly lows mark the principal sedimentary basins of the northern Colorado Plateau—the Uinta (UB), Piceance Creek (PB), Paradox (PXB), San Juan (SJB), and Kaiparowits (KB) Basins (fig. 1*A*). The lows are caused by thick, relatively low density sedimentary sections above structural depressions in the basement. Major basins peripheral to the plateau, including the North Park (NP), Salt Wash (SWB), Washakie (WB), and Bear River (BRB) Basins, and basins of the Virgin River depression (VRD), also have associated gravity lows, presumably of similar origin. However, two of the largest negative anomalies, both in breadth and amplitude, are not over depositional basins but over mid-Tertiary volcanic fields—the San Juan field (SJV) and the West Elk and Thirtynine Mile fields (WEV and 39MV). These lows are at least in part due to penecontemporaneous granitoid batholiths in the substrate—the roots of the volcanic systems. To an unknown extent, the lows probably also reflect the presence of intrusions of Laramide and Proterozoic age (Steven, 1975; also see Case, 1965; Plouff and Pakiser, 1972; Tweto and Case, 1972). The lows correspond closely to Phanerozoic “perforations” of the Precambrian basement as inferred by Tweto (1987). Prominent lows in the upper Sevier River basin region (USB), and in the Caliente (CCC), Indian Peak (IPCC), and Marysvale (MV) volcanic centers of the Pioche-Marysvale belt in southeastern Nevada and southwestern Utah (see Rowley and others, this volume) are probably also caused in part by concealed intrusives of mid-Tertiary age.

Areas of exposed Precambrian rock generally coincide with gravity highs. However, Precambrian rocks that crop out along the southwest front of the Uncompahgre uplift (UU) typically coincide with relative gravity lows, because of the low-angle contact between overthrust crystalline rock and low-density sedimentary rock of the Paradox Basin (PXB). (For seismic evidence of this relationship see Frahme and Vaughn, 1983.) Gravity is also relatively low in the Needle Mountains (NM) of southwestern Colorado and in much of the Front Range (FR) and Rampart Range (RR). Anomalously low gravity values in Precambrian crystalline terrane may reflect a predominance of silicic intrusive or metaclastic rock in the section. Where the exposed Precambrian section consists of sedimentary rocks yet is associated with an isostatic anomaly high, as in the Uinta Mountains (UM) and in the Canyon Mountains (CYM) of the eastern Great Basin, the residual isostatic high can be attributed to undercompensation of the range (regional rather than local compensation) or to a mean density of topography in excess of the reduction density (2.67 g/cm^3).

AEROMAGNETIC FIELD

A map of the anomalous aeromagnetic total-intensity field of the region is shown in figure 2*A*. Data are from the North American compilation (Committee for the Magnetic Anomaly Map of North America, 1987) and were supplied as Definitive Geomagnetic Reference Field (DGRF) residuals at a 2-km grid interval and subsequently reduced to the north geomagnetic pole with the assumption of magnetization parallel to the inducing field. It is conceivable that some anomalies that appear on the map are strictly artifacts, the result of errors introduced during digitization of analog records (most data were obtained from surveys performed in the 50’s and 60’s), for example, or during the manual merging of data from blocks flown at different times with different specifications, which can produce spurious anomalies of any spatial wavelength. Also, anomalies with short

Figure 1 (following pages). Isostatic residual gravity features of the northern Colorado Plateau and vicinity. *A* (facing page, above), Anomaly map. Color interval 5 milligals. Reductions based on Airy-Heiskanen model using the following parameters: crustal density ($\Delta\rho$) (topography) = 2.67 g/cm^3, density contrast ($\Delta\rho$) (crust/upper mantle) = 0.35 g/cm^3; crustal thickness (T) = 35 km (Simpson and others, 1986). Data from Geophysical Data Center, National Oceanic and Atmospheric Administration, Boulder, CO (North American Data Set, 4-km grid, regridded at 2 km). *B*, Loci of maximum horizontal gradients computed from isostatic residual gravity anomaly data of *A*. Teeth point in direction of lower anomaly values where gradients are strong. Symbols explained in table 1.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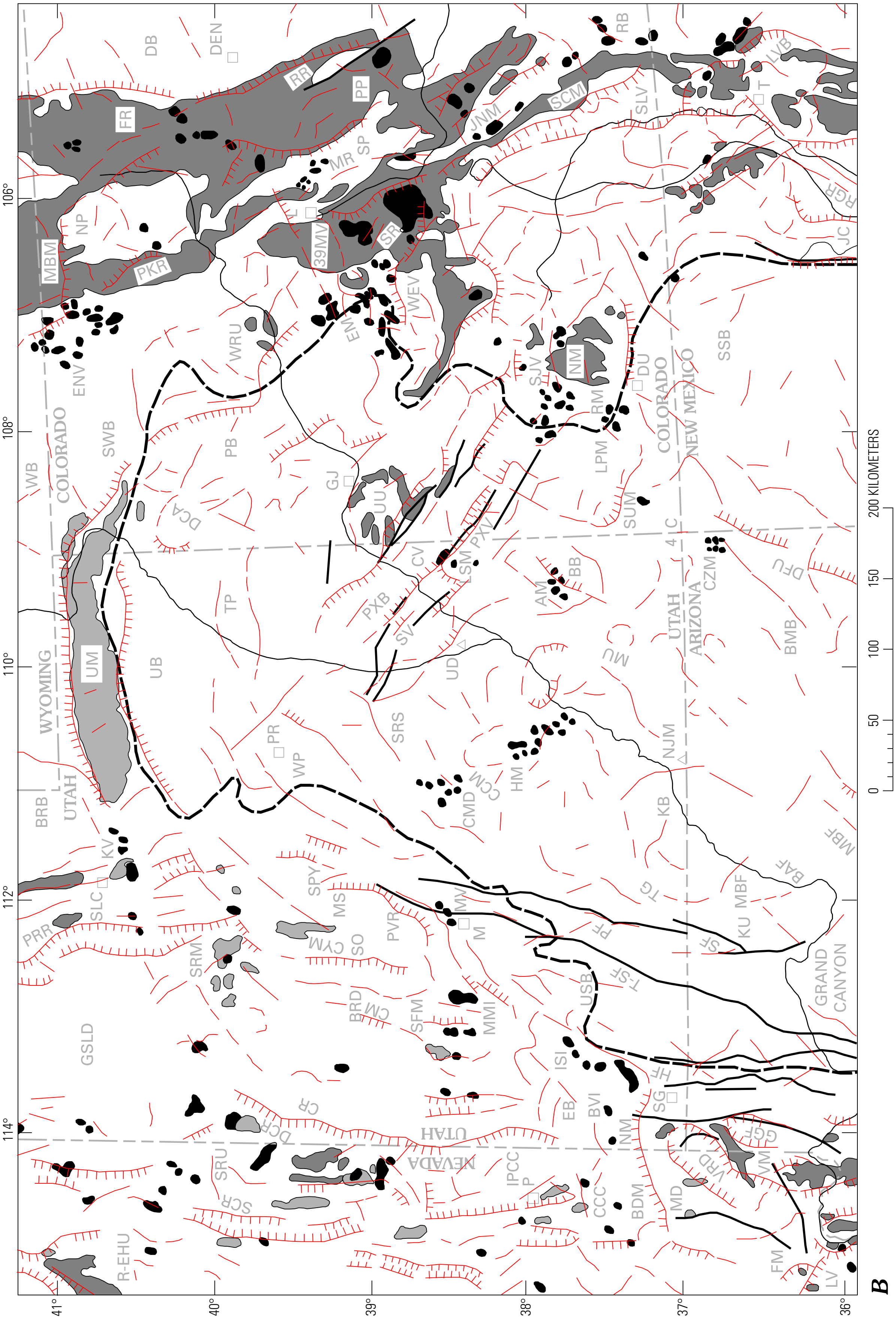
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IPCC
P
CCC
BDM
MD
VRD
GGF
VM
FM
LV

TABLE 1. Explanation of patterns and symbols used on figures 1*B* and 2*B*.

[Names of cities and towns in italics]

——	Fault
– – –	Outline of Colorado Plateau
	Cenozoic and Mesozoic intrusive rock
	Precambrian sedimentary rock
	Precambrian crystalline rock
□	City
AM	Abajo Mountains
BAF	Bright Angel Fault
BB	Blanding Basin
BDM	Beaver Dam Mountains
BMB	Black Mesa Basin
BRB	Bear River Basin
BRD	Black Rock Desert
BVI	Bull Valley intrusion
CCC	Caliente caldera complex
CCU	Circle Cliffs Uplift
CM	Cricket Mountains
CMD	Cedar Mountains dikes
CR	Confusion Range
CV	Castle Valley
CYM	Canyon Mountains
CZM	Carrizo Mountains
DB	Denver Basin
DCA	Douglas Creek Arch
DCR	Deep Creek Range
DEN	*Denver*
DFU	Defiance Uplift
DU	*Durango*
EB	Escalante Basin
EHV	Elkhead volcanic field
EM	Elk Mountains
FM	Frenchman Mountain
FR	Front Range
G-GF	Grand Wash–Gunlock Fault
GJ	*Grand Junction*
GSLD	Great Salt Lake Depression
HF	Hurricane Fault
HM	Henry Mountains
IPCC	Indian Peak caldera complex
ISI	Iron Springs intrusions
JC	Jemez caldera complex
KB	Kaiparowits Basin
KU	Kaibab Uplift
KV	Keetley volcanic field
L	*Leadville*
LPM	La Plata Mountains
LSM	La Sal Mountains
LV	*Las Vegas*
M	*Marysvale*
MBF	Mesa Butte Fault
MBM	Medicine Bow Mountains
MD	Mormon dome
MM	Mineral Mountain
MMI	Mineral Mountains intrusion
MR	Mosquito Range
MS	Middle Sevier Valley
MU	Monument Uplift
MV	Marysvale volcanic field
NJM	Navajo Mountain
NM	Needle Mountains
NP	North Park
P	*Pioche*
PB	Piceance Creek Basin
PF	Paunsaugunt Fault
PKR	Park Range
PP	Pikes Peak batholith
PR	*Price*
PRR	Promontory Range
PVR	Pavant Range
PXB	Paradox Basin
PXV	Paradox Valley
RB	Raton Basin
R-EHU	Ruby–East Humboldt uplift
RGR	Rio Grande Rift
RM	Rico Mountains
RR	Rampart Range
SCM	Sangre de Cristo Mountains
SCR	Schell Creek Range
SF	Sinyala Fault
SFM	San Francisco Mountains
SG	*St. George*
SJB	San Juan Basin
SJV	San Juan volcanic field
SLC	*Salt Lake City*
SLV	San Luis Valley
SO	Sevier oval[1]
SP	South Park
SPV	San Pitch Valley
SR	Sawatch Range
SRM	Sheep Rock Mountains
SRS	San Rafael Swell
SRU	Snake Range Uplift
SUM	Sleeping Ute Mountain
SV	Salt Valley
SWB	Salt Wash Basin
T	*Taos*
TC	The Coxscomb
TP	Tavaputs Plateau
T-SF	Toroweap-Sevier Fault
UB	Uinta Basin
UD	Upheaval Dome
UM	Uinta Mountains
USB	Upper Sevier River Basin
UU	Uncompahgre Uplift
VM	Virgin Mountains
VRD	Virgin River depression
WB	Washakie Basin
WEV	West Elk volcanic field
WM	Wet Mountains
WP	Wasatch Plateau
WRU	White River Uplift
39MV	Thirty-nine Mile volcanic field
4C	Four Corners

[1] Informal designation by T.A. Steven, *in* Mabey and Budding (1987).

wavelengths relative to the flight-line spacing (typically 2–5 km over the Colorado Plateau) probably do not accurately reflect the areal extent of their source rocks; indeed, disturbances due to some intensely magnetized but very localized and depth-limited sources may have been missed entirely, depending upon source location with respect to the flight path. A further filtering effect is imposed by the 2-km gridding.

With these caveats, the map of figure 2*A* can serve to illuminate many important structural and lithologic relations not evident on the gravity map (fig. 1*A*) nor on geologic compilations. Color is a useful adjunct; the interval employed here is 50 nanoteslas (nT). We caution, however, that choice of any particular color scheme can result in visual emphasis or de-emphasis of certain features.

