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Spatial and temporal relationships between mid-Tertiary magmatism and extension in southwestern Arizona

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Abstract. Cenozoic magmatism in southwestern Arizona, which is within the Basin and Range tectonic province, occurred almost entirely between 15 and 25 Ma. Volcanic rocks typically consist, in ascending order, of (1) a thin sequence of mafic to intermediate lava flows, (2) voluminous felsic lava flows and pyroclastic rocks with minor to moderate amounts of intermediate to mafic lava flows, and (3) basalt and andesite. Volcanic rock sequences rest disconformably on pre-Tertiary bedrock in most areas but locally overlie substantial coarse clastic debris that was deposited immediately before and during earliest magmatism. Prevolcanic clastic debris is interpreted as a consequence of local early normal faulting. In most regions, tilting related to extension began later and occurred during or after eruption of felsic volcanic rocks and before the end of younger mafic volcanism. Extension generally ended before about 17 Ma except in a northwest trending belt adjacent to the relatively unfaulted and topographically elevated Transition Zone tectonic province which is adjacent to the Colorado Plateau. Rapid cooling of metamorphic core complexes and tilting of young basalts and coarse clastic rocks continued in this belt until as recently as 11 Ma. Extension was extreme in this belt, whereas it was generally moderate to slight in other parts of southwestern Arizona. Large-magnitude extension was not associated with areas of greatest igneous activity, and rapid cooling and exhumation of core complexes postdated local magmatism. These relationships are inconsistent with theories that relate genesis of metamorphic core complexes to magma intrusion in the upper crust. Except for young extension in this northwest trending belt, there are no apparent regional migration trends for either magmatism or extension within southwestern Arizona. Lack of substantial extension before magmatism and general lack of magmatism during youngest extension are inconsistent with the hypothesis that magmatism was the product of decompression melting during lithospheric extension. The long duration and large magnitude of extension adjacent to the Transition Zone tectonic province and within an area of earlier crustal thickening are consistent with the hypothesis that extension was driven by the gravitational potential energy of elevated land mass and crustal roots. Regional magmatic heating apparently weakened the lithosphere and triggered extension but did not control extension locally.

Introduction

Overview

Migration patterns of late Cretaceous and early to middle Cenozoic magmatism in western North America are complex but are commonly thought to reflect the evolving configuration of subducted oceanic lithosphere. Latest Cretaceous eastward migration of the locus of magmatism and crustal shortening and associated Laramide orogenesis [*Dickinson and Snyder*, 1978] were followed by Cenozoic migration of magmatism that was complex but regionally westward [*Coney and Reynolds*, 1977; *Cross and Pilger*, 1978; *Clark et al.*, 1982]. Westward migration has been attributed to subduction of progressively younger, hotter, and weaker lithosphere [*Severinghaus and Atwater*, 1990; *Spencer*, 1994]. Contact between the North American and Pacific plates resulted in termination of subduction and fundamental changes in the nature of magmatism [*Christiansen and Lipman*, 1972].

Cenozoic magmatism was commonly associated with crustal extension that affected much of the Cordilleran orogen from southwestern Canada to central Mexico [*Coney*, 1980]. Proposed relationships between extension and magmatism generally fall into three groups, as follows: (1) Extension triggered magmatism by decompression melting [e.g., *Leeman and Harry*, 1993]. This hypothesis predicts that significant extension preceded magmatism. (2) Radio-

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genic heating following earlier crustal shortening weakened the lithosphere and triggered both magmatism and extensional thinning of overthickened, gravitationally unstable crust [*Glazner and Bartley*, 1985; *Sonder et al.*, 1987]. This hypothesis predicts that the laterally varying age and magnitude of late Cretaceous to early Tertiary crustal thickening and magmatic heating controlled the locus and timing of later extension [*Wernicke et al.*, 1987]. (3) Magmatism was initiated by subduction, and extension was caused by some combination of magmatic heating of unstable overthickened crust and reduced compressive stress from the plate boundary [*Coney and Harms*, 1984]. This hypothesis predicts that magmatism was unrelated to earlier structural and magmatic events and that extension was either triggered by local magmatic heating or occurred regionally in response to reduced plate boundary compression. Extension and magmatism have also been linked locally; uplift of metamorphic core complexes and associated large-magnitude extension have been attributed to magma injection in the upper crust [*Rehrig and Reynolds*, 1980; *Lister and Baldwin*, 1993].

