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The Fate of the Colorado Plateau—A View from the Mantle

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ABSTRACT

The Colorado Plateau is bordered by five passive hot spots: a southward extension of the Great Falls tectonic zone, the Colorado mineral belt, the northern Rio Grande Rift, the Great Basin regional gravity low, and the southern Basin and Range province. Each hot spot represents mantle upwelling induced by lithospheric extension related to plate-tectonic events. Manifestations of these hot spots include thin crust and lithosphere, hot low-density upper mantle, volcanism resulting from decompression melting of the mantle, and regional arching and rifting. As the hot spots developed and enlarged they progressively reduced the size of the stable cratonic block now represented by the Colorado Plateau.

PASSIVE HOT SPOTS BORDERING THE COLORADO PLATEAU

The Colorado Plateau is an isolated block of the Proterozoic craton which is being reduced in size by the lateral encroachment of a ring of Late Cretaceous to Holocene passive hot spots (fig. 1). Three features are characteristic of these hot spots: (1) Regional geophysical anomalies (figs. 2 and 3) indicative of thin crust, thin lithosphere, low-density upper mantle, and high heat flow. (2) Young and/or active volcanism resulting from decompression melting of rising hot mantle. Volcanism tends to be younger outward from the apex of a static hot spot or along the trend of a migrating hot spot. (3) Regional doming or arching above a rising and expanding mantle bulge. Crustal extension and thinning causes axial rifting of the regional dome above the area of mantle upwelling.

Hot spots, in general, may be either (1) active, resulting from deep-seated asthenospheric mantle thermal plumes (fig. 4; Courtney and White, 1986), or (2) passive, resulting from subcrustal lithospheric thinning (fig. 5; Eaton, 1987). Assuming that active, deep-source mantle plumes tend to remain stationary over periods of tens of millions of years (Irvine, 1989), they should leave "volcanic tracks" on lithosphere plates that move across them, as did the Hawaiian hot spot on the Pacific plate (Clague, 1987). There is, however, little evidence of long-lived volcanic-chronologic tracks for the hot spots bordering the Colorado Plateau, suggesting that they are passive features. The loci of these hot spots appear to have remained essentially fixed to the southwestward-traveling North American plate for tens of millions of years, suggesting that they reside in the lithosphere or are mechanically coupled to it. This implies that if passive hot spots form at sites of significant subcrustal thinning, once they are initiated they may be self-sustaining and travel with the host lithospheric plate.

Various mechanisms have been suggested for large-scale thinning of the subcrustal continental lithosphere, including (1) differential shifting of lithospheric blocks resulting from plate movements (Mutschler and others, 1991), (2) isostatic rebound and gravitational collapse of tectonically thickened orogenic welts (Mutschler and others, 1987; Wernicke and others, 1987), (3) release of regional compressive stress upon termination of adjacent continental margin subduction (Scholz and others, 1971), (4) lithospheric erosion by asthenospheric advection (Eggler and others, 1988), (5) back-arc spreading (Thompson and Burke, 1974), (6) lithospheric delamination (Bird, 1979), (7) lithospheric weakening by mantle degassing (Bailey, 1970, 1978), and (8) lateral transfer of a "great wave" of lower crustal material from the coast to beneath a distant area, producing thickened crust (Bird, 1988). Whatever their ultimate cause, most of the Cordilleran passive hot spots we describe show initial magmatic crustal penetration controlled by regional crustal structures, including crustal province boundaries such as the Great Falls tectonic zone and ancient fault systems such as the Colorado mineral belt (fig. 6). As they evolve, however, these hot spots usually expand across crustal blocks and sutures (fig. 7), suggesting that their ultimate source resides at least as deep as the subcrustal lithosphere.

We will examine the magmatic, tectonic, and chronologic evolution of the five passive hot-spot loci marginal to, and encroaching on, the Colorado Plateau:

1. The Great Falls tectonic zone (GFTZ), active from ≈70 to 20(?) Ma.

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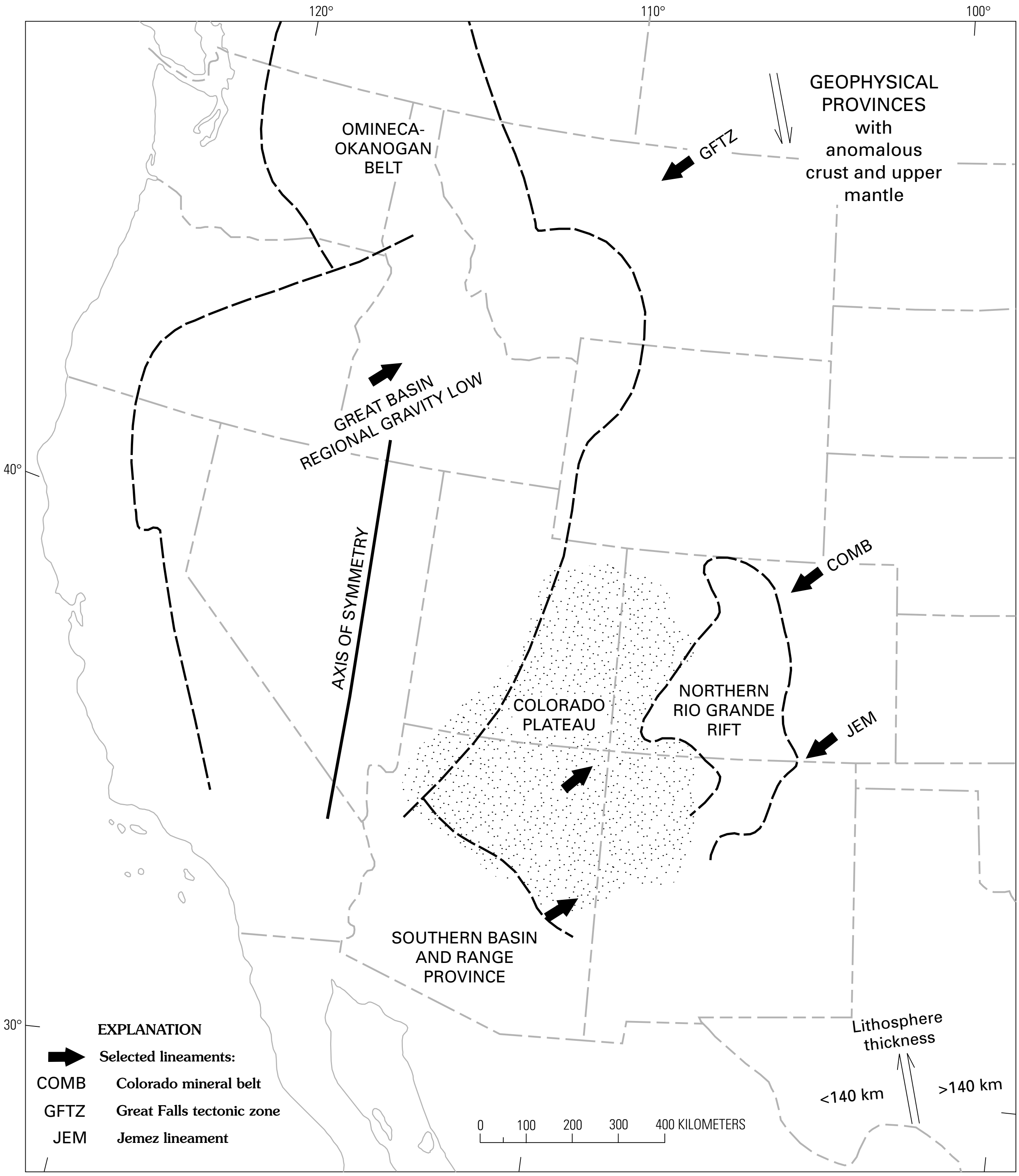


Figure 1. Relation of the Colorado Plateau to geophysical provinces characterized by crustal or upper mantle geophysical anomalies. Generalized axis of bilateral symmetry of observed Bouguer gravity and topography, in center of Great Basin regional gravity low, is from Eaton and others (1978, fig. 3–11–B). Colorado Plateau physiographic province (stippled) modified from Bayer (1983).

2. The Colorado mineral belt (COMB), active from ≈75 to 17(?) Ma.
3. The northern Rio Grande Rift (NRGR), starting at ≈35–26 Ma and active from ≈17 to 0 Ma.
4. The Great Basin regional gravity low (GBRGL), active from ≈17 to 0 Ma.
5. The southern Basin and Range province (SBR), active from ≈40 to 0 Ma.

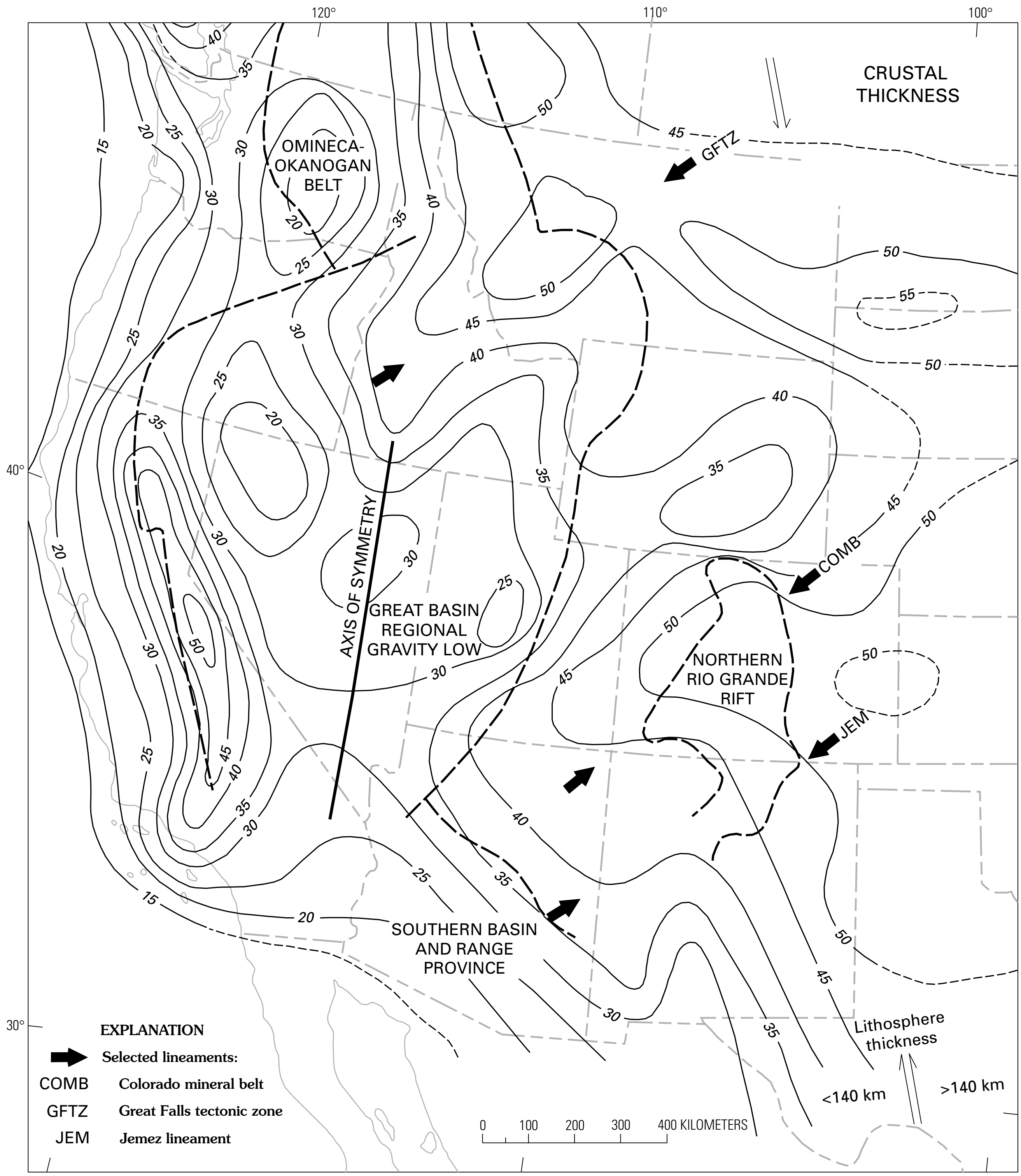


Figure 2. Crustal thickness in the Western United States. Contours show depth to reflection moho, in kilometers below sea level. See figure 1 for explanation of other lines and symbols. From Allenby and Schnetzler (1983, fig. 2).