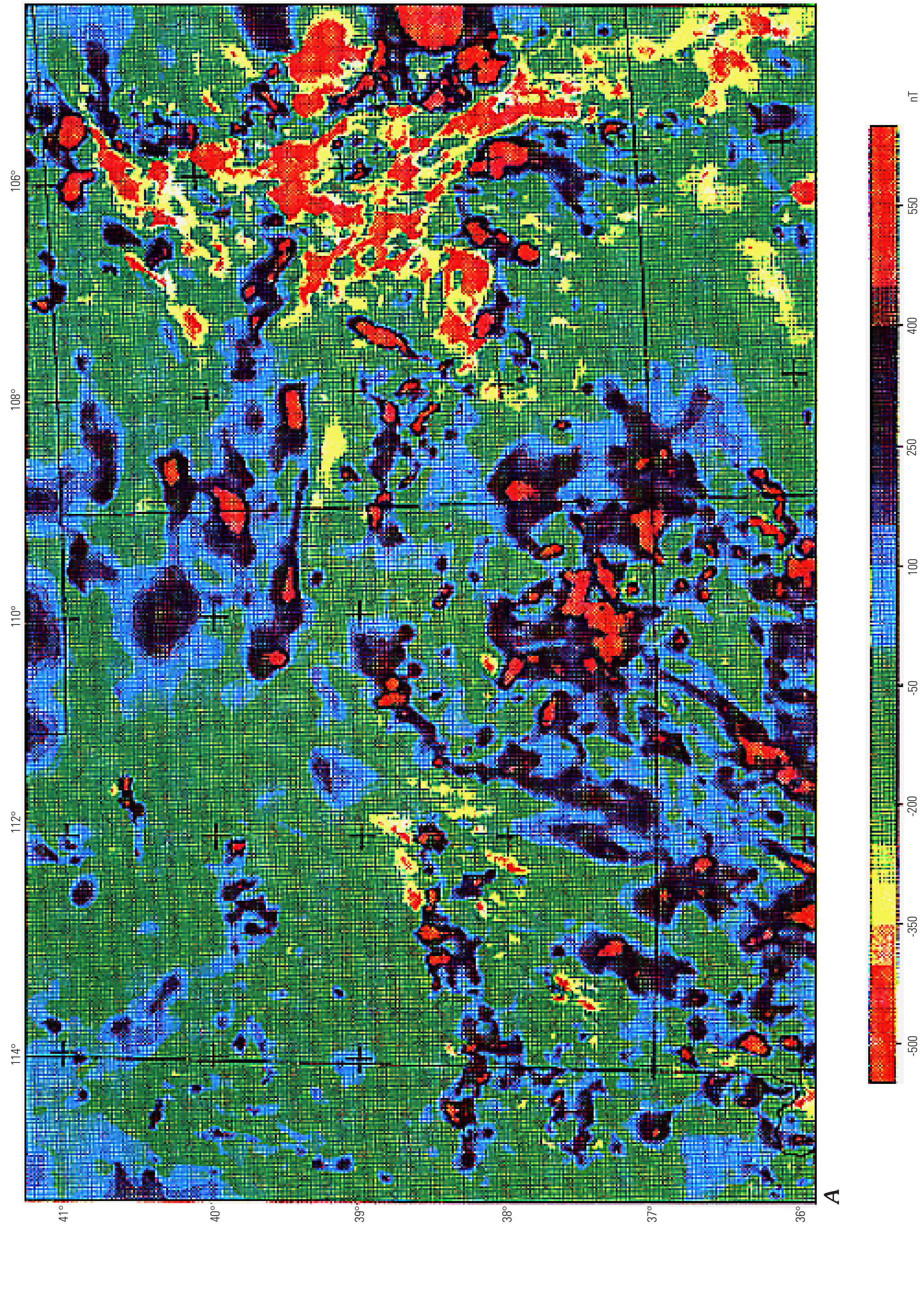
Figure 2*B* shows trends of horizontal gradient maxima of the magnetic field, as estimated by inspection of figure 2*A*. The trends are depicted on the same geologic and geographic base as used for figure 1*B*. We elected not to compute a new gradient map, in view of the constraints of the initial data sets and the compositing procedure, with their implied uncertainties in gradient magnitudes. Figure 2*B* can be considered to indicate approximate margins of major magnetic source bodies, although, analogous to the gravity case, the maximum gradient will directly overlie the upper edge of the boundary only where the magnetization boundary is vertical (and magnetization is parallel to the Earth's field). The depicted trends are commonly discontinuous, with many short segments that in aggregate create a somewhat "noisy" pattern overall, corresponding to the abundance of short-wavelength anomalies on the total-intensity map. (See below.) Aspects of this pattern are addressed in the section on regional trends.

Although the northern Colorado Plateau is predominantly a region of essentially nonmagnetic rocks in surface exposures (upper Paleozoic to Cenozoic sedimentary strata), it displays a remarkably rich and varied fabric of aeromagnetic anomalies (fig. 2*A*). Moreover, its mean residual-intensity level is higher than that of neighboring provinces to the west and east. (See fig. 2*A*.) Overall higher intensity here than in the Basin and Range province has been attributed to a higher effective crustal susceptibility or, alternatively, to a deeper regional Curie isotherm in the Colorado Plateaus province (Shuey and others, 1973). A regional magnetic-intensity boundary occurs well within the physiographic province boundary of the west side of the plateau, and approximately coincides with major lateral changes in other geophysical parameters (seismic refraction, geomagnetic variation) and geochemistry, as pointed out by Shuey and others (1973). The magnetic boundary also closely follows the Basin and Range–Colorado Plateau structural boundary; that is, it is at the eastern limit of basin-range-style extension. On the map of figure 2*A* the magnetic boundary appears as a set of *en echelon* color breaks that coincide, in part, with the Hurricane (HF)–Toroweap-Sevier (T-SF)–Paunsaugunt (PF) family of high-angle normal faults that produce successive down-to-the-west offsets of the Precambrian crystalline basement. "Basement" in much of the eastern Great Basin probably consists of Mesozoic and Cenozoic granitoid batholithic rocks emplaced above the relatively more magnetic Precambrian crystalline basement (Eaton and others, 1978).

East of the plateau, in the Southern Rockies, a lower mean intensity level is indicated by the prevalence of blues and deep greens in figure 2*A*. The extensive areas of very low field intensity in this province include areas inferred to be underlain by granitic batholiths and the deep basins of the northern Rio Grande Rift system (RGR). For example, concealed mid-Tertiary batholiths are probably responsible for low aeromagnetic intensity (as well as for low gravity anomaly values; see above) over much of the San Juan and West Elk volcanic fields (SJV, WEV) in western Colorado, and the partly concealed Proterozoic Pikes Peak batholith (PP) produces a substantial aeromagnetic anomaly depression. Sources of less intense long-wavelength lows in the Southern Rockies include thick blankets of sedimentary and volcanic strata, and weakly magnetic metamorphic belts of the Precambrian crystalline basement.

Comparison of the aeromagnetic and gravity anomaly fields (figs. 1*A* and 2*A*) over exposed Precambrian terrain in the Southern Rocky Mountains province shows that highs and lows of the two sets most commonly do not coincide. Several factors probably combine to account for this lack of agreement: the magnetic data are reduced to the pole but are not pseudogravity anomalies, and therefore depth-limited sources should produce flanking negative anomalies; the orientation of the magnetization vector is not necessarily parallel to the present Earth's field, due to remanence; anomalous magnetic fields are more sensitive to source depths than are anomalous gravity fields; and above all, magnetic heterogeneity obviously need not always correspond directly to density variations. The same general characteristics should also apply to fields produced by the concealed basement complex beneath the Colorado Plateau, and thus it is not surprising that discrete aeromagnetic and gravity anomalies on the plateau also typically do not coincide. However, broad zones of strong aeromagnetic anomaly relief on the plateau roughly correspond to zones of high gravity, and both data

Figure 2 (following pages). Aeromagnetic features of the northern Colorado Plateau and vicinity. *A* (facing page, above), Aeromagnetic residual total-intensity map (data reduced to the pole). Color interval 50 nanoteslas. Data from Geophysical Data Center, National Oceanic and Atmospheric Administration, Boulder, Colo. (North American Data Set, 2-km grid). *B*. Loci of maximum horizontal gradients visually estimated from residual aeromagnetic total-intensity data of *A*. Teeth point in direction of lower anomaly values where gradients are strong. Symbols explained in table 1.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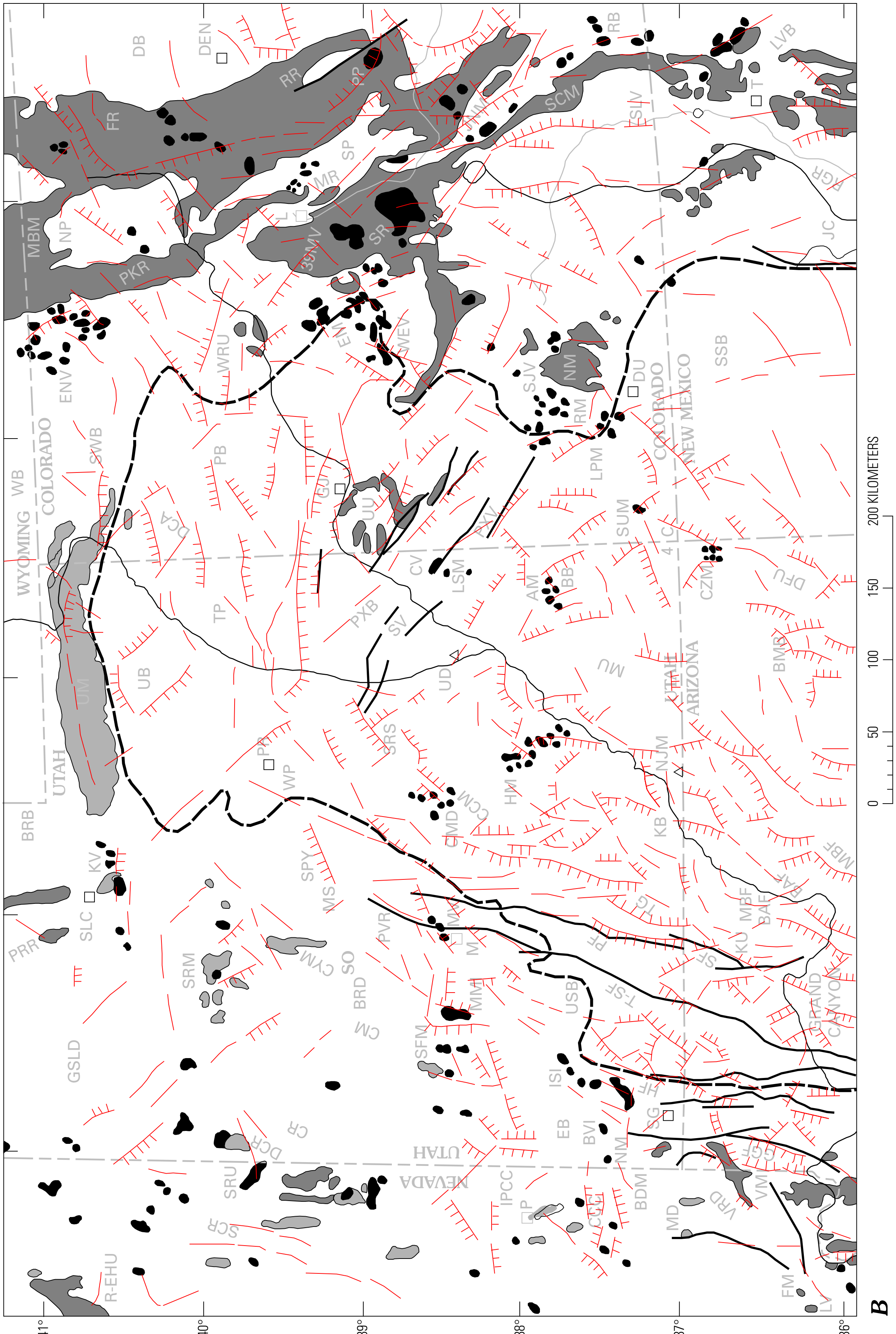
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B

sets tend to reflect large-scale structural relief on the surface of the crystalline basement, as will be documented in the following section.

In general, high-frequency (short spatial wavelength) subcircular anomalies are more conspicuous on the aeromagnetic map than on the corresponding gravity map, because of the widespread occurrence of surface or near-surface rocks that have much stronger local magnetization contrasts than density contrasts. The aeromagnetic map itself can be subdivided on the basis of relative abundance of short-wavelength anomalies. The field of the Colorado Plateau south of about lat 39° N., for example, seems to contain more fine structure than does the field of terrain farther north. Short-wavelength anomalies with steep gradients in the southerly domain suggest a relative abundance there of strongly magnetic sources above the basement. Such anomalies commonly coincide with hypabyssal intrusions, including mafic volcanic rocks and plugs as well as granitoid stocks and laccolithic bodies. Local anomalies in the Henry (HM) and La Sal (LSM) Mountains can be unequivocally attributed to exposed laccoliths, as can the anomaly over Sleeping Ute Mountain (SUM) in southwestern Colorado. Navajo Mountain (NJM), on the Utah-Arizona border, is represented by only a weak local anomaly, even though it also appears to consist largely of intrusive rock; the structure of Navajo Mountain is domoform, and syenite is exposed near the mountain crest (Condie, 1964). Strong residual positive anomalies in northeasternmost Arizona (the subcircular, short-wavelength features south and west of the Carrizo Mountains, CZM) are due to intrusive basaltic plugs near Canyon de Chelly and Monument Valley (Sumner, 1985). Many other examples can be cited to illustrate the relation of local anomalies to exposed igneous bodies on the plateau, yet many such sources are not exposed and remain speculative. We consider that most supra-basement sources that have no surface expression are likely to be highly magnetic Tertiary hypabyssal intrusions that failed to breach the level of the present erosion surface.

On the Colorado Plateau another, perhaps unexpected source may contribute to the mapped field—namely clinker, the remains of subterranean coal fires. Pyrometamorphism of overlying sedimentary rocks (Cosca and others, 1989) has been known to produce extremely strong local magnetic anomalies (for example, see Hasbrouck and Hadsell, 1978; Bartsch-Winkler and others, 1988, p. 11), which could register on an airborne detector if the clinker is overflown.