Some geologists have proposed on the basis of earlier compilations that Cenozoic magmatism and extension in the Mojave-Sonoran desert region of Arizona, California, and southernmost Nevada migrated from south to north. *Glazner and Supplee* [1982] proposed that northward migration of Cenozoic magmatism was due to northward movement of the southern edge of the subducted Farallon/Vancouver plate. *Glazner and Bartley* [1984] proposed that the onset of extension similarly migrated northward and that this was due to northward migration of the unstable triple junction where the Mendocino fracture zone contacted the continental margin [see *Ingersoll*, 1982].

The study area is within the southern part of the Basin and Range province and encompasses the southwestern one fourth of Arizona (Figure 1). Voluminous mafic and felsic magmatism and slight to extreme crustal extension affected southwestern Arizona between 30 and 10 Ma. The purpose of this study is (1) to synthesize geologic and geochronologic data that constrain the timing of magmatism and extension in southwestern Arizona, (2) to clarify regional migration patterns of extension and magmatism, and (3) to assess local and regional relationships between extension and magmatism and causes of each. This study builds on dozens of detailed (mostly 1:24,000 scale) geologic maps produced during the past 15 years, many as part of the COGEOMAP program between the Arizona Geological Survey and the U.S. Geological Survey, and on more than 160 K-Ar and $^{40}Ar/^{39}Ar$ dates, many of which are presented here.

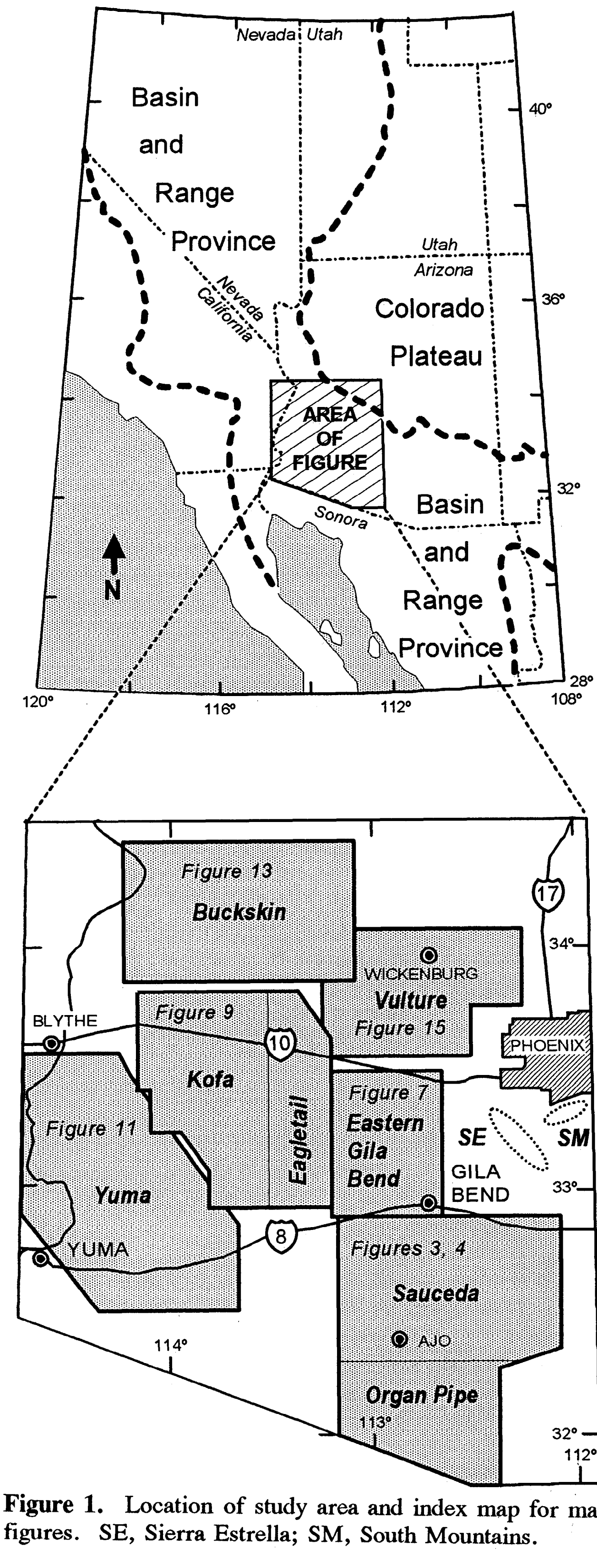


Figure 1. Location of study area and index map for map figures. SE, Sierra Estrella; SM, South Mountains.