GREAT FALLS TECTONIC ZONE (GFTZ)

The Late Cretaceous–Eocene central Montana alkaline province and the Eocene Challis volcanic field lie along the northeast-trending Great Falls tectonic zone (GFTZ), an ancient, repeatedly reactivated crustal flaw (O'Neill and Lopez, 1985), which essentially coincides with the northwest side of the Archean Wyoming province cratonic block (fig. 7).

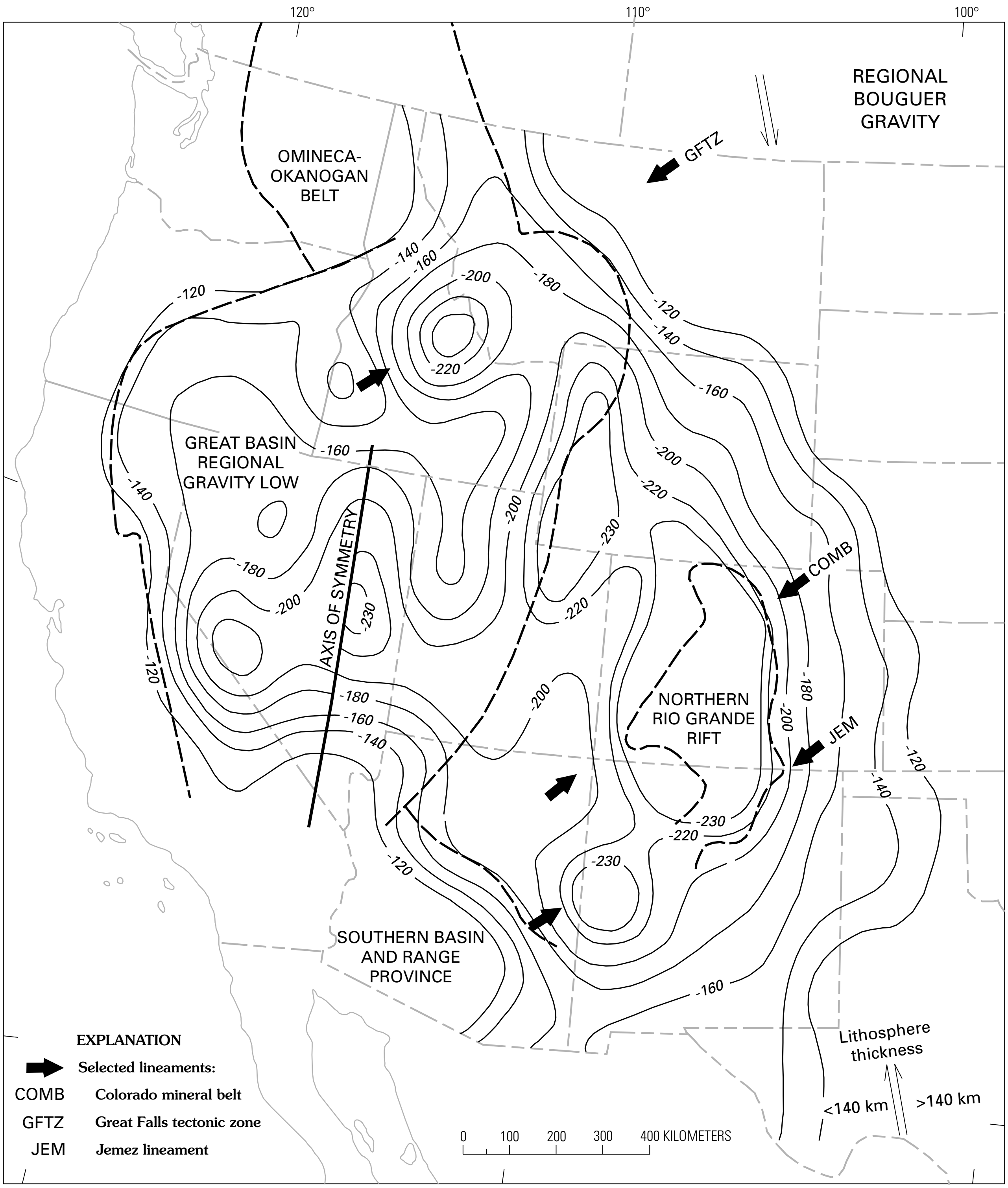


Figure 3. Regional Bouguer gravity of wavelengths greater than 250 km in the Western United States. Contours show gravity in milligals. See figure 1 for explanation of other lines and symbols. A comparison of this map with 1,000-km-filtered regional gravity maps (Hildenbrand and others, 1982) suggests that the major negative anomalies shown here represent low-density material at depths extending from the crust-mantle boundary to >125 km.

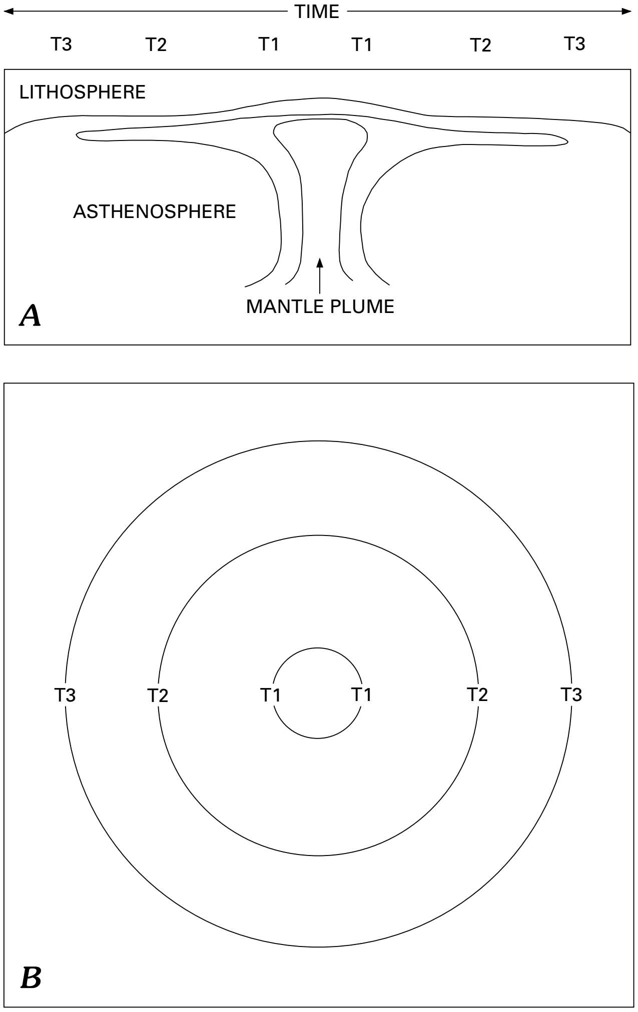


Figure 4. Development of an active hot spot over time. *A*, Generalized cross section showing temperature anomalies with respect to mean asthenosphere temperature in an axisymmetric convection model (after White and McKenzie, 1989, fig. 2). *B*, Map view showing isochrons with outward younging of inception of magmatism above an axisymmetric mantle plume. Similar isochron patterns may develop above passive hot spots.

The Late Cretaceous–early Tertiary tectonic setting of the Montana alkaline province and Challis volcanic field included the following elements as shown on figure 6:

1. A regional northeast-trending Eocene topographic dome defined on the basis of paleobotanical studies by Axelrod (1968). The axis of the dome was essentially coincident with the GFTZ.

2. Extensive Eocene (≈50–44 Ma) mildly alkaline shoshonitic to calc-alkaline magmatism in the Challis volcanic field (Moye, 1988; Norman and Mertzman, 1991) on the crest of the dome, and Late Cretaceous–Eocene (≈76–46 Ma) alkaline-dominated magmatism on the flanks of the dome and along its northeast projection—the central Montana alkaline province described by Larsen (1940) and many

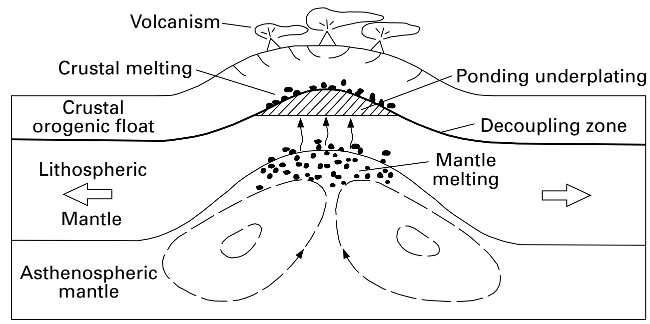


Figure 5. Cross section showing features of a passive hot spot resulting from subcrustal lithospheric thinning. Not to scale.

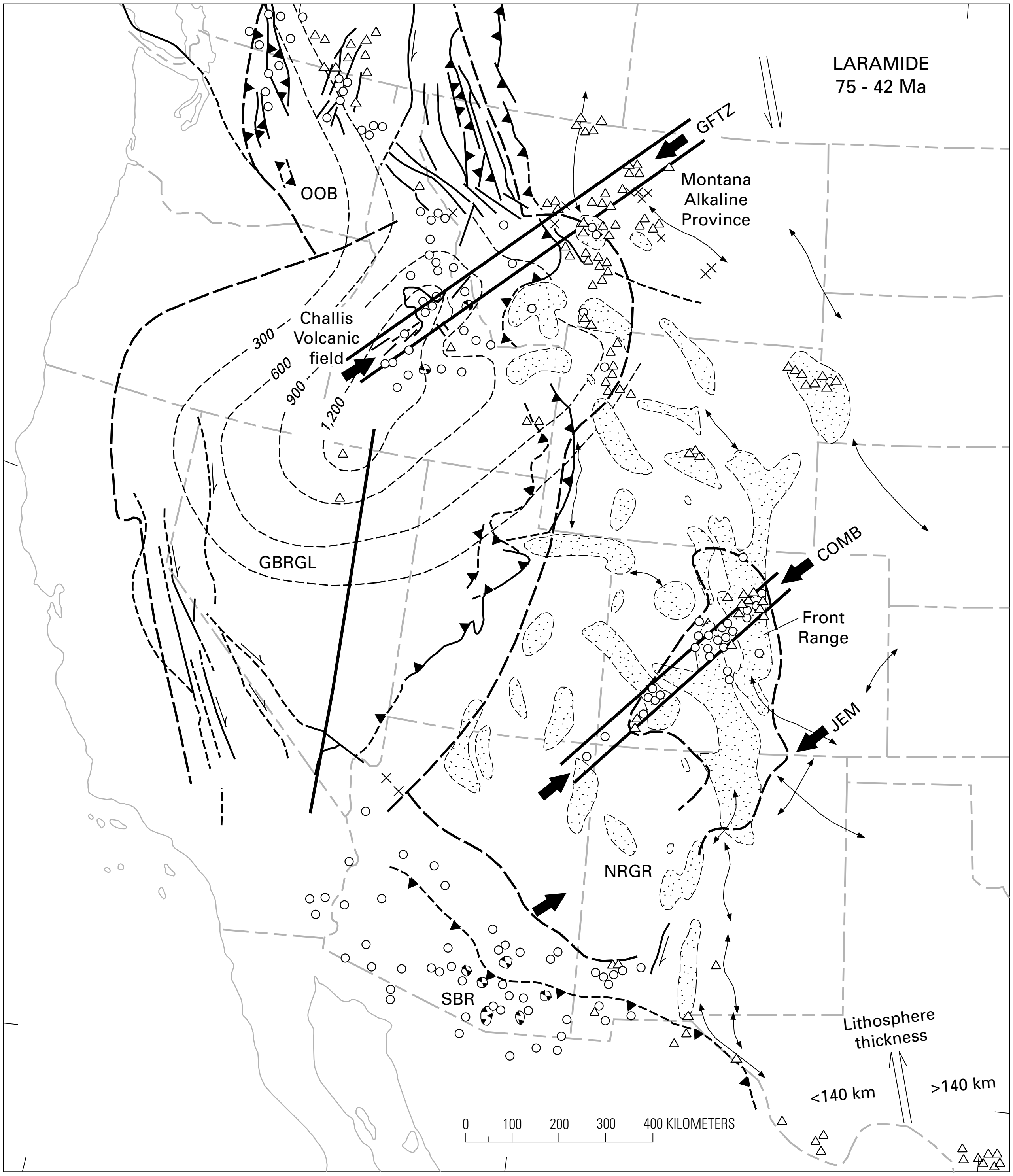
subsequent workers. (See papers in Baker and Berg, 1991, for instance.)