Twin west-northwest-aligned, intense, subcircular anomaly highs near the confluence of the Green and Colorado Rivers in Utah (fig. 2*A*, *B*), are of special interest among speculative sources because the more western of the two almost exactly coincides with Upheaval Dome (UD), which has been interpreted as an impact structure (Shoemaker and Henenhoff, 1984; also see Huntoon and Shoemaker, unpublished manuscript, 1994 GSA Rocky Mountain Section Field Trip no. 5). However, some workers attribute the structure to salt diapirism or salt extrusion (see Mattox, 1975, and Schultz-Ela and others, 1994). In contrast to Upheaval Dome, terrane around the eastern (Grays Pasture) anomaly is not structurally disrupted. Early (Joesting and Plouff, 1958) and recent (V.J.S. Grauch and G.A. Swayze, U.S. Geological Survey, oral commun., 1994) investigations have indicated that the anomaly sources crest within the sedimentary section, well above the general level of the Precambrian crystalline basement. The alignment of the dumbbell-shaped combined twin anomalies is parallel to the regional structural grain. Thus they may be due to fault-controlled, possibly laccolithic, intrusions and may have only a fortuitous relation to Upheaval Dome if indeed that structure is an astrobleme. Alternatively the structural disturbance may prove to have been produced by salt mobilization triggered by igneous intrusion.

BASEMENT OF THE COLORADO PLATEAU

In figure 3 we reproduce part of a newly completed map of the central and southern Colorado Plateau and vicinity showing elevation on the surface of the Precambrian basement (Butler and Kirkpatrick, in press). This map is an updated version of an earlier release (Butler, 1991). In the current version, basement elevations have been determined at a total of 3,763 control points, using outcrops of Precambrian rock on the plateau periphery (about a quarter of all data points), borehole data (340 out of 533 well logs examined yielded basement intercepts, and basement depths for the remaining wells were estimated by extrapolation of the stratigraphic data), seismic picks (from about 50 record sections), and depth estimated from a variety of published maps and stratigraphic sections. The irregularly spaced data were then gridded and computer contoured. As these maps were prepared primarily for use in petroleum resource assessment, elevations are shown in thousands of feet rather than meters. The map scale for figure 3 is the same as for the potential field maps of figures 1 and 2, but coverage does not extend north of the Paradox Basin and about 40 percent more area to the south of the current study area is included.

A gentle overall northeasterly tilt of the plateau basement can be discerned from the contours; this tilt conforms to the structure of the plateau as a whole, which resembles a tilted saucer. (See Hunt, 1969, fig. 62. Hunt's structure contour map was drawn on the top of the Lower Permian Kaibab Limestone.) Where figure 3 overlaps with the geophysical data, we find a convincing correlation of basement structural highs with gravity anomaly highs, particularly in the Defiance (DFU) and Monument (MU) Uplifts near the Four Corners, the San Rafael Swell (SRS) in the north, and the upthrown sides of major north-northeast-trending normal faults on the west, such as the Hurricane and

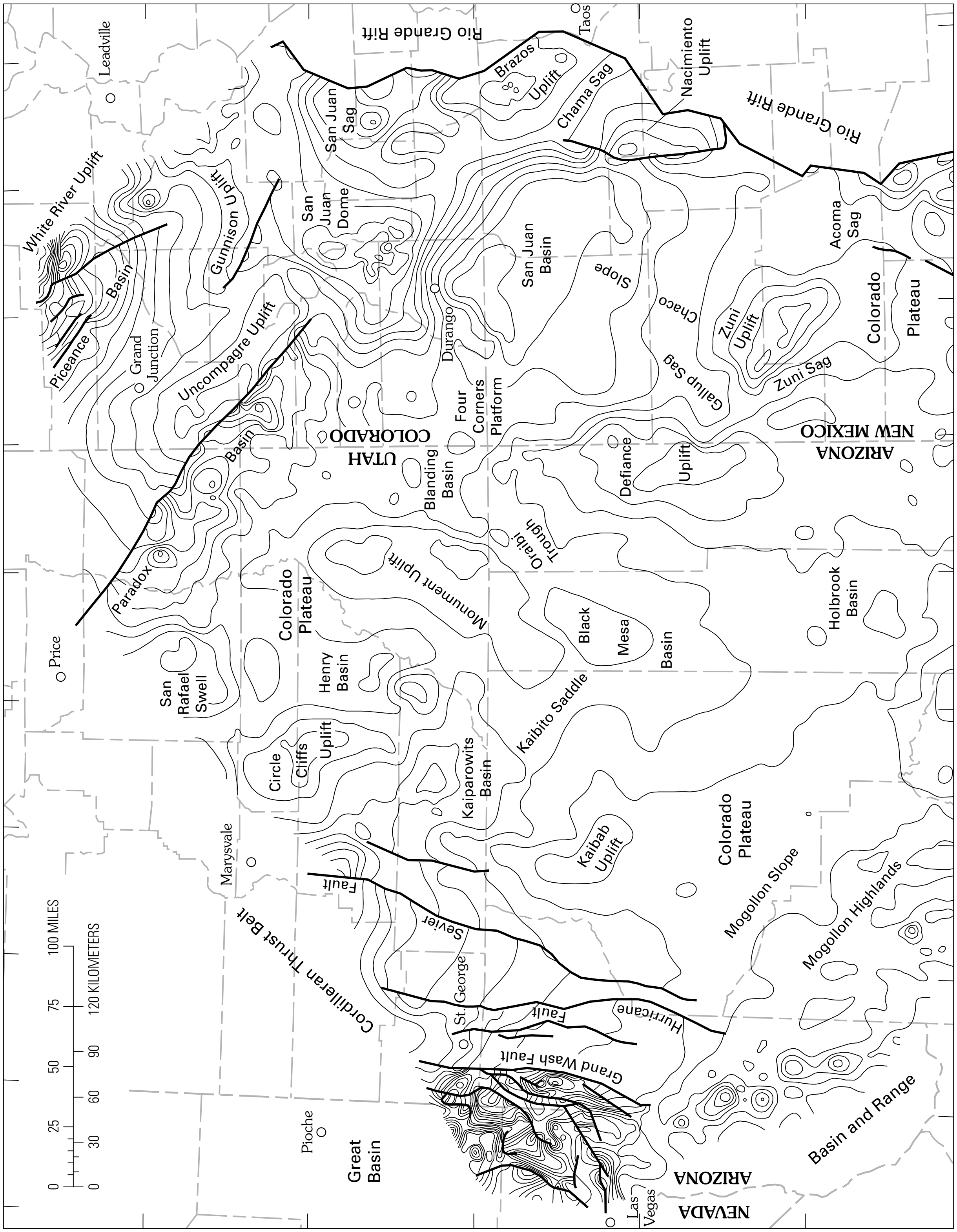

Figure 3. Structure contours showing elevation of surface of Precambrian crystalline basement for part of Colorado Plateau. Numbers give elevation in thousands of feet above sea level; contour interval 2,000 feet (610 m). Modified from Butler (1991).

Toroweap-Sevier zones. Correlation of basement highs with magnetic anomaly highs is less distinct, probably as a result of significant lateral heterogeneity of magnetization in the Precambrian section. However, the mapped southwestern margin of the Uncompahgre crystalline block has a well-defined aeromagnetic signature, even though this margin typically has a negligible gravity expression. (See discussion of gravity anomalies, above.) The signature results from strongly magnetized upper-plate crystalline rocks at or near the surface. Most basement uplifts on the plateau originated as Laramide compressional strucures (Coney, 1976), strongly influenced however by the preexisting tectonic fabric. On the western margins, where basin-range-style extension has encroached on the plateau, basement uplifts have developed as a result of tilting of large blocks on normal faults. Many plateau uplifts were later beveled by erosion and then rejuvenated.

The influence of deep-seated basement structures on the disposition of Tertiary laccolithic igneous centers of the northern Colorado Plateau is at most only weakly expressed at the map scale of figures 1–3. From these maps, we surmise that most igneous centers are located on the flanks of, or between, major basement uplifts rather than on their crests, which suggests structural control by deep-seated faults on the flanks of the uplifts rather than by flexure axial planes. However, when more detailed aeromagnetic maps are consulted, for instance maps at scales of 1:500,000 and larger, the influence of older, regional structures on laccolith emplacement is sometimes quite evident. For example, intrusions in the La Sal Mountains are elongated northwesterly, following the axial trend of the Castle and Paradox Valleys (CV, PXV) and other trends in the anomaly field that reflect the structural grain of the Precambrian basement (Joesting and Case, 1960; Case and Joesting, 1972). Also, centers in the Henry Mountains and dikes in the Cedar Mountains complex (CMD) are aligned north-northwesterly, in agreement with regional basement trends deduced from the aeromagnetics.

REGIONAL ANOMALY TRENDS

Loci of horizontal anomaly gradient maxima displayed in figures 1*B* and 2*B* delineate relatively steep density and magnetization contrasts, and therefore tend to highlight lithologic boundaries such as those produced by high-angle faults or steep-sided igneous intrusions. Where the causal structures dip at significantly less than vertical angles, the loci are nevertheless indicative of structural trends. In the following paragraphs we discuss groups of anomaly trends with more or less common orientation.

Northwesterly trends are conspicuous on both gravity and aeromagnetic maps (figs. 1*B* and 2*B*; refer also to figs. 1*A* and 2*A*) and occur throughout the study area. They are probably most prominent in the central part of the gravity map (fig. 1*B*), particularly in the Southern Rockies. On the Colorado Plateau, they are parallel to (or in some cases coincide with) mapped faults of Paradox Valley and the Uncompahgre Front, including structures on which the earliest movement dates at least as far back as late Paleozoic time (Stokes, 1982) and perhaps earlier (Larson and others, 1985).

Northeasterly trends are also found on both data sets (figs. 1*B*, 2*B*) but are most strongly expressed in the aeromagnetics (fig. 2*B*). In the southern and southeastern parts of the study area, northeasterly aeromagnetic trends align with the Sinyala, Mesa Butte, and Bright Angel fault zones and their inferred extensions across southeastern Utah and into Colorado (Case and Joesting, 1972; Shoemaker and others, 1978; Sumner, 1985). These fault zones and their northeastern extensions, along with parallel but less prominent structures, compose a broad northeast-trending belt (fig. 4) referred to as the Colorado lineament (Warner, 1978, 1980). Approximately at the southeast margin of the lineament belt is the Laramide and post-Laramide Colorado mineral belt (Lovering and Goddard, 1950; Tweto, 1968). Northeasterly anomaly trends also track the Jemez (Springerville-Jemez-Raton) lineament of northern New Mexico (Chapin and others, 1978; Aldrich, 1986; Lipman, 1980; see also Cordell and Keller, 1984). The Jemez lineament (J, fig. 4; also see fig. 6), about 200 km southeast of and parallel to the Colorado lineament (Colorado mineral belt), consists of a northeast alignment of several Neogene volcanic fields, including the Jemez caldera complex (JC). The significance of the Jemez and other northeast-trending Neogene volcanic lineaments of the Cordillera will be addressed in the next section. Sources of northeasterly anomaly trends on the Colorado Plateau include rejuvenated Precambrian and Paleozoic structures. (See, for example, Tweto and Sims, 1963.) Probably most structures delineated by trends of either northeast or northwest orientation involve offset of plateau strata (See, for example, Davis, 1978; Stevenson and Baars, 1986), but many do not closely correspond to any mapped features and may involve only rocks of the crystalline basement.

Northerly trends are present mainly in the eastern and western marginal zones of the northern plateau and in bordering domains, reflecting structures associated with the northern Rio Grande Rift on the east (the source of both gravity and aeromagnetic trends) and with Basin and Range faulting on the west (especially well expressed by gravity trends). On both sides of the plateau these trends tend to be arcuate and concave inward, toward the medial region of the plateau.

