CENOZOIC EVOLUTION OF THE NORTHERN COLORADO RIVER EXTENSIONAL CORRIDOR, SOUTHERN NEVADA AND NORTHWEST ARIZONA

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ABSTRACT

The northern Colorado River extensional corridor is a 70- to 100-km-wide region of moderately to highly extended crust along the eastern margin of the Basin and Range province in southern Nevada and northwestern Arizona. It has occupied a critical structural position in the western Cordillera since Mesozoic time. In the Cretaceous through early Tertiary, it stood just east and north of major fold and thrust belts and also marked the northern end of a broad, gently (~15°) north-plunging uplift (Kingman arch) that extended southeastward through much of central Arizona. Mesozoic and Paleozoic strata were stripped from the arch by northeast-flowing streams. Peraluminous 65 to 73 Ma granites were emplaced at depths of at least 10 km and exposed in the core of the arch by earliest Miocene time.

Calc-alkaline magmatism swept northward through the northern Colorado River extensional corridor during early to middle Miocene time, beginning at ~22 Ma in the south and ~12 Ma in the north. Major east-west extension followed the initiation of magmatism by 1 to 4 m.y., progressing northward at a rate of ~3 cm/yr. The style of volcanism changed during the course of east-west extension. Eruptions of calc-alkaline to mildly alkaline mafic to intermediate magmas predated extension. Calc-alkaline to mildly alkaline mafic, intermediate, and felsic magmas were prevalent during major extension. Tholeiitic and alkalic basalts were then erupted after significant block tilting. The most voluminous volcanism occurred in early Miocene time and was accompanied by mild north-south extension. Belts of east-west extension bordered the region to both the north and south in early Miocene time. Large-magnitude east-west extension engulfed nearly the entire region in middle Miocene time, beginning in most areas ~16 Ma and ending by ~9 Ma. Tilt rates commonly exceeded 80°/m.y. during the early stages of east-west extension. Although less voluminous than that in the early Miocene, volcanism generally spanned the entire episode of extension south of Lake Mead. Thus, thick volcanic sections, as opposed to sedimentary rock, accumulated in many growth-fault basins. The northward advancing magmatic front stalled, however, in the Lake Mead area along the southern margin of the southern Nevada amagmatic gap. Thus, Tertiary sections in the Lake Mead area are dominated by sedimentary units, including alluvial fan, continental playa, and lacustrine deposits. During middle Miocene extension, strain was partitioned into a west-dipping normal-fault system in the north and an east-dipping system in the south. The two fault systems and attendant opposing tilt-block domains overlap and terminate within the generally east-northeast-trending Black Mountains accommodation zone. Major east-west extension was contemporaneous on either side of the accommodation zone. The west-dipping normal fault system in the north is kinematically linked to major strike-slip faults along the northern margin of the corridor, where a complex three-dimensional strain field, involving both east-west extension and north-south shortening, characterized the middle to late Miocene.

The transition between the Colorado Plateau and the Basin and Range is unusually sharp along the eastern margin of the northern Colorado River extensional corridor and is marked by a single west-dipping fault zone, the Grand Wash fault zone. Subhorizontal, relatively unfaulted strata on the Colorado Plateau give way to moderately to steeply east-tilted fault blocks across the Grand Wash fault zone. Topographic and structural relief across this boundary developed during middle Miocene extension and was established by 9 Ma. The location and abruptness of the Colorado Plateau-Basin and Range transition in this region may have been controlled by an ancient north-trending crustal flaw, inasmuch as it follows a diffuse boundary between Early Proterozoic crustal provinces.

INTRODUCTION

The Basin and Range province of western North America is one of the broadest and best exposed extensional orogens on Earth. Magmatism and major extension swept across the Basin and Range in middle to late Tertiary time as the western margin of North America evolved from a convergent to a transform plate boundary (e.g., Severinghaus and Atwater, 1990; Atwater and Stock, 1998). Voluminous intermediate calc-alkaline magmatism preceded major extension and occurred in easterly trending belts that advanced southward during Eocene to middle Miocene time in the north and migrated northward from late Oligocene to middle Miocene time in the south (Fig. 1) (e.g., Christiansen and Yeats, 1992). Mild north-south extension probably accompanied this magmatism in some areas (Best, 1988; Bartley, 1990; Faulds, 1999), although Rowley (1998) has disputed this interpretation. Major east-west extension followed the onset of calc-alkaline magmatism, propagating southward in the north and northward in the south behind the respective magmatic fronts. Consequently, major east-west extension in one region may have coincided with mild north-south extension and magmatism in

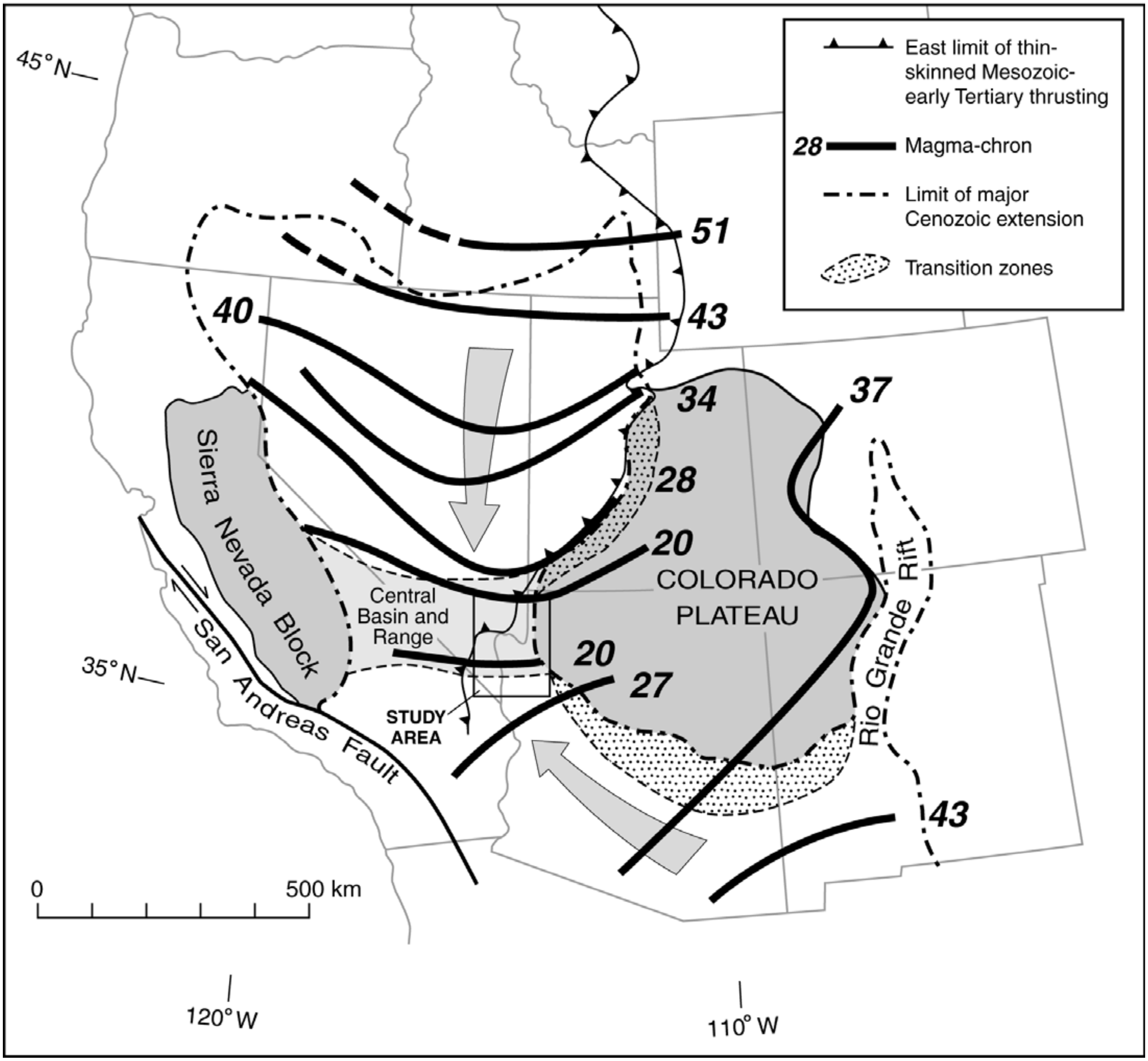


Figure 1. *Major Cenozoic geologic features of the western USA, including positions of mid-Tertiary magmatic belts. Modified from Wernicke (1992) and Christiansen and Yeats (1992). Box denotes the northern Colorado River extensional corridor.*

an adjacent region. Although the magmatic and extensional fronts propagated at overall rates of about 2 to 3 cm/yr (e.g., Gans and others, 1989; Faulds and others, 1999), their migration was not necessarily continuous. Some of the magmatic belts were immobile for protracted periods and served as long-term temporal domain boundaries for broad regions of east-west extension (e.g., Axen, 1998). Eruptive rates generally peaked just prior to or at the onset of major east-west extension and declined significantly during peak extension (e.g., Best and Christiansen, 1991; Faulds and others, 1995; Gans and Bohrson, 1998). A change from intermediate to bimodal volcanism commonly coincided with the early stages of east-west extension. However, felsic volcanism declined in some areas during peak extension.

In the western USA, the relatively undeformed blocks of the Colorado Plateau and the Sierra Nevada bound the Basin and Range province on the east and west, respectively (Fig. 1). The narrowest part of the province occurs near the latitude of Las Vegas and has been referred to as the central Basin and Range (Wernicke, 1992). This region is one of the more highly extended parts of the Basin and Range (e.g., Wernicke and others, 1988). The southward migrating magmatic and extensional fronts in the northern Basin and Range and northward advancing fronts in the south both converged on the central Basin and Range in early to middle Miocene time. The magmatic fronts stalled in this region leading to

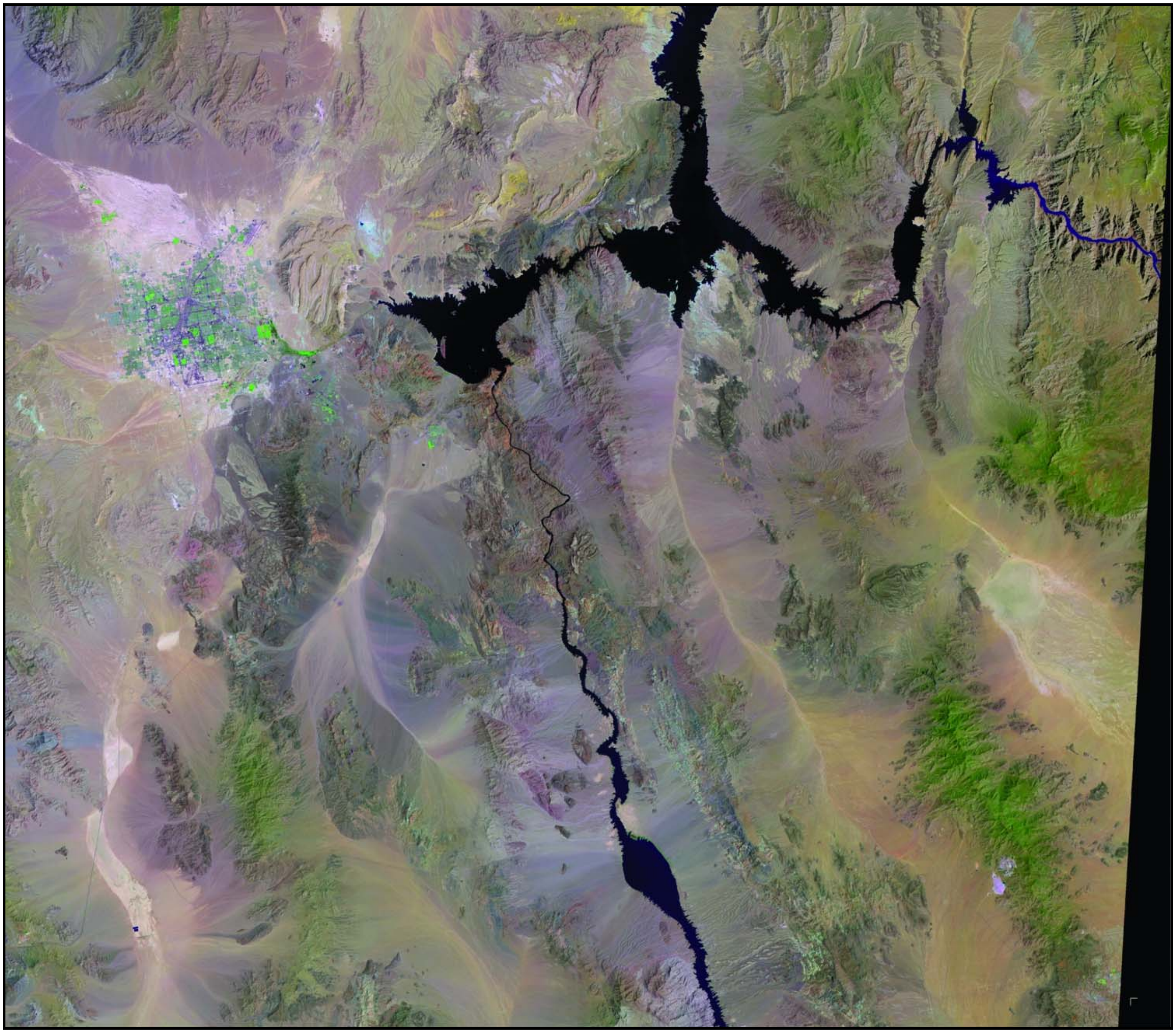


Figure 2. *Thematic mapper false-color satellite image of the northern Colorado River extensional corridor. The Grand Canyon is in the northeastern part of the image. Lake Mead and Lake Mohave are black.*

development of a 100-km-wide amagmatic gap, which stretches across southern Nevada and adjoining parts of eastern California and southwestern Utah (Eaton, 1982).

This report focuses on the Cenozoic evolution of the southeastern part of the central Basin and Range, which also corresponds to the northern part of the Colorado River extensional corridor (Figs. 2 and 3; Howard and John, 1987; Faulds and others, 1990). This highly extended part of the Basin and Range borders the Grand Canyon region of the Colorado Plateau on the west. The boundary between the Basin and Range and the Colorado Plateau is unusually abrupt in this region and is essentially marked by a single west-dipping normal fault zone. Upon crossing that fault zone, the Colorado River disgorges from the mouth of the Grand Canyon into the northern Colorado River extensional corridor. Thus, the evolution of this region has significant implications for development of both the Grand Canyon and the Colorado Plateau-Basin and Range transition.

NORTHERN COLORADO RIVER EXTENSIONAL CORRIDOR

The northern Colorado River extensional corridor is a 70- to 100-km-wide region of moderately to highly extended crust along the eastern margin of the Basin and Range province in southern Nevada and northwest Arizona (Faulds and others, 1990). It merges southward into the Colorado River extensional corridor of Howard and John (1987). The northern part of the corridor extends from about the latitude of the southern tip of Nevada northward to the Lake Mead area, where it terminates at the left-lateral Lake Mead fault system and right-

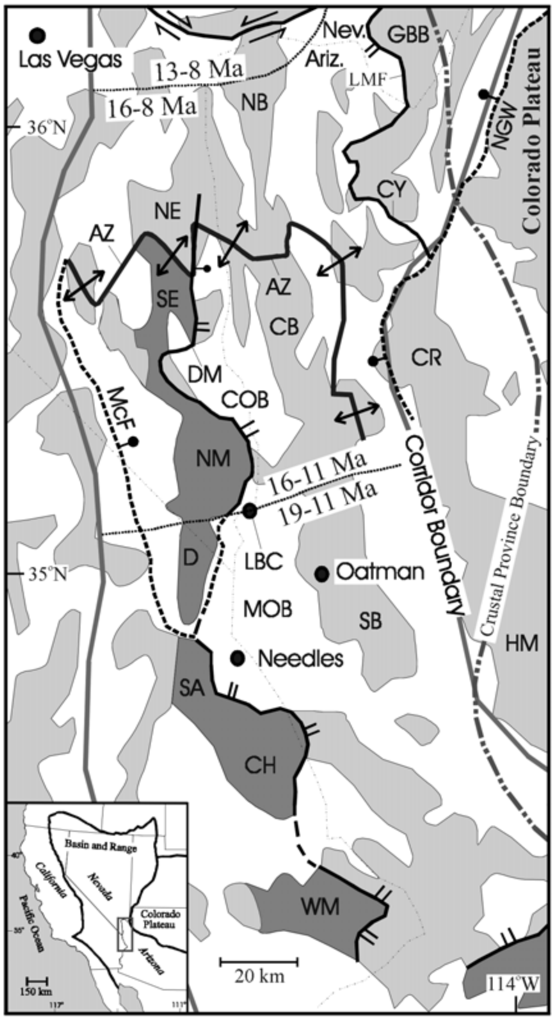
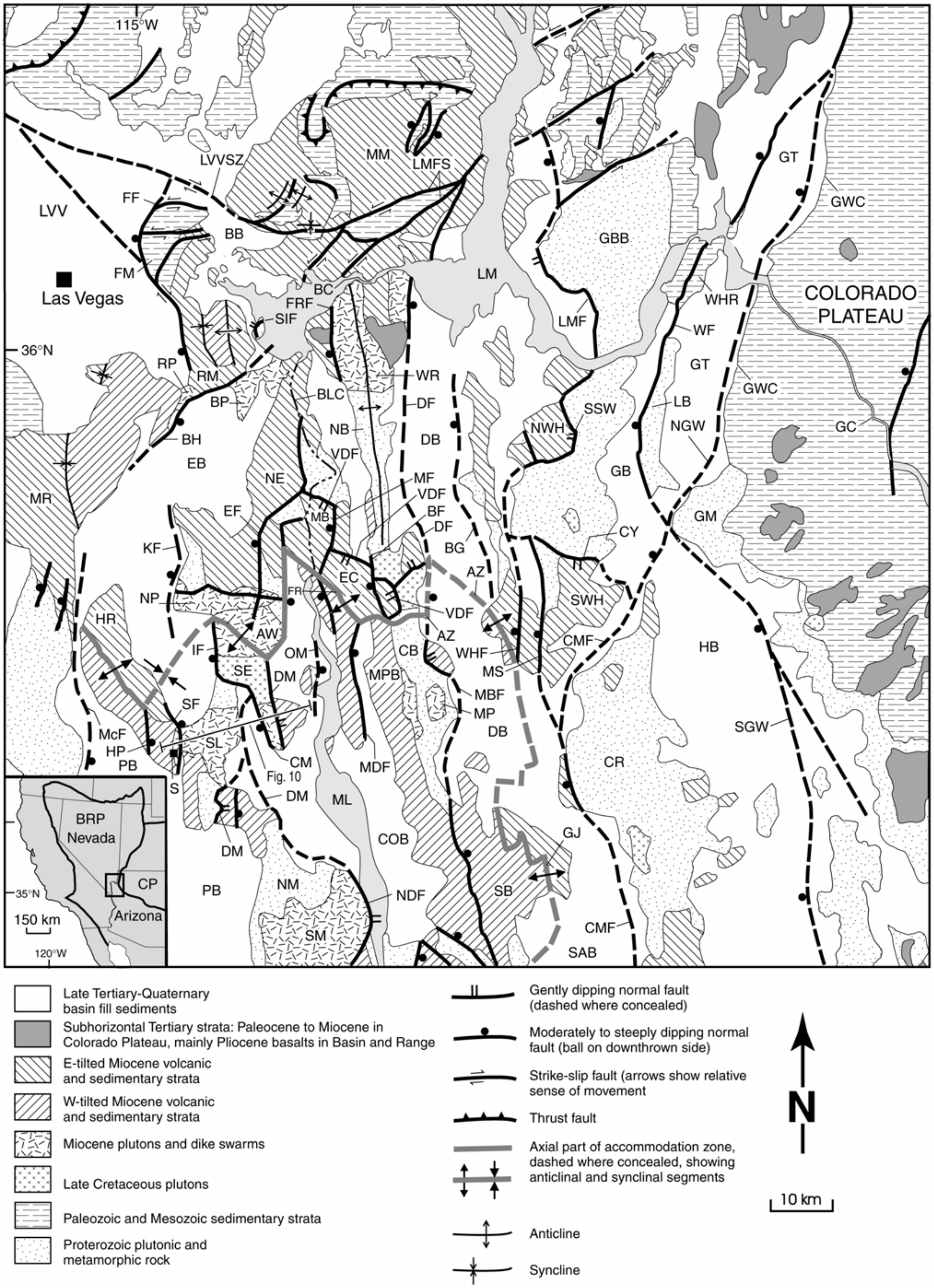