Geologic Setting

Mesozoic and Cenozoic magmatism and deformation in southwestern Arizona overprinted continental crust that consisted of early and middle Proterozoic crystalline rocks overlain by Paleozoic platformal sedimentary rocks similar to those exposed in the Grand Canyon [*Dickinson*, 1989]. Complex Mesozoic deformation, magmatism, sedimentation, and erosion greatly modified the pre-Mesozoic rocks but are incompletely understood because of widespread burial by Cenozoic supracrustal rocks. The significance of these different geologic processes varied greatly within southwestern Arizona. Mid-Jurassic magmatism affected much of the western and southern parts of southwestern Arizona but was unimportant in central Arizona [*Tosdal et al.*, 1989; *Reynolds*, 1988]. Younger, intense, thrust-related deformation in west central Arizona was preceded and accompanied by deposition of up to several kilometers of upper Jurassic to upper Cretaceous clastic sediments [e.g., *Reynolds et al.*, 1986b; *Tosdal and Stone*, 1994], and latest Cretaceous to earliest Tertiary deformation and magmatism were widespread in south central Arizona [*Haxel et al.*, 1984]. Proterozoic crystalline rocks that are widely exposed in central Arizona were largely unaffected by Mesozoic deformation and sedimentation [*Reynolds et al.*, 1988; *Reynolds and DeWitt*, 1991], and southwesternmost Arizona consists largely of a 62 Ma granitic batholith [*Reynolds*, 1988; R.M. Tosdal, written communication, 1994].

Southwestern Arizona is devoid of early Tertiary sedimentary and volcanic rocks and was the site of erosional denudation at this time. Widespread early Cenozoic clastic sediments deposited on the Colorado Plateau were derived from areas to the southwest of the modern Colorado Plateau [*Young and McKee*, 1978; *Cather and Johnson*, 1984; *Potochnik*, 1989] and possibly were derived in part from southwestern Arizona. The absence of early Tertiary sedimentary rocks in southwestern Arizona is interpreted to indicate that the entire area was elevated relative to surrounding areas, had a fairly mature geomorphology with integrated drainages and no internally drained basins, and was not undergoing fault-related landform development that could trap sediments in grabens or bury them by thrusts. Mesozoic crustal thickening due to magmatism and crustal shortening is the likely cause of the inferred moderate to high elevations. Mid-Tertiary extension and magmatism, which are the subject of this study, occurred within an area that had been tectonicly stable and topographically elevated for at least 30-50 m.y.

Areal Geology and Geochronology

The style of mid-Tertiary magmatism in southwestern Arizona was somewhat different than in most other large volcanic fields in the western United States and was characterized by emplacement of flows, dikes, domes, and laterally restricted pyroclastic deposits and a general absence of calderas and regional ash flow tuffs. As a result, precise stratigraphic correlations between ranges have not been possible. Simplified time-stratigraphic columns, presented here for each of six areas of volcanism and extension in southwestern Arizona, required correlating and merging stratigraphy from many mountain ranges, each containing a stratal sequence that is somewhat unique and only partially dated. Geochronology and broad lithologic similarity are the primary basis for the summary columns. Simplified geologic maps for each of these six areas represent volcanic rocks as either mafic or felsic based on published map unit descriptions typically derived from field and hand sample observations. Map units described as basaltic or andesitic are considered mafic, and those described as dacitic and rhyolitic are considered felsic. This simplification probably does not significantly misrepresent rock types at the regional scale of the map figures in this paper. The locations of K-Ar and $^{40}Ar/^{39}Ar$ dates used in this synthesis are shown on these map figures and in most cases reveal a fairly even sample distribution.