Trends oriented approximately east-west are well expressed by potential-field data over the east and west flanks of the Colorado Plateau in belts that include the axis of the San Juan volcanic field (Steven, 1975; Steven and others, 1984) and the Pioche-Marysvale igneous belt (P to M on fig. 2*B*) (Shawe and Stewart, 1976; Stewart and others, 1977; Rowley and others, 1978). Broad, irregular but east-west

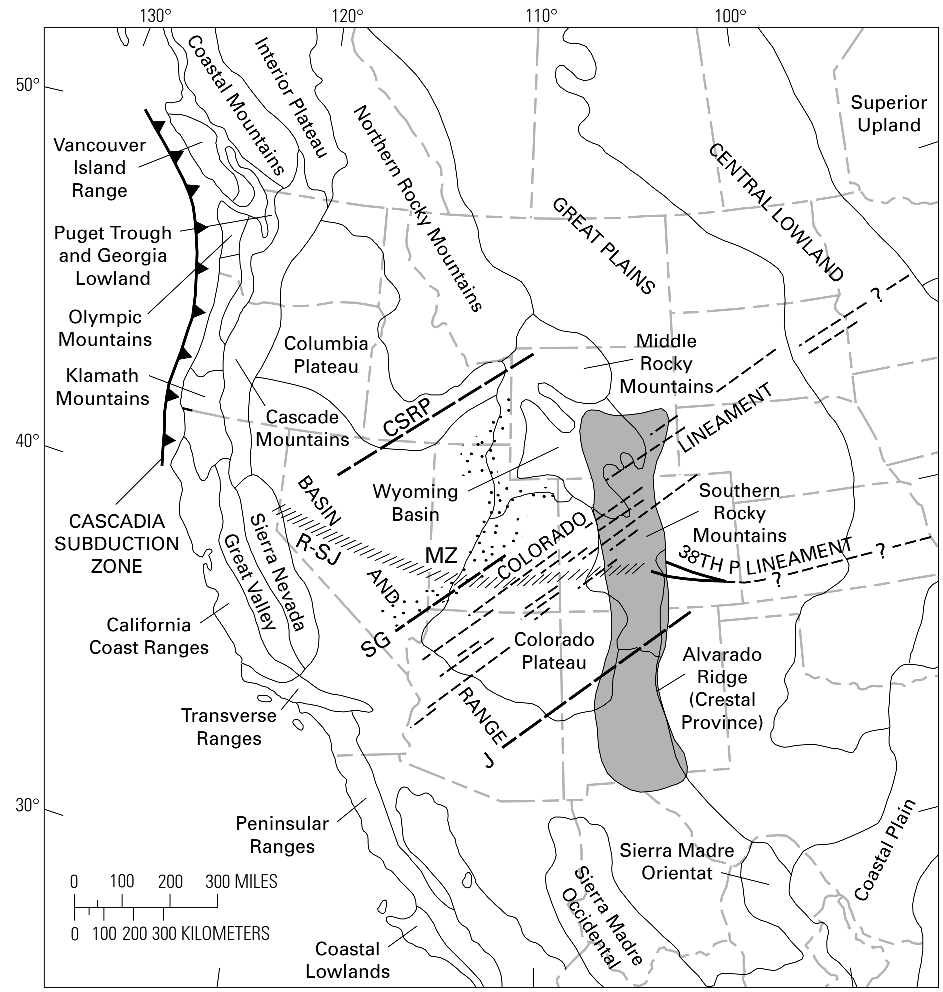

Figure 4.. Index map of a part of western North America, showing location of some large-scale tectonic features mentioned in the text. The Colorado lineament is sketched from Warner (1980, fig. 3); eSRP (eastern Snake River Plain–Yellowstone), SG (St. George), and J (Springerville-Jemez-Raton) lineaments (heavy dashed lines) are upper-mantle seismic low-velocity zones that coincide with Neogene volcanic trends, as indicated by Humphreys and Dueker (1994a, fig. 2); the Reno–San Juans magmatic zone (hachured band, R-SJ MZ) is after Nelson and others (1992, fig. 1); the 38th Parallel lineament (queried where highly uncertain) is after Heyl (1972, fig. 1); and the Cascadia subduction zone, a surviving remnant of the Pacific subduction zone after 30 Ma, is from Atwater (1989, fig. 9). The crestal province of the Alvarado Ridge (shaded area bounded by heavy line) is from Eaton (1986, fig. 1). Stippled areas denote the central and southern sectors of the Intermountain seismic belt, after Smith and others (1989, fig. 21). Base map with physiographic provinces is adapted from Stewart (1978, fig. 1–2).

elongated gravity lows are associated with root structures of the San Juan volcanic field and the Pioche-Marysvale igneous belt. The approximate alignment of these features with igneous centers between Pioche and Reno, Nevada, and the penecontemporaneity of their magmatic activity with that of laccolithic centers in southern Utah have suggested to some workers the existence of a more or less continuous, Oligocene to early Miocene magmatic zone extending east-west through Nevada, Utah, and western Colorado, termed the “Reno–San Juans magmatic zone” (Sullivan and others, 1991; Nelson and others, 1992; see also Rowley and others, this volume). If the full width of this zone (fig. 4) can be considered to approach two degrees of latitude (about 36°45' N. to 38°45' N.), then it encompasses all known laccolithic centers of the northern Colorado Plateau. Further, it is aligned with the 38th Parallel lineament (fig. 4), a zone of wrench faulting and other structural disturbances, locally accompanied by igneous activity and mineralization, which extends westward through the Eastern and Central United States and has been intermittently active from Cambrian until at least early Tertiary time (Heyl, 1972, 1983; Lidiak and Zietz, 1976). No clearly defined geophysical trends indicate structural continuity between either Marysvale and the San Juans, or the San Juans and the 38th Parallel lineament, however, and the implications of their alignment are unclear. We note that the 1,000-km-long Reno–San Juans magmatic zone is oriented roughly normal to the mid-Tertiary to present Cascadia subduction zone (fig. 4) and by inference, to the corresponding segment of the Pacific subduction zone that preceded it, as well as to the orientation of the associated mid-Tertiary magmatic arc. Thus it may be an intracontinental analog to a leaky transform zone of seafloor-spreading models.

Other prominent trends of the east-west set occur well north of Colorado Plateau laccolith centers, in the north-central part of the study area (Uinta Mountains, Uinta Basin, and Tavaputs Plateau). Long, arcuate, concave-to-the-south trends on the gravity map (fig 1*B*) delineate master faults of the Uinta block, which have produced substantial offsets of the Precambrian basement. Faults of the Tavaputs Plateau and associated blocks (including the southern margin of the Uinta Basin) are reflected in strong magnetic trends that are less continuous than those bounding the Uinta block, and mostly straight, with little surface expression.

In sum, northeasterly (Colorado mineral belt) and northwesterly (Paradox Basin) trends are prevalent over large areas, both inside and outside the plateau margins; northerly trends are best developed outside the plateau in the extreme east (Front Range; Rio Grande Rift) and extreme west (Basin-Range); and easterly trends are also most strongly expressed outside the plateau (San Juan Mountains and Pioche-Marysvale areas). However, in many areas no trend dominates but, rather, trends are mostly curvilinear. Arcuate anomaly trends form a swath that envelops the northern plateau. The swath includes elements internal as well as external to the plateau, but their arcuate character is much less conspicuous in the interior. The center of curvature of arcuate elements seems to be in a region west or southwest of the Four Corners, near the Carrizo Mountains (CZM), where gravity trends are weak and most magnetic trends are northeasterly to northwesterly, reflecting the structural fabric of the basement. This region is also near the geographical center of the plateau.

The symmetry of the pattern of arcuate trends with respect to the northern plateau, particularly those derived from gravity data (fig. 1*A*, *B*), suggests a genetic relationship between the causal structures and the tectonic evolution of the plateau. In many places, the sources are clearly identified as mapped faults or fold axes. (For example, compare Hamilton, 1988, fig. 1.) Steep density discontinuities indicated by prominent horizontal gradients of gravity commonly are located at or near mountain fronts (they are produced by the contrast between basin fill and bedrock of any lithology), and thus can be directly related to structural margins of uplifts and basins, or horsts and grabens, that make up the present topography. Sharply delineated grabens in places merge along strike with less well delineated basinal depressions, or with gaps within the Precambrian crystalline basement that are inferred to be largely occupied by granitoid mid-Tertiary plutons concealed beneath volcanic cover. In many such cases, the geophysical data suggest a structural continuity not otherwise evident.

The north- to north-northwest-trending Rio Grande Rift is illustrative. As a continuous system of grabens, it terminates near Leadville, Colo. (L), although a narrower belt of related block faulting continues north almost to the Wyoming border (Tweto, 1979b, 1980). West-northwest to westerly Neogene trends in northern and northwestern Colorado and northeastern Utah have previously been associated with a major east-west tectonic zone, rather than with the predominantly north trending Rio Grande Rift system. (See, for instance, Tweto, 1979b.) But elements of these two tectonic zones are not necessarily unrelated. Near Leadville, combined gravity and aeromagnetic trends suggest structural linkage of the Rio Grande Rift with a broad depression beneath the Sawatch Range (SR), the Elk Mountains (EM), and the West Elk Mountains (coincides with WEV). This depression, largely occupied by middle to late Tertiary volcanic rocks and their subjacent plutons, flares to the northwest; its gravity signature is contiguous with that of the Piceance Creek Basin (PB). As noted previously, plutons in this region include granitoid rocks of Proterozoic and Laramide as well as Tertiary age. Together these rocks produce a composite regional gravity and aeromagnetic anomaly low. The gravity lows of the volcanic-plutonic zone and the Piceance Creek Basin represent generally northwest trending structural depressions and probably imply significant southwest-directed Neogene extension.

A nearly continuous system of gravity lows, interpreted as structural depressions, links the following features in a grand arc (clockwise from southwestern Utah; see fig. 1*A*, *B*): upper Sevier Basin (USB), Marysvale volcanic field (MV), San Pitch–middle Sevier Valleys (between Pavant Range (PVR) and Wasatch Plateau (WP)), Uinta Basin (UB), Piceance Creek Basin (PB), West Elk volcanic field (WEV), San Luis Valley (SLV), and northern Rio Grande Rift (RGR). This system of depressions is interrupted by the Douglas Creek Arch (DCA), a Laramide uplift whose subsequent structural development was related to differential subsidence between the Uinta and Piceance Creek Basins (Johnson and Finn, 1986). Other prominent arcuate structures that bound depressions, as inferred from the gravity trends, include steep marginal faults of the Schell Creek Range (SCR) in Nevada; the Confusion Range (CR), Uinta Mountains (UM), Tavaputs Plateau (TP), and San Rafael Swell (SRS) in Utah; and North Park (NP) and the Medicine Bow Mountains (MBM), Front Range (FR), and Rampart Range (RR) in Colorado.

Fault-bounded depressions on the east and west flanks of the northern Colorado Plateau (grabens of the Rio Grande

Rift and the Basin and Range province), which trend north to north-northwesterly or north to north-northeasterly, respectively, are well-known manifestations of late Tertiary (Neogene) extension. Basement depressions or perforations now occupied by plutons in the substrate of the Elkhead, West Elk, and San Juan volcanic fields (EHV, WEV, and SJV) of western Colorado also reflect Neogene extension.

The Uinta and Piceance Creek Basins and other elements of the arcuate system in northwest Colorado and northeast Utah are older structures with a complex history of recurrent deformation. Surface mapping, well logs, and seismic reflection data all support the interpretation that major northwest-trending faults in this area are Laramide compressional structures (high-angle reverse faults), many of which have Neogene extensional overprints of lesser magnitude (A.C. Huffman, written commun., 1994). Northwesterly to northerly trending reverse faults comprise a northward-widening splay pattern (fig. 1*A*, *B*) from New Mexico into Colorado; the pattern has been attributed to a northerly increase in total crustal shortening resulting from the clockwise rotation of the Colorado Plateau of 4° or more about an Euler pole in central New Mexico during the Laramide (Steiner, 1986; Hamilton, 1981, 1989; Van der Voo, 1989).

However, a tensional stress field has probably prevailed in Neogene time. (For example, see Verbeek and Grout, 1993.) Normal faults with late Cenozoic movement tend to be localized along zones of Laramide faulting that had movement in the opposite sense (Izett, 1975). Axes of Miocene uplifts and downwarps, as recorded in the distribution of clastic sedimentary formations such as the Browns Park (upper Oligocene and Miocene) and North Park (upper Miocene) Formations (Izett, 1975), tend to be roughly parallel to Laramide axes or, as in the eastern Uintas, to an Archean-Proterozoic terrane boundary (Hansen, 1986; Bryant and Nichols, 1988). In northwest Colorado and northeast Utah, Neogene and older structures alike are roughly parallel to the present northern margin of the Colorado Plateau, which makes this segment of the overall arcuate pattern difficult to resolve in terms of Neogene extension. Nevertheless, on the basis of gravity data and known structures, it appears that the northern plateau is bordered by an envelope of extensional deformation, which is variable in magnitude and possibly discontinuous.

Trends of aeromagnetic anomaly gradient maxima (fig. 2*B*) tend to be less continuous than the gravity trends (fig. 1*B*), and less easily related to mapped structures, structural trends, and topography. This lack of obvious correlation with surface features is at least partly due to strong magnetization contrasts within the concealed Precambrian crystalline basement of the plateau, as noted earlier. Therefore the sources of most magnetic anomalies over the plateau are unidentified. For example, one of the most prominent and continuous gradient trends—that representing the east-west-striking anomaly step north of Grand Junction (figs. 2*A*, 2*B*)—corresponds to no surface feature, nor to any major gravity trend, although it does coincide with very weak gravity gradients (not shown on the trend map of fig. 1*B*). Parallelism of this step with gravity and magnetic anomaly steps over the Tavaputs Plateau and Uinta Basin to the north suggests that all of these east-west anomaly trends are related: they may reflect intrabasement structures, but they could also be produced by high-angle basement faults (block faults) that did not propagate through the suprajacent plateau strata.

North to northeasterly aeromagnetic trends predominate on the west side of the northern plateau and in the transitions to the eastern Basin and Range province, where, on structures such as the Paunsaugunt fault, the anomaly offsets are clearly related to offsets of crystalline basement rocks that result from Neogene normal faulting. On the east side of the plateau and in the Southern Rockies, north to northwesterly trends predominate. Except in a few localities, though, their interpretation as signatures of Neogene extensional structures can be debated. However, the aeromagnetic trend pattern for the region as a whole is very similar to that of the gravity trends: an envelope of arcuate trends encompasses the northern Colorado Plateau, and in most places represents a system of Neogene high-angle normal faults that have produced extensional displacements of the crystalline basement.