3. Synvolcanic axial rifting along the crest of the dome indicated by recurrent movements on the trans-Challis fault system, northeast-trending dike swarms and volcano-tectonic grabens and calderas (Moye, 1988).

These features can be integrated into a generalized model in which decompression melting of rising mantle yielded mafic alkaline magmas, some of which parked in the crust. These accumulated mantle melts triggered partial crustal melting, generating the voluminous calc-alkaline magmas of the Challis volcanic field, which are the surface manifestations of large batholithic bodies (Mabey and Webring, 1985). Surface doming resulted from both emplacement of the granite batholiths at shallow levels and deep-level upward movement of thermally expanded mantle. The areal extent of the plutonic and volcanic loci and the topographic dome is comparable to that of similar features that surround recognized modern mantle hot spots.

Mutschler and others (1991) suggested that this passive hot spot developed in response to an offset in large-scale northwest-trending Cretaceous strike-slip zones that resulted from oblique convergence of the North American and Pacific plates (fig. 8). The mid-Cretaceous to Paleocene right-lateral transcurrent faults of the Columbia tectonic belt extend southeastward from British Columbia (Oldow and others, 1989) but do not continue south of the GFTZ. Similar Mesozoic right-lateral transcurrent faults, however, are present south of the projection of the GFTZ, in the Central tectonic belt of eastern California and western Nevada (Kistler, 1990; Oldow and others, 1989). In both the Columbia and Central tectonic belts, late Mesozoic movement on the transcurrent structures amounted to hundreds of kilometers. Thus, the GFTZ may have acted as a transtensional zone, or releasing bend, between the Columbia and Central tectonic belt transcurrent systems. This

Figure 6 (facing page). Laramide (75–42 Ma) igneous rocks and selected tectonic elements in the Western United States. Modified from Mutschler and others (1987, fig. 4).



EXPLANATION

△	Alkaline igneous center		**Major lineament:**
×	Lamproites, kimberlites, and other lamprophyric rocks	COMB	Colorado mineral belt
○	Calc-alkaline igneous center	GBRGL	Great Basin regional gravity low
	Calc-alkaline caldera	GFTZ	Great Falls tectonic zone
	Rocky Mountain uplift	JEM	Jemez lineament
	Frontal Laramide thrust fault—sawteeth on upper plate	NRGR	Northern Rio Grande Rift
	High-angle faults—dashed where concealed or inferred	OOB	Omineca-Okanogan belt
	Paleotopographic contours, in meters (Modified from Axelrod (1968)	SBR	Southern Basin and Range Province

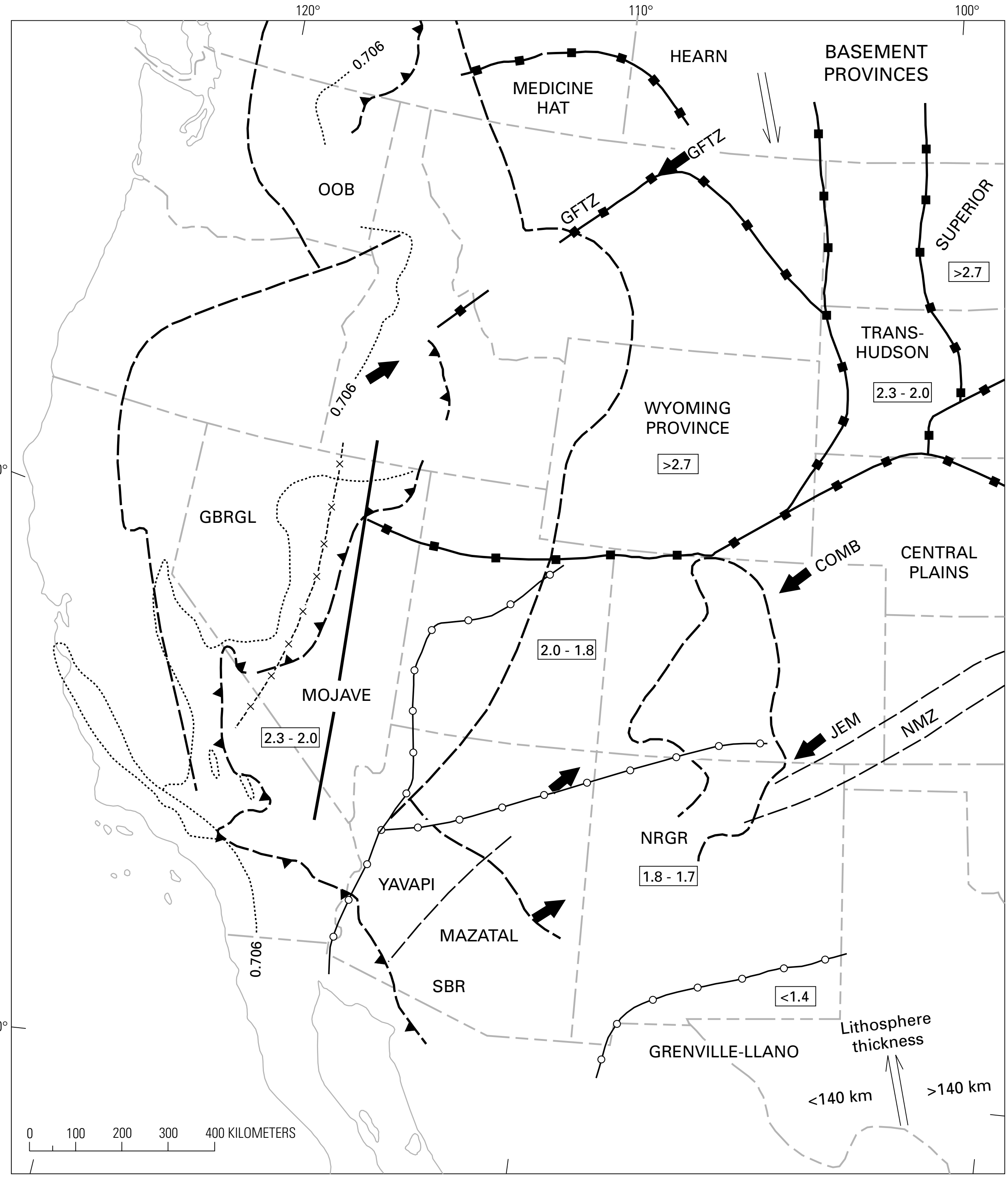


Figure 7 (above and facing page). Crustal provinces of the Western United States.

model is diagrammed in figure 8*B*, showing lithospheric mantle extension across the GFTZ axis beneath a decoupling zone. If the decoupling zone were fairly deep, evidence of the event in the crustal "orogenic float" could be sparse. Extension (shown in fig. 8*B* as occurring by pure shear) would have thinned the lithospheric mantle, resulting in upflow of hot deeper (asthenospheric) mantle. The influx of thermal energy, and perhaps magma, into the extended lithosphere would have set off the sequence of decompression melting, diapiric magma rise, local crustal

EXPLANATION

▲— —▲	Edge of terranes accreted in the Phanerozoic—sawteeth on outboard side
■——■	Major crustal province, or orogen, boundary (suture zone)
CBZ	Cheyenne belt suture zone (1.8 - 1.7 Ga)
GFTZ	Great Falls tectonic zone (≈1.8 Ga)
— — —	Second order crustal province boundary
NMZ	New Mexico-Michigan zone. Possible northern edge of 1.65 Ga accredted terranes. Based on filtered gravity data. Modified from van Schmus and others (1987)
....	Initial $^{87}Sr/^{86}Sr$ isopleth = 0.706 for Mesozoic plutons. Aprroximates edge of Precambrian crust. Modified from Carlson and others (1991), Fleck and Criss (1985), and Kistler (1990)
--x-----x--	εNd = -7 and initial $^{87}Sr/^{86}Sr$ = 0.708 contour in Nevada and California which is interpreted as edge of Precambrian crust by Farmer and DePaolo (1983)
o——o >2.7	Crust-formation province age in Ga. Based on depleted mantle Nd-model ages from Bennett and Depaolo (1987)
WYOMING	Archean crustal province name
Mojave	Proterozoic crustal province name

ponding or penetration, and ultimately development of the paleotopographic and volcanic features recognized in the near-surface rock record of the Montana alkaline province and the Challis volcanic field. This model shares some features with the uplift and decompression scenarios suggested by Dudás (1991).

From its ≈50- to 45-Ma position beneath the Challis volcanic field, the magmatic focus of the GFTZ hot spot appears to have migrated southward during the ensuing 30 m.y. into central Nevada, as indicated by the successive 40-, 30-, and 20-Ma magmatic and caldera fronts shown on figure 9. The switch from northwest-directed extension across the GFTZ (with magmatism concentrated along the GFTZ) to east-northeast-directed extension (with southward-migrating magmatism) occurred at ≈48 Ma in east-central Idaho (Janecke, 1992). The Eocene-Miocene southward magmatic migration was essentially coeval with a southward sweep of upper crustal extensional domains (Seedorff, 1991). The ≈38- to 20-Ma ignimbrite flareup in the Great Basin (Best and others, 1989) resulted from the high-level emplacement of major calc-alkaline batholiths (fig. 10) during early, dominantly ductile, crustal extension (Gans and others, 1989). The southern limit of ≈30- to 20-Ma caldera-forming eruptions (fig. 9) approximately coincides with the east-trending Blue Ribbon–Warm Springs lineament (Rowley and others, 1978), possibly marking a major zone of transform accommodation between areas having different amounts of crustal extension (Eaton and others, 1978; Rowley and others, this volume).