Figure 3. *Generalized map of the Colorado River extensional corridor, showing major temporal domains, faults, metamorphic core complexes (dark shading), and Proterozoic crustal province boundary. Light shading indicates bedrock exposures. A major east-dipping normal-fault system, which culminates in a chain of metamorphic core complexes, terminates northward in the Black Mountains accommodation zone. The accommodation zone (AZ) separates the Whipple domain on the south from the Lake Mead domain on the north. CH, Chemehuevi Mountains; D, Dead Mountains; HM, Hualapai Mountains; LBC, Laughlin and Bullhead City; MOB, Mohave basin; SA, Sacramento Mountains; WM, Whipple Mountains. Other abbreviations are the same as in Figure 4.*

lateral Las Vegas Valley shear zone (Fig. 4). The Colorado Plateau and the Spring Range-Old Woman Mountains region bound the northern part of the corridor on the east and west, respectively. Dissection by the Colorado River and its tributaries has generated spectacular exposures of extensional structures (Fig. 2) and volcanic centers within the corridor. The dramatic landscape in the Black Canyon area of the Colorado River formed the backdrop for the classic studies of thin-skinned extension by Anderson (1971) and Anderson and others (1972).

The northern Colorado River extensional corridor has occupied a critical structural position in the western Cordillera since Mesozoic time. In Cretaceous to early Tertiary time, this region resided directly north, east, and south of major thrust sheets and at the northern margin of a broad uplifted terrane that was stripped of its Paleozoic and Mesozoic cover by erosion (e.g., Bohannon, 1983, 1984). In addition, the polarity of thrust faults essentially reversed across the region from predominantly northeast dips in the Maria fold and thrust belt to the south (Spencer and Reynolds, 1990) to mainly west dips in the Clark, Spring, and Muddy Mountains to the west and north (e.g., Bohannon, 1983; Burchfiel and Davis, 1988). In Miocene time, the southward and northward advancing magmatic and extensional fronts converged toward the northern Colorado River extensional corridor. Thus, this region was one of the last parts of the Basin and Range to experience widespread volcanism and large-magnitude exten-

Figure 4 (opposite page). *Generalized geologic map of the northern Colorado River extensional corridor. Basins: BB, Boulder basin; COB, Cottonwood basin; DB, Detrital basin; EB, Eldorado basin; EC, Eldorado Canyon basin; GB, Gregg basin; GT, Grand Wash trough; HB, Hualapai basin; MB, Malpais basin; MPB, Mount Perkins basin; NWH, northern White Hills basin; PB, Piute basin; SAB, Sacramento basin; SWH, southern White Hills basin. Faults: BF, Bighorn fault; BG, Blind Goddess fault; BH, Black Hills fault; CM, Copper Mountain fault; CMF, Cerbat Mountains fault; CY, Cyclopic fault; DF, Detrital fault; DM, Dupont Mountain fault; EF, Eldorado fault; FF, Frenchman fault; FRF, Fortification Ridge fault; HP, Highland Pass fault; IF, Ireteba fault; KF, Keyhole Canyon fault; LMF, Lakeside Mine fault; LMFS, Lake Mead fault system; LVV, Las Vegas Valley; LVVSZ, Las Vegas Valley shear zone; MBF, Mockingbird Mine fault; McF, McCullough Range fault; MDF, Mount Davis fault; MF, Malpais fault; MS, Mountain Spring fault; NDF, Newberry detachment fault; NGW, northern Grand Wash fault; OM, Opal Mountain fault; SF, Searchlight fault; SGW, southern Grand Wash fault; SIF, Saddle Island fault; SSW, Salt Spring Wash fault; VDF, Van Deemen fault; WHF, White Hills fault; WF, Wheeler fault. Major physiographic features: BC, Boulder Canyon; BLC, Black Canyon; BRP, Basin and Range province; CB, central Black Mountains; CP, Colorado Plateau; CR, Cerbat Range; FM, Frenchman Mountain; GC, Grand Canyon; GM, Garnet Mountain; GWC, Grand Wash Cliffs; HR, Highland Range; LB, Lost Basin Range; LM, Lake Mead; ML, Lake Mohave; MM, Muddy Mountains; MR, McCullough Range; NB, northern Black Mountains; NE, northern Eldorado Mountains and basin; NM, Newberry Mountains; RM, River Mountains; S, Searchlight (townsite); SB, southern Black Mountains; SE, southern Eldorado Mountains; WHR, Wheeler Ridge. Other structures: AW, Aztec Wash anticline; AZ, Black Mountains accommodation zone; FR, Fire Mountain anticline; GBB, Gold Butte block; GJ, Grasshopper Junction anticline. Plutons: BP, Boulder City pluton; MP, Mount Perkins pluton; NP, Nelson pluton; RP, Railroad Pass pluton; SL, Searchlight pluton; SM, Spirit Mountain pluton; WR, Wilson Ridge pluton.*


115°W
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LVV
Las Vegas
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FF
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COLORADO PLATEAU
WHR
WF
RP
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BP
BLC
WR
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SSW
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VDF
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Fig. 10
MDF
CR
SGW
ML
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Nevada
CP
Arizona
150 km
NM
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SB
SM
SAB
Late Tertiary-Quaternary basin fill sediments
Subhorizontal Tertiary strata: Paleocene to Miocene in Colorado Plateau, mainly Pliocene basalts in Basin and Range
E-tilted Miocene volcanic and sedimentary strata
W-tilted Miocene volcanic and sedimentary strata
Miocene plutons and dike swarms
Late Cretaceous plutons
Paleozoic and Mesozoic sedimentary strata
Proterozoic plutonic and metamorphic rock
Gently dipping normal fault (dashed where concealed)
Moderately to steeply dipping normal fault (ball on downthrown side)
Strike-slip fault (arrows show relative sense of movement
Thrust fault
Axial part of accommodation zone, dashed where concealed, showing anticlinal and synclinal segments
Anticline
Syncline
N
10 km

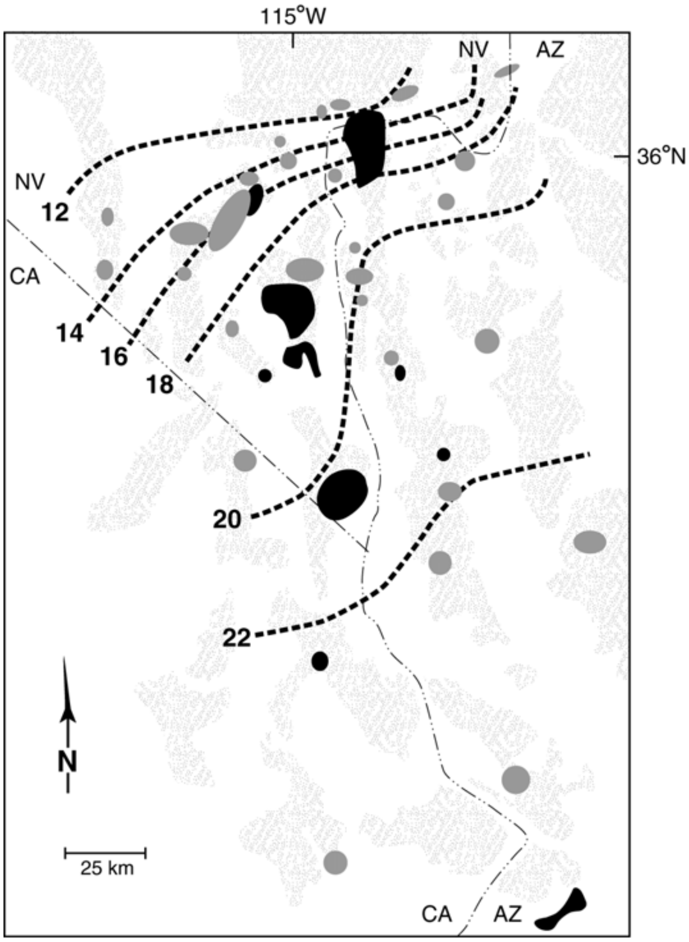

Figure 5. Magma-chrons chrons for the northern Colorado River extensional corridor, showing the age (in Ma) at which magmatism began. Light stipple pattern represents bedrock exposures. Light shaded circles and ellipsoids are major Miocene volcanic centers. Black areas correspond to Miocene plutons.

sion. An extensive region of extreme Cenozoic extension, which includes several metamorphic core complexes in western Arizona and southeastern California, terminates northward in the northern Colorado River extensional corridor (Fig. 3). The northern part of the corridor also contains a major extensional accommodation zone (Fig. 4), referred to as the Black Mountains accommodation zone, where oppositely dipping normal-fault systems and attendant tilt-block domains terminate in a belt of overlapping fault tips (Faulds and others, 1990; Faulds and Varga, 1998). In addition, an unusually sharp boundary between the Basin and Range province and the Colorado Plateau epitomizes this region. Flat-lying unextended strata in the Grand Canyon region of the Colorado Plateau give way to steeply tilted fault blocks within the northern part of the extensional corridor across a single major west-dipping normal fault zone, the Grand Wash fault zone (e.g., Lucchitta, 1966; Lucchitta and Young, 1986). This contrasts with broad transition zones (e.g., Peirce, 1985) that separate the Colorado Plateau and the Basin and Range province in southwest Utah and central Arizona (Fig. 1).

GENERAL STRATIGRAPHIC FRAMEWORK

The stratigraphy of the northern Colorado River extensional corridor is characterized by thick sections (generally >3 km) of Tertiary volcanic and sedimentary strata that rest directly on Proterozoic and Late Cretaceous metamorphic and plutonic rock (Longwell, 1963; Anderson, 1971, 1977, 1978; Bohannon, 1984; Faulds, 1993b, 1995, 1996; Sherrod and Nielson, 1993) (Fig. 4). Although preserved to the north, east, and west of the region, Paleozoic and Mesozoic strata are missing from all but the northernmost part of the corridor (Lake Mead region), where southward beveling of such strata is well documented (Bohannon, 1984; Lucchitta and Young, 1986; Castor and others, 2000). Basement rocks include Early Proterozoic (~1.6 to 1.8 Ga) gneiss and amphibolite, 1.4 Ga rapakivi granite, late Cretaceous granites, and early to middle Miocene silicic to intermediate plutons and mafic to felsic dike swarms (e.g., Anderson, 1977, 1978; Theodore and others, 1982; Anderson and Bender, 1989; Wooden and DeWitt, 1991; Fryxell and others, 1992; Falkner and others, 1995; Faulds and others, 1990, 1995; Faulds, 1993b; Bachl and others, in press). Tertiary sections in the bulk of the northern Colorado River extensional corridor are dominated by Miocene volcanic rocks, including felsic to mafic lavas, volcanic breccia, and ash-flow tuffs, which commonly interfinger with lesser amounts of clastic sedimentary rocks and rock avalanche deposits (Anderson, 1971, 1977, 1978; Anderson and others, 1972; Weber and Smith, 1987; Turner and Glazner, 1990; Faulds and others, 1990, 1995, in press; Faulds, 1993a, 1995, 1996). In contrast, Miocene sedimentary rocks, including alluvial fan, continental playa, and lacustrine deposits, prevail in the Lake Mead region and along the eastern margin of the corridor (Lucchitta, 1966, 1979; Anderson and others, 1972; Bohannon, 1984; Beard, 1993, 1996; Faulds and others, 1997; Castor and others, 2000). Accordingly, the Miocene plutons and dike swarms are largely confined to the volcanic terrane south of the Lake Mead area.

PATTERNS OF MAGMATISM AND EXTENSION

Calc-alkaline magmatism swept northward through the northern Colorado River extensional corridor during early to middle Miocene time, beginning at approximately 22 Ma in the south (e.g., Oatman area) and about 12 Ma in the north (western Lake Mead area) (Glazner and Bartley, 1984; Gans and others, 1989; Faulds and others, 1994, 1999; Smith and Faulds, 1994) (Figs. 3 and 5). The rate of northward migration of the magmatic front ranged from about 2.4 cm/yr between the Needles area and northern Black and Eldorado Mountains to about 0.45 cm/yr in the Lake Mead area. In its journey north, the magmatic front appears to have stalled in two areas. The first was a temporary halt at about 19 Ma near the southern tip of Nevada. Sequences of 21 to 19 Ma intermediate to felsic lavas are thick to the south of this area (e.g., Oatman area, DeWitt and others, 1986; Howard and others, 2000b) but scant to the north (e.g., Mount Perkins area; Faulds and others, 1995). The magmatic front then stalled

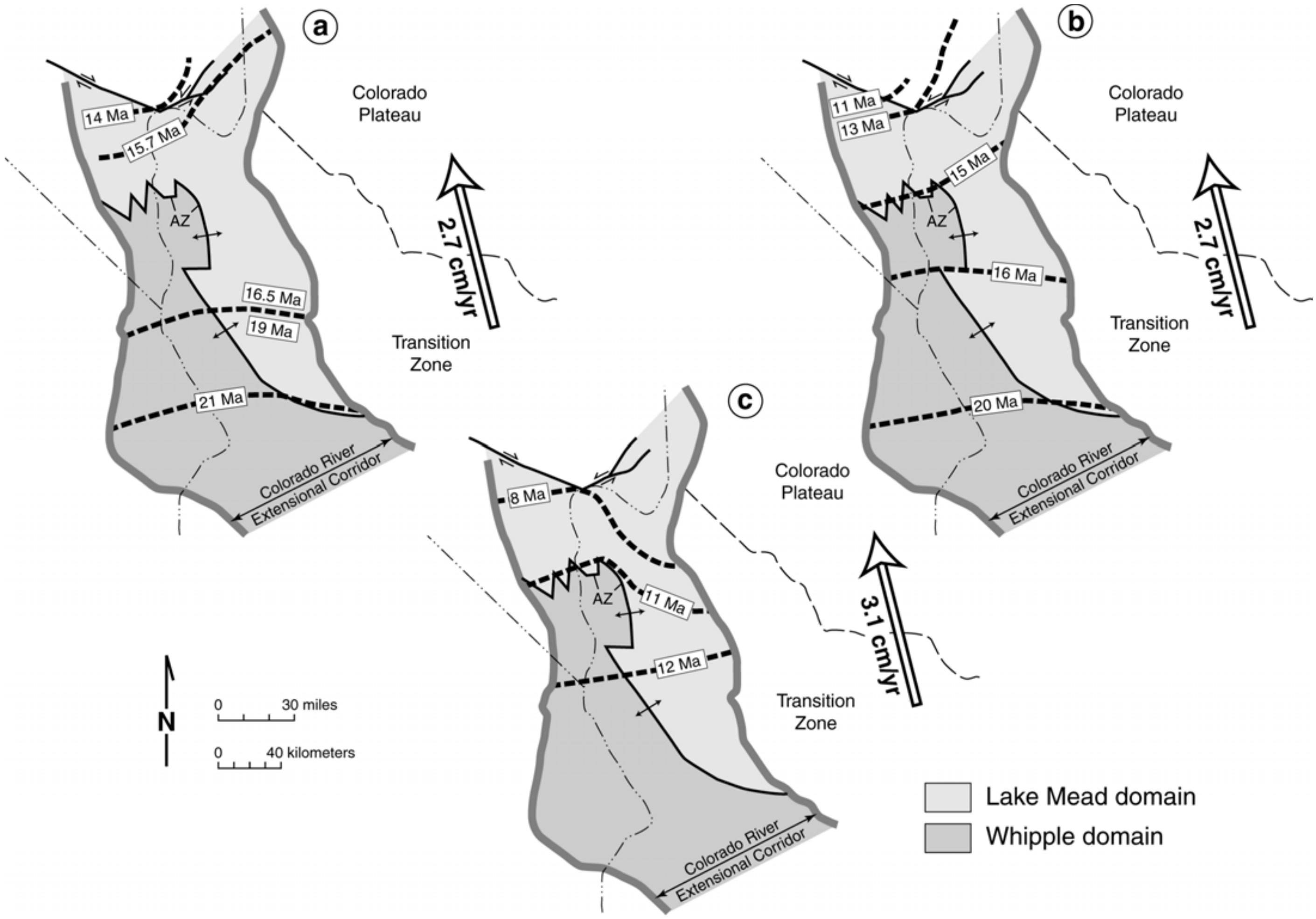

Figure 6. *Extension-chrons for the northern Colorado River extensional corridor, showing (a) timing of onset of extension, (b) peak extension as defined by maximum rates of tilting, and (c) end of extension. Modified from Faulds and others (1999).*

permanently at about 12 Ma in the Lake Mead area along the southern margin of the aforementioned amagmatic gap. The east-west extent of the magmatic front also narrowed considerably as it approached the Lake Mead area. Thus, the eastern margin of the northern part of the corridor has been largely unscathed by volcanism. Magmatism ceased at about 11 Ma in the southern part of the northern Colorado River extensional corridor but continued until about 4 Ma in the north.