DISCUSSION

The Colorado Plateau has been called an "enigmatic crustal block," or microplate, as it has survived nearly intact though much of Phanerozoic time despite being translated, rotated, elevated, and contiguous to provinces of voluminous magmatism. Gravity and aeromagnetic anomalies of the northern Colorado Plateau and vicinity delineate the Precambrian basement fabric and loci of Cenozoic magmatism. In addition, they reveal the regional continuity of broadly arcuate features that can be interpreted as horst-graben structures circumferential to the plateau interior, a pattern that suggests a middle to late Cenozoic stress regime of radial outward extension. To the east and west of the present plateau margins, these structures include the Rio Grande Rift and normal faults of the easternmost Basin and Range province, respectively; in parts of northern Utah and northwestern Colorado, they include arcuate Laramide or earlier structures reactivated in the Neogene with normal (extensional) displacements.

Figure 5*A* (from fig. 3 of Zoback and Zoback, 1989; see also fig. 1 of the same paper) depicts the generalized results of a compilation of probable least-principal-stress directions from various Quaternary indicators, including earthquake focal mechanisms, elliptical well-bore enlargements ("breakouts"), *in situ* stress measurements, and young vent alignments and fault offsets. Tensile stresses are oriented north-northeast near the northeastern and southwestern

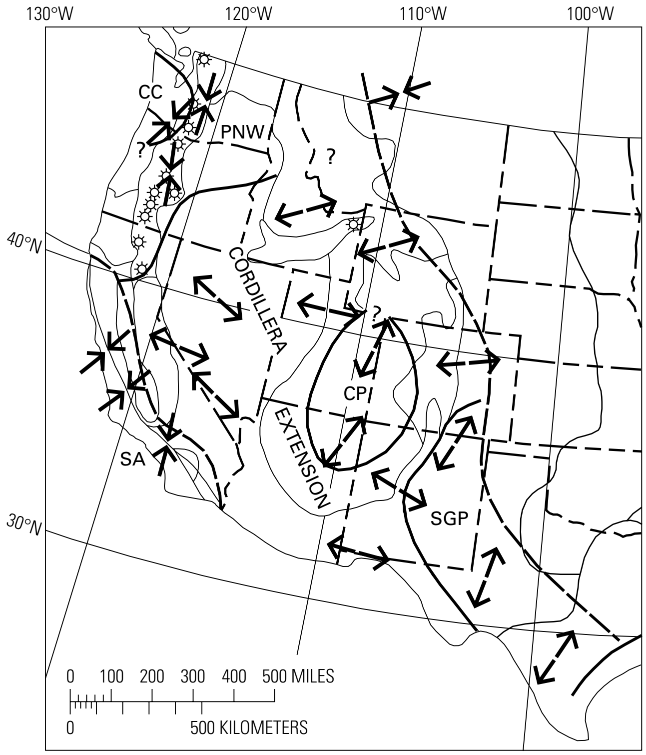

Figure 5. Generalized stress map for western U.S. Outward-pointing arrows indicate areas of extensional deformation; inward-pointing arrows show areas dominated by compressional tectonics. Heavy lines are stress-province boundaries. CP, Colorado Plateau interior; CC, Cascade convergent province; PNW, Pacific Northwest; SA, San Andreas province; SGP, Southern Great Plains. From Zoback and Zoback (1989, fig. 3).

margins of the plateau and nearly east-west on the western and eastern margins. Thus, at least on the basis of the sparsely distributed data presently available, the late Cenozoic stress field for the Colorado Plateau and its margins seems to accord with radial extension, perhaps superimposed on the predominantly east-west or southwest-northeast least principal stress expressed in neighboring provinces.

Radial outward extension of the plateau, if it happened, may simply indicate an ongoing process of gravitational collapse and lateral spreading more or less concurrent with uplift. The plateau is situated on the axial crest and west flank of the regional elevation anomaly of the Western United States (the Cordilleran "geanticline" of Hunt, 1956). This long-wavelength topographic feature corresponds very closely to the 1,000-km low-pass Bouguer gravity anomaly depicted on the map of figure 6 (modified from Hildenbrand and others, 1982, and Kane and Godson, 1989; a color plate accompanying the latter paper also displays a map of the elevation anomaly). This map shows the deep low that remains after removal from the Bouguer data set of all spectral components with wavelengths less than 1,000 km. Also shown on the map are an outline of the Colorado Plateau (bold line) and three Neogene volcanic trends that coincide with upper-mantle seismic low-velocity zones (after Humphreys and Dueker, 1994a, fig. 2). These trends will be discussed later.

The regional Bouguer anomaly (fig. 6) is seen as a bulbous trough extending from Canada into Mexico; on continent-scale maps it appears as a local widening of a linear negative Bouguer anomaly that coincides with highly elevated terrain along the full length of the Cordillera in western North America inboard of the convergent plate margin. The anomaly minimum in this wide zone in the U.S. Cordillera is located in westernmost Colorado, over the northeastern part of the Colorado Plateau, where it corresponds to a regional elevation maximum of about 2.5 km. The axis of the regional elevation high/Bouguer gravity low approximately coincides with the axis of maximum flexural subsidence and Late Cretaceous sedimentation in the Sevier foreland. (See, for instance, Pang and Nummedal, 1995; Bird, 1984.)

The plateau bears a similar relation to the regional geoidal high of the Western United States, which also has a local maximum in western Colorado (Milbert, 1991).

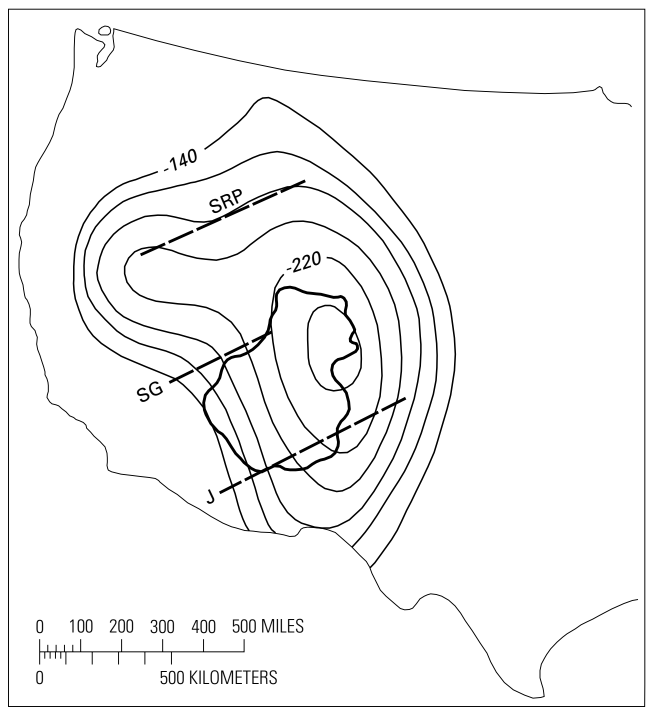

Figure 6. Long-wavelength (λ >1,000 km) regional Bouguer gravity anomaly map of the western United States, showing disposition of Colorado Plateau (bold outline) with respect to gravity minimum (after Kane and Godson, 1989, fig. 4). Contour interval is 20 milligals, but values higher than –140 milligals are not shown. Dashed lines are Neogene volcanic trends that coincide with upper-mantle seismic low-velocity zones (from Humphreys and Dueker, 1994a, fig. 2). eSRP, eastern Snake River Plains trend; SG, St. George trend; J, Jemez trend.

However, the regional geoidal anomaly is more nearly equidimensional than the other two anomalies and crests exactly over the Yellowstone hotspot (Pierce and Morgan, 1992), a point to which we shall return later in this section.

Various mechanisms of plateau uplift are reviewed in McGetchin and Merrill (1979). It has been emphasized elsewhere that in the case of the Colorado Plateau, uplift must be considered in the context of tectonic evolution of the entire western interior Cordilleran region. That is, uplift of the plateau must be closely related to development of the huge anomalous "root" zone responsible for the long-wavelength gravity, geoid, and elevation anomalies (as in Bird, 1984; Beghoul and Barazangi, 1989; Parsons and others, 1994). Models that specifically seek to explain the 2-km average elevation of the Colorado Plateau include (1) those that require the presence of a mantle plume (such as Wilson, 1973, and Parsons and others, 1994; see also Parsons and McCarthy, 1995) or group of plumes (Sbar and Sykes, 1973) beneath the plateau and its environs, resulting in thermal thinning of the lithosphere and, possibly, crustal thickening by magmatic underplating (as described by Morgan and Swanberg, 1985), and (2) those that ascribe the uplift to processes related directly to subhorizontal subduction during the Laramide orogeny. Models of this latter class generally require delamination of the overriding North American plate (Bird, 1979) or of the subducted Farallon plate (Bird, 1988; Beghoul and Barazangi, 1989), leading to the replacement of lithosphere by hot asthenosphere, and probable crustal thickening. Bird (1988) proposed large-scale shear decoupling and translation of lithosphere eastward to the anomalous Cordilleran "root" zone. However, simple buoyancy of a flattish Farallon slab was invoked by Lowell (1974) and Gries (1983) to explain the plateau uplift.

In support of the concept of low-angle subductions, modern analogs with many characteristics similar to those of the U.S. western interior have been documented for the Andean margin of South America, where terrane above a seismically delineated low-angle slab far inboard of the convergent plate margin has been uplifted, deformed, and subjected to magmatism (Isacks and Barazangi, 1977). The low subduction angle has been attributed to a high convergence rate (Engebretson and others, 1984), to youthfulness (and therefore relatively high temperature) of the slab, or to a slab containing thick crustal elements such as aseismic ridges or oceanic plateaus. (See Livaccari and others, 1981, for instance.) Possibly all of these factors contributed to the flattening.

Eaton (1986, 1987) investigated the highly elevated region between Wyoming and El Paso, Texas (in his terminology, the Southern Rockies *sensu lato*), and noted that it straddles a much broader, north-south elongated topographic swell, for which he proposed the name "Alvarado Ridge" (fig. 4; only the crestal province of the ridge is shown in the figure). This swell appears to be virtually identical to the long-wavelength Cordilleran elevation/Bouguer gravity anomaly, although Eaton pointed out that axes of the two features are somewhat displaced and have slightly different orientations. The High Plains (part of the Great Plains physiographic province, fig. 4) are on the east flank of the ridge, the Colorado Plateau is on its west flank, and the Rio Grande Rift coincides with its axial zone. Eaton showed that transverse profiles of the Alvarado Ridge bear a striking resemblance to those of mid-ocean spreading ridges, which led him to suggest that the ridge is, in fact, a "continental rise." From the sedimentary record, including age and distribution of the Ogallala Formation (Miocene), he inferred that major uplift of the Southern Rockies *sensu lato* occurred in the interval from about 17 Ma to between 7 and 4 Ma. That is, the rise of the Alvarado Ridge is mainly a late Cenozoic phenomenon, although some uplift of the ridge, and initiation of the Rio Grande Rift, probably occurred as early as mid-Oligocene time.

Possible origins of the long-wavelength Cordilleran anomaly, in consideration of gravity and seismic data, have been discussed by Kane and Godson (1989). In their view the Bouguer gravity low cannot be accounted for by crustal variations alone and must involve a buoyant upper mantle (75 percent of the buoyancy residing in the upper 160 km) in order to maintain a condition of regional isostatic equilibrium as implied by near-zero average (long-wavelength) free-air anomalies (as shown by Simpson and others, 1987, for instance). Because the regional gravity low corresponds to generally low velocities of both compressional (P_n) and shear (S) waves, Kane and Godson postulated the existence of anomalously high mean upper mantle temperatures to account for the required low density.

In an analysis of all available teleseismic *p*-wave travel-time residuals, Dueker and Humphreys (1990) and Humphreys and Dueker (1994a, b) demonstrated that both high- and low-velocity domains are present in low-density upper mantle of the U.S. western interior. Humphreys and Dueker (1944a, b) concluded that elevated mantle temperatures locally produce partial melts that depress the *P*-wave velocities and lead to observed lateral variations in velocity structure. Three principal low-velocity zones were delineated (see figs. 4 and 6), each trending northeasterly and each corresponding to a belt of generally northeast younging Neogene (mainly) bimodal volcanism: the eastern Snake River Plain–Yellowstone zone (eSRP, figs. 4 and 6), the St. George (Utah) zone (SG, figs. 4 and 6), and the Jemez (Springerville-Jemez-Raton) zone (J, figs. 4 and 6) across northwestern New Mexico (Humphreys and Dueker, 1994a). The latter two zones are on or near the northwest and southeast borders, respectively, of the Colorado Plateau. All three low-velocity zones are on the west flank of the long-wavelength Cordilleran anomaly, and all three coincide with belts of relatively steep crustal isopach gradients that separate regions of thick crust (40 to 50 km in central Idaho and western Montana and in the Colorado Plateau) from regions of thinner crust, according to data from seismic refraction profiles. (See Allenby and Schnetzler, 1983, fig. 2.) Also, all three are parallel to or coincident with known Proterozoic terrane boundaries (Bowring and Karlstrom, 1990), and lie on great circle arcs through the Eulerian pole of relative motion between the North American and Pacific tectonic plates (Eaton, 1979, fig. 1*B*). The significance of these relations lies in the following: (1) ancient deep-crustal flaws are implicated in the localization of late Cenozoic magmatism over a large region of the Cordillera; and (2) the parallelism of the zones and the general tendency for Neogene volcanism to young northeastward within each zone (see below) suggest common underlying factors in their tectono-magmatic evolution. The common factors may be (1) the presence of a mantle plume beneath the wide (transverse axis >>1,000 km) central part of the long-wavelength Cordilleran anomaly, and (2) dominantly southwestward movement of the North American plate across the plume head during Neogene time. In this scenario, late Cenozoic uplift of the entire interior Cordilleran region is attributable to the presence of a plume in the broadest sense—that is, a vast convective upwelling of hot asthenosphere, regardless of its relationship to subduction or the maximum depth of mantle involved in the total convective system. The Colorado Plateau remains high because it has been relatively little extended.