The follow review and synthesis incorporates a large amount of geochronologic data, including 166 K-Ar and $^{40}Ar/^{39}Ar$ dates (Figure 2). In areas where a single flow or intrusive rock was dated more than once, either from different minerals in a single sample or from different samples, an error-weighted mean is given as the age. The

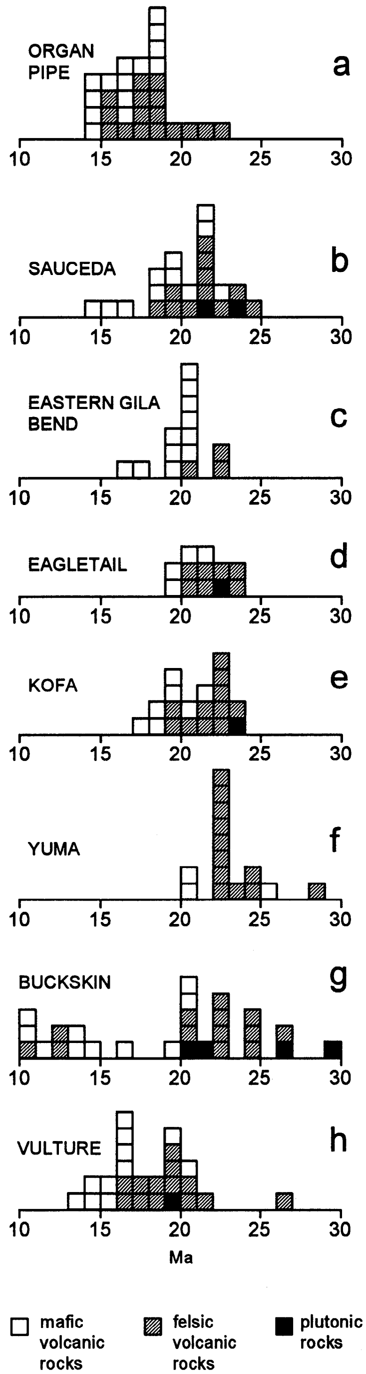


Figure 2. Histograms of K-Ar, $^{40}Ar/^{39}Ar$, and U/Pb dates of 10-30 Ma igneous rocks in the areas shown in Figures 1, (a) and (b) 3, (c) 7, (d) and (e) 9, (f) 11, (g) 13, and (h) 15.

standard deviation of the mean was calculated from the standard deviations of each date, and the sample standard deviation was calculated from the difference between each date and the error-weighted mean. The larger of the two calculated standard deviations is given as the error [*Long and Rippeteau*, 1974]. Published K-Ar dates with a standard deviation of more than 1 m.y. were generally not used in this compilation. The large error in these dates is presumably due to poor sample quality or technical problems in analysis. Ages with standard deviations of greater than 1 m.y. are reported here in cases where the error results from