Major east-west extension followed magmatism by 1 to 4 m.y., progressing northward at a rate of about 2.7 cm/yr (Fig. 6a). The northward migration of both magmatism and extension suggest that the northern Colorado River extensional corridor is more closely affiliated with the southern rather than the northern Basin and Range. In the metamorphic core complexes to the south of the area, major extension began as early as approximately 23 Ma (e.g., Simpson and others, 1991; Campbell and John, 1996). In the northern Colorado River extensional corridor, east-west extension began at about 19 Ma near the southern tip of Nevada, 16 Ma near the latitude of the accommodation zone, and 12 to 14 Ma in the western Lake Mead area (e.g., Faulds and others, 1999). The onset, peak, and end of extension all migrated northward at similar rates of about 3 cm/yr (Fig. 6; Faulds and others, 1999). Extension ceased by about 11 Ma in the southern part of the region (Faulds and others, 1995). In the north, east-west extension ended about 8 Ma in many areas (e.g., Harlan and others, 1998) but has locally continued to the present (e.g., dePolo, 1996). The onset of extension was determined by dating the youngest, most steeply tilted unit, above which significant tilt fanning began (Fig. 7). Peak extension was defined by maximum rates of tilting. An upper limit of extension was constrained by dating flat-lying, essentially unfaulted strata. It is important to note that the Black Mountains accommodation zone had little, if any, effect on the temporal patterns of deformation and did not inhibit the northward migrating fronts of magmatism or extension.

MIOCENE VOLCANISM

Lavas were erupted before, during, and after Miocene extension in the northern Colorado River extensional corridor. The style of volcanism changed, however, during the course of extension. In general, calc-alkaline to mildly alkaline mafic to intermediate magmas predated extension. Calc-alkaline to mildly alkaline magmatism continued during extension but typically trended toward bimodal compositions. Tholeiitic and alkalic basalts erupted after major extension (Smith and others, 1990; Feuerbach and others, 1993; McDaniel, 1995).

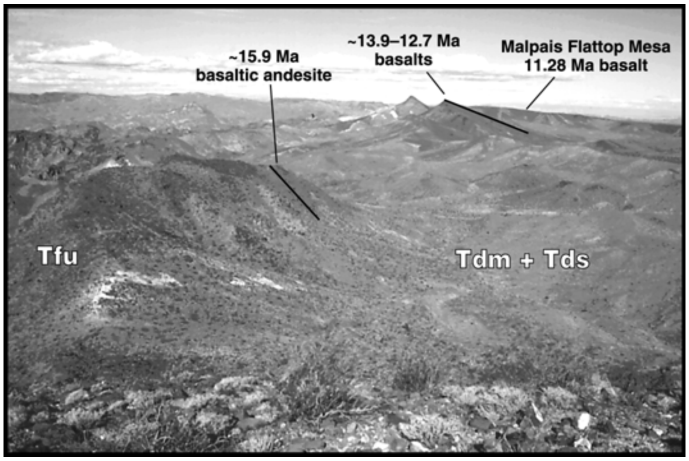

Figure 7. *Looking north at the east-tilted half graben of the Eldorado Canyon basin. This basin lies in the hanging wall of the Van Deemen and Bighorn faults. In this part of the basin, tilts decrease up-section from ~45^o in 15.9 Ma basaltic andesite lavas, to 20-30^o in 12.7-13.9 Ma basalt lavas, to <5^o in capping 11.3 Ma basalt lavas. Tfu, basaltic andesite lavas of the upper part of the volcanics of Fire Mountain; Tdm, mafic lavas of the Mount Davis Volcanics; Tds, conglomerate and sandstone of the Mount Davis Volcanics.*

This pattern of extension-related volcanism has been noted elsewhere in the Basin and Range (Eaton, 1982; Smith, 1982; Otton, 1982; Glazner and Ussler, 1989; Glazner, 1990).

The major episodes of volcanism in the northern Colorado River extensional corridor include: (1) localized 21 to 18.5 Ma mafic to intermediate lavas or "Pre-Patsy Mine Volcanics"; (2) the widespread 18.5 Ma Peach Springs Tuff (Glazner and others, 1986; Nielson and others, 1990); (3) thick sections of 18.5 to 15.2 Ma intermediate to felsic lavas of the Patsy Mine Volcanics (Anderson and others, 1972), which includes the volcanics of Dixie Queen Mine and Red Gap Mine exposed in the Mount Perkins and Fire Mountain areas of the Black Mountains (Faulds and others, 1995; Faulds, 1996); (4) the widespread 15.2 Ma tuff of Bridge Spring (Anderson and others, 1972; Morikawa, 1994; Faulds and others, 1995) and 15.0 Ma tuff of Mount Davis (Faulds, 1995; Faulds and Bell, 1999); (5) sequences of 15 to 11.35 Ma mafic lavas of the Mount Davis Volcanics (e.g., Anderson and others, 1972; Faulds, 1995); (6) isolated fields of 11.9 to 8.7 Ma tholeiitic basalts, as best exposed at Malpais Flattop Mesa in the northern Black Mountains; (7) local sequences of 10.6 to 8.0 Ma basaltic andesites, as best exemplified at Callville Mesa; and (8) several small volcanic fields of 6.0 to 4.5 Ma alkalic basalts (Feuerbach and others, 1993), referred to as the Fortification Hill basalts (Figs. 4 and 8).

The above episodes of volcanism can be grouped into three distinct magmatic stages on the basis of age, relative timing with respect to extension, and compositions (Feuerbach, 1998). Stage 1 magmas (>16.5 Ma) are pre-extensional and characterized by highly tilted, mafic to intermediate lavas, ranging from basalt to trachyandesite as well as significant exposures of trachydacites. This stage includes pre-Patsy Mine Volcanics and the lower sections of both the Patsy Mine Volcanics and volcanics of Dixie Queen Mine. Stage 2 magmas (16.5-15.2 Ma) are pre- to synextensional and characterized by moderate- to highly-tilted intermediate to felsic lavas, ranging from trachyandesite to rhyolite. Included in stage 2 magmas are the upper portions of the volcanics of Dixie Queen Mine, volcanics of Red Gap Mine, and upper portions of the Patsy Mine Volcanics. Stage 3 magmas (<15.2 Ma) are trachybasalts and basaltic trachyandesites that are tilted between 0 and 50^o and are, therefore, syn- to post-extensional. Stage 3 magmas incorporate the Mount Davis Volcanics, as well as younger mafic volcanic fields (e.g., Callville Mesa, Malpais Flattop Mesa, and Fortification Hill). Feuerbach and others (1999) described the general distribution of these volcanic rocks.

As in many areas of continental extension, mafic magmas in the northern Colorado River extensional corridor that erupted prior to and during major extension have relatively low (<0) $\square_{Nd}$ and high $^{87}Sr/^{86}Sr$ (~0.708), suggesting derivation from enriched sub-continental lithospheric mantle (Feuerbach and others, 1993; Feuerbach, 1998). However, mafic magmas derived shortly after major extension have relatively high $\square_{Nd}$ (>0) and low $^{87}Sr/^{86}Sr$ (~0.705), implying derivation of post-extensional mafic magmas from a source that contains an asthenospheric component (Feuerbach and others, 1993, 1998; Perry and others, 1993).

The calc-alkaline intermediate to felsic lavas that erupted in the corridor and elsewhere in the Basin and Range contain significant proportions of partially melted continental crust (Suneson and Lucchitta, 1983; Feeley and Grunder, 1991). Based on high $^{87}Sr/^{86}Sr$ ratios (0.7093 to 0.7141) in synextensional rhyolites, Suneson and Lucchitta (1983) inferred that the dominant source for rhyolites in the Castaneda Hills area in western Arizona was continental crust. Feeley and Grunder (1991) suggested that synextensional andesite to rhyolite flows in east-central Nevada were formed predominantly from mixing mantle derived mafic magmas and crustal derived melts. They concluded that at least 50% of the hybrid is basaltic. Perry and others (1993) noted that Oligocene and Miocene felsic rocks erupted in the western USA were largely a product of crystal fractionation of mantle derived mafic magmas and simultaneous crustal assimilation (i.e., AFC processes). Gans and others (1989) used Nd and Sr isotopes and trace elements to show that synextensional intermediate to felsic lavas in east-central Nevada were produced by AFC processes, whereby mantle derived mafic magma commingled with magmas derived from the continental crust. Calc-alkaline traits found in other extension-related lavas in the Basin and Range have been attributed to crustal contamination (e.g., Hawkesworth and others, 1995) or, for the mafic lavas, to enriched lithospheric mantle-source compositions (e. g., Hooper and others, 1995).

MIOCENE PLUTONS

Exposed plutons in the northern Colorado River extensional corridor are more restricted in age than the volcanic rocks. They range from about 17 to 13 Ma and were emplaced 2 to 4 m.y. after volcanism began. Eight of nine of the exposed plutons were emplaced during the interval 15 to 17 Ma. From south to north, these include the 15 Ma Mirage and 17 Ma Spirit Mountain plutons in the Newberry Mountains

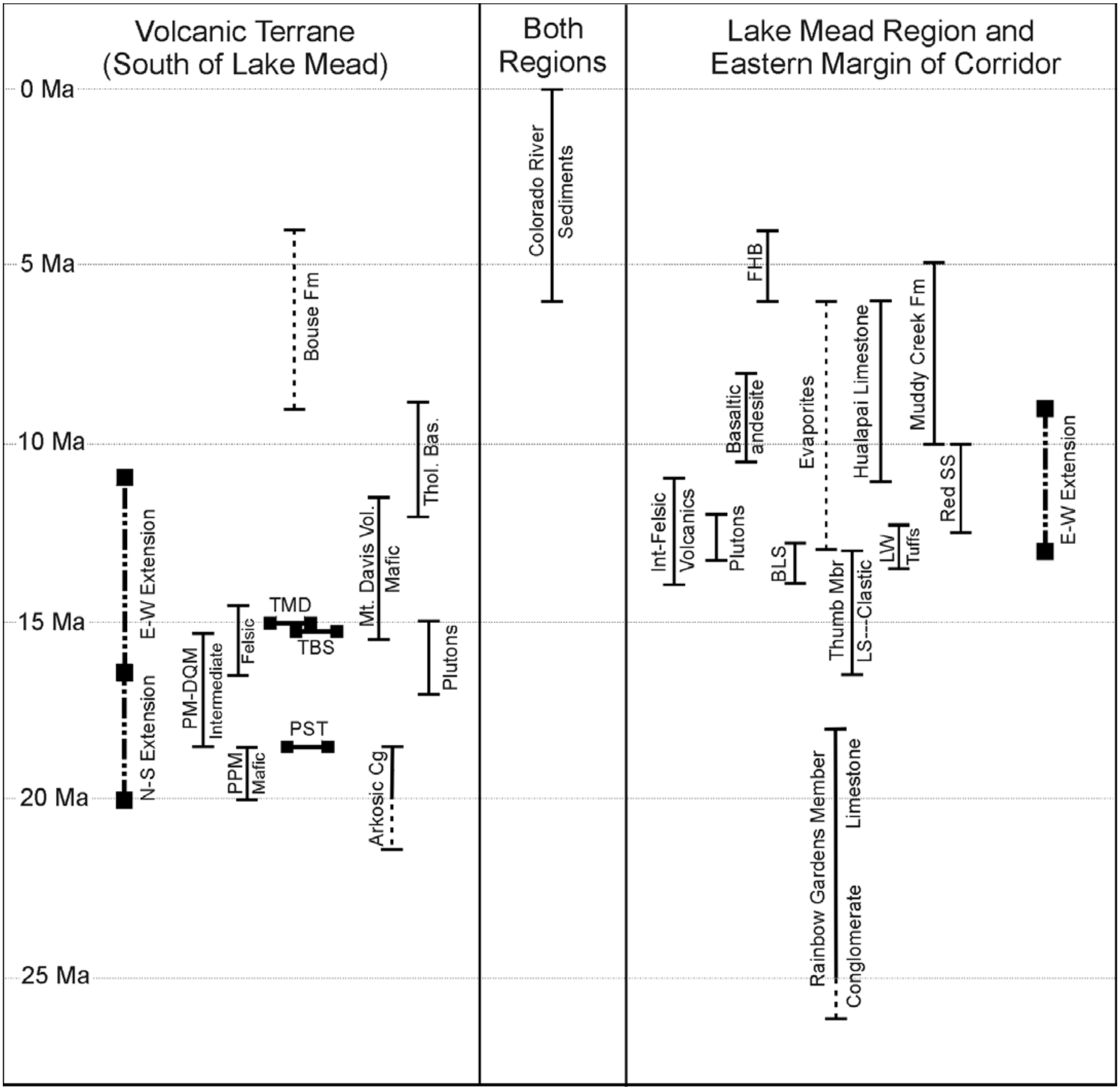

Figure 8. *Generalized stratigraphic time column of Tertiary strata and plutons in the northern Colorado River extensional corridor. The terms felsic, intermediate, and mafic indicate the predominant type of volcanic rocks. The Rainbow Gardens, Thumb, and Lovell Wash Members are part of the Horse Spring Formation. The intermediate and felsic volcanics, as well as the plutons, shown for the Lake Mead region actually straddle the boundary between the volcanic terrane and Lake Mead region. Abbreviations: Bas., Basalt; BLS, Bitter Ridge Limestone; Cg, conglomerate; DQM, volcanics of Dixie Queen Mine; Fm, Formation; FHB, Fortification Hill alkali basalts; LS, Limestone; LW, Lovell Wash Member; Int, Intermediate volcanics; Mbr, Member; PM, Patsy Mine Volcanics; PPM, pre-Patsy Mine basaltic andesite lavas; PST, Peach Springs Tuff; SS, sandstone; TBS, tuff of Bridge Spring; Thol., tholeiitic; TMD, tuff of Mount Davis; Vol., Volcanics.*

(Howard and others, 1996), the 16.4 Ma Searchlight pluton in the southern Eldorado Mountains (Bachl and others, in press), the 16.0 Ma Mount Perkins pluton in the central Black Mountains (Faulds and others, 1995; Metcalf and others, 1995), the 15.7 Ma Aztec Wash (Falkner and others, 1995) and 16.3 Ma Nelson pluton (Lee and others, 1995) in the central Eldorado Mountains, the 15.0 Ma Railroad Pass pluton in the northern McCullough Range (Anderson, 1977; age from P. Gans, personal commun., 1997), and the Boulder City pluton (Anderson, 1977). The only younger exposed pluton is the 13.1 Ma Wilson Ridge pluton near the northern end of the corridor (Larsen and Smith, 1990; Anderson and others, 1994;

age reported in Faulds and others, 1999). All of the plutons reached shallow crustal levels (roofs at ~5 km or less), and most intruded the base of the Miocene section.

As a consequence of subsequent extension, nearly all of the plutons are tilted appreciably. The Aztec Wash, Searchlight, Wilson Ridge, and Mt. Perkins plutons are exposed from top to bottom, and a considerable part of the Spirit Mountain pluton is also revealed (Larsen and Smith, 1990; Hopson and others, 1994; Faulds and others, 1995; Patrick and Miller, 1997; Bachl and others, in press). Paleomagnetic data, hornblende barometry, and geologic relations indicate that the steeply west-tilted Searchlight pluton is 10 km thick, extending into the ductile middle crust (Faulds and others, 1998; Bachl and others, in press). The Aztec Wash pluton lies between the steeply west-tilted structural block of the southern Eldorado Mountains and steeply east-tilted northern Eldorado Mountains. Paleomagnetic data and magmatic structures indicate that the western portion of the pluton is tilted west-southwest and the eastern portion is tilted northeast, consistent with its location in a broad northwest-trending anticlinal segment of the Black Mountains accommodation zone (Faulds and others, 1992; Patrick and Miller, 1997; Faulds unpublished data).

Most workers consider it probable that all, or at least most, of the plutons represent magma chambers that erupted and that coeval volcanic strata are therefore at least in part comagmatic with the plutons. Specific plutonic-volcanic links have been proposed for the Mount Perkins pluton, a felsic dike swarm, and a volcanic section to the west in the Black Mountains (Faulds and others, 1995); the Wilson Ridge pluton and volcanic rocks of the River Mountains (Weber and Smith, 1987; Larsen and Smith, 1990; Duebendorfer and others, 1998); and the Boulder City pluton and the widespread 15.2 Ma tuff of Bridge Spring (considered to represent a caldera-forming eruption; Gans and others, 1994).

Evidence for mingling between mafic and felsic magmas is preserved in all plutons, suggesting that, for the most part, magmas entering the upper crust were bimodal. The Wilson Ridge, Mount Perkins, and Aztec Wash plutons reveal especially widespread mafic-felsic interaction (Larsen and Smith, 1990; Metcalf and others, 1995; Patrick and Miller, 1997). Mixing is also evident but not generally extensive. Only the Nelson pluton is predominantly intermediate in composition (quartz monzodiorite; Lee and others, 1995). The felsic magmas were predominantly K-rich, biotite ± hornblende-bearing true granites, whereas the mafic magmas were generally basaltic but included monzodiorite. Olivine is present locally and clinopyroxene is widespread in the mafic rocks, but hydrous minerals (hornblende ± biotite) typically dominate the mafic assemblages. All rocks in the plutons are relatively rich in incompatible elements. Almost all have evolved isotopic ratios (high $^{87}Sr/^{86}Sr$, low □□d) and most have calc-alkaline, subduction-like elemental geochemistry. Metcalf and others (1995, 2000) have pointed out variability among the mafic rocks noting that, in addition to calc-alkaline basalts, some have ocean island basalt-like (OIB) elemental chemistry and a few are isotopically primitive (bulk Earth or depleted mantle ratios). Only a single mafic component has been identified in most plutons, but the Mount Perkins pluton contains both enriched OIB and depleted mantle basaltic compositions (Metcalf and others, 1995). The granites are interpreted to have been generated by deep crustal hybridization between ancient crust and mantle-derived basalts (Falkner and others, 1995; Metcalf and others, 1995; Bachl and others, in press). Metcalf and others (2000) suggested that the mafic magmas were derived both from the ancient, enriched lithospheric mantle (calc-alkaline and enriched OIB) and from the asthenosphere (bulk Earth to depleted OIB).