Of the three Humphreys-Dueker zones, the eastern Snake River Plain–Yellowstone zone offers the most compelling case for a hotspot track and underlying mantle plume (Morgan, 1972; Pierce and Morgan, 1992; Smith and Braile, 1993; Parsons and others, 1994). The orientation of the volcanic axis and the migration of magmatism at a rate of about 3 cm yr^{-1} (well determined for the interval 10–2 Ma) in a northeasterly direction (about N. 54° E.) to its culmination at Yellowstone (Pierce and Morgan, 1992) are in good agreement with independent global reconstructions that yield the absolute motion of the North American plate. (For example, see Stock and Molnar, 1988; Atwater, 1989.) Furthermore, the pattern of deformation and the amplitude and wavelength of the Yellowstone geoidal anomaly (about +10 m and 1,000 km, respectively) are similar to properties of hotspots worldwide (Crough, 1983; Sleep, 1990; Duncan and Richards, 1991), although most known examples occur over oceanic, rather than continental crust. The St. George zone is only weakly delineated as a magmatic belt but, together with the western Grand Canyon area, shows a distinct northeasterly younging (as documented, for instance, by Nealey and Sheridan, 1989, and by unpublished data of Nealey). This zone follows the northeasterly trend of the Intermountain Seismic Belt, which bifurcates in central Utah, one branch continuing northeasterly (fig. 4); the zone may also mark a mini-plate boundary (Suppe and others, 1975). The Springerville-Jemez-Raton zone, which extends from near the middle of Arizona's eastern border across northern New Mexico into southern Colorado (Chapin and others, 1978; Smith and Luedke, 1984), exhibits no systematic age migration as a whole (Lipman, 1980), but within each discrete field of the zone the age progression is northeasterly (Nealey, oral commun., 1995). Magmatism in these latter two zones appears to be more diffusely distributed than on the well-defined Snake River Plain axis, but in all three cases, the fundamental structural control may consist of first-order preexisting tectonic lineaments oriented approximately in the direction of absolute motion of the lithosphere.

Interpretation of the long-wavelength Cordilleran topographic/gravity anomaly as an upwelling of hot asthenospheric material, or a very broad mantle plume, provides a genetic linkage for the three northeast-trending Humphreys-Dueker low-velocity and magmatic zones, and places the Yellowstone hotspot and its presumed source plume in a wider context. The proposition that several hotspots can be identified in the Cordillera is discussed elsewhere in this volume (see Mutschler and others). Hotspot magmatism is attributed to decompression melting of asthenospheric mantle ascending in a narrow conduit ("chimney") above a fixed plume (Duncan and Richards, 1991; Richards and others, 1989; see also White and McKenzie, 1989). There is no apparent *a priori* reason why a broad plume head should not produce multiple chimneys, provided favorable structural environments are present. It seems possible that extensional faults peripheral to the Colorado Plateau, particularly where they intersect major structural flaws in the basement complex, could facilitate egress of magma. For the Basin and Range province it has been shown that magmatism is most closely related in space and time to crustal extension of 100 percent or more (Leeman and Harry, 1993). Thus the relatively weak magmatic activity on the Colorado Plateau (in contrast to that on its periphery) may be due to a lack of adequate crustal preconditioning. (See, for example, Best and Christiansen, 1991.)

Whereas a very broad mantle upwelling (plume) may be the ultimate source of Cordillera-wide Neogene uplift and bimodal magmatism, the existence of such a feature prior to about 17 Ma is highly speculative, and any connection with earlier post-Laramide deformation and magmatism is tenuous. The timing of early uplift on the plateau is also uncertain (Lucchitta, 1979). Most workers agree that the Colorado Plateau and its surroundings were uplifted only a kilometer or so during post-Laramide Paleogene time—probably in the Oligocene, coinciding with voluminous magmatism in neighboring areas (Hunt, 1969; Bird, 1988). This amount of uplift contrasts with Neogene uplift that has probably exceeded 3 km.

Products of Laramide (Late Cretaceous to early Eocene) to mid-Tertiary magmatism peripheral to the plateau typically have calc-alkaline affinities (Steven, 1975; Lipman and others, 1978; Lipman, 1981; Rowley and others, this volume) and are likely derived from partial melting of the mantle lithosphere together with crustal anatexis, which suggests a close association with Laramide subduction. In contrast, many Neogene bimodal products throughout the

Cordilleran region have asthenospheric signatures, particularly those products emplaced within the last 6 million years. (See Fitton and others, 1991, for example.) This suggests a deeper origin of the later products, and a temporal evolution of crust-mantle plutonism related to the evolution of the postulated mantle plume. The plume need not have originated as deep as the core-mantle boundary (see Anderson, 1994; but also see Grand, 1994, and Zhong and Gurnis, 1995), but seems likely to have involved large-scale overturning in a deep-mantle convection system in conjunction with several hundred million years of east-dipping subduction (as reviewed by Atwater, 1989) beneath what is now western North America.

SUMMARY AND CONCLUSIONS

1. Regional gravity anomalies and, less distinctly, regional aeromagnetic anomalies over the Colorado Plateau primarily reflect relief on the surface of the Precambrian basement as determined from stratigraphic data, borehole data, and seismic reflection picks, rather than basement inhomogeneity. In the plateau interior, this relief is a result mainly of Laramide compression.

2. Gravity and aeromagnetic anomaly fields of the northern Colorado Plateau and vicinity delineate northwest- and northeast-trending structures that correspond to the well-known Paradox Basin and Colorado lineament trends, respectively, and transect the plateau and its environs.

3. The nearly east-west Pioche-Marysvale and San Juan anomaly trends strike into the plateau from either side but do not appear to transect the plateau interior, although they are essentially collinear with one another and with the 38th Parallel lineament. The plateau thus may represent a major hiatus in east-west-trending magmatic and hydrothermal activity brought about through a lack of adequate “tectonic conditioning.”

4. Other anomaly trends in the vicinity of the northern plateau delineate arcuate structures that wrap around the plateau and its margins. Many of these structures were initially compressional but have subsequently been reactivated with normal (extensional) movement; others are purely extensional. Taken together they suggest a radial outward extension of the plateau as a whole relative to the plateau interior. A northwest-trending structural depression connecting the northern Rio Grande Rift with the Piceance Creek Basin is a key element of the circumferential pattern.

5. Radial outward extension is in general agreement with least-principal-stress orientations for the late Cenozoic as determined from other indicators.

6. The Colorado Plateau is situated near the crest of the long-wavelength topographic high and Bouguer gravity anomaly low of the U.S. western interior. Radial outward extension of the plateau may be primarily a manifestation of gravitational collapse and lateral spreading penecontemporaneous with some 3 km of Neogene uplift.

7. The preceding (mid-Tertiary) uplift amounted to only about a third as much but may have initiated radial extension; the swath of arcuate normal faults around the northern plateau includes loci of voluminous mid-Tertiary magmatism in crust that perhaps has been “tectonically conditioned” on the plateau periphery.

8. The interior Cordilleran topographic high/gravity low, in turn, is probably caused by upwelling of relatively hot, light asthenosphere—a broad mantle “plume.” Rise of the plume produced the Alvarado Ridge of Colorado and New Mexico and the Yellowstone hotspot in the Neogene, and the changing character of the plume promoted the evolution of crust-mantle magmatism from calc-alkaline to bimodal in character during middle to late Cenozoic time, as subduction-related processes came to be dominated by deep-mantle convection.

REFERENCES CITED

Abrams, Gerda, 1993, Complete Bouguer gravity anomaly map of the state of Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF–2263, scale 1:500,000.

Aiken, C.L.V., 1975, Residual Bouguer gravity anomaly map of Arizona: Arizona University Geophysical Lab., Tucson, Ariz., scale 1:1,000,000.

Aldrich, M.J., Jr,. 1986, Tectonics of the Jemez lineament in the Jemez Mountains and Rio Grande rift: Journal of Geophysical Research, 91, p. 1753–1762.

Allenby, R.J., and Schnetzler, C.C., 1983, United States crustal thickness: Tectonophysics, v. 93, p. 13–31.

Anderson, D.L., 1994, Superplumes or supercontinents?: Geology, v. 22, p. 39–42.

Anderson, D.L., Tanimoto, T., and Zhang, Y.-S., 1992, Plate tectonics and hotspots: Science, v. 256, p. 1645–1651.

Atwater, Tanya, 1989, Plate tectonic history of the northeast Pacific and western North America, *in* Winterer, E.L., Hussong, D.M., and Decker, R.W., eds., The Geology of North America; DNAG Series, v. N: The Eastern Pacific Ocean and Hawaii: Boulder, Colo., Geological Society of America, p. 21–72.

Bartsch-Winkler, Susan, Barton, H.N., Cady, J.W., Cook, K.L., and Martin, C.M., 1988, Mineral resources of the Fifty Mile Mountain Wilderness Study Area, Kane County, Utah: United States Geological Survey Bulletin 1747–A, 20 p.

Bayer, K.C., 1983, Generalized structural, lithologic, and physiographic provinces in the fold and thrust belts of the United States (exclusive of Alaska and Hawaii): Washington, D.C., U.S. Geological Survey, map scale 1:2,500,000 (3 sheets).

Bayley, R.W., and Muehlberger, W.R., 1968, Basement rock map of the United States exclusive of Alaska and Hawaii: Washington, D.C., U.S. Geological Survey, scale 1:2,500,000 (2 sheets).

Beghoul, N., and Barazangi, M., 1989, Mapping hi P_n velocity beneath the Colorado Plateau constrains uplift models: Journal of Geophysical Research 94, v. B6, p. 7083–7104.

Best, M.G., and Christiansen, E.H., 1991, Limited extension during peak Tertiary volcanism, Great Basin of Nevada and Utah: Journal of Geophysical Research, v. 96, no. B8, p. 13509–13528.

Bird, Peter, 1979, Continental delamination and the Colorado Plateau: Journal of Geophysical Research, v. 84, no. B13, p. 7561–7571.

———1984, Laramide crustal thickening event in the Rocky Mountain foreland and Great Plains: Tectonics 3, p. 741–758.

———1988, Formation of the Rocky Mountains, western United States—A continuum computer model: Science, v. 239, p. 1501–1507.

Blakely, R.J., and Simpson, R.W., 1986, Approximating edges of source bodies from magnetic or gravity anomalies: Geophysics, v. 51, no. 7, p. 1494–1498.

Bowring, S.A., and Karlstrom, K.E., 1990, Growth, stabilization and reactivation of Proterozoic lithosphere in the southwestern United States: Geology, v. 18, p. 1203–1206.

Bryant, Bruce, and Nichols, D.J., 1988, Late Mesozoic and Early Tertiary reactivation of an ancient crustal boundary along the Uinta trend and its interaction with the Sevier orogenic belt: p. 411–430 *in* Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of the Rocky Mountains Foreland and the Cordilleran Thrust Belt: Geological Society of America Memoir 171, 582 p.

Butler, W.C., 1991, Elevation data for the Precambrian surface in the central and southern Colorado Plateau and vicinity: U.S. Geological Survey Open-File Report 92–194, 75 p., with map, scale 1:1,250,000.

Butler, W.C., and Kirkpatrick, J.C., in press, Topographic contour map on top of Precambrian age rocks, central and southern Colorado Plateau and vicinity: U.S. Geological Survey Miscellaneous Field Studies Map MF–2310.

Case, J.E., 1965, Gravitational evidence for a batholithic mass of low density along a segment of the Colorado Mineral Belt: Geological Society of America Special Paper 82, Abstracts for 1964, p. 26.

Case, J.E., and Joesting, H.R., 1972, Regional geophysical investigations in the central Colorado Plateau: U.S. Geological Survey Professional Paper 736, 31 p.

Chapin, C.E., Chamberlin, R.M., Osburn, G.R., White, D.W., and Sanford, A.R., 1978, Exploration framework of the Socorro geothermal area, New Mexico: p. 115–130, *in* Chapin, C.E., and Elston, W.E., eds., Field guide to selected cauldrons and mining districts of the Datil-Mogollon volcanic field, New Mexico: New Mexico Geological Society Special Paper 7.

Committee for the Magnetic Anomaly Map of North America, 1987, Magnetic anomaly map of North America: Geological Survey of America, 4 sheets, scale 1:5,000,000.

Committee for the Magnetic Anomaly Map of North America, 1993, Magnetic anomaly map of part of the conterminous United States and some adjacent parts of Canada, scale 1:5,000,000; plate 3 *in* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., eds., DNAG Series, The Geology of North America, vol. C–2, Precambrian—Conterminous U.S.: Boulder, Colo., Geological Society of America, 657 p.

Condie, K.C., 1964, Crystallization Po_2 of syenite porphyry from Navajo Mountain, southern Utah: Geological Society of America Bulletin, v. 75, p. 359–362.

Coney, P., 1976, Plate tectonics and the Laramide orogeny: New Mexico Geological Society Spec. Publication 6, p. 5–10.