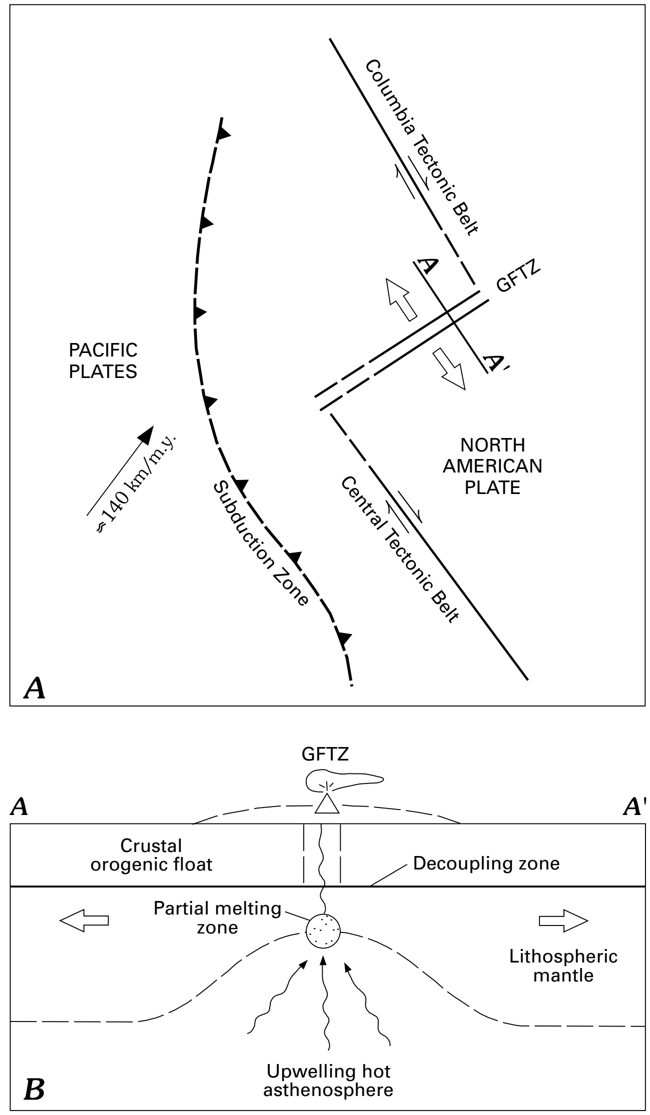
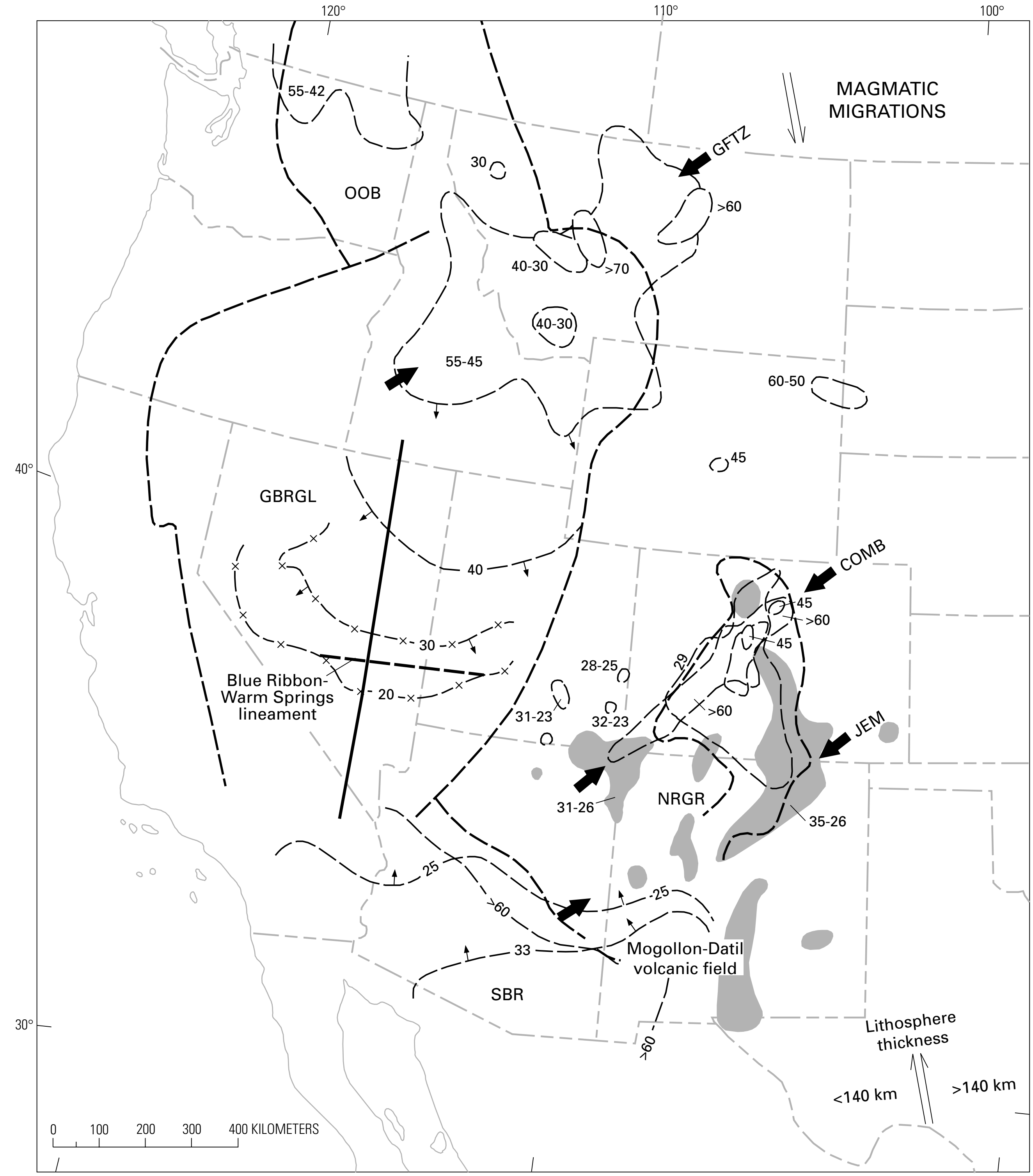


Figure 8. Diagrammatic map (*A*) and cross section (*B*) showing the Great Falls tectonic zone (GFTZ) as a Late Cretaceous–Eocene transtension zone between the Columbia and Central tectonic belt transcurrent fault systems (not to scale). From Mutschler and others (1991, fig. 2).

COLORADO MINERAL BELT (COMB)

The COMB hot spot initially developed along the Colorado mineral belt, a segment of a regional northeast-trending basement shear zone of Proterozoic origin (Tweto and Sims, 1963; Warner, 1980). During the Laramide orogeny, the COMB was oriented essentially parallel to the axis of maximum compression. Magmatism began shortly after the start of uplift of the Laramide ranges in Colorado (Mutschler and others, 1987) and was closely restricted to the axis of the COMB, which appears to have "unzipped" along a strike length of more than 500 km. The activity extended from the Carrizo Mountains, Ariz., in the Four Corners area, to the eastern edge of Colorado's Front Range (figs. 6, 11*A*)



EXPLANATION

Magmatic isochron (in Ma)

Limit (in Ma) of caldera-forming eruptions in Great Basin

Area including Oligocene shoshonites, lamprophyres, and minettes. ≈ 35-26 Ma in Colorado and New Mexico; ≈ 31-26 Ma in Navajo volcanic field on Colorado Plateau

Figure 9. Magmatic migration patterns in the Western United States from about 75 to 20 Ma. See figure 1 for explanation of lines and symbols not explained here. Data from Best and others (1989), and Mutschler and others (1987). Arrows on isochrons show interpreted magmatic migration patterns.

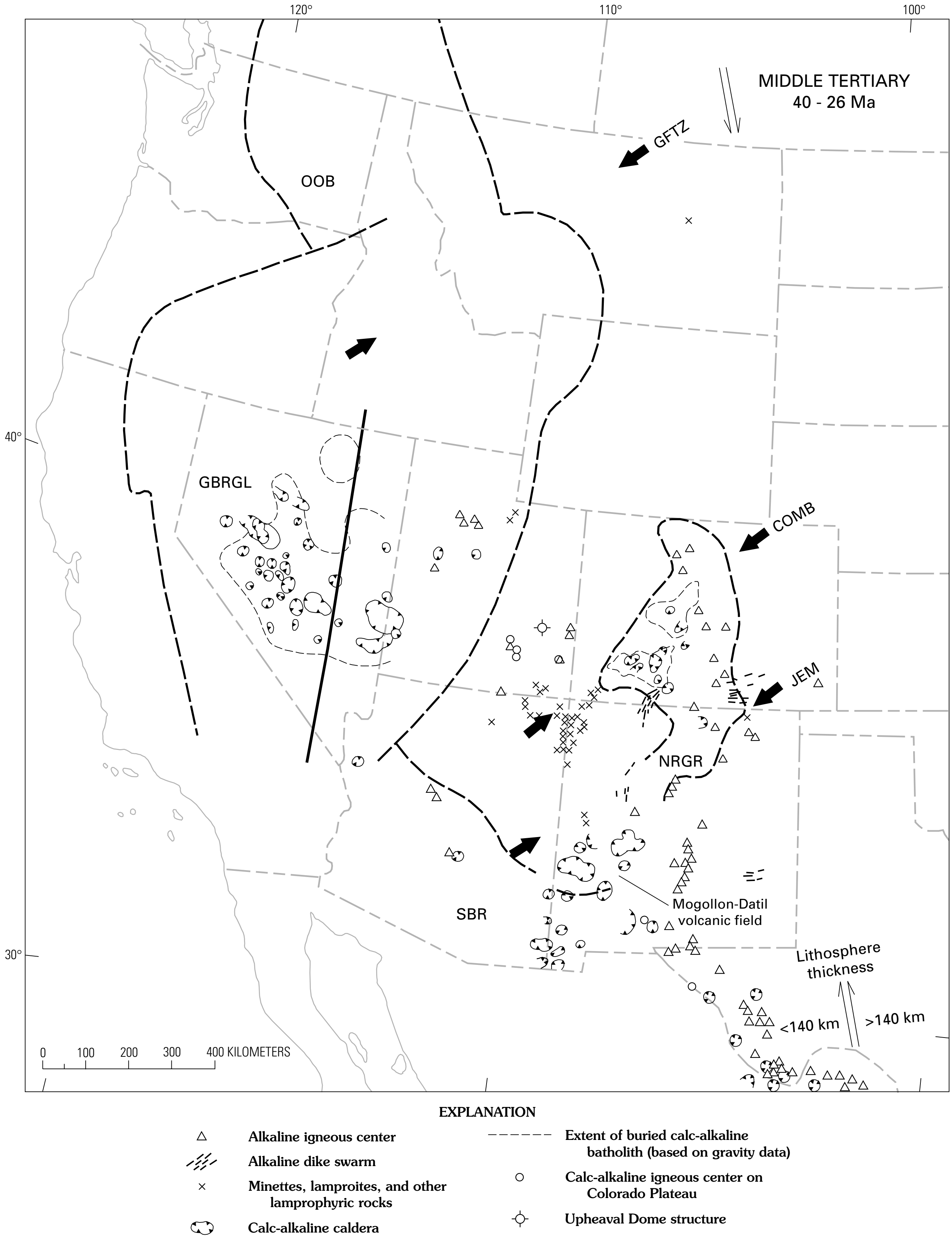


Figure 10. Selected middle Tertiary (40–26 Ma) igneous features in the Southwestern United States. See figure 1 for explanation of lines and symbols not explained here. Modified from Mutschler and others (1987, fig. 10).