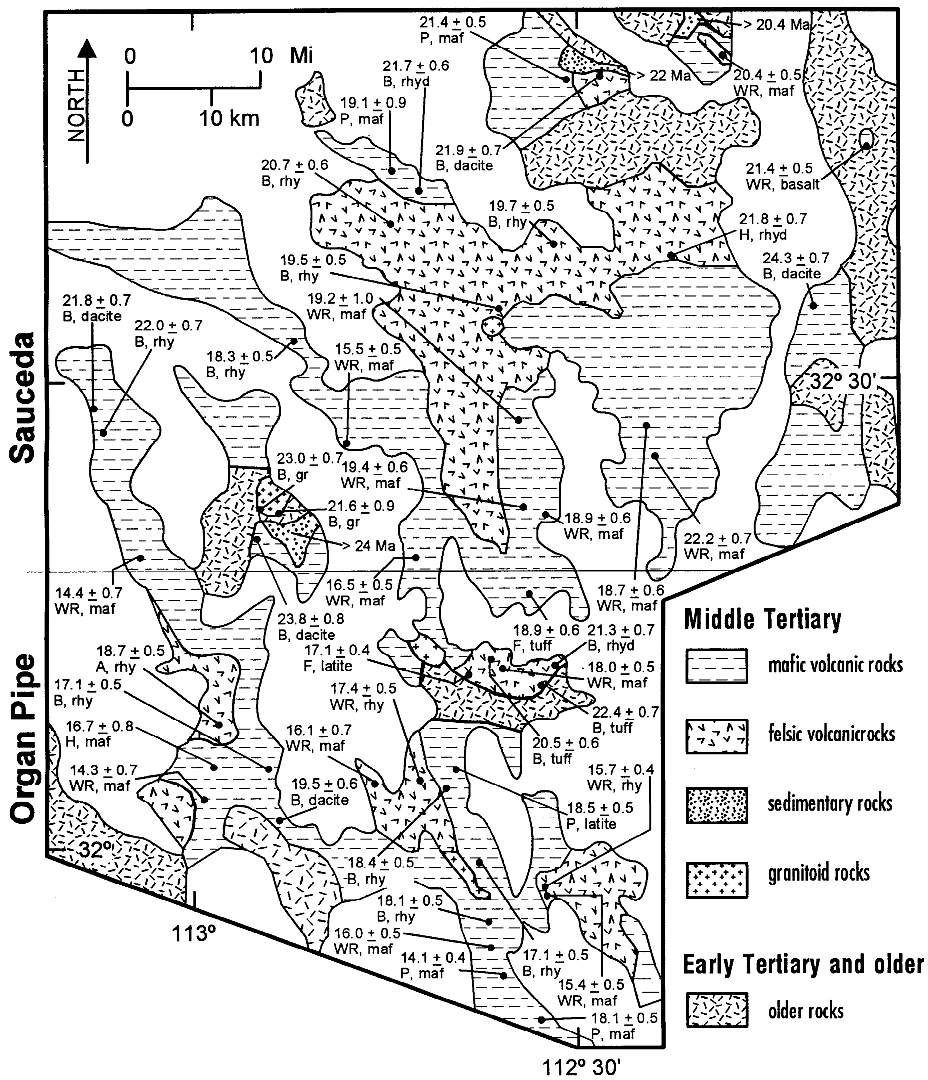


Figure 3. Simplified geologic map of the Organ Pipe-Sauceda area showing the areal extent of the Ajo volcanic field and K-Ar dates and locations. K-Ar data from *Shafiqullah et al.* [1980], *Tosdal* [1982], *Gray and Miller* [1984], *Gray et al.* [1985a], and R. Miller (unpublished data, 1991). Horizontal line divides map into southern area (Organ Pipe area) represented by Figure 2a and northern area (Sauceda area) represented by Figure 2b. Not all dates represented in Figure 2a are plotted here.

discordance between two or more high-precision dates of a single unit.

Organ Pipe-Sauceda Area (Ajo Volcanic Field)

Magmatism. Volcanic rocks near Ajo, Arizona (Figure 1), form the Ajo volcanic field (Figures 3 and 4) and are generally divisible into a three suites (Figure 5). The lower suite consists of basaltic and andesitic lava flows and subordinate felsic lava flows and pyroclastic rocks. The middle suite consists of compositionally diverse, voluminous mafic and felsic volcanic rocks, including the Childs latite. The upper suite consists of basaltic and andesitic lava flows [*Gray et al.*, 1988].

Fifty-five K-Ar dates from the Ajo volcanic field reveal the chronology of magmatism (Figures 2a, 2b, and 3). Six dates at 22.0-24.3 Ma from widely spaced sample areas record initiation of magmatism. Most of the older dates are from felsic volcanic rocks. Mafic volcanic rocks generally do not contain minerals suitable for K-Ar dating, and older mafic volcanic rocks in mid-Tertiary sequences are typically too altered for whole rock K-Ar dating. Most magmatism occurred in the southern Organ Pipe area between 19 and 14 Ma and in the northern Sauceda area between about 22 and 18 Ma (Figures 2a, 2b, and 3). The Childs latite was erupted at 18-19 Ma. Magmatism ended abruptly at about 14 Ma.