Existing radiometric data indicate that most plutons were emplaced within about 0.2 to 0.5 m.y. of the local onset of east-west extension. The northerly orientation of mafic and felsic injections in the Aztec Wash magma chamber suggests that the Aztec Wash pluton was emplaced during at least modest east-west extension (Falkner and others, 1995). The northerly striking dike-on-dike character of the northern part of the Wilson Ridge pluton also suggests synextensional emplacement (Anderson and others, 1994). However, east-west dikes cutting and apparently emanating from the Mount Perkins and Searchlight plutons suggest that these intrusions were emplaced before the onset of major east-west extension (Faulds and others, 1995, 1998; Ruppert, 1999; Bachl and others, in press). Only two plutons were emplaced decidedly before or after the onset of east-west extension. The east-west orientation of the Nelson pluton and associated dikes and its 16.3 Ma age indicate emplacement well before the onset of east-west extension (Lee and others, 1995; Unkefer and others, 1995). On the other hand, the relatively little-studied Mirage pluton has been dated at 15 Ma (Howard and others, 1996), which coincides with the main episode of east-west extension in the Newberry Mountains.

STRUCTURAL FRAMEWORK

With respect to Tertiary extension, the northern Colorado River extensional corridor consists of two major domains separated by the Black Mountains accommodation zone. East-dipping normal faults and west-tilted fault blocks of the Whipple domain (e.g., Spencer and Reynolds, 1989) dominate south of the zone, whereas west-dipping normal faults and east-tilted fault blocks of the Lake Mead domain prevail to the north (Fig. 4). Major normal faults in both the Lake Mead and Whipple domains overlap and terminate within the Black Mountains accommodation zone. Major faults and basins within the Lake Mead and northern Whipple domains, as well as the Black Mountains accommodation zone, are described in detail in subsequent sections.

Although less extended than areas to the south, the magnitude of extension within the north-trending axial or central part of the northern Colorado River extensional corridor may exceed 100%, as suggested by fault-block tilting typically in excess of 60^{o} and commonly approaching and locally surpassing 90^{o}. On the basis of stretching lineations in mylonitic rocks, the average strike of tilted strata, sliplines in cataclasites, and the attitudes of conjugate normal-fault systems, the extension direction changes from northeast/southwest to east-northeast/west-southwest (~N75^{o}E) between the Whipple Mountains (e.g., Davis and others, 1986; Reynolds and others, 1986) and Lake Mead regions (Anderson, 1971; Angelier and others, 1985; Price and Faulds, 1999; Faulds, unpublished data), remaining approximately orthogonal to the Colorado

Plateau-Basin and Range boundary (Fig. 1). Particularly extreme extension affected the southern part of the extensional corridor, where rocks originating at middle crustal depths prior to extension are juxtaposed against unmetamorphosed Miocene strata along gently east-dipping detachment faults in the metamorphic core complexes of the Whipple, Chemehuevi, and Sacramento Mountains (Fig. 3) (Davis and others, 1980, 1986; Spencer, 1985; Howard and John, 1987; Anderson and others, 1988; Davis and Lister, 1988; Yin and Dunn, 1992; John and Foster, 1993; Campbell and John, 1996). This system of detachment faults may extend northward into the northern part of the corridor and terminate within the accommodation zone (e.g., Faulds and others, 1990). Conversely, west-dipping detachment faults in the Lake Mead domain (e. g., Wernicke and Axen, 1988; Duebendorfer and others, 1990) may die out southward in the accommodation zone.

It is important to note that the three-dimensional strain field near the northern margin of the Lake Mead domain and extensional corridor differed markedly from that to the south in the bulk of the corridor. East-west extension and northerly striking normal faults, with virtually no strike-slip faulting, dominated to the south. In contrast, a complex system of kinematically related strike-slip and normal-fault systems characterized the northern margin of the corridor (Anderson, 1973; Weber and Smith, 1987; Duebendorfer and Wallin, 1991; Duebendorfer and Black, 1992; Anderson and Barnhard, 1993; Anderson and others, 1994; Duebendorfer and Simpson, 1994; Campagna and Aydin, 1994; Çakir and others, 1998). Thus, many of the west-dipping normal faults in the Lake Mead domain merge northward with major strike-slip faults (e.g., Duebendorfer and others, 1998). Total offset along the left-lateral Lake Mead fault system may exceed 65 km (Anderson, 1973; Bohannon, 1984; Rowland and others, 1990; Duebendorfer and others, 1998). Offset of the Mesozoic Keystone thrust between the Spring Range west of Las Vegas and Muddy Mountains to the north of Lake Mead indicates as much as 65 km of dextral motion on the Las Vegas Valley shear zone (Longwell, 1974, Wernicke and others, 1988). In addition, a significant component of north-south shortening accompanied east-west extension in the Lake Mead region, particularly in the vicinity of the Las Vegas Valley shear zone and Lake Mead fault system (e.g., Anderson and Barnhard, 1993; Duebendorfer and Simpson, 1994). One of the more conspicuous manifestations of the north-south shortening is an east- to northeast-trending fold belt near the intersection of the Las Vegas Valley shear zone and Lake Mead fault system (Fig. 4; Anderson and others, 1994; Castor and others, 2000; Duebendorfer, in press; Anderson, in press). The Neogene north-south contractional strain field extended northward through much of the Great Basin (e.g., Frizzell and Zoback, 1987; Michel-Noël and others, 1990; Anderson and Barnhard, 1993; Catteau and Varga, 1993; Anderson and others, 1994). The strike-slip faulting along the northern margin of the extensional corridor has been attributed to transfer zones (cf., Faulds and Varga, 1998) that partitioned strain between nonaligned extensional terranes (e.g., Liggett and Childs, 1977; Duebendorfer and Black, 1992), intracontinental transform faults that accommodated a realignment in axes of extension associated with mantle upwelling to the south (Faulds and others, 1990), primary features along which offset induced nearby extension (e.g., Campagna and Aydin, 1994), and regional north-south shortening (Anderson and others, 1994).

Lake Mead Domain

The Lake Mead domain comprises the system of west-dipping normal faults and east-tilted fault blocks north of the Black Mountains accommodation zone. Roughly from east to west, major faults within this domain include the northern and southern Grand Wash, Cerbat Mountains, Wheeler, Cyclopic-Salt Spring Wash-Lakeside Mine, Mountain Spring, White Hills, Blind Goddess, Detrital, Van Deemen, Bighorn, Malpais Flattop, Eldorado, Keyhole Canyon, Black Hills, Saddle Island, and Frenchman faults (Fig. 4). Major east-tilted half grabens associated with these faults include the Grand Wash trough and the Gregg, Hualapai, northern and southern White Hills, Malpais, northern Eldorado, and Eldorado basins. Most of the major west-dipping normal faults and their associated east-tilted half grabens terminate southward within the Black Mountains accommodation zone. However, the Grand Wash fault zone and Cerbat Mountains fault extend farther southward to at least the latitude of Needles, California. Accordingly, an arm of the east-tilted Lake Mead domain extends southward in the hanging wall of the Grand Wash fault zone along the Colorado Plateau-Basin and Range boundary (Fig. 4).

The Grand Wash fault zone, which consists of two major strands, bounds the Colorado Plateau on the west and serves as the breakaway fault to the west-dipping normal-fault system in the Lake Mead domain. Listric geometries are inferred for major segments of the zone, because the hanging walls are consistently tilted more steeply than the footwalls. The northern Grand Wash fault forms a particularly abrupt boundary between the Colorado Plateau and extensional corridor, as east-tilting of the hanging wall (Grand Wash trough) is as much as 90^o, in sharp contrast to the essentially flat-lying strata of the Colorado Plateau within the footwall. The Lost Basin Range, Wheeler Ridge, and South Virgin Mountains (Gold Butte block) all correspond to the upthrown western parts of east-tilted fault blocks in the hanging wall of the northern Grand Wash fault. The northern Grand Wash fault appears to connect southward with the Cerbat Mountains fault (Fig. 4). The southern Grand Wash fault also bounds the Colorado Plateau on the west, but its hanging wall is tilted only 15 to 30^o east. The hanging wall of the southern Grand Wash fault includes the east-tilted half graben of the Hualapai basin and, in its upthrown western part, the Cerbat Mountains. The southern Grand Wash fault appears to merge northward with the Wheeler fault, which bounds the Lost Basin Range and Wheeler Ridge on the west (Fig. 4). The Wheeler fault links northward with the northern Grand Wash fault in the northern part of the Grand Wash trough and is associated with Quaternary scarps in the Lake Mead area (Menges and Pearthree, 1989; Wallace and others, in press). The Gregg basin is a narrow east-tilted half graben within the hanging wall of the Wheeler fault and merges northward with the Grand Wash trough. The Gold Butte block (Fryxell and others, 1992) essentially lies in the mutual hanging wall of the

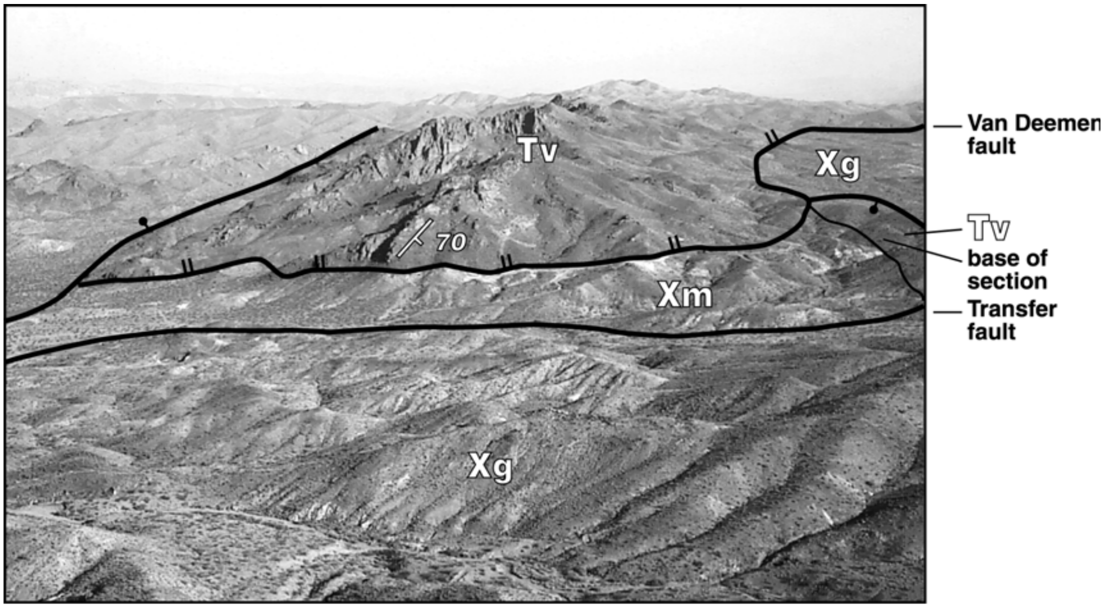

Figure 9. *Looking north at the gently west-dipping Van Deemen normal fault, which juxtaposes steeply east-tilted early Miocene volcanic rock (Tv) in the hanging wall against pre-Miocene (Proterozoic?) mylonite (Xm), Proterozoic gneiss (Xg), and the base of the Miocene section in the footwall. The Proterozoic (?) mylonite in the footwall is dragged along the Van Deemen normal fault, giving the false impression of a Tertiary detachment fault.*

northern Grand Wash and Wheeler faults.

The Cerbat Mountains fault bounds the gently east-tilted Cerbat Mountains on the west. It is noteworthy that the Cerbat Mountains fault, north of the Sacramento basin, separates steeply tilted, highly extended terrane to the west from the gently tilted, mildly extended northwesternmost part of the transition zone. Within the Sacramento basin, the Cerbat Mountains fault appears to lose displacement southward, as the boundary between mildly and highly extended terrane steps westward to the southern Black Mountains. Nevertheless, from the northern part of the Grand Wash trough to the southern end of Detrital basin, the northern Grand Wash-Cerbat Mountains fault forms a 100-km-long boundary between unextended to mildly extended terrane to the east and the highly extended part of the northern Colorado River extensional corridor.

The Cyclopic-Salt Springs Wash-Lakeside Mine fault is a major gently east-dipping normal fault zone that accommodates progressively greater displacement toward the north (Cascadden, 1991; Duebendorfer and Sharp, 1998). Displacement may be as little as 6 km on the Cyclopic segment of the fault zone (Myers and others, 1986) and as much as 17 km on the Lakeside Mine segment (Brady, 1998; Brady and others, 2000). The Lakeside Mine segment appears to merge northward with major northeast-striking left-lateral faults in the Lake Mead fault system (Fig. 4; e.g., Duebendorfer and others, 1998). The Cyclopic fault appears to merge southeastward with the Cerbat Mountains fault (Fig. 4). The northern White Hills basin is a large moderately east-tilted half graben developed in the hanging wall of the Salt Springs Wash fault (Duebendorfer and Sharp, 1998). The southern White Hills basin is a large moderately to steeply east-tilted half graben in the hanging wall of both the Cyclopic and Cerbat Mountains faults (Price, 1997; Price and Faulds, 1999). The Mountain Spring and White Hills faults are relatively minor west-dipping normal faults that link the Cyclopic and Cerbat Mountains faults (Price and Faulds, 1999). Displacement on the Mountain Spring and White Hills faults decreases toward the south.

The Detrital basin is a poorly understood graben developed between the west-dipping Blind Goddess and related faults on the east (Price and Faulds, 1999) and east-dipping Detrital fault on the west. The Detrital fault is a major antithetic fault within the Lake Mead domain. The Blind Goddess and Detrital faults are poorly exposed but are imaged on seismic reflection profiles (Faulds, 1999; Price and Faulds, 1999). The Detrital fault is more prominent and appears to have accommodated modest west-tilting of the Detrital basin, as evidenced by gently west-dipping reflectors in the upper part of the basin.

Wilson Ridge within the northern Black Mountains (Fig. 4) is an anomalous structural block in the Lake Mead domain. As initially shown by Anderson (1978), Wilson Ridge corresponds to a broad north-trending anticline. Even the 13.1 Ma Wilson Ridge pluton (Larsen and Smith, 1990) is deformed by the anticline (Anderson and others, 1994). Conjugate normal-fault systems dip inward toward the hinge of the anticline. Although the anticlinal form of Wilson Ridge does not require any range-bounding faults, unpublished seismic reflection data suggest that the east-dipping Detrital fault bounds the entire length of Wilson Ridge on the east. West-dipping normal faults bound the northern (Fortification Ridge fault of Mills, 1994) and southernmost (Bighorn fault of Faulds, 1993b) parts of Wilson Ridge on the west. A continuous west-dipping normal fault along the west flank of Wilson Ridge has not been documented, but it may be covered by late Tertiary alluvium.

The Van Deemen fault (formerly the Van Deemen Mine fault of Faulds and others, 1990) is a major gently (5-30^o) west-dipping normal fault that extends northward from the accommodation zone to the eastern part of the northern Eldorado Mountains (Figs. 4 and 9). It generally accommodated more than 6 km of displacement. Early Miocene strata are tilted about 75^o east in both the hanging wall and footwall of the fault, which suggests that the fault has a relatively planar geometry and nucleated at a steep dip but was subsequently rotated to a gentle dip by domino-like block-tilting (e.g., Proffett, 1977). The Van Deemen fault intersects several easterly striking, steeply dipping transfer faults and is also cut by several moderately to steeply west-dipping normal faults. As a result, the exposed trace of the Van Deemen fault steps to the west toward the north. The Eldorado Canyon and Malpais basins are moderately to steeply east-tilted half grabens developed in the hanging wall of the Van Deemen fault. The Bighorn and Malpais Flattop faults are moderately to steeply west-dipping normal faults that cut the Van Deemen fault and were partly responsible for development of the Eldorado Canyon and Malpais basins. Mylonites are spatially associated with the southern part of the Van Deemen fault, but detailed mapping showed that these mylonites are part of the pre-Tertiary basement and were dragged against, rather than formed along, the Van Deemen normal fault (Faulds, 1989, 1993b). The Van Deemen fault dies out abruptly toward the axial part of the accommodation zone, with displacement decreasing along strike from 6 km to negligible within 5 km of the axis of the accommodation zone.

The Eldorado fault is a major gently to moderately west-dipping normal fault in the northern Eldorado Mountains (Fig. 4) that accommodated as much as 5 km of displacement (Anderson, 1971). The Eldorado fault may merge northward with the Van Deemen fault just northwest of the Malpais basin (Fig. 4). Much of the northern Eldorado Mountains is a large moderately to steeply east-tilted growth-fault basin developed in the hanging wall of the Eldorado fault (Anderson, 1971; Anderson and others, 1972; Darvall, 1991). To the south, the Eldorado fault cuts the Nelson pluton and appears to lose displacement rapidly southward toward the accommodation zone.

The Keyhole Canyon and Ireteba faults are poorly exposed west-dipping normal faults inferred to bound the Eldorado basin on the east. Isostatic residual gravity data (Langenheim and Schmidt, 1996) support the inferred location of the Keyhole Canyon fault. The Ireteba fault connects southward with the Copper Mountain fault, a major antithetic west-dipping normal fault in the northern part of the Whipple domain (Fig. 4). The northeastern and central parts of the Eldorado basin probably consist of a series of east-tilted half grabens. The magnitude of tilting in the northern McCullough Range is much less than that in the northern Eldorado Mountains, suggesting that major west-dipping normal faults in this region have convex upward (i.e., anti-listric) geometries.

The northwestern margin of the Eldorado basin is bounded by the southeast-dipping Black Hills fault (Anderson and O'Connell, 1993), which is marked by a significant gradient in the isostatic residual gravity (Langenheim and Schmidt, 1996). The Black Hills fault displays evidence for the youngest (probably mid-Holocene) surface faulting in the region along a 4.5 km long scarp (Anderson, 1996).