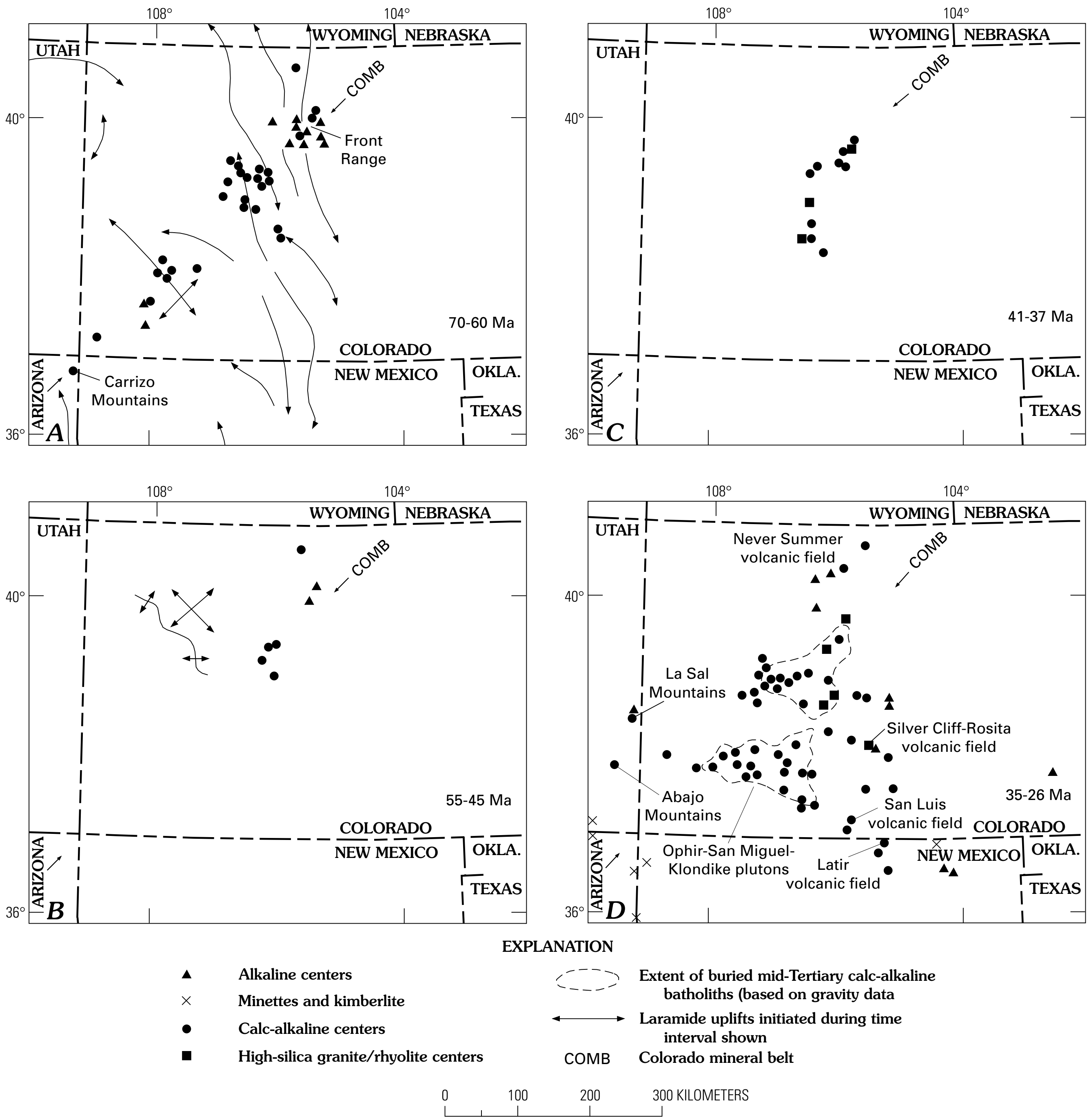


Figure 11. Laramide–middle Tertiary magmatic migration patterns, Colorado and environs. Modified from Mutschler and others (1987, fig. 11).

during the interval ≈74–64 Ma. No systematic age trends are apparent in rocks representing this time span along the COMB igneous belt, but mantle-derived alkaline rocks tend to be concentrated near the ends of the COMB, whereas calc-alkaline rocks containing significant crustal components predominate in the central part of the belt. By late Eocene time, igneous activity was restricted to the central and northeastern parts of the COMB (fig. 11*C*). The onset of regional crustal extension during middle Tertiary (Oligocene) time was marked by a rapidly enlarging ignimbrite flareup in central Colorado (fig. 11*D*), probably in response to massive basalt accumulation in or beneath the lower crust. This accumulation resulted in large-scale crustal melting, rise of the resulting calc-alkaline magmas to form shallow batholiths, and ignimbrite eruptions from at least 16 calderas during the period 36–27 Ma (Lipman, 1984; Steven and Lipman, 1976).

Small calc-alkaline centers—including the Abajo (32–23 Ma), Henry (31–23 Ma), and La Sal (28–25 Ma) Mountains, Utah; the Latir (26–19 Ma) volcanic field, New Mexico; and the San Luis (29–28 Ma), Silver Cliff–Rosita (33–27 Ma), Never Summer (29–28 Ma) volcanic fields, and the Ophir–San Miguel–Klondike (≈26 Ma) plutons, Colorado—developed outside of the central and southwestern Colorado batholithic area. Many of these peripheral centers began about 31–26 Ma, several million years after the onset of the voluminous mid-Tertiary batholithic magmatism along the COMB. Thus, from an early focus in central Colorado, the areas involved in middle Tertiary partial melting appear to have spread outward for about 10–12 m.y. (fig. 11).

Mutschler and others (1987) suggested that the COMB passive hot spot developed in response to decompression-triggered partial melting beneath isostatically rebounding crustal and lithospheric roots produced by Laramide compression. The model may be overly simplistic, especially as it failed to take into account possible regional lithospheric thinning resulting from differential subcrustal movements. Chapin (1983) documented a series of north-trending Eocene right-lateral faults and fault-bounded basins extending the length of the eastern Rocky Mountain uplifts of Colorado and New Mexico. Perhaps these crustal wrench structures reflect the thinning of partially decoupled lithosphere in a manner similar to that suggested for the GFTZ hot spot.

NORTHERN RIO GRANDE RIFT (NRGR)

The NRGR hot spot is in the north-central part of the Alvarado Ridge of Eaton (1986, 1987), which is a >1,200-km-long, north-trending, Neogene thermotectonic uplift (fig. 12). Eaton (1987) convincingly modeled the ridge crest as a feature that rose rapidly above the axis of a developing linear asthenospheric bulge beneath thinning lithospheric mantle. The model is supported by geophysical data (Eaton, 1987; Olsen and others, 1987; Cordell and others, 1991; Gibson and others, 1993) indicative of thinned crust and anomalously low-density mantle, and by regional heat-flow observations. Eaton (1986, 1987) suggested that the topographic ridge began to form at ≈17–12 Ma, and that uplift peaked between 7 and 4 Ma. The NRGR passive hot spot, however, may have a significant older history, including north-trending Precambrian shear zones (Cordell, 1978; Eaton, 1979; Tweto, 1979), which were reactivated in the Eocene wrenching event, and a magmatic episode of initial mantle melting between 35 and 26 Ma.[4] This magmatic precursor to the Miocene-Pliocene uplift event is represented by a north-trending belt of Oligocene mantle-derived shoshonitic plutons and lamprophyres extending from northern Colorado through New Mexico (fig. 9). In contrast, the Neogene period of rapid ridge uplift was characterized by bimodal basalt-rhyolite volcanism. Both tholeiitic and alkali basalts occur, representing lithospheric and asthenospheric mantle melting (Livaccari and Perry, 1993). The coeval high-silica rhyolites may represent melting of crustal granulites.

The differing locations and eruption times of Neogene lithosphere- and asthenosphere-derived basalts in different segments of the rift (Baldridge and others, 1984, 1991; Lipman, 1969; Perry and others, 1987, 1988) may result from local differences in the shear mechanisms involved in subcrustal lithospheric extension (fig. 13). Northeast-trending accommodation zones transverse to the Rio Grande Rift also appear to separate distinct tectonic and magmatic crustal blocks. The most striking accommodation zone is part of the Jemez lineament, which has acted as a >800-km-long locus for Neogene magmatism (Aldrich, 1986). The 15- to 0.001-Ma magmatism along the lineament marks a northwestward volcanic encroachment onto the Colorado Plateau (Aldrich and Laughlin, 1984; Baldridge and others, 1991).

GREAT BASIN REGIONAL GRAVITY LOW (GBRGL)

The Great Basin regional gravity low (GBRGL) of Eaton and others (1978) has long been recognized as a site of relatively rapid Neogene crustal extension. Lower crustal ductile extension of thickened Nevadan and Sevier lithosphere may have begun in the Cretaceous (Hodges and Walker, 1992), and significant normal faulting occurred during Eocene time (Gans and others, 1993). However, the majority of upper crustal brittle extension (basin-range faulting) did not begin until ≈20–17 Ma (Eaton and others, 1978) and it postdates the major part of the Oligocene great ignimbrite flareup. Upper crustal brittle extension is continuing today (Smith, 1978). As a result of this long-lived extension, the Great Basin is characterized by thin (≈30 km) crust underlain by anomalous mantle, high heat flow, regional doming, many calderas and voluminous ash-flow tuffs succeeded by modest amounts of bimodal (basalt-rhyolite) volcanics, and topography developed by basin-range faulting. Basaltic volcanism generally becomes more recent toward the Sierra Nevada and Wasatch transition zones bordering the Great Basin, and it has progressively overstepped these zones (Smith and Luedke, 1984; Stewart and Carlson, 1976). Neogene peralkaline rhyolites, probably derived from fractionation of trachybasalts, form an irregular ring around the periphery of the Great Basin (fig. 12). All of these features indicate regional mantle upwelling within a passive hot spot.

[4] Gregory and Chase (1992) used paleobotanical analysis to suggest that the Alvarado Ridge had reached essentially its present elevation by 35 Ma. This early uplift may be related to the ≈30-Ma low-angle normal faulting in the rift region discussed by Olsen and others (1987).