Cook, K.L., Bankey, Viki, Mabey, D.R., and DePangher, Michael, 1989, Complete Bouguer gravity anomaly map of Utah: Utah Geological and Mineral Survey Map 122, scale 1:1,000,000.

Cordell, Lindrith, 1983, Composite residual total intensity aeromagnetic map of New Mexico: New Mexico State University Energy Institute, Geothermal Resources of New Mexico—Scientific Map Series, overlay 2, scale 1:500,000. (Available from National Geophysical Data Center, Boulder, CO, 80303, as report 84–TGB–05.)

Cordell, Lindrith, and Keller, G.R., 1984, Regional structural trends inferred from gravity and aeromagnetic data in the New Mexico–Colorado border region, *in* New Mexico Geological Society Guidebook 35, p. 21–23.

Cordell, Lindrith, Keller, G.R., and Hildenbrand, T.G., 1982, Bouguer gravity anomaly map of the Rio Grande rift, Colorado, New Mexico, and Texas: U.S. Geological Survey Geophysical Investigations Map GP–949, scale 1:1,000,000.

Cosca, M.A., Essene, E.J., Geissman, J.W., Simmons, W.B., and Coates, D.A., 1989, Pyrometamorphism of rocks associated with natural burns in coal seams, Powder River Basin: American Mineralogist, v. 74, p. 85–100.

Crough, T.S., 1983, Hotspot swells, *in* Wetherill, G.W., Arden, A.L., and Stehli, F.G., eds., Annual Review of Earth and Planetary Sciences, v. 11, 1983: Palo Alto, Calif., Annual Reviews, Inc., p. 165–194.

Davis, G.H., 1978, Monoclinal fold pattern of the Colorado Plateau: p. 215–234 *in* Matthews, Vincent III, ed., Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, 370 p.

Dueker, K.G., and Humphreys, E.D., 1990, Upper-mantle velocity structure of the Great Basin: Geophys. Research Letters, v. 17, p. 1327–1330.

Duncan, R.A., and Richards, M.A., 1991, Hotspots, mantle plumes, flood basalts, and true polar wander: Reviews of Geophysics, v. 29, p. 31–50.

Eaton, G.P., 1979, A plate-tectonic model for late Cenozoic crustal spreading in the western United States, p. 7–32 *in* Riecker, R.E., ed., 1979, Rio Grande Rift—Tectonics and magmatism: Washington, D.C., American Geophysical Union, 438 p.

Eaton, G.P., 1986, A tectonic redefinition of the Southern Rocky Mountains: Tectonophysics, v. 132, p. 163–194.

———1987, Topography and origin of the southern Rocky Mountains and Alvarado Ridge, p. 355–369 *in* Coward, M.P., Dewey, J.F., and Hancock, P.L., eds., Continental extension tectonics: Geological Society of London, Special Publication 28, 637 p.

Eaton, G.P., Wahl, R.R., Protska, H.J., Mabey, D.R., and Kleinkopf, M.D., 1978, Regional gravity and tectonic patterns—Their relation to late Cenozoic epeirogeny and lateral spreading in the western Cordillera, p. 51–92 *in* Smith, R.B., and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics of the Western Cordillera: Geological Society of America Memoir 152, 388 p.

Engebretson, D.C., Cox, Allan, and Thompson, G.A., 1984, Correlation of plate motions with continental tectonics—Laramide to Basin and Range: Tectonics, v. 3, no. 2, p. 115–119.

Fitton, J.G., James, Dodie, and Leeman, W.P., 1991, Basic magmatism associated with late Cenozoic extension in the western United States—Compositional variations in space and time: Journal of Geophysical Research, v. 96, no. B8, p. 13693–13711.

Frahme, C.W., and Vaughn, E.B., 1983, Proterozoic geology and seismic stratigraphy of the northern Uncompahgre front, Grant County, Utah: p. 201–211 *in* Lowell, J.D., ed., Rocky Mountain Foreland Basins and Uplifts: Denver, Colo., Rocky Mountain Association of Geologists, 392 p.

Grand, S.P., 1994, Mantle shear structure beneath the Americas and surrounding oceans: Journal of Geophysical Research, v. 99, no. B6, p. 11591–11621.

Gries, Robbie, 1983, North-south compression of Rocky Mountain structures: p. 9–32 *in* Lowell, J.D., ed., Rocky Mountain foreland basins and uplifts: Denver, Colo., Rocky Mountain Association of Geologists, 392 p.

Hamilton, W.B., 1981, Plate-tectonic mechanism of Laramide deformation, *in* Boyd, D.W., and Lillegraven, J.A., eds., Rocky Mountain foreland basement tectonics: University of Wyoming Contributions to Geology, v. 19, p. 87–92.

Hamilton, W.B., 1988, Laramide crustal shortening, *in* Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of the Rocky Mountains Foreland and the Cordilleran Thrust Belt: Geological Society of America Memoir 171, p 27–39.

Hamilton, W.B., 1989, Crustal geologic processes of the United States, *in* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the Continental United States: Geological Society of America Memoir 172, p. 743–782.

Hansen, W.R., 1986, History of faulting in the eastern Uinta Mountains, Colorado and Utah, p. 5–17 *in* Stone, D.S., ed., New interpretations of Northwestern Colorado geology: Denver, Colo., Rocky Mountain Association of Geologists, 308 p.

Hasbrouck, W.P., and Hadsell, F.A., 1978, Geophysical techniques for coal exploration and development, p. 187–218 *in* Hodgson, H.E., ed., Proceedings of the Second Symposium on the Geology of Rocky Mountain Coal—1977: Denver, Colo., Colorado Geological Survey, Department of Resources.

Hauser, E.C., and Lundy, J., 1989, COCORP deep reflections—Moho at 50 km (16s) beneath the Colorado Plateau: Journal of Geophysical Research, v. 94, no. B6, p. 7071–7081.

Heyl, A.V., 1972, The 38th Parallel lineament and its relation to ore deposits: Economic Geology, v. 67, p. 879–894.

———1983, Some major lineaments reflecting deep-seated fracture zones in the central United States, and mineral districts related to the zones, p. 75–89 *in* Global Tectonics and Metallogeny, v. 2, nos. 1 & 2.

Hildenbrand, T.G., and Kucks, R.W., 1988, Filtered magnetic anomaly maps of Nevada: Nevada Bureau of Mines and Geology Map 93B, scales 1:1,000,000 and 1:2,500,000 (5 sheets).

Hildenbrand, T.G., Simpson, R.W., Godson, R.H., and Kane, M.F., 1982, Digital colored residual and regional Bouguer gravity maps of the conterminous United States with cut-off wavelengths of 250 km and 1000 km: U.S. Geological Survey Geophysical Investigations Map GP–953–A, scale 1:7,500,000 (2 sheets).

Hintze, L.F., 1975, Geological highway map of Utah: Provo, Utah, Brigham Young University, scale 1:1,000,000.

Hintze, L.F., compiler, 1980, Geologic map of Utah: Salt Lake City, Utah, Utah Geological and Mineral Survey, scale 1:500,000 (2 sheets).

Humphreys, E.D., and Dueker, K.G., 1994a, Western United States upper mantle structure: Journal of Geophysical Research, v. 99, no. B5, p. 9615–9634.

———1994b, Physical state of the western U.S. upper mantle: Journal of Geophysical Research, v. 99, no. B5, p. 9635–9650.

Hunt, C.B., 1956, Cenozoic geology of the Colorado Plateau: U.S. Geological Survey Professional Paper 279, 99 p.

———1969, Geologic history of the Colorado River: U.S. Geological Survey Professional Paper 669–C, p. C59–C130.

Isacks, B.L., and Barazangi, Muawia, 1977, Geometry of Benioff zones—Lateral segmentation and downward bending of the subducted lithosphere, *in* Talwani, Manik, and Pitman, W.C., III, eds., Island arcs, deep sea trenches and back-Arc basins: Washington, D.C., American Geophysical Union, p. 99–111.

Izett, G.A., 1975, Late Cenozoic sedimentation and deformation in northern Colorado and adjoining areas, p. 179–209 *in* Curtis, B.F., ed., Cenozoic History of the Southern Rocky Mountains: Geological Society of America Memoir 144, 279 p.

Jachens, R.C., Simpson, R.W., Blakely, R.J., and Saltus, R.W., 1993, Isostatic residual gravity map of the conterminous United States and some adjacent parts of Canada, scale 1:5,000,000, Plate 4 *in* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., 1993, eds., The Geology of North America, vol. C–2, Precambrian: Conterminous U.S.: Boulder, Colo., Geological Society of America, 657 p.

Joesting, H.R., and Case, J.E., 1960, Salt anticlines and deep-seated structures in the Paradox basin, Colorado and Utah, *in* Short papers in the geological sciences: U.S. Geological Survey Professional Paper 400–B, p. B252–B256.

Joesting, H.R., and Plouff, Donald, 1958, Geophysical studies of the Upheaval Dome area, San Juan County, Utah, p. 86–92 *in* Sanborn, A.F., ed., International Association of Petroleum Geologists Ninth Annual Field Conference: Guidebook to the Geology of the Paradox Basin, 308 p.

Johnson, R.C., and Finn, T.M., 1986, Cretaceous through Holocene history of the Douglas Creek arch, Colorado and Utah, p. 75–77 *in* Stone, D.S., ed., New interpretations of Northwestern Colorado Geology: Denver, Colo., Rocky Mountain Association of Geologists, 308 p.

Kane, M.F., and Godson, R.H., 1989, A crust/mantle structural framework of the conterminous United States based on gravity and magnetic trends, p. 383–404 *in* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the Continental United States: Geological Society of America Memoir 172, 826 p.

Keller, G.R., and Cordell, Lindrith, 1983, Bouguer gravity anomaly map of New Mexico: New Mexico State University Energy Institute, Geothermal Resources of New Mexico—Scientific Map Series, overlay 1, scale 1:500,000. (Available from National Geophysical Data Center, Boulder, CO 80303, as report 84–TGB–05.)

Larson, E.E., Patterson, P.E., Curtis, G., Drake, R., and Mutschler, F.E., 1985, Petrologic, paleomagnetic, and structural evidence of a Proterozoic rift system in Oklahoma, New Mexico, Colorado and Utah: Geological Society of America Bulletin, v. 96, no. 11, p. 1364–1372.

Leeman, W.P., and Harry, D.L., 1983, A binary source model for extension-related magmatism in the Great Basin, western North America: Science, v. 262, p. 1550–1554.

Lidiak, E.G., and Zietz, Isidore, 1976, Interpretation of aeromagnetic anomalies between latitude 37°N and 38°N in eastern and central United States: Geological Society of America Special Paper 167, 37 p.

Lipman, P.W., 1980, Cenozoic volcanism in the western United States—Implications for continental tectonics, p. 161–174 *in* Studies in geophysics—Continental tectonics: Washington, D.C., National Academy of Sciences.

———1981, Volcano-tectonic setting of Tertiary ore deposits, southern Rocky Mountains, p. 199–213 *in* Dickinson, W.R., and Payne, W.D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14.

Lipman, P.W., Doe, B.R., Hedge, C.E., and Steven, T.A., 1978, Petrologic evolution of the San Juan volcanic field, southwestern Colorado—Pb and Sr isotopic evidence: Geological Society of America Bulletin, v. 89, p. 59–82.

Livacarri, R.F., Burke, Kevin, and Sengor, A.M.C., 1981, Was the Laramide orogeny related to subduction of an oceanic plateau?: Nature, v. 289, p. 276–278.

Lovering, T.S., and Goddard, E.N., 1950, Geology and ore deposits of the Front Range, Colorado: U.S. Geological Survey Professional Paper 223, 319 p.

Lowell, J.D., 1974, Plate tectonics of foreland basement deformation: Geology, v. 2, p. 275–278.

Lucchitta, Ivo, 1979, Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent lower Colorado River region: Tectonophysics, v. 61, p. 63–95.

Mabey, D.R., and Budding, K.E., 1987, High-temperature geothermal resources of Utah: Utah Geological and Mineral Survey Bulletin 123.

Mattox, R.B., 1975, Upheaval Dome, a possible salt dome in the Paradox Basin, Utah, p. 225–234 *in* Fassett, J.E., ed., Canyonlands Country: Four Corners Geological Society Guidebook, Eighth Field Conference, 281 p.

McGetchin, T.R., and Merrill, R.B., eds., 1979, Plateau uplift—Mode and mechanism: Tectonophysics (special issue), v. 61, 336 p.

Milbert, D.G., 1991, GEOID90—A high-resolution geoid for the United States: EOS, v. 72, no. 49, p. 545, 554.

Morgan, P., and Swanberg, C.A., 1985, On the Cenozoic uplift and tectonic stability of the Colorado Plateau: Journal of Geodynamics, v. 3, p. 39–63.

Morgan, W.J., 1972, Deep mantle convection plumes and plate motions: American Association of Petroleum Geologists Bulletin, v. 56, p. 203–213.

Muehlberger, W.R., compiler, 1992, Tectonic map of North America: Tulsa, Okla., American Association of Petroleum Geologists, scale 1:5,000,000 (2 sheets).

Nealey, L.D., and Sheridan, M.F., 1989, Post-Laramide volcanic rocks of Arizona and northern Sonora, Mexico, and their inclusions, p. 609–647 *in* Jenny, J.P., and Reynolds, S.J., eds., Geological evolution of Arizona: Tucson, Arizona, Arizona Geological Society Digest, v. 17.