The Saddle Island fault is a gently west-dipping normal fault in the western Lake Mead region that has been interpreted as a major detachment fault (Smith, 1982; Duebendorfer and others, 1990). The Boulder basin (Fig. 4) may correspond, at least in part, to an east-tilted half graben in the hanging wall of the Saddle Island detachment (Duebendorfer and Wallin, 1991). However, the northern extent of the Saddle Island detachment is poorly defined. It may link eastward with strands of the northeast-striking left-lateral Lake Mead fault system. Movement on the Saddle Island detachment and the possibly kinematically linked left-lateral Lake Mead fault zone may have been responsible for translating the River Mountains to the west relative to the Wilson Ridge pluton (Weber and Smith, 1987; Duebendorfer and others, 1998). Moreover, the northern part of the Boulder basin is complicated by an east- to northeast-trending fold belt. If once a half graben or series of half grabens, the Boulder basin has since been significantly modified by north-south shortening, possibly associated with the intersection of the left-lateral Lake Mead fault system and right-lateral Las Vegas Valley shear zone (see Duebendorfer and Simpson, 1994; Anderson and others, 1994). The southern extent of the Saddle Island detachment is also poorly defined. It may link with inferred left-lateral strike-slip faults that separate the River and Eldorado Mountains and both the southeast-dipping Black Hills fault and west-dipping Keyhole Canyon fault to the southwest.

Both the River Mountains and northern McCullough Range are characterized by broad northerly trending folds of middle Miocene strata. The River Mountains contain both a north-trending anticline and syncline (R.E. Anderson, unpublished mapping), whereas the northern McCullough Range is warped into a broad syncline (Boland, 1996). These folds appear to be associated with areas in which the characteristic west-dipping normal-fault system of the Lake Mead domain locally gives way to east-dipping faults. Thus, the folds are presumably extensional in origin (see Faulds and Varga, 1998). It is noteworthy that volcanoes in the McCullough Range and River Mountains occur on or near the hinge zones of these folds.

The moderately (~50^o) east-tilted Frenchman Mountain block (Castor and others, 2000) forms the western margin of the Boulder basin. Paleozoic, Mesozoic, and Tertiary stratigraphic sections at Frenchman Mountain have strong affinities to sections far to the east near the western margin of the Colorado Plateau. The Frenchman Mountain block may have originated 60 km or more to the east, having been transported to its present position by systems of strike-slip and normal faults (Bohannon, 1984; Rowland and others, 1990; Duebendorfer and others, 1998).

The Frenchman fault bounds both the Frenchman Mountain block on the west and much of Las Vegas Valley on the east. It cuts late Pleistocene and possibly Holocene alluvium (Matti and others, 1993; Castor and others, 2000) and therefore poses a potential seismic risk to Las Vegas Valley. The southern part of the Frenchman fault strikes northwest, dips steeply to both the northeast and southwest, and accommodated normal dextral and reverse dextral motion (R. E. Anderson, personal commun., 1998). The fault appears to bifurcate northward. The main strand continues northward as a major gently to moderately west-dipping normal fault on the west flank of Frenchman Mountain. A second strand may continue northwestward into the Las Vegas Valley, as indicated by northwest-trending isostatic gravity and aeromagnetic discontinuities, and may ultimately link northwestward with the Las Vegas Valley shear zone (Langenheim and others, 1998, 2001).

The Las Vegas Valley consists of several subbasins associated with both major normal faults and strands of the Las Vegas Valley shear zone, as evidenced by isostatic residual and aeromagnetic data (Langenheim and others, 1998, 2001). The deepest part of the basin (~7 km) lies in the hanging wall of the Frenchman fault and may correspond to an east-tilted half graben. Other subbasins in the northern part of the valley are associated with right steps in the northwest-striking right-lateral Las Vegas Valley shear zone and probably represent small pull-aparts along the shear zone (Langenheim and others, 1998).

Whipple Domain

The Whipple domain comprises the system of east-dipping normal faults and west-tilted fault blocks south of the accommodation zone. From west to east, major faults within the domain include the McCullough Range, Highland Pass, Searchlight, Dupont Mountain, Opal Mountain, Mount Davis, and Mockingbird Mine faults. Major west-tilted half grabens associated with these faults include the Piute, Cottonwood, Mount Perkins, and part of the Detrital basins (Fig. 4).

The McCullough Range fault is a major poorly exposed east-dipping fault zone that essentially bounds the extensional corridor on the west and flanks the southern McCullough Range, Castle Mountains, and Piute Range on the east (Faulds and others, in press). The west-tilted half graben of the Piute basin lies in the hanging wall of the McCullough Range fault. Displacement on this fault increases appreciably toward the south away from the accommodation zone, as evidenced by southward broadening of the Piute basin in the hanging wall and southward increasing uplift of the McCullough Range in the footwall. The McCullough Range fault probably links southward with a breakaway fault, described by Spencer (1985), that separates highly extended crust in the Colorado River extensional corridor from much less extended terrane to the west. Spencer (1985) surmised that the breakaway fault is part of a major east-dipping detachment system related to uplift and tectonic denudation of several metamorphic core complexes. Similarly, Turner and Glazner (1990) concluded that major east-dipping normal faults in the Castle Mountains, which lie directly west of the Piute basin to the south of the McCullough Range, are part of the same breakaway system. The McCullough Range fault may project into the Lake Mead domain as a major antithetic fault, as suggested by the abrupt eastern front of the northern part of the McCullough Range adjacent to the Eldorado basin. From north to south in the McCullough Range, thick Miocene volcanic sections (Schmidt, 1987; Smith and others, 1988; Bridwell, 1991; Boland, 1996; Sanford, 2000) give way to Early Proterozoic crystalline basement (Fig. 4). This change is probably associated with southward increasing displacement on the McCullough Range fault, which induced greater footwall uplift to the south. This, in turn, promoted erosion of early Miocene sections and may have prevented deposition of middle Miocene synextensional deposits in the southern part of the range. Significantly greater tilting of the hanging wall relative to the footwall suggests that the McCullough Range fault has a listric geometry. Displacement on the McCullough Range fault near the latitude of Searchlight probably exceeds 8 km. The southern Eldorado and Newberry Mountains, as well as parts of the Highland Range, are the upthrown eastern parts of west-tilted fault blocks in the hanging wall of the McCullough Range fault.

The southern Highland Range consists of two prominent west-tilted half grabens that merge southward with the Piute basin and are separated by the east-dipping Highland Pass fault. Synextensional Miocene volcanic and sedimentary strata are well exposed in these half grabens (Davis, 1984; Olson, 1996; Faulds and Bell, 1999; Faulds and others, in press). Two major east-dipping normal faults, the Highland and Searchlight faults, cut the southeastern part of the Highland Range and accommodated several kilometers of offset. The Highland fault dips gently and is cut by moderately to steeply dipping normal faults. The Searchlight fault is a major east-dipping normal fault that bounds much of the southern Highland Range on the east (Faulds and Bell, 1999) and continues southward into the Searchlight mining district. Displacement on the fault is about 3 km just north of Searchlight but probably increases to both the north and south of that area. The Searchlight fault is probably responsible for truncation and significant down-to-the-east offset of orebodies in the Searchlight mining district. The hanging wall of this fault comprises much of the southern end of the Eldorado basin and northeasternmost part of the Piute basin.

The Dupont Mountain fault is the most prominent normal fault in the northern part of the Whipple domain. It can be traced southward from a steeply dipping tip near the accommodation zone to a gently east-dipping shear zone that accommodated more than 12 km and possibly as much as 20 km of displacement on the flanks of the southern Eldorado and Newberry Mountains (Figs. 4 and 10) (Faulds, 1995, 1996; Faulds and others, 1996). As displacement increases southward, the fault dip rotates from 70° to less than 20°, a large steeply west-tilted crystalline terrane emerges in the footwall, and the large west-tilted half graben of the Cottonwood basin opens in the hanging wall. The Dupont Mountain fault extends northward into the southernmost part of the Lake Mead domain as a major antithetic normal fault. To the south of the Eldorado Mountains, it links with the gently east-dipping Newberry detachment fault of Mathis (1982) on the east flank of the Newberry Mountains (Faulds and House, 2000). The Newberry detachment continues southward along the east flank of the Dead Mountains and appears to link with major east-dipping detachment faults that bound the Sacramento and Chemehuevi metamorphic core complexes (Fig. 3). Steep tilting of the hanging wall and footwall of the Dupont Moun-

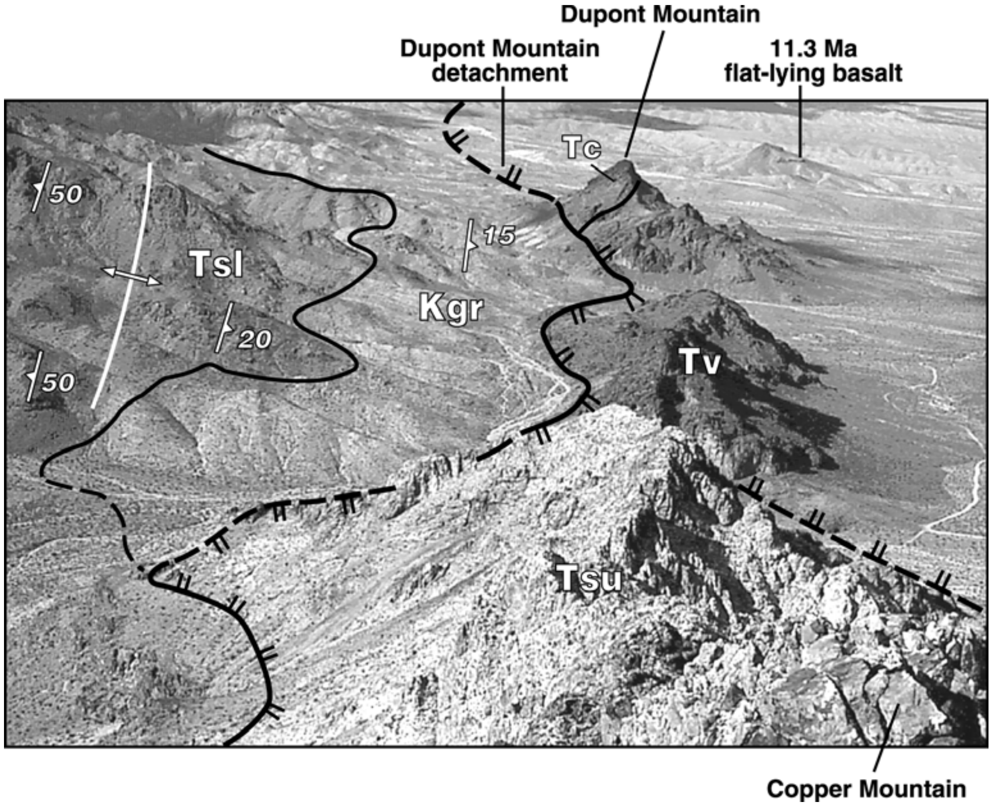

Figure 10. Looking north at the Dupont Mountain fault from the summit of Copper Mountain. The eastern and western splays of the detachment join directly north of Copper Mountain. A major antiform in the footwall of the fault results from normal drag of a steeply west-dipping foliation (coaxial deformation) in the footwall granitoids. These granites are locally mylonitized along this segment of the Dupont Mountain fault. Tv, middle Miocene dacite and andesite lavas; Tc, middle Miocene conglomerate that contains clasts of the lower Searchlight pluton and overlies a 13.85 Ma dacite lava; Tsu, 16.4 Ma upper Searchlight pluton; Tsl, 16.4 Ma lower Searchlight pluton; Kgr, 65 Ma peraluminous granite (Ireteba pluton).

tain fault suggests a relatively planar geometry and nucleation at a steep dip, with subsequent rotation to a gentle dip by domino-like block tilting. However, unlike most other gently dipping normal faults in the region (e.g., Van Deemen and Highland faults), the gently dipping (15-20^o) part of the Dupont Mountain fault cuts strata tilted as little as about 10^o and therefore accommodated slip at a low angle.

Near the latitude of Searchlight (Fig. 4), the footwall of the Dupont Mountain fault consists of a large steeply west-tilted fault block that is largely composed of the 16.4 Ma Searchlight pluton (Fig. 11; Miller and others, 1995, 1998; Bachl, 1997; Bachl and others, in press) and extends westward from the trace of the fault through the southern Eldorado Mountains and southern Highland Range (Faulds and others, 1996, 1998). This fault block exposes a cross-sectional view of approximately 15 km of crust. Paleomagnetic data indicate that the pluton is tilted at least 55^o to the west (Faulds and others, 1998). The Searchlight pluton invades Early Proterozoic gneiss and the 65 Ma Ireteba pluton (Townsend and others, 2000) in its lower reaches and the lower part of the Miocene volcanic section in its upper hypabyssal part (Faulds and Bell, 1999). A relict middle Miocene brittle-ductile transition is exposed within the pluton in the southern Eldorado Mountains (Fig. 11).

$^{40}Ar/^{39}Ar$ dating of variably tilted volcanic units brackets east-west extension between about 16.2 and 11 Ma in the Cottonwood basin, central Black Mountains, and Highland Range (Faulds and others, 1995, in press). These relations indicate that the 10-km-thick 16.4 Ma Searchlight pluton was emplaced just prior to the onset of major east-west extension. Post-15 Ma fanglomerates in the Highland Range and Cottonwood basin record erosional denudation of crystalline terranes in the southern McCullough Range and southern Eldorado Mountains, respectively (e.g., Faulds, 1995; Faulds and others, in press). For example, 14.0 to 12.8 Ma basaltic andesite lavas in the Cottonwood basin area are intercalated with conglomerate and rock avalanche deposits that contain clasts of the lower ductilely deformed part of the Searchlight pluton.

The crystalline terranes of the southern Eldorado and Newberry Mountains link southward with the belt of metamorphic core complexes in southeast California and western Arizona (Fig. 3). Geologic and paleomagnetic data suggest, however, that these crystalline terranes correspond to the lower structural levels of steeply tilted fault blocks rather than to the lower plate of a regional detachment system (Faulds and others, 1992, 1998; Hopson and others, 1994). The southern Eldorado and Newberry Mountains do, however, have many characteristics of metamorphic core complexes, including major gently dipping normal fault zones on their

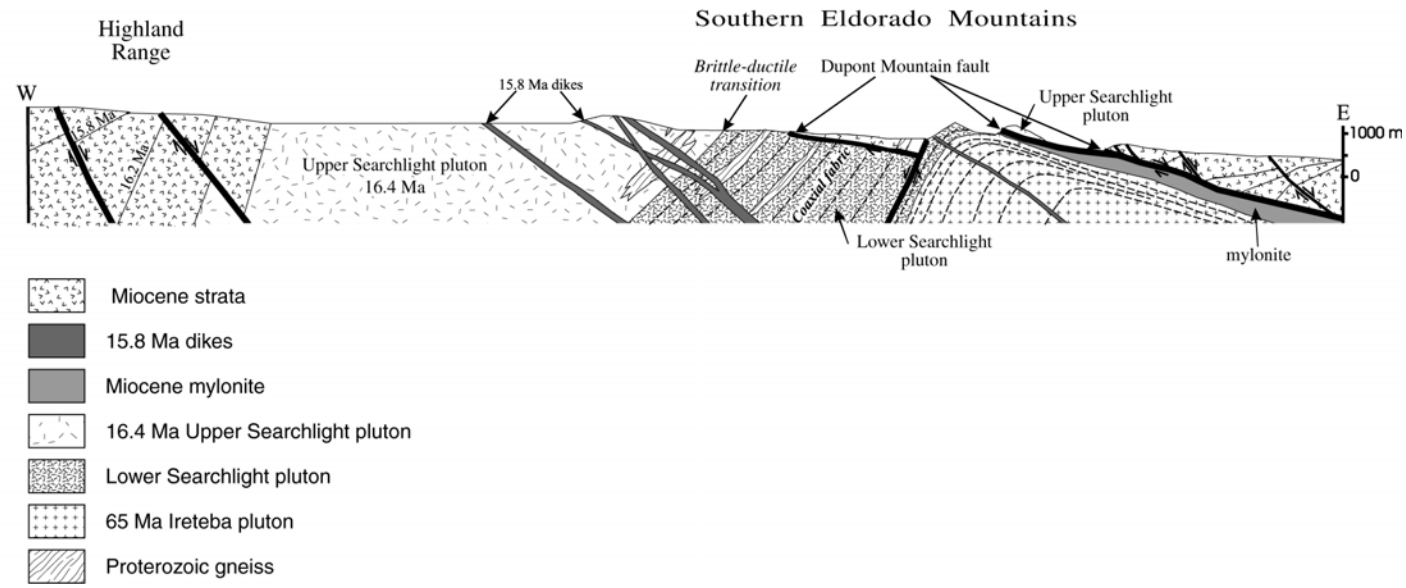

Figure 11. *Generalized cross section of the southern Eldorado Mountains and easternmost southern Highland Range (location shown on Fig. 4). The southern Eldorado Mountains expose an approximately 15 km thick crustal section, which is largely composed of the 16.4 Ma Searchlight pluton. The middle Miocene brittle-ductile transition is exposed within the pluton. Paleomagnetic data and geologic relations indicate that the pluton is tilted >70^o to the west. The lower part of the pluton contains a subsolidus coaxial fabric characterized by a steep west-dipping foliation and west-trending lineation. The upper part of the pluton is only brittlely deformed. The Dupont Mountain fault truncates the pluton on the east and accommodated more than 12 km of normal displacement. The floor of the pluton is exposed near the trace of the Dupont Mountain fault. The roof of the pluton is exposed near the town of Searchlight.*

flanks and ductilely deformed Tertiary rocks in the footwalls of the bounding low-angle faults. Furthermore, a 10 mgal isostatic residual gravity high that characterizes the metamorphic core complexes to the south extends northward into the Newberry and southern Eldorado Mountains, ending just north of the accommodation zone (Mariano and others, 1986; Simpson and others, 1986). These relations suggest that the southern Eldorado and Newberry Mountains may represent incipient metamorphic core complexes (Faulds and others, 1996).