Extension. Earliest extension is revealed by prevolcanic basin genesis. In most areas, volcanic rocks were deposited on pre-middle Tertiary igneous and metamorphic rocks or on several to several tens of meters of clastic rocks derived from underlying bedrock. In the Little Ajo, northern Sand Tank, and southern Maricopa mountains, however, thick Tertiary clastic sequences were deposited before local volcanism (Figures 3 and 4). The Locomotive fanglomerate in the Little Ajo Mountains consists of an eastward thickening wedge of conglomerate with an apparent thickness of up

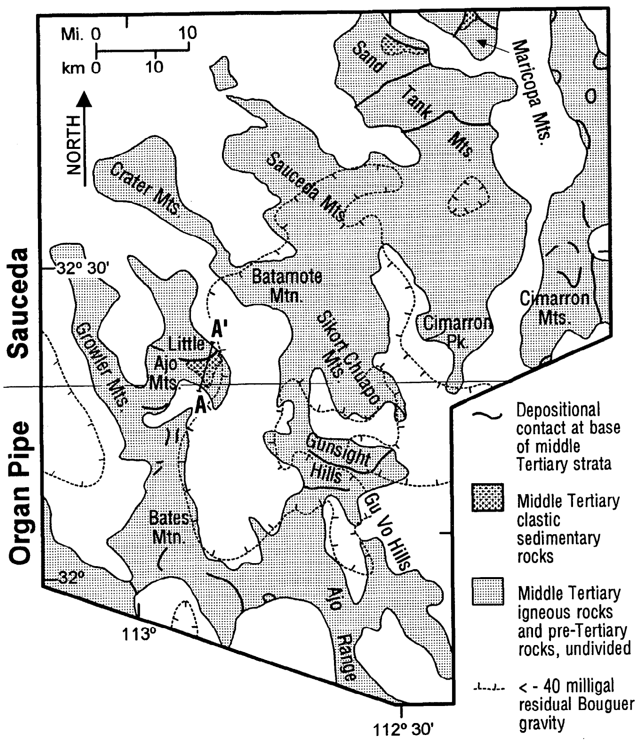


Figure 4. Map showing names of ranges in Figure 3, locations of depositional contacts at base of mid-Tertiary volcanic and sedimentary sequences, locations of areas that contain significant amounts of prevolcanic Tertiary sandstone and conglomerate, and Bouguer gravity contour from *Lysonski et al.* [1980].

to several thousand meters. The fanglomerate is coarser toward the west where bedrock resembles clast rock types. The Ajo volcanics are interbedded with the upper part of the fanglomerate and conformably overlie it [*Gilluly*, 1946]; an interbedded flow yielded a biotite K-Ar date of 23.8±0.8 Ma [*Gray and Miller*, 1984] (Figure 6, cross section AA'). A Tertiary section in the Maricopa Mountains, several hundred meters thick, consists of a basal conglomerate that is overlain by interbedded volcanic and conglomeratic strata [*Cunningham et al.*, 1987]. Basalt in this sequence yielded a whole rock K-Ar date of 20.4±0.5 Ma [*Shafiqullah et al.*, 1980]. Conglomerate in the northern Sand Tank Mountains overlies crystalline rocks and contains a tuff that yielded a K-Ar biotite date of 21.7±0.7 Ma [*Gray and Miller*, 1984; *Gray et al.*, 1988]. These clastic sequences are interpreted as recording extension and extensional basin formation that immediately preceded or accompanied initial magmatism.

Field relationships and K-Ar geochronology in the Ajo volcanic field indicate that normal faulting, tilting, and magmatism were regionally synchronous and that extension was slight to moderate. Normal faults that cut and tilt the volcanic sequences are common but generally do not have large displacements. In the Little Ajo Mountains the Locomotive fanglomerate and overlying Ajo volcanics dip 30°-65° SSW (Figure 6, cross section AA'), whereas nearby Childs latite and Batamote andesite dip 2°-12° [*Gilluly*, 1946], bracketing tilting between 18 and 24 Ma. The northwest striking Little Ajo Mountain fault separates tilt blocks and probably accommodated tilting. In the Ajo Range, the 18-19 Ma Childs latite is exposed over a large area where it dips 12°-34°E and is cut by several NNW striking normal faults with stratigraphic separations of less than several hundred meters [*Tosdal et al.*, 1986]. Basaltic and rhyolitic lava flows in the nearby Gu Vo Hills, dated at 15.7-15.4 Ma, are not tilted and apparently postdate extension [*Shafiqullah et al.*, 1980]. The volcanic and sedimentary rocks that make up the Growler Mountains (as old as 22 Ma) are generally tilted to the east less than about 10° except locally near minor northwest striking normal faults where stratal dips are up to 35° [*Gray et al.*, 1985b]. In the northern Sand Tank Mountains, lowermost (19-20 Ma) Tertiary strata dip 10°-40°, whereas the youngest basalts are flat lying [*Gray et al.*, 1985a]. Dips of basal Tertiary strata are locally greater than 45° in the Quijotoa and Cimarron Mountains, but most exposed Tertiary strata dip less than 30° [*Briskey et al.*, 1978; *Rytuba et al.*, 1978].