Nelson, S.T., Davidson, J.P., and Sullivan, K.R., 1992, New age determinations of central Colorado Plateau laccoliths, Utah; Reorganizing disturbed K-Ar systematics and re-evaluating tectonomagmatic relationships: Geological Society of America Bulletin, v. 104, no. 12, p. 1547–1560.

New Mexico Geological Society, 1982, New Mexico highway geologic map: Socorro, N. Mex., New Mexico Bureau of Mines and Mineral Resources, scale 1:1,000,000.

Pakiser, L.C., and Mooney, W.D., eds., 1989, Geophysical framework of the Continental United States: Geological Society of America Memoir 172, 826 p.

Pang, Ming, and Nummedal, Dag, 1995, Flexural subsidence and basement tectonics of the Cretaceous Western Interior basin, United States: Geology, v. 23, no. 1, p. 173–176.

Parsons, Tom, and McCarthy, Jill, 1995, The active southwest margin of the Colorado Plateau: uplift of mantle origin: Geological Society of America Bulletin, v. 107, no. 2, p. 139–147.

Parsons, Tom, Thompson, G.A., and Sleep, N.H., 1994, Mantle plume influence on the Neogene uplift and extension of the U.S. western Cordillera?: Geology, v. 22, p. 83–86.

Pierce, K.L., and Morgan, L.A., 1992, The track of the Yellowstone hot spot: Volcanism, faulting, and uplift, p. 1–53 *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, 322 p.

Plouff, Donald, and Pakiser, L.C., 1972, Gravity study of the San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 800–B, p. B183–B190.

Prodehl, Claus, and Lipman, P.W., 1989, Crustal structure of the Rocky Mountain region, p. 249–284 *in* Pakiser, L.C., and Mooney, W.D., eds., Geophysical Framework of the Continental United States: Geological Society of America Memoir 172, 826 p.

Reed, J.C., Jr., 1993, compiler, Precambrian rocks of the conterminous United States, scale 1:5,000,000, Plate 1 *in* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., 1993, eds., The Geology of North America, vol. C–2, Precambrian; Conterminous U.S.: Boulder, Colo., Geological Society of America, 657 p.

Reynolds, S.J., 1988, Geologic map of Arizona: Arizona Geological Survey Map 26, scale 1:1,000,000.

Richards, M.A., Duncan, R.A., and Courtillot, V.E., 1989, Flood basalts and hot spot tracks; Plume heads and tails: Science, v. 246, p. 103–107.

Rowley, P.D., Lipman, P.W., Mehnert, H.H., Lindsey, D.A., and Anderson, J.J., 1978, Blue Ribbon lineament, an east-trending structural zone within the Pioche mineral belt of southwestern Utah and eastern Nevada: U.S. Geological Survey Journal of Research, v. 6, no. 2, p. 175–192.

Saltus, R.W., 1988, Regional, residual, and derivative gravity maps of Nevada: Nevada Bureau of Mines and Geology Map 94B, scales 1:1,000,000 and 1:2,500,000 (4 sheets).

Sauck, W.A., and Sumner, J.S., 1970a, Residual aeromagnetic map of Arizona: Tucson, Univ. of Arizona, scale 1:1,000,000.

_____1970b, Total intensity aeromagnetic map of New Mexico: Tucson, Univ. of Arizona, scale 1:1,000,000.

Sbar, M.L., and Sykes, L.R., 1973, Contemporary compressive stress and seismicity in eastern North America; An example of intraplate tectonics: Geological Society of America Bulletin 84, p. 1861–1882.

Schultz-Ela, D.D., Jackson, M.P.A., Hudec, M.R., Fletcher, R.C., Porter, M.L., and Watson, I.A., 1994, Constraints on the origin of Upheaval Dome, Paradox Basin, Utah: American

Association of Petroleum Geologists 1994 Annual Convention, Denver, Colorado, June 12–15, 1994, Abstracts with Programs, p. 253.

Shawe, D.R., and Stewart, J.H., 1976, Ore deposits as related to tectonics and magmatism, Nevada and Utah: American Inst. of Mining, Metallurgical, and Petroleum Engineers Transactions, v. 260, p. 225–232.

Shoemaker, E.M., and Henenhoff, K.E., 1984, Upheaval Dome impact structure, Utah [abs.]: Lunar and Planetary Science Conference, v. 15, pt. 2, p. 778–779.

Shoemaker, E.M., Squires, R.L., and Abrams, M.J., 1978, The Bright Angel and Mesa Butte fault systems of northern Arizona, p. 341–367 *in* Smith, R.B., and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics of the Western Cordillera: Geological Society of America Memoir 152, 388 p.

Shuey, R.T., Schellinger, D.K., Johnson, E.H., and Alley, L.B., 1973, Aeromagnetics and the transition between the Colorado Plateau and Basin Range provinces: Geology, v. 1, no. 11, p. 107–110.

Simpson, R.W., Hildenbrand, T.G., Godson, R.H., and Kane, M.F., 1987, Digital colored Bouguer gravity, free-air gravity, station location, and terrain maps for the conterminous United States: U.S. Geological Survey Geophysical Investigations Map GP–953–B, scale 1:7,500,000 (2 sheets).

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, p. 8348–8372.

Sleep, N.H., 1990, Hotspots and mantle plumes; Some phenomenology: Journal of Geophysical Research, v. 95, no. B5, p. 6715–6736.

Smith, R.B., and Braile, L.W., 1993, Topographic signature, space-time evolution, and physical properties of the Yellowstone–Snake River Plain volcanic system; The Yellowstone hotspot, p. 694–754 *in* Snoke, A.W., Steidtmann, J.R., and Roberts, S.M., eds., Geology of Wyoming: Geological Survey of Wyoming Memoir No. 5, 937 p.

Smith, R.B., Nagy, W.C., Julander, K.A. (Smith), Viveiros, J.J., Barker, C.A., and Gants, D.G., 1989, Geophysical and tectonic framework of the eastern Basin and Range—Colorado Plateau—Rocky Mountain transition, p. 205–234 *in* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the Continental United States: Geological Society of America Memoir 172, 826 p.

Smith, R.L., and Luedke, R.G., 1984, Potentially active volcanic lineaments and loci in western conterminous United States, p. 47–66 *in* Explosive volcanism—Inception, evolution, and hazards: Washington, D.C., National Academy Press, Studies in Geophysics, 176 p.

Steiner, M.B., 1986, Rotation of the Colorado plateau: Tectonics, v. 5, p. 649–660.

Steven, T.A., 1975, Middle Tertiary volcanic field in the Southern Rocky Mountains, p. 75–94 *in* Curtis, B.F., ed., Cenozoic history of the Southern Rocky Mountains: Geological Society of America Memoir 144, 279 p.

Steven, T.A., Rowley, P.D., and Cunningham, C.G., 1984, Calderas of the Marysvale volcanic field, west-central Utah: Journal of Geophysical Research, v. 89, no. B10, p. 8751–8764.

Stevenson, G.M., and Baars, D.L., 1986, The Paradox—A pull-apart basin of Pennsylvanian age, p. 513–539 *in* Peterson, J.A., Paleotectonics and sedimentation: American Association of Petroleum Geologists Memoir 41.

Stewart, J.H., 1978, Basin-range structure in western North America—A review, p. 1–32 *in* Smith, R.B., and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, 388 p.

Stewart, J.H., and Carlson, J.E., 1977, Geologic map of Nevada, one million scale set: Nevada Bureau of Mines and Geology Map 57, scale 1:1,000,000.

Stewart, J.H., and Carlson, J.E., compilers, 1978, Geologic map of Nevada: U.S. Geological Survey, scale 1:500,000 (2 sheets).

Stewart, J.H., Moore, W.J., and Zietz, Isidore, 1977, East-west patterns of Cenozoic igneous complexes, aeromagnetic anomalies, and mineral deposits: Geological Society of America Bulletin 88, p. 67–77.

Stock, J., and Molnar, P., 1988, Uncertainties and implications of the late Cretaceous and Tertiary position of North America relative to the Farallon, Kula and Pacific plates: Tectonics, v. 7, no. 6, p. 1339–1384.

Stokes, W.L., 1982, Geologic comparisons and contrasts, Paradox and Arapien Basins, p. 1–12 *in* Nielson, D.L., ed., Overthrust belt of Utah: 1982 Symposium and Field Conference: Salt Lake City, UT, Utah Geological Association Publication 10, 334 p.

Sullivan, K.R., Kowallis, B.J., and Mehnert, H.H., 1991, Isotopic ages of igneous intrusions in southeastern Utah—Evidence for a mid-Cenozoic Reno–San Juan magmatic zone: Brigham Young University Geology Studies, v. 37, p. 139–144.

Sumner, J.S., 1985, Crustal geology of Arizona as interpreted from magnetic, gravity, and geologic data, p. 164–180 *in* Hinze, W.J., ed., The utility of regional gravity and magnetic anomaly maps: Tulsa, Okla., Society of Exploration Geophysicists, 454 p.

Suppe, J., Powell, J.C., and Berry, R., 1975, Regional topography, seismicity, Quaternary volcanism and the present-day tectonics of the western United States: American Journal of Science, v. 275–A, p. 397–436.

Thompson, G.A., and Zoback, M.L., 1979, Regional geophysics of the Colorado Plateau: Tectonophysics, v. 61, p. 149–181.

Tweto, O.L., 1968, Geologic setting and interrelationships of mineral deposits in the mountain province of Colorado and south-central Wyoming, p. 551–558 *in* Ridge, J.D., ed., Ore deposits of the United States, 1933–1967 (Graton-Sales Volume): New York, American Institute of Mining, Metall., and Petroleum Engineers, v. 1, 991 p.

———1979a, Geologic map of Colorado: Reston, VA, U.S. Geological Survey, scale 1:500,000.

———1979b, The Rio Grande Rift system in Colorado, *in* Riecker, R.E., ed., 1979, Rio Grande Rift—Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 33–56.

———1980, Precambrian geology of Colorado, p. 37–46 *in* Kent, H.C., and Porter, K.W., eds., Colorado Geology: Denver, Colo., Rocky Mountain Association of Geologists, 258 p.

———1987, Rock units of the Precambrian basement in Colorado: U.S. Geological Survey Professional Paper 1321–A, 54 p.; with colored geologic map, scale 1:1,000,000.

Tweto, O.L., and Case, J.E., 1972, Gravity and magnetic features as related to geology in the Leadville 30-minute quadrangle, Colorado: U.S. Geological Survey Professional Paper 726–C, 31 p.

Tweto, O.L., and Sims, P.K., 1963, Precambrian ancestry of the Colorado Mineral Belt: Geological Society of America Bulletin, v. 74, v. 8, p. 991–1014.

Van der Voo, Rob, 1989, Paleomagnetism of North America; the craton, its margins, and the Appalachian Belt, p. 449–470 *in* Pakiser, L.C., and Mooney, W.D., eds., Geophysical Framework of the Continental United States: Geological Society of America Memoir 172, 826 p.

Verbeek, E.R., and Grout, M.A., 1993, Geometry and structural evolution of gilsonite dikes in the eastern Uinta Basin, Utah: United States Geological Survey Bulletin 1787–HH, 42 p.

Warner, L.A., 1978: The Colorado lineament: a middle Precambrian wrench fault system: Geological Society of America Bulletin 89, p. 161–171.

———1980, The Colorado lineament, *in* Kent, H.C., and Porter, K.W., eds., Colorado geology: Denver, Colo., Rocky Mountain Association of Geologists, p. 11–21.

Western Geographics/Colorado Geological Survey, 1991, Colorado geological highway map: Canon City, Colo., Western Geographics, scale 1:1,000,000.

Western Geographics/Geological Survey of Wyoming, 1991, Wyoming geological highway map: Canon City, Colo., Western Geographics, scale 1:1,000,000.

White, R.S., and McKenzie, D., 1989, Magmatism at rift zones; The generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, v. 94, p. 7685–7729.

Wilson, E.D., Moore, R.T., and Cooper, J.R., 1969, Geologic map of Arizona, scale 1:500,000: Washington, D.C., U.S. Geological Survey.

Wilson, J.T., 1973, Mantle plumes and plate motions: Tectonophysics, v. 19, p. 149–164.

Zhong, Shijie, and Gurnis, Michael, 1995, Mantle convection with plates and mobile, faulted plate margins: Science, v. 267, p. 838–843.

Zietz, Isidore, and Kirby, J.R., Jr., 1972a, Aeromagnetic map of Colorado: U.S. Geological Survey Geophysical Investigations Map GP–836, scale 1:500,000.

———1972b, Aeromagnetic map of Colorado: U.S. Geological Survey Geophysical Investigations Map GP–880, scale 1:1,000,000.

Zietz, Isidore, Shuey, Ralph, and Kirby, J.R., Jr., 1976, Aeromagnetic map of Utah: U.S. Geological Survey Geophysical Investigations Map GP–907, scale 1:1,000,000.

Zietz, Isidore, Stewart, J.H., Gilbert, F.P., and Kirby, J.R., Jr., 1977, Aeromagnetic map of Nevada: U.S. Geological Survey Miscellaneous Field Studies Map MF–902, scale 1:500,000 (2 sheets, with accompanying text).

Zoback, M.L., and Zoback, M.D., 1989, Tectonic stress field of the continental United States, p. 523–540 *in* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the Continental United States: Geological Society of America Memoir 172, 826 p.

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