The Cottonwood basin is a large west-tilted half graben or series of half grabens developed in the hanging wall of the Dupont Mountain fault (Fig. 4). The Cottonwood basin and west-tilted Whipple domain terminate northward in conjunction with the loss of displacement on the Dupont Mountain fault. Several narrow west-tilted fault blocks, such as the Mount Davis block on the east side of Lake Mohave, and associated half grabens (or subbasins) comprise the Cottonwood basin. The east-dipping Mount Davis and Opal Mountain faults, which bound two of these half grabens, each accommodate 2 to 5 km of throw (Faulds, 1995). The Mount Perkins basin (Faulds, 1993a) lies in the hanging wall of the Mount Davis fault and represents the easternmost subbasin of the Cottonwood basin. An east-trending bedrock high separates the Cottonwood basin from the Mohave basin to the south. The Mohave basin is also a large west-tilted half graben situated in the hanging wall of the Dupont Mountain-Newberry detachment fault and extends southward to the Needles area (Fig. 3).

Much of the central and southern Black Mountains are the upthrown parts of west-tilted fault blocks in the hanging wall of the Dupont Mountain fault. The Mount Perkins block in the central Black Mountains exposes a 10-km-thick crustal section that exposes a cross section of a pre- to synextensional magmatic system, including a small 16 Ma pluton (Mount Perkins pluton), hypabyssal dike swarm, and surficial volcanic edifices (Faulds and others, 1995). A large stratovolcano evolved into a rhyolite dome complex during early to middle Miocene time in the Mount Perkins area. The Mount Perkins volcanic complex is located nearly due east of the 16.4 Ma Searchlight pluton, parallel to both the regional extension direction and stretching lineations in the lower ductilely deformed part of the Searchlight pluton. Considering 12 to 20 km of normal slip on the Dupont Mountain fault, the Mount Perkins volcanic complex would restore to a position directly astride and partially on top of the Searchlight pluton. We therefore suggest that the Searchlight pluton is genetically related to the Mount Perkins volcanic complex.

The Mockingbird Mine fault is a major gently (5-30^o) east-dipping normal fault that bounds the Mount Perkins block on the east. It accommodated about 6 km of normal displacement in the northern part of the Mount Perkins block (Faulds and others, 1995). It may link northward with the antithetic east-dipping Detrital fault in the Lake Mead domain. To the south, it appears to lose displacement toward the Union Pass area of the southern Black Mountains in conjunction with the eastward step in that area of the Lake Mead domain. The southwestern part of the Detrital basin is probably a west-tilted half graben developed in the hanging wall of the Mockingbird Mine fault. The magnitude of west-tilting decreases across the Detrital basin toward the easternmost anticline in the Black Mountains accommodation zone. This suggests that the Mockingbird Mine fault and/or related east-dipping faults have convex upward or anti-listric geometries.

Black Mountains Accommodation Zone

The Black Mountains accommodation zone separates the Whipple and Lake Mead domains and accommodates the lateral termination of the corresponding east- and west-dipping normal-fault systems (Fig. 4) (Faulds and others, 1990, 1992, in press; Faulds, 1993b, 1994, 1996; Varga and others, 1996). Accordingly, major basins in the hanging walls of individual fault zones (e.g., Cottonwood, Malpais, and northern Eldorado basins) also terminate within or near the accommodation zone (Figs. 2 and 4). Coeval tilting of major growth-fault basins to either side of the accommodation zone demonstrates that the east- and west-dipping normal-fault systems in the northern Whipple and Lake Mead domains were active simultaneously in middle Miocene time (Faulds and others, 1999). At all scales, the accommodation zone is characterized by a zigzag pattern defined by the overlapping tips of oppositely dipping normal faults, with the area of overlap between opposed faults defining extensional anticlines or synclines (Fig. 4).

The geometry of these extensional folds is controlled by the dip direction of, and magnitude of along-strike overlap between, oppositely dipping normal faults (Faulds and Varga, 1998). Anticlines develop between listric normal faults that dip toward one another. Each limb of the anticline is a rollover fold developed in the hanging wall of one of the listric normal faults. Synclines form between outwardly dipping listric faults, as adjacent fault blocks are tilted toward one another, possibly through a combination of reverse drag (e.g., Hamblin, 1965) and footwall uplift. Depending on the amount of along-strike overlap between the oppositely dipping fault systems and the severity of the displacement gradient, these folds may trend parallel, oblique, or transverse to the strike of the normal faults. Strike-parallel folds develop between oppositely dipping normal faults or systems of faults characterized by complete along-strike overlap and minimal displacement gradients. Oblique folds form between en echelon normal faults or fault systems characterized by partial along-strike overlap and/or significant displacement gradients.

An east-trending, transverse segment of the zone in the central Black Mountains is a narrow 5-km-wide region of subdued structural relief into which normal faults of the opposing domains enter, overlap, and terminate (Faulds and others, 1990). Stratal tilts within the transverse segment are complex but invariably much lower than in the adjacent domains. Because offset along any single fault within this area is not great, both the subsidence of half grabens and uplift of the upthrown parts of fault blocks are muted. Consequently, topography and structural relief within this region are both greatly subdued. It is noteworthy, however, that this area of subdued structural and topographic relief is only about 5 km wide and that fault blocks to either side of this zone are tilted nearly 90^{o}, albeit in opposite directions.

The transverse segment of the zone is linked to major strike-parallel to oblique segments both to the east and west. Strike-parallel to oblique, anticlinal segments of the zone include the Fire Mountain (Faulds, 1996), Aztec Wash, Highland Range (Olson, 1996; Faulds and others, in press), and White Hills-Grasshopper Junction-Warm Springs anticlines (Varga and Faulds, 1995; Varga and others, 1996; Price and Faulds, 1999). An oblique, synclinal segment of the zone is also exposed in the Highland Range (Olson, 1996; Faulds and others, in press). The regionally extensive strike-parallel anticline that constitutes the easternmost part of the zone owes its length to considerable overlap between the east- and west-dipping fault systems (Fig. 4). The lack of major transversely oriented faults and paleomagnetic evidence indicative of negligible vertical-axis rotation (Faulds and others, 1992; Olson and others, 1999) preclude a significant strike-slip component across the zone.

Because they reflect reversals in the dip direction of normal-fault systems, the extensional folds in northern McCullough Range, River Mountains, and Wilson Ridge can be considered synclinal and anticlinal accommodations zones (cf., Faulds and Varga, 1998). However, none of these folds link southward with the Black Mountains accommodation zone. Localized flips in the polarity of the normal-fault system can also be found within the Whipple domain (e.g., southernmost Lake Mohave area near Bullhead City; Faulds and House, 2000).

CENOZOIC EVOLUTION

Ancient Crustal Influences

The eastern margin of the northern Colorado River extensional corridor corresponds approximately with both the eastern margin of an early Tertiary uplift and a major Proterozoic lithospheric boundary (Fig. 3). The Proterozoic boundary separates terranes referred to as the Mojave and Arizona provinces. The Mojave province extends east from the Death Valley region to the southwestern edge of the Colorado Plateau (Bennett and DePaolo, 1987). Proterozoic silicic plutonic rocks from the Mojave province yield Nd model ages between 2.0 and 2.3 Ga, which are somewhat older than their 1.65 to 1.8 Ga crystallization ages (Bennett and DePaolo, 1987). The Arizona province extends from central and northern Arizona to New Mexico and Colorado. Silicic plutons in the Arizona crust have Nd model ages ranging from 1.8 to 2.0 Ga (Bennett and DePaolo, 1987). The Nd isotopic compositions of Proterozoic silicic igneous rocks indicate that the boundary between the Mojave and Arizona lithospheric provinces extends southward along the eastern margin of the extensional corridor from west of the Gold Butte block, to east of the Cerbat Mountains, and through the northwest portion of the Hualapai Mountains (Fig. 3). The proximity of this boundary to the Grand Wash fault zone suggests that the abrupt transition between the Colorado Plateau and the Basin and Range in this region reflects an ancient crustal flaw inherited from the Early Proterozoic amalgamation of the North American craton.

The northern margin of the corridor may also be controlled by an ancient easterly striking crustal flaw. The Lake Mead region marks the northward terminations of the early Tertiary arch, early to middle Miocene volcanic terrane, and middle to late Miocene northern Colorado River extensional corridor. Even the petrogenesis of late Miocene lavas differs across the Lake Mead fault system, with an asthenospheric contribution to the south but only a mantle lithospheric component to the north (Feuerbach and others, 1993). This region also appears to correspond to the southern edge of both the aforementioned Neogene north-south contractional strain field observed throughout much of the southern Great Basin and, as evidenced by the distribution of Quaternary fault scarps (e. g., Menges and Pearthree, 1989; Thenhaus and Barnhard, 1998), the actively extending Great Basin region. Thus, the Lake Mead region may also represent a fundamental lithospheric boundary that has partitioned strain and magmatism for at least the past 75 Ma. It may have originated as part of a discontinuity or transfer zone during Late Proterozoic extension.

Cretaceous-Eocene

In late Cretaceous to early Tertiary time, the northern Colorado River extensional corridor stood at the northern edge of a large uplifted terrane that was stripped of its Paleozoic and Mesozoic cover by erosion (e.g., Bohannon, 1984). This north-plunging arch linked southward with a broad northwesterly trending uplift that stretched across several hundred kilometers of the transition zone and the Basin and Range province of Arizona (Peirce, 1985) and has been referred to as the Kingman uplift (Goetz and others, 1975) and the Kingman arch (Herrington, 2000). Development of the arch at least partly postdated emplacement of 64 to 73 Ma two-mica, garnet-bearing peraluminous granites and predated deposition of the 18.5 to 19.9 Ma basal part of the Tertiary section, which locally rests unconformably on the 64 to 73 Ma granites (e.g., Faulds, 1993b, 1995). Uplift and erosion of the arch coincided, at least in part, with deposition of Paleocene-Eocene "rim gravels" along the western and southwestern margins of the Colorado Plateau (e.g., Young and Brennan, 1974; Lucchitta, 1979; Young, 1982). Based on fission track and $^{40}Ar/^{39}Ar$ thermochronology (Herrington, 2000), 4.5 km of Paleozoic and Mesozoic cover was removed from the region between late Cretaceous (~85 Ma) and early Miocene time. In the Grand Canyon area to the east, exhumation of 2.7 to 4.5 km of the Mesozoic and Paleozoic section occurred in Laramide and post-Laramide time (Kelley and others, 2000), more or less contemporaneously with uplift of the Kingman arch.

The early Tertiary arch was probably associated with crustal thickening brought about by shortening and magmatism during the subduction-induced Laramide orogeny (e.g., Spencer and Reynolds, 1989). Due to the lack of Paleozoic and Mesozoic strata, Laramide reverse faults cannot be easily documented in the northern Colorado River extensional corridor. However, the Proterozoic rocks are cut by abundant shear zones, some of which could be Laramide in age. Minor pre-Miocene shear zones cut a 73 Ma granite in the central Black Mountains but have not been systematically studied.

In northwest Arizona, the east margin of the arch is roughly aligned with the present abrupt boundary between the Colorado Plateau and northern Colorado River extensional corridor, which is marked by the west-dipping Grand Wash normal fault zone. South of the Lake Mead area, Paleozoic strata are preserved east of the northern and southern Grand Wash faults but are largely absent in ranges to the west (Fig. 4). Gentle regional Cretaceous-early Tertiary northeast tilting, as documented across a wide swath of the transition zone in central Arizona (e.g., Peirce, 1985), and subsequent erosion may be largely responsible for stripping of Mesozoic and Paleozoic strata from the northern part of the corridor (Bohannon, 1984). However, this may not explain the lack of Paleozoic strata in much of the Lost Basin Range, considering the proximity of this range to relatively thick Paleozoic sections directly to the east along the Grand Wash Cliffs (Fig. 4). This may imply that the early Tertiary arch ended rather abruptly eastward in the vicinity of the Grand Wash fault zone. Thus, some segments of the Grand Wash fault zone may represent reactivated, west-dipping Laramide reverse faults that partly accommodated development of the Kingman arch. As evidenced by the composition of Laramide plutons, this possibility is especially likely for the southern part of the northern Grand Wash and Cerbat Mountains faults. Laramide plutons within the corridor to the west of these connected faults are deep-seated two-mica, garnet-bearing peraluminous plutons, whereas relatively shallow-level Laramide plutons are found to the east in the Cerbat Mountains and along the Grand Wash Cliffs (Fig. 4).

The progressive southward beveling of Mesozoic and Paleozoic strata in the Lake Mead region indicates that the northern margin of the arch was not fault bounded but instead plunged relatively gently to the north (Bohannon, 1984). Assuming that the 64 to 73 Ma two-mica, garnet-bearing peraluminous granites were emplaced at depths of at least 10 km (e. g., Zen, 1988), a plunge of approximately 15^{o} is inferred for the northern part of the arch between the Lake Mead area and central Black Mountains. In the Lake Mead area, 1 to 2 km thick sections of Paleozoic and Mesozoic strata remain, whereas the base of the Miocene section rests directly on a 73 Ma peraluminous granite in the central Black Mountains (Fig. 4). It is possible that the early Tertiary arch was a Laramide basement-cored uplift (e.g., Matthews, 1978) that was locally bounded on the east by west-dipping reverse faults. Southward increasing displacement on the reverse faults away from the Lake Mead area may have generated greater uplift to the south and accentuated the northward plunge of the uplift.

It is also important to note that the northern Colorado River extensional corridor resided directly north, east, and south of Mesozoic fold and thrust belts. Major west-dipping thrusts advanced as far east as the Spring and Clark Mountains to the west and Muddy Mountains to the north of the corridor (Bohannon, 1983; Burchfiel and Davis, 1988; Walker and others, 1995) (Fig. 4). Prior to Cenozoic offset on the right-lateral Las Vegas Valley shear zone, however, thrusts in the Spring Mountains connected northward with those in the Las Vegas Range and Muddy Mountains (e.g., Wernicke and others, 1988). Foreland basin deposits of Albian age have been identified in the Muddy Mountains (Bohannon, 1983) but are absent within the northern part of the corridor. The southern part of the corridor was severely deformed by the Maria fold and thrust belt (Spencer and Reynolds, 1990), where north- to northeast-dipping thrusts predominated. Interestingly, the dip of Tertiary normal faults in the two regions mimics that of the thrust faults, further suggesting that the style and geometry of Cenozoic extension in the region was at least partly controlled by preexisting structures.

Oligocene to Middle Miocene

The early Tertiary episode of erosion ended in latest Oligocene to early Miocene time with the deposition of a widespread, prevolcanic pebble-cobble conglomerate, which marks the base of the Tertiary section in most parts of the northern Colorado River extensional corridor (e.g., Herrington, 2000). In the McCullough and Lucy Gray Ranges the conglomerate was deposited between 40 and 18.5 Ma in channels cut in Proterozoic basement. The thickness of this conglomerate is typically less than 20 m but is 70 m in the Lucy Gray Range, 100 m in the McCullough Range (Herrington, 2000), and as much as 200 m in the southern part of the region just north of Laughlin, Nevada (Faulds and House, 2000; Figs. 3 and 4). In the Lake Mead region, clasts of Paleozoic and Mesozoic rocks dominate the conglomerate (Beard, 1996). In contrast, clasts in the prevolcanic conglomerate to the south of Lake Mead, within both the volcanic terrane and along the eastern margin of the corridor, are composed of Proterozoic gneiss, granite and quartzite, late Cretaceous granite, and Paleozoic carbonate. Anderson and others (1985) identified quartzite clasts as the Late Proterozoic Stirling Quartzite and Late Proterozoic-Cambrian Wood Canyon Formation. In both areas, clasts are subrounded to subangular. In the Lake Mead region, the basal conglomerate may be as old as 24 Ma (Beard, 1996). South of Lake Mead, thin (<10 m thick) sequences of 19.6 to 19.9 Ma basalt lavas, the 18.5 Ma Peach Springs Tuff, and 18.3 to 18.5 Ma dacitic breccia rest conformably on the basal conglomerate and form the base of the volcanic section (e.g., Faulds and others, 1995; Faulds, 1996). Thus, the base of the Tertiary section in the northern part of the corridor is bracketed between about 24 and 18.3 Ma. This conglomerate probably correlates with at least the upper part of the Buck and Doe Conglomerate, which accumulated in early Tertiary paleocanyons etched into the western part of the Colorado Plateau (Young, 1966; Beard, 1996). It is noteworthy that clasts of Proterozoic rock are rare north of Lake Mead, where the conglomerate rests on Paleozoic and Mesozoic strata, despite proximity to the Kingman arch, and that Paleozoic clasts are sparse to absent in much of the region south of Lake Mead east of the McCullough Range, despite proximity to thick Paleozoic sections to the east and north. Paleozoic carbonate clasts are common, however, in the conglomerate in the Lucy Gray and McCullough Ranges. These relations imply that (a) the Lake Mead region and westernmost part of the corridor were topographically isolated from areas to the south and east, possibly by south- and east-facing paleoscarps of resistant limestone (e.g., Permian, Mississippian, and Cambrian units) on the northern and western margins of the Kingman arch (e.g., Beard, 1996), and (b) the vigorous northeast-flowing fluvial systems responsible for deposition of the Paleocene-Eocene “rim” gravels along the western margin of the Colorado Plateau (e.g., Young, 1982) had dissipated by latest Oligocene to early Miocene time.

The 18.5 Ma Peach Springs Tuff is an important regional stratigraphic marker that reflects the approach of the northward advancing magmatic front. This distinctive rhyolite ignimbrite crops out across a broad region of the Southwest, extending from Barstow, California on the west to the western part of the Colorado Plateau on the east and from near Lake Mead on the north to Parker, Arizona, on the south (Young and Brennan, 1974; Glazner and others, 1986; Nielson and others, 1990). South of the Laughlin-Bullhead City area, the Peach Springs Tuff overlies relatively thick (>1 km) volcanic sections, whereas to the north it generally lies near or at the base of the Miocene section, with only the arkosic conglomerate and localized, relatively thin accumulations of 18.5 to 19.9 Ma basaltic andesite lavas beneath. Thus, it is the first widespread volcanic unit deposited in much of the northern Colorado River extensional corridor. The Peach Springs Tuff has been observed as far north as the central Cerbat Mountains on the east (R.J. Varga, unpublished mapping), southern part of the northern Black and northern Eldorado Mountains in the central part of the corridor (Faulds and others, 1995), and central McCullough Range and southeastern Highland Range on the west (Wells and Hillhouse, 1989; Faulds and Bell, 1999). It thickens considerably southward in the northern part of the corridor from about 2 m at its northern distal end to as much as 100 m in the Laughlin area. On the basis of flow fabric defined by anisotropy of magnetic susceptibility, Hillhouse and Wells (1991) suggested that the source caldera for the Peach Springs Tuff may be buried under younger deposits in the Mohave basin just south of Laughlin (Fig. 3). Although no calderas have been identified, it is noteworthy that the Peach Springs Tuff in the Laughlin area commonly contains large (as much as 30 cm in length) lithic fragments of andesite and Proterozoic gneiss (Faulds and House, 2000). Lithic fragments in ash-flow tuffs are typically largest proximal to the source caldera.