Summary. In most of the Ajo volcanic field, basal volcanic strata were deposited on a bedrock surface that had not been sufficiently disrupted by normal faulting to produce extensional basins and associated sedimentary deposits. The oldest volcanic rocks, dated at 24-20 Ma, locally overlap and are interbedded with conglomerates that are interpreted to reflect early extensional faulting. Voluminous volcanism between 22 and 14 Ma was accompanied by minor to moderate normal faulting and tilting, and the youngest volcanic rocks are generally flat lying. In general, magmatism was voluminous and widespread, extensional faulting and fault-block tilting were minor to moderate, and magmatism and extensional faulting were synchronous except for local normal faulting inferred from premagmatic clastic sedimentation.

Eastern Gila Bend Mountains Area

Magmatism. The eastern Gila Bend Mountains and adjacent ranges consist primarily of andesitic to basaltic lava flows and flow breccias with significant felsic volcanic rocks primarily in the Painted Rock Mountains (Figure 7) [*Peterson et al.*, 1989; *Skotnicki*, 1993b, 1994; *Reynolds and Skotnicki*, 1993; *Ort and Skotnicki*, 1993; *Gilbert and Skotnicki*, 1993]. In some areas the mafic volcanic rocks have been divided into a lower group of typically altered, variably tilted mafic lava flows and an upper group of less altered, commonly mesa-forming basalts (Figure 8) [*Peterson et al.*, 1989; *Skotnicki*, 1993a, 1994; *Gilbert and Skotnicki*, 1993].

Widespread mafic and felsic magmatism at 19-21 Ma is indicated by nine of eleven whole rock K-Ar dates from moderately tilted mafic volcanic rocks, mostly in the Palo Verde Hills [*Shoustra et al.*, 1976; *Shafiqullah et al.*, 1980], and a biotite K-Ar date of 20.0±0.6 Ma from a tuff in the Painted Rock Mountains (Table 1 and Figure 7). Older tuffs in the easternmost Gila Bend Mountains are dated at 22-23 Ma (Table 1), and tilted mafic flows are dated in two places at 16.9 and 17.9 Ma (Figure 7). K-Ar samples are not well distributed in the eastern Gila Bend Mountains, and the mesa-forming basalts have not been dated.

K-Ar dates of 29.4±0.6 Ma (biotite) and 27.4±0.7 Ma (whole rock) were obtained from volcanic rocks near the northern end of the easternmost Gila Bend Mountains [*Shoustra et al.*, 1976; *Shafiqullah et al.*, 1980]. The locations from which these samples were collected are