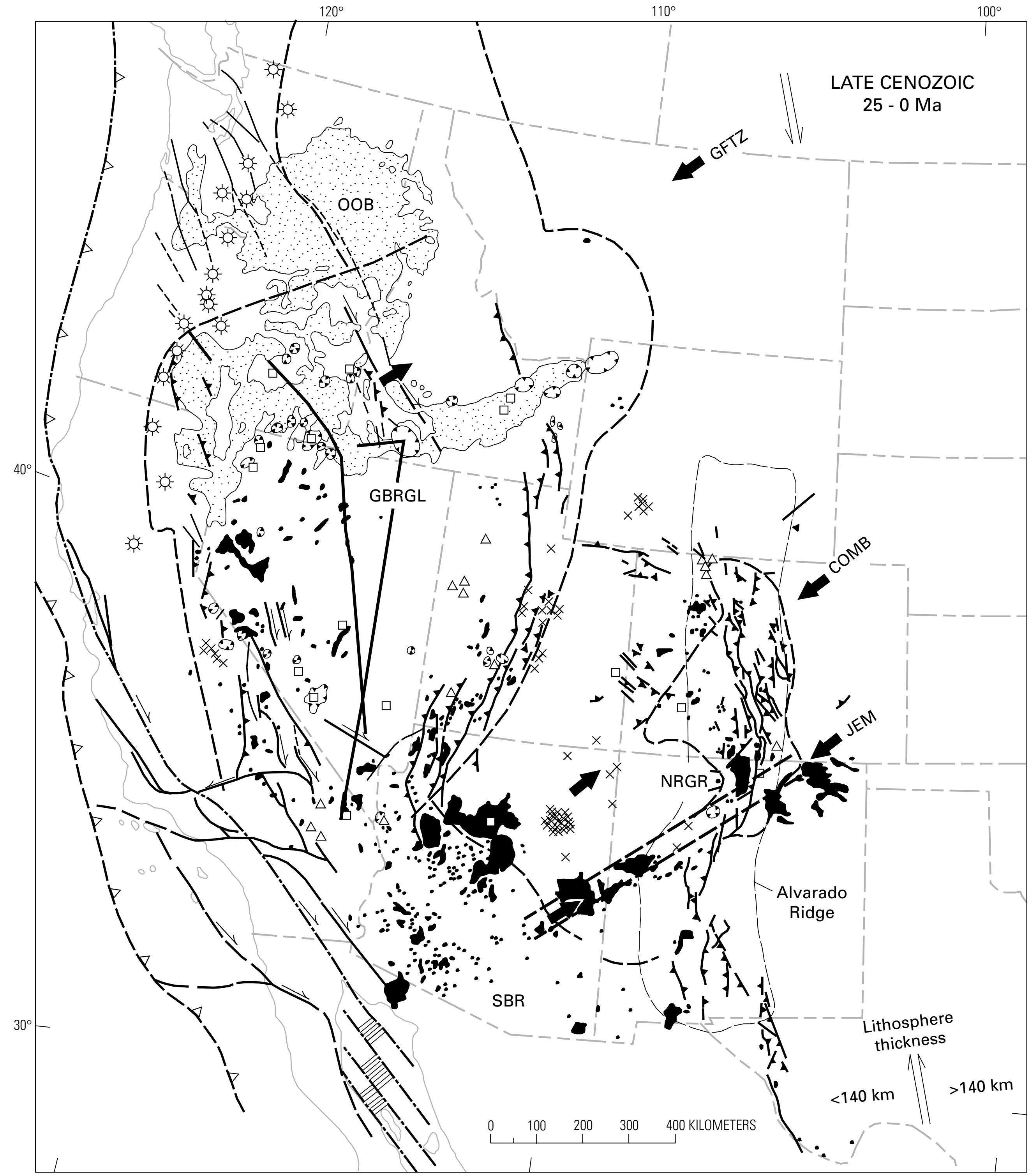


Figure 12 (above and facing page) Late Cenozoic (25–0 Ma) igneous rocks and selected tectonic features in the Western United States. Modified from Mutschler and others (1987, fig. 14).

The northern and southern borders of the Great Basin also show the effects of an evolving passive hot spot. The northwest-trending Brothers fault zone in Oregon (Lawrence, 1976) and the northeast-trending Snake River Plain in Idaho meet and form a "triple junction" with the south-southeast-trending northern Nevada or Oregon-Nevada magnetic lineament (Blakely, 1988; Stewart and others, 1975) near the common boundary of Oregon,

EXPLANATION

- Alkaline igneous center
- Lamproites, lamprophyres
- Peralkaline rhyolite/granite center (includes calderas)
- Basalts, largely alkaline (south of 42°N). Locally includes small to moderate amounts of intermediate and silicic lavas
- Flood basalts of Oregon Plateau, Columbia Plateau, and Snake River Plain
- Major High Cascade stratovolcano
- Caldera. Most result from rhyolitic eruptions
- Extensional faults, shown only in Southern Rockies. Wasatch transition zone, and western edge of Great Basin
- Major strike-slip fault
- Other faults
- Alvarado Ridge crestal province (Eaton 1986, 1987)
- Major lineament. JEM, Jemez Lineament
- Magnetic lineament in Nevada; transform accomodation zones in Oregon and Idaho
- Active transform plate boundary
- Active subduction plate boundary
- Spreading ridge crust formed in last one million years

Nevada, and Idaho (fig. 14). This "triple junction" is similar to the radial rift geometry on a rising dome or on an inflating shield volcano, and may mark the crestal area of passive mantle upwelling. Neogene volcanism at the "triple junction" has an age of 17–16 Ma, but the volcanic features, especially silicic centers, become progressively younger outward on two of the three arms: northwestward along the Brothers fault zone to Newberry Crater (MacLeod and others, 1976) and northeastward along the Snake River Plain to Yellowstone (Christiansen, 1993; Christiansen and McKee, 1978). These two lineaments can be interpreted as "***diffuse (and very leaky) zones of transform accommodation between regions of greater and lesser cumulative tectonic (basin-range) extension to the south and north, respectively" (Hildreth and others, 1991, p. 65). The Quaternary Yellowstone Plateau volcanic field, therefore, is probably not the site of an active hot spot, but rather the northeast corner of a very large shield-shaped area of extended lithosphere located above the expanding passive hot spot that underlies the GBRGL. The southern end of the GBRGL can be interpreted in a similar fashion, with the Garlock fault (Davis and Burchfiel, 1973) and the Las Vegas shear zone serving as diffuse (but relatively dry) zones of transform accommodation.

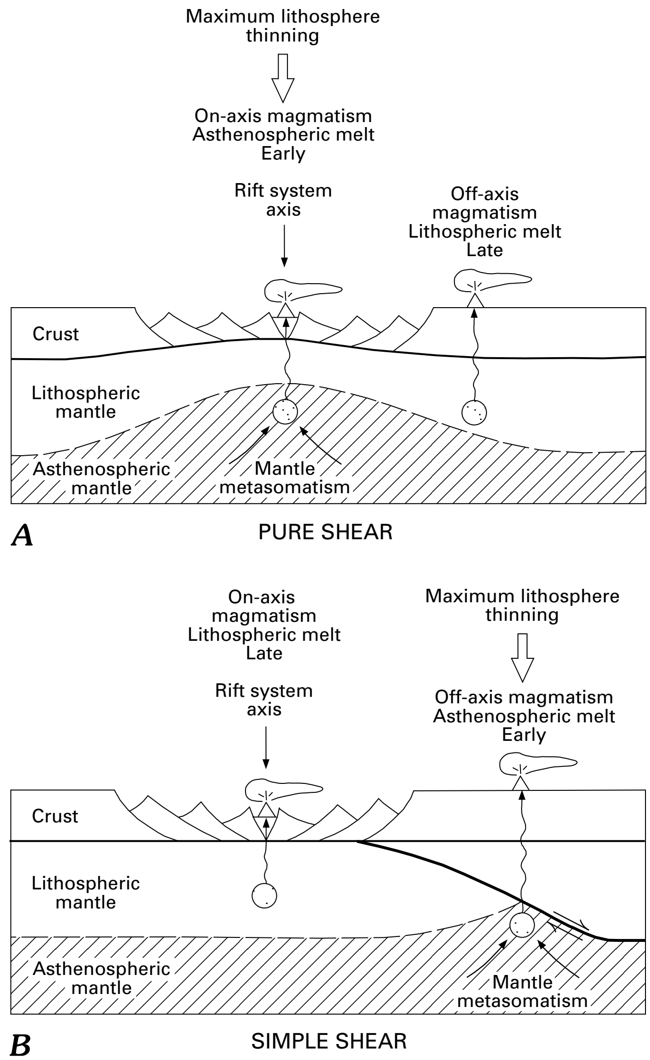


Figure 13. Hypothetical timing and distribution of mantle-derived magmatism and lithospheric thinning resulting from pure shear (*A*) and simple shear (*B*) modes of crustal extension. Modified from Farmer and others (1989, fig. 1).

SOUTHERN BASIN AND RANGE PROVINCE (SBR)

Laramide northeast-southwest compression destroyed a Cretaceous marine trough in southeastern Arizona and southwestern New Mexico between ≈80 and 50 Ma. Deformation included uplift of basement welts and thrust faulting accompanied by extensive ≈75- to 50-Ma calc-alkaline plutonism and volcanism (Krantz, 1989). In southwestern Arizona, regional greenschist-facies metamorphism accompanied thrusting and plutonism. These Laramide events almost certainly resulted in significant crustal thickening. Yet today the southern Basin and Range province (SBR) is characterized by thin crust (fig. 2), evidence of large-scale lithospheric extension, high heat flow, and recent volcanism. These features, typical of passive hot spots, evolved during post-Laramide time.

Middle Tertiary ductile lithosphere extension involved development of major regional low-angle detachment faults and the isostatic uplift of metamorphic core complexes

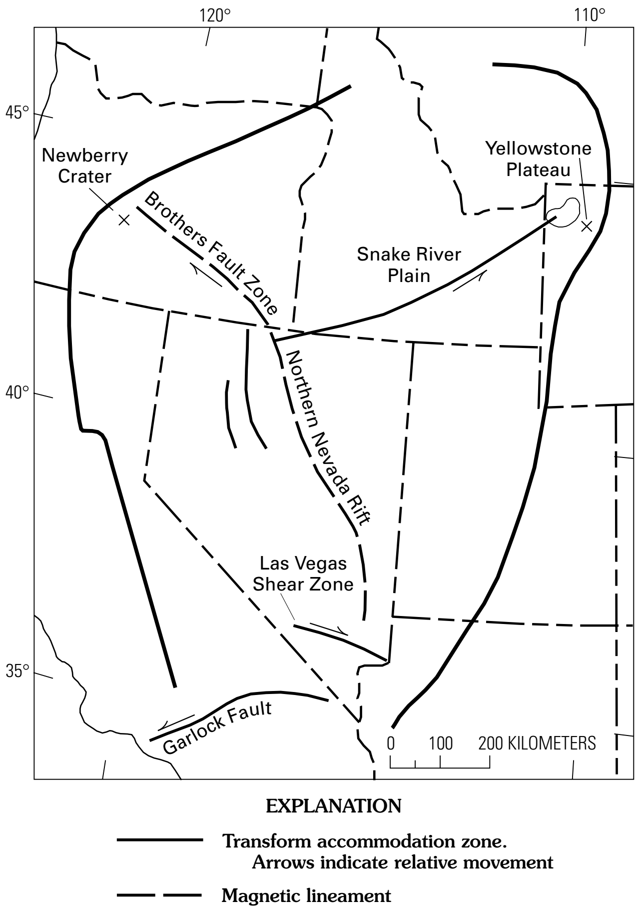


Figure 14. Late Cenozoic (≈17–0 Ma) major crustal tectonic elements that indicate an expanding passive hot spot beneath the Great Basin regional gravity low (GBRGL).

(Spencer and Reynolds, 1989). Middle Tertiary calc-alkaline-dominated magmatism shows a general westward and northwestward progression in the SBR, from a ≈40- to 36-Ma inception in the Mogollon-Datil volcanic field of southwestern New Mexico (Elston and Bornhorst, 1979; McIntosh and others, 1992) to an onset at ≈25 Ma in western Arizona (fig. 9). Major caldera formation and ignimbrite eruptions occurred between 36 and 24 Ma in the Mogollon-Datil field (fig. 10; McIntosh and others, 1992), and between ≈32 and 15 Ma in the Arizona part of the SBR (Nealey and Sheridan, 1989).

About 15–13 Ma, styles of deformation and magmatism changed significantly in the SBR (Menges and Pearthree, 1989). Brittle crustal extension began, in the form of high-angle normal (basin-range) faulting, and bimodal (basalt-rhyolite) magmatism became dominant. Bimodal volcanic features and, especially, rhyolitic centers show a northeastward migration from the SBR onto the Colorado Plateau since ≈15 Ma (Moyer and Nealey, 1989; Nealey and Sheridan, 1989).

The main pulse of basin-range faulting and magmatism ended at ≈5–2 Ma, although some normal faulting and seismic activity continue today, and at least four alkali basalt eruptions have occurred in and near Arizona in Holocene time (Lynch, 1989). Seismic reflection data suggest the presence of a horizontal basaltic magma body and solidified intrusions within the lower crust of the transition zone between the SBR and the Colorado Plateau (Parsons and others, 1992).