After deposition of the 18.5 Ma Peach Springs Tuff, volcanism spread rapidly northward across the northern part of the corridor with development of several major stratovolcanoes and eruptions of thick sections of intermediate to mafic lavas. Between 18.5 and 16.0 Ma, stratovolcanoes emerged in the northern Black and Eldorado Mountains (e.g., Anderson, 1971; Anderson and others, 1972), Mount Perkins and Fire Mountain areas of the central Black Mountains (Faulds and others, 1995; Faulds, 1996), Highland Range (Feuerbach and others, 1999), and northern Newberry Mountains (Ruppert, 1999). Sections of intermediate composition lavas commonly approach or exceed 3 km in thickness near these stratovolcanoes. Major early Miocene volcanic sequences include the lower Patsy Mine Volcanics in the northern Eldorado and Black Mountains (Anderson, 1971, 1977, 1978; Darvall, 1991), volcanics of Dixie Queen Mine in the southeastern Highland Range (Faulds and Bell, 1999) and southern Eldorado and central Black Mountains (Faulds and others, 1995; Faulds, 1995), and the volcanics of Fire Mountain in the central Black Mountains (Faulds, 1996). The northern and eastern ends of the volcanic terrane roughly mirror the margins of the early Tertiary Kingman arch.

Voluminous early Miocene calc-alkaline volcanism in the igneous terrane south of Lake Mead was not accompanied by large-magnitude east-west extension, as evidenced by conformable relations (i.e., lack of tilt fanning) in the lower Mio-

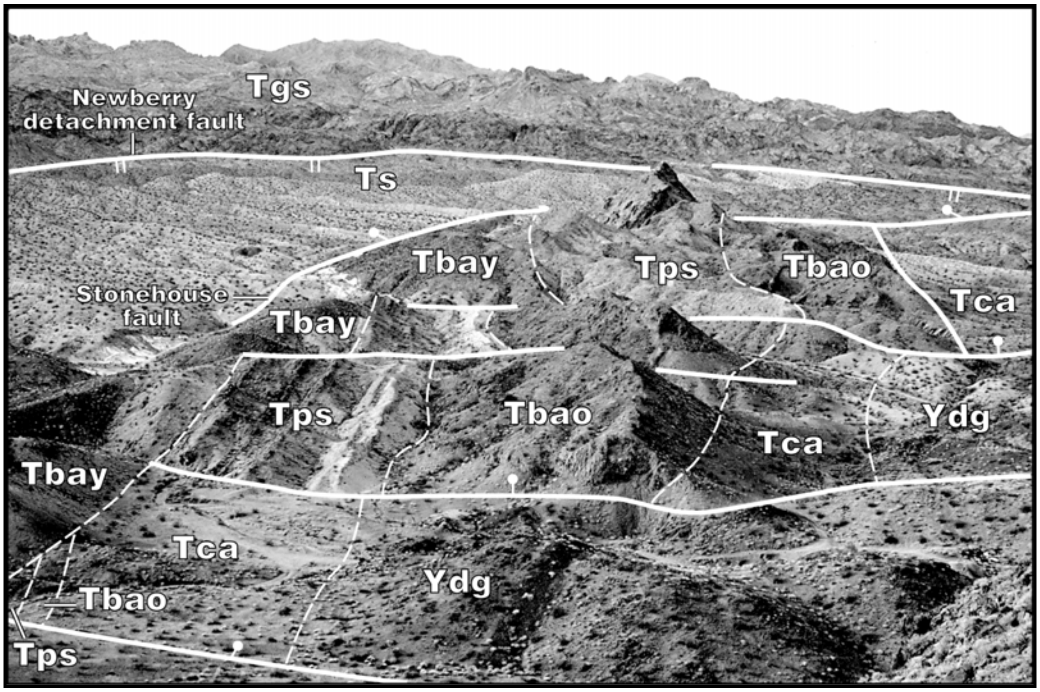

Figure 12. *Early Miocene easterly striking normal faults, east flank of Newberry Mountains (looking north). Steeply west-tilted strata within the hanging wall of the Newberry detachment fault, including the 18.5 Ma Peach Springs Tuff (Tps) are cut by the east-striking normal faults. The Peach Springs Tuff is generally thicker in the hanging walls of these faults, which terminate up section in approximately 17 to 18 Ma basaltic andesite lavas (Tbay) and dacitic breccia (not shown). The steep west-tilting of the strata was accommodated by movement on the Newberry detachment fault during middle Miocene east-west extension. The Newberry detachment links northward with the Dupont Mountain fault. Tgs, Spirit Mountain pluton; Ts, middle to late Miocene conglomerate; Tbao, basaltic andesite lava flows; Tca, basal arkosic conglomerate; Ydg, 1.4 Ga Davis Dam granite.*

cene sections. For example, essentially concordant tilt magnitudes characterize the lower 2 km of section in the southeast Highland Range and central Black Mountains (Faulds and others, 1995; Faulds and Bell, 1999). It is important to note, however, that the voluminous early Miocene magmatism in the Lake Mohave region did coincide with large-magnitude east-west extension in the region directly to the south (e.g., Needles-Oatman areas).

Moreover, mild north-south extension (as opposed to east-west extension) appears to have coincided with early Miocene magmatism in the northern Colorado River extensional corridor. Evidence for early Miocene north-south extension includes abundant easterly striking normal faults (Fig. 12), dikes, and veins in many parts of the region (Faulds, 1996, 1999; Ruppert and Faulds, 1998; Ruppert, 1999; Faulds and House, 2000), as well as west-northwest-striking dikes just to the south in the southern Sacramento Mountains (Campbell-Stone and others, 2000). Because some of the easterly striking faults and dikes cut units as young as 16.5 to 16.7 Ma and these faults control depositional patterns within the lower part (20 to 16.5 Ma) of the Miocene section (e.g., 18.5 Ma Peach Springs Tuff; Fig. 12), the episode of north-south extension is roughly constrained between 20 and 16.0 Ma. The lack of appreciable north or south tilting suggests, however, that the magnitude of early Miocene north-south extension was small. Mild Oligocene to early Miocene, synvolcanic north-south extension has also been documented elsewhere in the Basin and Range province (e.g., Best, 1988; Bartley, 1990).

Granitic plutons were emplaced in the northern Colorado River extensional corridor during early Miocene to earliest middle Miocene time, just prior to the onset of major east-west extension. The east-west elongated Nelson pluton intrudes the lower part of the Miocene section. The 17 Ma Spirit Mountain, 16.4 Ma Searchlight, and 16.0 Ma Mount Perkins plutons appear to have been emplaced as thick subhorizontal tabular bodies and possibly thick plugs. The Searchlight pluton is cut, however, by an easterly striking felsic dike swarm (Ruppert and Faulds, 1998). In addition, in the southern Black Mountains near the southern edge of the Cottonwood basin (Fig. 4), an early Miocene easterly striking rhyolite dike swarm feeds thick sills that invade the basal part of the Miocene section (Faulds, unpublished mapping). The presence of both easterly striking dike swarms and subhorizontal intrusions indicates that mild north-south extension may have alternated with a nearly isotropic stress field.

In the Lake Mead area, thick sedimentary sections accumulated in broad basins contemporaneously with early Miocene volcanism to the south. Some of the more prominent units include lacustrine and clastic sedimentary rocks in the Rainbow Gardens and Thumb Members of the Horse Spring Formation (e.g., Bohannon, 1984; Beard, 1996). Because tuffaceous fluvial facies dominate northern exposures, Beard (1996) suggested that the Rainbow Gardens Member was largely derived from the Caliente caldera complex to the north in eastern Nevada. Thus, it would appear that the Lake Mead

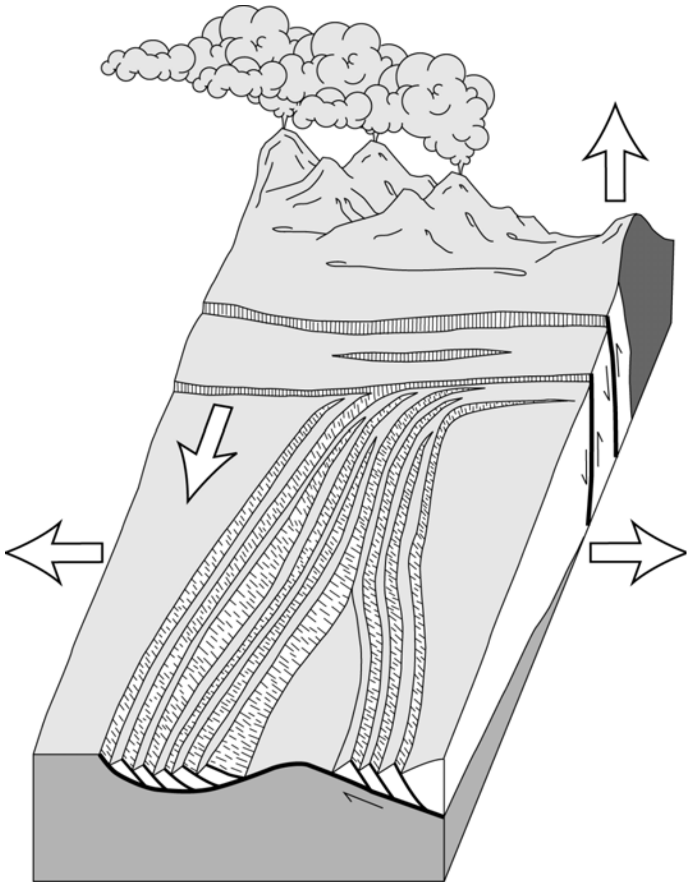

Figure 13. *Schematic depiction of the early Miocene paleogeography. Mild north-south extension and voluminous volcanism in the northern Colorado River extensional corridor coincided with large-magnitude east-west extension to the south. North-south extension may have been induced by partial collapse of the elevated terrain to the north into the topographically lower, highly extended region to the south.*

region remained topographically isolated from areas to the south well into Miocene time. Concordant tilts within the early Miocene sedimentary deposits in the Lake Mead region indicate deposition prior to the onset of major east-west extension. It is possible that the early Miocene basins in this region were associated with mild north-south extension.

The apparent early Miocene paleogeography in the northern Colorado River extensional corridor suggests a transitional setting between the early Tertiary highland of the Kingman arch and the developing Basin and Range. The distribution of the 18.5 Ma Peach Springs Tuff suggests that at least some early Miocene drainages continued to flow east or northeast off the Kingman arch onto the Colorado Plateau (Young and Brennan, 1974). It is important to note that while relatively little deformation affected the northern part of the corridor in early Miocene time, large-magnitude northeast-southwest extension, including development of several metamorphic core complexes, was occurring directly to the south (e.g., Davis and Lister, 1988; John and Foster, 1993; Campbell and John, 1996), where the Peach Springs Tuff accumulated in growth-fault sequences in north-trending half grabens (Nielson and others, 1990). Large-magnitude extension was also affecting regions to the north in central and eastern Nevada (e.g., Taylor and others, 1989; Axen and others, 1993). Thus, much of the northern Colorado River extensional corridor in early Miocene time may have formed a relatively undeformed but elevated western prong of the Colorado Plateau that had succumbed to magmatism but had yet to experience major east-west or northeast-southwest extension. The mild early Miocene north-south extension may have been induced by plutonism (see Campbell-Stone and others, 2000) or partial collapse of this relatively undeformed and topographically elevated region into the widening and deepening trough of extension to the south (Fig. 13). As implied by the paleomagnetic data of Hillhouse and Wells (1991), the Peach Springs Tuff may have erupted from a caldera near the southern margin of the broad plateau constituting the northern part of the corridor and therefore flowed northeastward onto the Colorado Plateau, southward into multiple half grabens in the already extending region, and also northward, albeit pinching out, across much of the elevated terrain in the northern part of the corridor.

Middle Miocene

The northern Colorado River extensional corridor finally yielded to east-west extension in middle Miocene time (e.g., Anderson and others, 1972; Duebendorfer and Wallin, 1991; Faulds and others, 1994, 1999; Beard, 1996; Harlan and others, 1998; Duebendorfer and Sharp, 1998; Castor and others, 2000). Large-magnitude east-west extension engulfed much of the region between 16.5 and 15.5 Ma. It began first in the south and east and migrated toward the northwest, reaching the western Lake Mead region between 13 and 11 Ma (Fig. 6a). The east- and west-dipping normal-fault systems accommodated west- and east-tilting of panels of fault blocks in the northern Whipple and Lake Mead domains, respectively. During the early stages of extension, tilt rates commonly exceeded 80^{o}/m.y. (Faulds and others, 1995, 1999, in press). Most fault blocks were tilted in excess of 50^{o}. Thus, the entire region was fragmented into complex arrays of tilted fault blocks and associated half grabens.

As evidenced by the thicknesses of pre- to synextensional volcanic units, eruptive rates peaked somewhat before to immediately after the onset of extension and tailed off considerably in most areas during extension (Faulds and others, 1995; Gans and Bohrson, 1998; Ruppert, 1999). Although less voluminous than early Miocene magmatism, volcanism spanned the entire episode of extension in many areas to the south of Lake Mead. Thus, thick volcanic sections, as opposed to sedimentary rock, accumulated in many of the half grabens. Some half grabens, such as the Mount Perkins and northern Eldorado basins, are filled almost entirely with lavas and tuffs. As extension continued, older lavas were progressively tilted to steeper dips concurrent with deposition of younger sequences on subhorizontal erosion surfaces. Consequently, many of the basins contain well-developed tilt fanning, whereby tilts within the synextensional parts of the section progressively decrease upwards.

In many areas, intermediate composition volcanism gave way to bimodal activity near the onset of extension. This is best exemplified in the Mount Perkins area, where a major stratovolcano evolved into a rhyolite dome complex near the onset of major east-west extension about 15.7 to 15.9 Ma (Faulds and others, 1995). Voluminous felsic magmatism coincided with the onset of extension in many areas, including the southern and central Black Mountains, southern Highland Range, and northern Newberry Mountains. However, felsic magmatism generally died out abruptly during peak extension (i.e., period of maximum tilting). Mafic volcanism dominated thereafter, but in most areas was much less voluminous than the preextensional intermediate volcanism. Major synextensional volcanic suites include the 16.0 to 14.5 Ma felsic volcanics of Red Gap Mine in the Mount Perkins area of the central Black Mountains (Faulds and others, 1995), 16.2 to 15.2 Ma bimodal sequences in the northern Eldorado Mountains (middle and upper Patsy Mine Volcanics; Anderson and others, 1972; Darvall, 1991) and Highland Range (volcanics of the Highland Range; Olson, 1996; Faulds and Bell, 1999; Faulds and others, in press), the 15 to 12 Ma mafic lavas of the Mount Davis Volcanics (e.g., Anderson and others, 1972; Faulds, 1995), and the 15.6 to 13.1 Ma bimodal lavas and rhyolitic ash-flow tuffs of the McCullough Range (Schmidt, 1987; Bridwell, 1991; Sanford, 2000). The Mount Davis Volcanics are commonly intercalated with thick clastic wedges and rock avalanche deposits shed from nearby footwall terranes.

At least two major ash-flow tuffs were erupted during middle Miocene extension in the northern Colorado River extensional corridor, the 15.2 Ma tuff of Bridge Spring and 15.0 Ma tuff of Mount Davis. These distinctive, regionally extensive ash-flow tuffs originally blanketed much of the region. The tuff of Bridge Spring extends from the southern White Hills on the east (Price and Faulds, 1999) to the McCullough Range on the west (Morikawa, 1994) and from the northernmost Eldorado Mountains southward (Anderson, 1971; Gans and others, 1994) to the southern Black Mountains. The tuff of Mount Davis may not be as widespread as the tuff of Bridge Spring. Its known distribution stretches from the central Black Mountains westward to the Highland Range (Faulds, 1995; Faulds and Bell, 1999) (Fig. 4). The tuff of Mount Davis can be easily mistaken for an upper cooling unit of the tuff of Bridge Spring, because it commonly rests directly on, and is compositionally similar to, the tuff of Bridge Spring. The tuff of Mount Davis may therefore be more widespread than presently thought. The two tuffs can, however, be distinguished by minor differences in phenocryst assemblages, paleomagnetic reference directions (Faulds and Olson, 1997), $^{40}Ar/^{39}Ar$ dates, and in some areas by intervening sequences of conglomerate, megabreccia, and/or mafic lavas (Faulds and others, in press). The tuff of Bridge Spring may have been derived from a caldera in the northern part of the Eldorado basin and is possibly associated with the Boulder City pluton (Gans and others, 1994). The source of the tuff of Mount Davis is unknown, but similarities in age, composition, and distribution suggest that both tuffs may have been erupted from the same cauldron. It is important to note that the Railroad Pass pluton along the northwestern margin of the Eldorado basin has yielded an $^{40}Ar/^{39}Ar$ age of 14.99±0.08 Ma on biotite (P. Gans, written commun., 1997), which is essentially identical to the age of the tuff of Mount Davis. In any case, both tuffs are important time-stratigraphic and structural markers in the northern Colorado River extensional corridor and nicely chronicle increments of Tertiary extension. Several other tuffs of more local extent, such as the 14.1 Ma tuff of McCullough Pass erupted from the 2-km diameter McCullough Pass caldera in the central McCullough Range (Sanford, 2000) and 13.9 Ma tuff of Hoover Dam (Mills, 1994), have been described in the northern Colorado River extensional corridor.

At least three granitic plutons were emplaced during east-west extension. These are the 15.0 Ma Mirage pluton in the Newberry Mountains (Howard and others, 1996), 15.7 Ma Aztec Wash pluton in the central Eldorado Mountains (Falkner and others, 1995), and 13.1 Ma Wilson Ridge pluton in the northern Black Mountains (Feuerbach, 1986; Larson and Smith, 1990; Anderson and others, 1994). Both the Aztec Wash and Wilson Ridge plutons occupy the hinge zones of extensional anticlines.