SCENARIO FOR THE EVOLUTION OF CONTINENTAL PASSIVE HOT SPOTS

A generalized model for the sequential development of the passive hot spots described is given herein. Some features of individual hot spots vary from this model.

1. Lithospheric thinning may be initiated by differential movements between lithospheric blocks, by back-arc spreading, or by gravitational collapse of an orogenic welt, all of which are common results of large-scale plate tectonic motions and reorganizations.

2. Thinning of the lithospheric mantle, which may be mechanically uncoupled from the crust, results in an upflow of the expanding asthenosphere, triggering decompression melting in the mantle. Early melts tend to be of two types: (a) Small volumes of mafic potassic magmas (such as alkaline lamprophyres or minettes) representing minimal mantle melting. These highly volatile-charged magmas generally transit through the lithosphere rapidly, with only minor fractionation en route. (b) Shoshonites, representing crustal-level fractionation and contamination of nepheline-normative alkaline basalts (Meen and Curtis, 1989). These may form moderate-size volcanic-plutonic complexes.

3. Continuing extension of the lithosphere causes increased mantle melting; the resulting basalt magmas rise and park at neutral buoyancy levels near the base of the crust (Glazner and Ussler, 1988) and (or) form distributed dike intrusion networks in the lower lithosphere and crust (Lachenbruch and Sass, 1978). Gentle regional crustal doming begins at this stage. Heat loss from gravitationally stalled basalts causes partial crustal melting, yielding calc-alkaline magmas which rise and collect at upper crustal neutral buoyancy levels, ultimately forming batholiths. Initial eruptions from the batholiths form intermediate-composition stratovolcano fields. These early andesites represent mixed mantle and crustal melts. As crustal melting continues, the bulk composition of the batholiths becomes increasingly silicic (dacitic to rhyolitic), and as the batholiths enlarge they contribute to crustal arching and thermally weaken the crust so that it extends ductilely (Armstrong and Ward, 1991; Gans and others, 1989). With time, as mantle melting spreads over a broader area, the zone of parked basalt in the lower crust spreads laterally, resulting in outward migration of the area of calc-alkaline magmatism as the zone of crustal melting widens and moves upward. (See figs. 9, 11.)

Eventually, many of the roofs of the fractionated calc-alkaline batholiths fail, producing multiple caldera eruptions and regional ignimbrite fields.

4. Finally, the thermally weakened upper crust may fail by listric (basin-range) faulting above the zone of ductile flow and distributed magmatic extension in the lower crust and uppermost mantle. Bimodal (basalt and rhyolite and (or) trachybasalt and peralkaline rhyolite) magmatism accompanies the basin-range faulting stage. These bimodal assemblages tend to be concentrated peripheral to earlier calc-alkaline batholiths, perhaps because the low-density batholiths inhibit the passage of mantle-derived magmas. The basalt and high-silica rhyolite suite probably represents limited crustal melting, inasmuch as the high-silica rhyolites have minimum melting compositions. The peralkaline rhyolites, which tend to be slightly older than the high-silica rhyolites, may represent fractionation of mantle-derived trachybasalts.

SUMMARY AND CONCLUSIONS

In the area we discuss, inboard passive hot-spot magmatism began in Late Cretaceous to Paleocene time with the development of the Great Falls tectonic zone and the Colorado mineral belt. Both these features started as linear volcanic-plutonic zones and expanded into large volcanic fields overlying calc-alkaline batholithic complexes.

Today, the Colorado Plateau is surrounded by Neogene passive hot spots, including the Great Basin regional gravity low to the west, the northern Rio Grande Rift to the east, and the southern Basin and Range province to the south and southwest. Magmatism in these areas is dominated by predominantly bimodal (alkali basalt-rhyolite) suites. Magmatic migration patterns (Nealey and Sheridan, 1989; Smith and Luedke, 1984) show that late Cenozoic magmatism is overstepping the plateau from all of these passive hot spots. Can basin-range faulting be far behind?

Armstrong and Ward (1991) and Ward (1991) have recently outlined and commented on many of the plate-tectonic scenarios invoked to explain Cordilleran magmatism. They emphasized, as have many other workers, a close spatial and temporal correlation between areas of crustal extension and inboard Cenozoic magmatism throughout the length of the Cordillera. Anderson (1992) has succinctly stated that the location of a hot spot is controlled by lithospheric conditions, and that even if the asthenosphere is relatively hot, a hot spot will not form unless the lithosphere is under extension. Lithospheric extension occurred at all the hot spots we describe, but different plate-motion phenomena were responsible for extension at different localities. For example, in the early Great Falls tectonic zone, oblique plate convergence produced intraplate transcurrent fault systems offset by a transtensional zone across which the lithosphere thinned. On the other hand, the late Cenozoic Great Basin regional gravity low, in Atwater's (1970) model, developed through gravitational collapse of an orogenic welt when a bounding plate margin changed from a subduction mode to a transform mode. In other cases (such as the Laramide to mid-Cenozoic Colorado mineral belt), it remains uncertain how plate interactions and motions relate to demonstrable inboard lithospheric extension and magmatism.

Since different plate-tectonic scenarios are involved in the development of different hot spots, it appears that direct involvement of a subducted oceanic slab is not a requisite for generation of the passive hot-spot magmatism we describe. Consequently, to term the igneous rocks of these inboard hot spots "subduction related" or "arc related" is perhaps misleading. Rather, the magmatism we describe can be considered to be "continental magmatism" in the sense of Ward (1991).

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Our subcrustal flights of fancy are largely based on interpretation of local and regional geological, geochemical, geochronological, and geophysical studies by the many enthusiastic workers who, for over a century, have contributed to the literature of Cordilleran geology. Space does not permit us to list all the references we used, or perhaps abused, but many of them are listed in Mutschler and others (1987, 1994). Our views were sharpened, and tempered, by discussions with the participants of the July 1992 U.S. Geological Survey Workshop on Laccolithic Complexes of Southeastern Utah convened by Jules Friedman and Curt Huffman. We especially thank Dave Nealey and Bill Steele, who reviewed the manuscript and made constructive and thoughtful suggestions to improve it.

REFERENCES CITED

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

Aldrich, M.J., Jr., and Laughlin, A.W., 1984, A model for the tectonic development of the southeastern Colorado Plateau boundary: Journal of Geophysical Research, ser. B, v. 89, p. 10207–10218.

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

Anderson, D.L., 1992, Mantle dynamics—The hotcell model [abs.]: Eos, v. 73, no. 14, Spring Meeting Supplement, p. 272.

Armstrong, R.L., and Ward, Peter, 1991, Evolving geographic patterns of Cenozoic magmatism in the North American Cordillera—The temporal and spatial association of magmatism and metamorphic core complexes: Journal of Geophysical Research, ser. B, v. 96, p. 13201–13224.

Atwater, Tanya, 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513–3536.

Axelrod, D.I., 1968, Tertiary floras and topographic history of the Snake River basin, Idaho: Geological Society of America Bulletin, v. 79, p. 713–734.

Bailey, D.K., 1970, Volatile flux, heat-focusing and the generation of magma: Geological Journal (London), Special Issue 2, p. 177–186.

———1978, Continental rifting and mantle degassing, *in* Neumann, E.-R., and Ramberg, I.B., eds., Petrology and geochemistry of continental rifts: Dordrecht, Holland, D. Reidel, p. 1–13.

Baker, D.W., and Berg, R.B., eds., 1991, Guidebook of the central Montana alkalic province—Geology, ore deposits and origin: Montana Bureau of Mines and Geology Special Publication 100, 201 p.

Baldridge, W.S., Olsen, K.H., and Callender, J.F., 1984, Rio Grande Rift—Problems and perspectives: New Mexico Geological Society Guidebook, 35th Field Conference, Rio Grande Rift—Northern New Mexico, p. 1–12.

Baldridge, W.S., Perry, F.V., Vaniman, D.T., Nealey, L.D., Laughlin, A.W., Kyle, P.R., Bartov, Yosef, Steinitz, Gideon, and Gladney, E.S., 1991, Middle to late Cenozoic magmatism of the southeastern Colorado Plateau and central Rio Grande Rift (New Mexico and Arizona, U.S.A.)—A model for continental rifting: Tectonophysics, v. 197, p. 327–354.

Bayer, K.C., 1983, Generalized structural, lithologic, and physiographic provinces in the fold and thrust belts of the United States: U.S. Geological Survey special map, 2 sheets, scale 1:2,500,000.

Bennett, V.C., and DePaolo, D.J., 1987, Proterozoic crustal history of the Western United States as determined by neodymium isotopic mapping: Geological Society of America Bulletin, v. 99, p. 674–685.

Best, M.G., Christiansen, E.H., Deino, A.L., Grommé, C.S., McKee, E.H., and Noble, D.C., 1989, Eocene through Miocene volcanism in the Great Basin of the Western United States: New Mexico Bureau of Mines and Mineral Resources Memoir 47, p. 91–133.

Bird, Peter, 1979, Continental delamination and the Colorado Plateau: Journal of Geophysical Research, v. 84, p. 7561–7571.

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

Blakely, R.J., 1988, Curie temperature isotherm analysis and tectonic implications of aeromagnetic data from Nevada: Journal of Geophysical Research, ser. B, v. 93, p. 11817–11832.

Carlson, D.H., Fleck, R.J., Moye, F.J., and Fox, K.F., 1991, Geology, geochemistry and isotopic character of the Colville igneous complex, northeastern Washington: Journal of Geophysical Research, ser. B, v. 96, p. 13313–13333.

Chapin, C.E., 1983, An overview of Laramide wrench faulting in the Southern Rocky Mountains with emphasis on petroleum exploration, *in* Lowell, J.D., ed., Rocky Mountain foreland basins and uplifts: Denver, Colo., Rocky Mountain Association of Geologists, p. 169–179.

Christiansen, R.L., 1993, The Yellowstone hot spot—Deep mantle plume or upper mantle melting anomaly [abs.]: Eos, v. 74, no. 43, supplement, p. 602.

Christiansen, R.L., and McKee, E.H., 1978, Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia Intermontane regions, *in* Smith, R.B., and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 283–311.

Clague, D.A., 1987, Hawaiian alkaline volcanism, *in* Fitton, J.G., and Upton, B.G.J., eds., Alkaline igneous rocks: Geological Society of London Special Publication 30, p. 227–252.

Cordell, Lindrith, 1978, Regional geophysical setting of the Rio Grande Rift: Geological Society of America Bulletin, v. 89, p. 1073–1090.

Cordell, Lindrith, Zorin, Y.A., and Keller, G.R., 1991, The decompensative gravity anomaly and deep structure of the region of the Rio Grande Rift: Journal of Geophysical Research, ser. B, v. 96, p. 6557–6568.

Courtney, R.C., and White, R.S., 1986, Anomalous heat flow and geoid across the Cape Verde Rise—Evidence of dynamic support from a thermal plume in the mantle: Geophysical Journal of the Royal Astronomical Society, v. 87, p. 815–868.

Davis, G. A., and Burchfiel, B. C., 1973, Garlock Fault—An intracontinental transform structure, southern California: Geological Society of America Bulletin, v. 84, p.1407–1422.

Dudás, F.ö., 1991, Geochemistry of igneous rocks from the Crazy Mountains, Montana, and tectonic models for the Montana alkalic province: Journal of Geophysical Research, ser. B, v. 96, p. 13261–13277.

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

———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, *in* Coward, M.P., Dewey, J.F., and Hancock, P.L., eds., Continental extensional tectonics: Geological Society of London Special Publication 28, p. 355–369.

Eaton, G.P., Wahl, R.R., Prostka, 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, *in* Smith, R.B., and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 51–91.

Eggler, D.H., Meen, J.K., Welt, Fred, Dudas, F.O., Furlong, K.P., McCallum, M.E., and Carlson, R.W., 1988, Tectonomagmatism of the Wyoming province: Colorado School of Mines Quarterly, v. 83, no. 2, p. 25–40.

Elston, W.E., and Bornhorst, T.J., 1979, The Rio Grande Rift in context of regional post-40 m.y. volcanic and tectonic events, *in* Riecker, R.E., ed., Rio Grande Rift—Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 416–438.

Farmer, G.L., and DePaolo, D.J., 1983, Origin of Mesozoic and Tertiary granite in the Western United States and implications for pre-Mesozoic crustal structure—1, Nd and Sr isotopic studies in the geocline of the northern Great Basin: Journal of Geophysical Research, ser. B, v. 88, p. 3379–3401.

Farmer, G.L., Perry, F.V., Semken, S., Crowe, B., Curtis, D., and DePaolo, D.J., 1989, Isotopic evidence on the structure and origin of subcontinental lithospheric mantle in southern Nevada: Journal of Geophysical Research, ser. B, v. 94, p. 7885–7898.

Fleck, R.J., and Criss, R.E., 1985, Strontium and oxygen isotopic variations in Mesozoic and Tertiary plutons of central Idaho: Contributions to Mineralogy and Petrology, v. 90, p. 291–308.

Gans, P.B., Mahood, G.A., and Schermer, Elizabeth, 1989, Synextensional magmatism in the Basin and Range province; a case study from the eastern Great Basin: Geological Society of America Special Paper 233, 53 p.

Gans, P.B., Miller, E.L., and Lee, J., 1993, The Mesozoic-Cenozoic tectonic evolution of the eastern Great Basin—A revised history [abs.]: Eos, v. 74, no. 43, p. 608.

Gibson, S.A., Thompson, R.N., Leat, P.T., Morrison, M.A., Hendry, G.L., Dickin, A.P., and Mitchell, J.G., 1993, Ultrapotassic magmas along the flanks of the Oligo-Miocene Rio Grande Rift, USA—Monitors of a zone of lithospheric mantle extension and thinning beneath a continental rift: Journal of Petrology, v. 34, p. 187–228.

Glazner, A.F., and Ussler, William, III, 1988, Trapping of magma at midcrustal density discontinuities: Geophysical Research Letters, v. 15, p. 673-675.

Gregory, K.M., and Chase, C.G., 1992, Tectonic significance of paleobotanically estimated climate and altitude of the late Eocene erosion surface, Colorado: Geology, v. 20, p. 581–585.

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.

Hildreth, Wes, Halliday, A.N., and Christiansen, R.L., 1991, Isotopic and chemical evidence concerning the genesis and contamination of basaltic and rhyolitic magma beneath the Yellowstone Plateau volcanic field: Journal of Petrology, v. 32, p. 63–138.

Hodges, K.V., and Walker, J.D., 1992, Extension in the Cretaceous Sevier orogen, North American Cordillera: Geological Society of America Bulletin, v. 104, p. 560–569.

Irvine, T.N., 1989, A global convection framework—Concepts of symmetry, stratification, and system in the Earth's dynamic structure: Economic Geology, v. 84, p. 2059–2114.

Janecke, S.U., 1992, Kinematics and timing of three superposed extensional systems, east-central Idaho—Evidence for an Eocene tectonic transition: Tectonics, v. 11, p. 1121–1138.

Kistler, R.W., 1990, Two different lithosphere types in the Sierra Nevada, California, *in* Anderson, J.L., ed., The nature of Cordilleran magmatism: Geological Society of America Memoir 174, p. 271–281.

Krantz, R.W., 1989, Laramide structures of Arizona, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 463–483.

Lachenbruch, A.H., and Sass, J.H., 1978, Models of an extending lithosphere and heat flow in the Basin and Range province, *in* Smith, R.B., and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 209–250.

Larsen, E.S., 1940, Petrographic province of central Montana: Geological Society of America Bulletin, v. 51, p. 887–948.

Lawrence, R.D., 1976, Strike-slip faulting terminates the Basin and Range province in Oregon: Geological Society of America Bulletin, v. 87, p. 846–850.

Lipman, P.W., 1969, Alkalic and tholeiitic basaltic volcanism related to the Rio Grande depression, southern Colorado and northern New Mexico: Geological Society of America Bulletin, v. 80, p. 1343–1354.

______ 1984, The roots of ash flow calderas in western North America—Windows into the tops of granite batholiths: Journal of Geophysical Research, ser. B, v. 89, p. 8801–8841.

Livaccari, R.F., and Perry, F.V., 1993, Isotopic evidence for preservation of Cordilleran lithospheric mantle during the Sevier-Laramide orogeny, Western United States: Geology, v. 21, p. 719–722.

Lynch, D.J., 1989, Neogene volcanism in Arizona—The recognizable volcanoes, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 681–700.

Mabey, D.R., and Webring, M.W., 1985, Regional geophysical studies in the Challis quadrangle, chap. E *of* McIntyre, D.H., ed., Symposium on the geology and mineral deposits of the Challis 1˚x2˚ quadrangle, Idaho: U.S. Geological Survey Bulletin 1658, p. 69–79.

MacLeod, N.S., Walker, G.W., and McKee, E.H., 1976, Geothermal significance of eastward increase in age of upper Cenozoic rhyolitic domes in southeastern Oregon, *in* Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources: Washington, D.C., U.S. Government Printing Office, v. 1, p. 465–474.

McIntosh, W.C., Chapin, C.E., Ratté, J.C., and Sutter, J.F., 1992, Time-stratigraphic framework for the Eocene-Oligocene Mogollon-Datil volcanic field, southwest New Mexico: Geological Society of America Bulletin, v. 104, p. 851–871.

Meen, J.K., and Curtis, P.C., 1989, What are shoshonites? [abs.]: Eos, v. 70, p. 1421.

Menges, C.M., and Pearthree, P.A., 1989, Late Cenozoic tectonism in Arizona and its impact on regional landscape evolution, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 649–680.

Moye, F.J., 1988, Extensional control of Eocene volcanism and plutonism, Idaho and Washington: Geological Society of America Abstracts with Programs, v. 20, no. 6, p. 434.

Moyer, T.C., and Nealey, L.D., 1989, Regional compositional variations of late Tertiary bimodal rhyolite lavas across the Basin Range/Colorado Plateau boundary in western Arizona: Journal of Geophysical Research, ser. B, v. 94, p. 7799–7816.

Mutschler, F.E., Johnson, D.C., and Mooney, T.C., 1991, A speculative plate kinematic model for the central Montana alkalic province and related gold deposits, *in* Baker, D.W., and Berg, R.B., eds., Guidebook of the central Montana alkalic province—Geology, ore deposits and origin: Montana Bureau of Mines and Geology Special Publication 100, p. 121–124.

——— 1994, ALK.BIB—A selected bibliography of alkaline igneous rocks and related mineral deposits, with an emphasis on western North America: U.S. Geological Survey Open-File Report 94–624, 222 p.

Mutschler, F.E., Larson, E.E., and Bruce, R.M., 1987, Laramide and younger magmatism in Colorado—New petrologic and tectonic variations on old themes: Colorado School of Mines Quarterly, v. 82, no. 4, p. 1–47.

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

Norman, M.D., and Mertzman, S.A., 1991, Petrogenesis of Challis volcanics from central and southwestern Idaho—Trace element and Pb isotopic evidence: Journal of Geophysical Research, v. 96, p. 13279–13293.

Oldow, J.S., Bally, A.W., Avé Lallemant, H.G., and Leeman, W.P., 1989, Phanerozoic evolution of the North American Cordillera; United States and Canada, *in* Bally, A.W., and Palmer, A.R., eds., The geology of North America—An overview: Boulder, Colo., Geological Society of America, The Geology of North America, v. A, p. 139–232.

Olsen, K.H., Baldridge, W.S., and Callender, J.F., 1987, Rio Grande Rift—An overview: Tectonophysics, v. 143, p. 119–139.

O'Neill, J.M., and Lopez, D.A., 1985, Character and significance of Great Falls tectonic zone, east-central Idaho and west-central Montana: American Association of Petroleum Geologists Bulletin, v. 69, p. 437–447.

Parsons, Tom, Howie, J.M., and Thompson, G.A., 1992, Seismic constraints on the nature of lower crustal reflectors beneath the extending southern transition zone of the Colorado Plateau, Arizona: Journal of Geophysical Research, ser. B, v. 97, p. 12391–12407.

Perry, F.V., Baldridge, W.S., and DePaolo, D.J., 1987, Role of asthenosphere and lithosphere in the genesis of late Cenozoic basaltic rocks from the Rio Grande Rift and adjacent regions of the southwestern United States: Journal of Geophysical Research, ser. B, v. 92, p. 9193–9213.

———1988, Chemical and isotopic evidence for lithospheric thinning beneath the Rio Grande Rift: Nature, v. 332, p. 432–434.

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, p. 175–192.

Scholz, C.H., Barazangi, Muawia, and Sbar, M.L., 1971, Late Cenozoic evolution of the Great Basin, Western United States, as an ensialic interarc basin: Geological Society of America Bulletin, v. 82, p. 2979–2990.

Seedorff, Eric, 1991, Magmatism, extension, and ore deposits of Eocene to Holocene age in the Great Basin—Mutual effects and preliminary proposed genetic relationships, *in* Raines, G.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W.H., eds., Geology and ore deposits of the Great Basin: Reno, Nev., Geological Society of Nevada, p. 133–177.

Smith, R.B., 1978, Seismicity, crustal structure, and intraplate tectonics of the interior of the western Cordillera, *in* Smith, R.B., and Eaton, G.P., eds., Cenozoic tectonics and regional geophysics of the western Cordillera: Geological Society of America Memoir 152, p. 111–144.

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

Spencer, J.E., and Reynolds, S.J., 1989, Middle Tertiary tectonics of Arizona and adjacent areas, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 539–574.

Steven, T.A., and Lipman, P.W., 1976, Calderas of the San Juan volcanic field, southwestern Colorado: U.S. Geological Survey Professional Paper 958, 35 p.

Stewart, J.H., and Carlson, J.E., 1976, Cenozoic rocks of Nevada: Nevada Bureau of Mines and Geology Map 52, 4 sheets, scale 1:1,000,000.

Stewart, J.H., Walker, G.W., and Kleinhampl, F.J., 1975, Oregon-Nevada lineament: Geology, v. 3, p. 265–268.

Thompson, G.A., and Burke, D.B., 1974, Regional geophysics of the Basin and Range province: Earth and Planetary Science Annual Reviews, v. 2, p. 213–238.

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

Tweto, Ogden, and Sims, P.K., 1963, Precambrian ancestry of the Colorado mineral belt: Geological Society of America Bulletin, v. 74, p. 991–1014.

Ward, P.L., 1991, On plate tectonics and the geological evolution of southwestern North America: Journal of Geophysical Research, ser. B, v. 96, p. 12479–12496.

Warner, L.A., 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.

Wernicke, B.P., Christiansen, R.L., England, P.C., and Sonder, L.J., 1987, Tectonomagmatic evolution of Cenozoic extension in the North American Cordillera, *in* Coward, M.P., Dewey, J.F., and Hancock, P.L., eds., Continental extensional tectonics: Geological Society Special Publication 28, p. 203–221.

White, Robert, and McKenzie, Dan, 1989, Magmatism at rift zones—The generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, ser. B, v. 94, p. 7685–7729.

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