Although volcanism did not accompany east-west extension in much of the Lake Mead region, several stratovolcanoes and at least one caldera did develop along the southern margin of the amagmatic gap. For example, stratovolcanoes developed in the River Mountains (Smith, 1982), directly north of Boulder Canyon (Hamblin-Cleopatra volcano; Anderson, 1973; Thompson, 1985), and in the northern McCullough Range (Bridwell, 1991; Boland, 1996) between 11 and 14 Ma. In addition, two small calderas formed in the northern McCullough Range between about 10 and 14 Ma (Smith and others, 1988; Bridwell, 1991). Elsewhere, however, only small isolated volcanic centers developed. Thus, thick sections of fanglomerate, lacustrine limestone, and evaporites (e.g., Thumb, Bitter Ridge Limestone, and Lovell Wash Members of Horse Spring Formation and Red Sandstone) accumulated within developing half grabens in the Lake Mead region (Bohannon, 1984; Beard, 1993, 1996) in contrast to the volcanic-dominated sections to the south. Middle Miocene sedimentary deposits in both the Lake Mead region and volcanic terrane to the south were invariably locally derived. Thus, the middle Miocene paleogeography was characterized by internally drained basins, with no through-flowing drainage.

Miocene strata within the half grabens along the eastern margin of the corridor chronicle the evolution of the Colorado Plateau-Basin and Range boundary in this region. Major basins in the hanging wall of the Grand Wash fault zone began developing as early as 16.5 Ma (Price and Faulds, 1999). A thick sequence of fanglomerate was shed eastward from the western margin of the Colorado Plateau into the southern White Hills basin as early as 15.2 Ma, as evidenced by abundant boulders of Proterozoic rapakivi granite within the fanglomerate, for which the most likely source is the Garnet Mountain area of the Grand Wash Cliffs. A 15.2 Ma tuff is intercalated within the sequence of fanglomerates (Price and Faulds, 1999). Thus, the regional northeast-flowing drainage that predominated in early Tertiary time had been dismantled by 15.2 Ma. Gently tilted ($<10^{o}$) 13 to 8 Ma strata within the Grand Wash trough and southern White Hills suggest that displacement on the Grand Wash fault zone (as much as 5 km) and development of major hanging-wall half grabens occurred primarily between about 16 and 13 Ma and was largely complete by 8 Ma. Accordingly, the structural and topographic demarcation of the Colorado Plateau-Basin and Range boundary in northwest Arizona began developing about 16 Ma, was essentially established by 13 Ma, and has changed little since about 8 Ma.

The antiquity and abruptness of the Colorado Plateau-Basin and Range boundary in this region, as well as the stratigraphic record in the southern White Hills, suggest that significant headward erosion into the high-standing plateau began in middle Miocene time. Many deep canyons have since been carved into the Colorado Plateau, the most prominent of which is the Grand Canyon of the Colorado River. It is therefore possible that incipient excavation of the western part of the Grand Canyon by an originally small west-flowing stream also began in the middle Miocene.

Considering the proximity of both the eastern margin of the early Tertiary Kingman arch and Early Proterozoic crustal province boundary, the location of the eastern margin of the northern Colorado River extensional corridor and Grand Wash fault zone may have been dictated by an inherent crustal weakness, including an Early Proterozoic shear zone partially reactivated as reverse faults in Laramide time. Interestingly, the northern Grand Wash-Cerbat Mountains fault, which is the most likely candidate for a reactivated Laramide reverse fault based on the distribution of Paleozoic strata and composition of Laramide plutons, consistently separates highly extended parts of the corridor to the west from mildly extended to relatively unextended terrane to the east.

It is noteworthy that prior to the middle Miocene, the northern Colorado River extensional corridor had far greater affinity to the Colorado Plateau and the broad uplifted region along the southern margin of the plateau than to the western Cordillera. This is best exemplified by the continuation of northwest-trending erosional escarpments of resistant Paleozoic strata, which define the southern margin of the Colorado Plateau through most of Arizona and are associated with gentle Cretaceous-early Tertiary northeast tilting (Peirce, 1984, 1985), into the northernmost part of the corridor (Lucchitta and Young, 1986). By early Miocene time in northwestern Arizona and southern Nevada, the relatively narrow western prong of the Colorado Plateau structural block would have probably been unstable considering its proximity to actively extending regions to the south and north. Weakened by magmatism, the region was rapidly engulfed by large-magnitude middle Miocene east-west extension, effectively pruning a western promontory from the more stable structural block of the Colorado Plateau and transferring it to the Basin and Range. This process was probably facilitated by the growth and northward propagation of normal faults (and dilational cracks) from the region of extreme extension to the south.

Late Miocene to Present

Major east-west extension had abated in the northern Colorado River extensional corridor by late Miocene time in all but the western Lake Mead region, where it continued until about 9 Ma (Duebendorfer and Wallin, 1991; Harlan and others, 1998). In the Frenchman Mountain area, most of the tilting occurred between 11.7 and 6 Ma (Castor and others, 2000). Late Miocene extension in the Lake Mead region was accompanied by major strike-slip faulting, as evidenced by 19 km of left-lateral offset of the 11 to 13 Ma Hamblin-Cleopatra volcano along the Lake Mead fault system (e.g., Anderson, 1973) and kinematic linkages between some of the strike-slip and normal faults (e.g., Duebendorfer and Simpson, 1994; Castor and others, 2000). It is also noteworthy that the Lake Mead region is still actively extending, as evidenced by Quaternary fault scarps in the Lake Mead and Las Vegas regions (e.g., Menges and Pearthree, 1989; dePolo, 1996). The Wheeler fault in the eastern Lake Mead region has accommodated about 300 m of normal displacement since about 6 Ma and cuts alluvial fan surfaces of probable Pleistocene age (Wallace and others, in press).

Mafic lavas continued to erupt in late Miocene to Pliocene time but from isolated volcanic fields. These include (a) 11.9 to 11 Ma tholeiitic basalts, best exposed at Malpais Flattop Mesa in the northern Black Mountains; (b) 10.6 to 8.0 Ma basaltic andesites, best exemplified at Callville Mesa in the western Lake Mead area; and (c) 6.0 to 4.4 Ma alkalic basalts, which are largely confined to the Lake Mead region (Feuerbach and others, 1993) (Fig. 8). Although best exposed at Fortification Hill in the northern Black Mountains, the largest field of 6.0 to 4.4 Ma alkalic basalts crops out in the northern Grand Wash trough (Cole, 1989) (Fig. 4).

As magmatism and extension both waned in the late Miocene, thick sections of alluvial fan, continental playa, and lacustrine deposits accumulated in major basins until about 6 Ma. Among the more noteworthy and widespread late Miocene sedimentary deposits are the relatively fine-grained approximately 10 to 5 Ma clastic sedimentary rocks of the Muddy Creek Formation in the Lake Mead area (e.g., Bohannon, 1984), thick 13 to 6 Ma evaporite deposits in several basins (e.g., Hualapai, Detrital, and Overton Arm basins; Mannion, 1974; Peirce, 1976; Faulds and others, 1997), the 11 to 6 Ma Hualapai Limestone in the Lake Mead area (e.g., Lucchitta, 1966, 1979; Blair and Armstrong, 1979; Wallace, 1999; Faulds and others, in review), and limestone within the approximately 9 to 4 Ma Bouse Formation in the Laughlin-Bullhead City area (Metzger and Loeltz, 1973; Buising, 1990; Spencer and Patchett, 1997). The thickest known evaporite deposit in the region is a 2.5-km-thick accumulation of halite in the Hualapai basin along the eastern margin of the corridor. The texture and bromine content of this halite and S and O isotopic values of intercalated and capping anhydrite indicate that deposition took place in an intracontinental playa mainly through regional groundwater discharge (Faulds and others, 1997).

The Hualapai Limestone is confined to the Lake Mead area and crops out as far west as the northern Detrital basin and as far east as the southern Grand Wash trough, where its thickness approaches 300 m. Ancestral Colorado River gravel locally overlies the Hualapai Limestone (Blacet, 1975; Howard and others, 2000a) but has not been observed either beneath or intercalated within the limestone. Thus, the Hualapai Limestone is the youngest deposit formed before integration of the Lake Mead region into a through-flowing Colorado River drainage (Blair and Armstrong, 1979). Blair and Armstrong (1979) suggested a marine-estuarine origin for the Hualapai Limestone and suggested that an ancestral Gulf of California extended northeastward to the Grand Wash trough and base of the Colorado Plateau. However, comprehensive analysis of the compositional, petrographic, and $\delta^{13}C$ and $\delta^{18}O$ isotopic characteristics, as well as fossil assemblages, indicate that the 11 to 6 Ma Hualapai Limestone was deposited in warm, shallow lakes fed by a relatively continuous source of fresh water (Wallace, 1999).

The Bouse Formation is a widespread unit of upper Miocene-lower Pliocene siltstone and limestone in the lower Colorado River region that has long been interpreted as marine in origin on the basis of vertebrate and invertebrate fossils (Metzger, 1968; Smith, 1970; Buising, 1990). Limestone within the Bouse Formation has been noted as far north as the central part of the Cottonwood basin (Fig. 4; Metzger and Loeltz, 1973) and is widespread in the lower Colorado River region from the Laughlin-Bullhead City area south to the Gulf of California (Metzger, 1968; Metzger and Loeltz, 1973; Buising, 1990). Lucchitta (1979) and Buising (1990) concluded that the Bouse Formation records the northern extent of an ancestral Gulf of California. Spencer and Patchett (1997) showed, however, that Sr isotopic values from barnacles and calcareous sediments within the Bouse Formation are consistent with a lacustrine origin.

The timing of possible Colorado Plateau uplift during late Cenozoic time (McKee and McKee, 1972) has been extrapolated from interpretations of the Bouse Formation as a marine deposit (e.g., Lucchitta, 1979). Lucchitta (1979) used the elevations of the highest erosional remnants of the Bouse Formation to infer 550 to 800 m of uplift of the lower Colorado River region and western Colorado Plateau since late Miocene time. This uplift presumably induced rapid downcutting of the Grand Canyon by the Colorado River since 6 Ma (Lucchitta, 1979, 1989). If not marine or estuarine, however, the Hualapai Limestone and Bouse Formation, as well as the thick middle to late Miocene evaporite deposits (e.g., Hualapai basin salt), cannot be used as evidence to support: 1) a late Miocene to recent uplift of the southwestern Colorado Plateau; 2) the northern extent of the ancestral Gulf of California; and 3) rapid downcutting of the Grand Canyon since 6 Ma. On the basis of available data, the nonmarine origin of the Hualapai Limestone and late Miocene evaporite deposits in the Lake Mead region seems unequivocal, whereas the origin of the Bouse Formation is debatable.

In any case, the late Miocene lacustrine and evaporite deposits in the Lake Mead region suggest an influx of large volumes of fresh water. The most likely sources of this water are the central Nevada carbonate aquifer (e.g., Schmidt and Dixon, 1995; Dixon and Katzer, 2000) and the Colorado Plateau. Considering the proximity, age, and abruptness of the Colorado Plateau-Basin and Range boundary in this region, much of this water may have been derived from the western part of the Colorado Plateau through (1) springs issuing from aquifers in Paleozoic limestone (e.g., Huntoon, 1996, 2000), and/or (2) a system of headward eroding streams that eventually captured larger streams and ultimately evolved into the Colorado River. The lack of interbedded fluvial sediments in the Hualapai Limestone favors the former hypothesis.

A through-flowing Colorado River finally developed in the Lake Mead region between about 6 and 4.4 Ma, as evidenced by a 6.0 Ma age of the uppermost Hualapai Limestone (Spencer and others, 1998) and a 4.4 Ma basalt flow intercalated in Colorado River gravels 100 m above the present grade of the Colorado River in the Gregg basin (Wallace and others, in press). Thick sequences of Colorado River sediments, consisting of interfingering sequences of rounded gravel, sand, silt, and mudstone, have since accumulated in both the Lake Mead and Lake Mohave areas (Longwell, 1946, 1963; Metzger and Loeltz, 1973; Faulds, 1995, 1996; Blair, 1996; Howard and others, 2000a). With rare exceptions (e.g., Longwell, 1946; Faulds, 1995; Anderson, in press), these deposits are flat-lying and unfaulted. The gravels are generally dominated by pebbles and cobbles of Paleozoic limestone, chert, and sandstone, for which the Grand Canyon is the most likely source. Mudstone-siltstone deposits commonly grade laterally into rounded gravel and sand, which suggests that most of the finer-grained deposits accumulated in paleofloodplains of the Colorado River (Faulds, 1995). The Colorado River sediments commonly interfinger with locally derived alluvial fan deposits (Faulds, 1995, 1996; Faulds and House, 2000).

The Colorado River flows across the structural grain produced by Miocene extension in the Lake Mead area (e.g., Howard and others, 2000a) but closely follows the axes of major west-tilted half grabens (e.g., Cottonwood and Mohave basins) south of the Black Mountains accommodation zone. It is noteworthy that even though the Colorado River has an enormous drainage net that includes much of the Rocky Mountains and has excavated many deep canyons into the Colorado Plateau, large basins proximal to the river in the northern part of the corridor (e.g., Eldorado and Hualapai basins) remain internally drained. Such relations may attest to the relative youthfulness of the river and aridity of this region. However, minor isostatic rebound of the highly extended extensional corridor may have also played a role in maintaining the isolation of these basins.

CONCLUSIONS

The northern Colorado River extensional corridor is a 70- to 100-km-wide region of moderately to highly extended crust along the eastern margin of the Basin and Range province in southern Nevada and northwestern Arizona. The abrupt western margin of the Colorado Plateau borders the northern Colorado River extensional corridor on the east. A diffuse north-trending boundary between Early Proterozoic crustal provinces follows the eastern margin of the corridor and may have controlled the location and abruptness of the Colorado Plateau-Basin and Range transition in this region. Major events that have shaped the landscape of this region are summarized below.

Late Cretaceous to early Tertiary:

- Broad uplift and erosion south of Lake Mead with development of the gently (15^{o}) north-plunging Kingman arch.
- Erosional stripping of Mesozoic and Paleozoic from Kingman arch.
- Emplacement of 64 to 73 Ma two-mica, garnet-bearing peraluminous granites at 10+ km depth and their subsequent uplift and exposure.
- Deposition of Paleocene-Eocene "rim gravels" along mar-

gin of Colorado Plateau by northeast-flowing regional drainage.
- Fold and thrust belts active to north, west, and south of region.

Oligocene to middle Miocene:

- Early Tertiary erosion ends with widespread deposition of latest Oligocene to early Miocene prevolcanic conglomerate.
- 18.5 Ma Peach Springs Tuff blankets much of region and flows northeastward onto Colorado Plateau.
- Magmatic front sweeps northward, with development of several stratovolcanoes, eruption of thick sections of calc-alkaline intermediate to mafic volcanic rocks, and emplacement of several felsic to intermediate plutons.
- Mild north-south extension accompanies volcanism.
- Thick sedimentary sections accumulate in broad basins in amagmatic Lake Mead area.
- South-facing paleoscarps of resistant Paleozoic strata on north margin of Kingman arch isolate Lake Mead area from volcanic terrane to south.
- Large-magnitude east-west extension occurring north and south of region.
- Transitional setting between early Tertiary highland of the Kingman arch and the developing Basin and Range.

Middle Miocene:

- Large-magnitude east-west extension begins 16.5 to 15.5 Ma in the south and east and migrates northwestward into the western Lake Mead region by ~13 Ma.
- Arrays of tilted fault blocks and associated half grabens develop; most blocks tilted >50^{o}.
- Eruptive rates peak just before to immediately after onset of extension and tail off considerably in most areas during extension.
- Intermediate composition volcanism generally gives way to bimodal activity near the onset of extension.
- Three synextensional, felsic to intermediate composition plutons emplaced.
- Two major ash-flow tuffs erupted: 15.2 Ma tuff of Bridge Spring and 15.0 Ma tuff of Mount Davis.
- Magmatic front stalls in Lake Mead area ~12 Ma.
- Thick volcanic sections accumulate in most half grabens south of Lake Mead, whereas thick sedimentary sections accumulate in half grabens in Lake Mead region.
- Sedimentary deposits were locally derived, indicating predominance of internally drained basins, with no through-flowing drainage.
- Structural and topographic demarcation of the Colorado Plateau-Basin and Range boundary begins developing ~16 Ma and was essentially established by 13 Ma.
- Headward erosion into western margin of Colorado Plateau begins as early as 15.2 Ma.

Late Miocene to present:

- Major east-west extension ends in most areas by ~9 Ma.
- East-west extension in Lake Mead area accompanied by major strike-slip faulting and north-south shortening.
- Activity on some faults in Lake Mead-Las Vegas areas continues into Quaternary.
- Mafic lavas erupt from isolated volcanic fields in late Miocene to Pliocene time.
- Thick sections of alluvial fan, continental playa, and lacustrine deposits accumulate in major basins until about 6 Ma.
- Widespread late Miocene lacustrine and evaporite deposits in the Lake Mead region suggest a large influx of fresh water.
- Through-flowing Colorado River develops between ~6.0 and 4.4 Ma.

ACKNOWLEDGMENTS

This research has been supported by grants from the National Science Foundation (EAR91-20383, EAR93-16770, and EAR98-96032 awarded to Faulds; EAR92-19860 and EAR96-28380 awarded to Miller), the EDMAP program of the U.S. Geological Survey (Agreements No. 1434-HQ-96-AG-01546 and 1434-HQ-97-AG-07146), the STATEMAP program of the U.S. Geological Survey (Agreement No. HQ-AG-2036), and the Nevada Agency for Nuclear Projects. In addition, the U.S. Geological Survey in Las Vegas kindly provided a field vehicle for substantial amounts of this work, for which we thank Gary Dixon and Peter Rowley. We also thank the National Park Service at the Lake Mead National Recreation Area for extensive logistical support over the past several field seasons, including boat access into remote areas and housing. Glenn Anderson, Jim Riley, Kent Turner, and Darlene Carnes with the Lake Mead National Recreation Area have been especially helpful. This research has also benefited enormously from many fruitful discussions with Ernie Anderson, Sue Beard, Gary Dixon, Ernie Duebendorfer, Eric Olson, Linda Price, and Robert Varga. Reviews by Gary Dixon, Mel Erskine, and Peter Rowley were very helpful. We also thank Susan Tingley and Kris Pizarro for their assistance in preparing many of the figures.

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