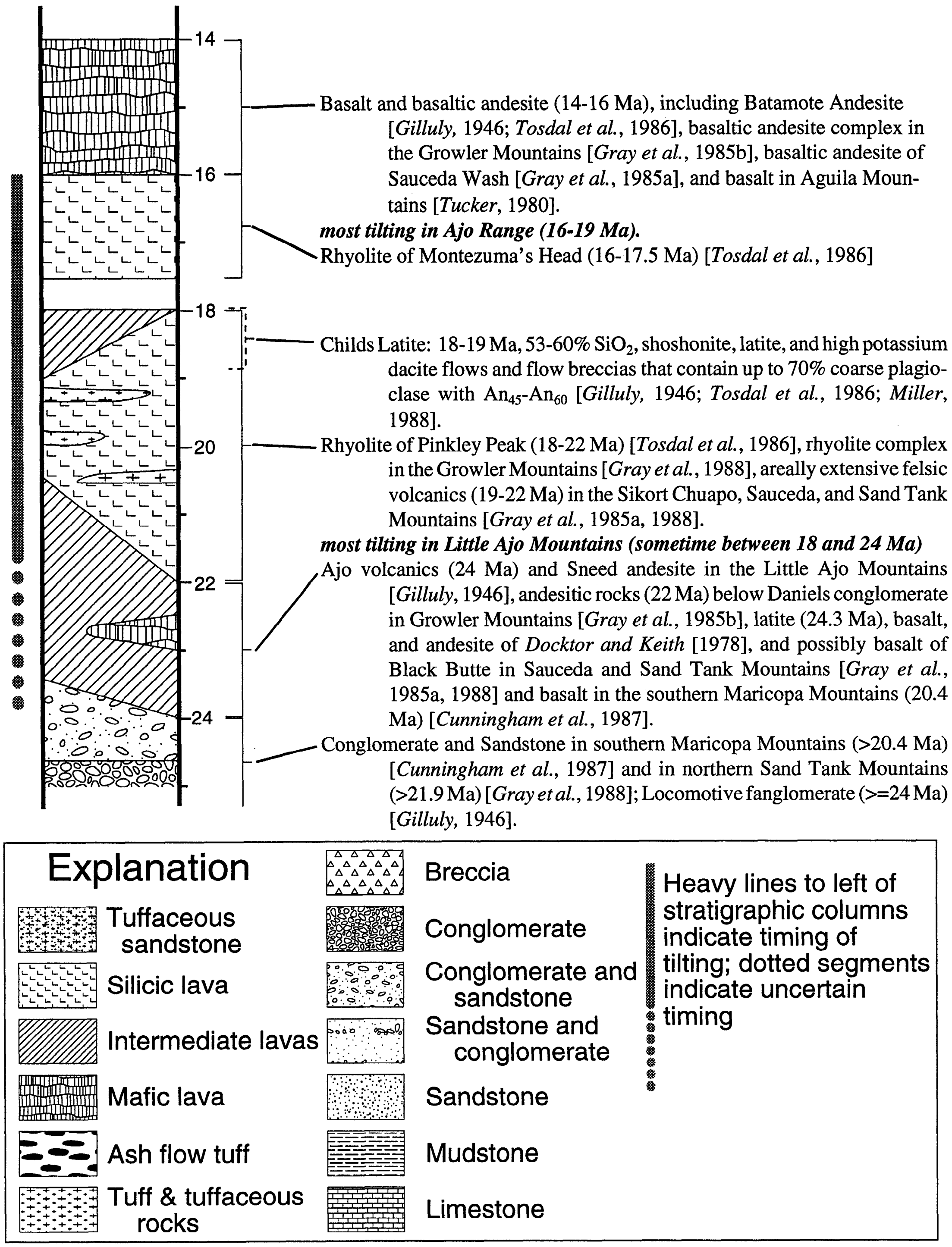


Figure 5. Simplified stratigraphy of the Organ Pipe-Sauceda area.

poorly known but were probably within a 500 x 200 m area of interbedded mafic volcanic flows, tuff, and conglomerate that rest depositionally on Proterozoic basement [*Gilbert*, 1991]. These dates are not included in Figures 2 and 7 because the location and stratigraphic position of the sampled rocks are poorly known, the volume of rock represented by the suspected sample area is small, and the dates are quite dissimilar to those from surrounding areas. These dates may indicate, however, that minor volcanism and sedimentation occurred well before main phase volcanism.

Extension. Proterozoic crystalline rocks in the easternmost Gila Bend Mountains are depositionally overlain by up to 1 km of conglomerate and sandstone that are in turn depositionally overlain by a tuff unit dated at 22.2$\pm$0.5 Ma and 22.8$\pm$0.5 Ma (Table 1 and Figures 6, cross section BB', and 7). These southwest dipping Tertiary rocks are on strike with lithologically similar sediments 30 km to the southeast in the northern Sand Tank Mountains that are interbedded with a tuff dated at 21.7$\pm$0.7 Ma [*Gray et al.*, 1988]. Between the two areas near Gila Bend, seismic reflection profiles reveal a southwest dipping stratal se-

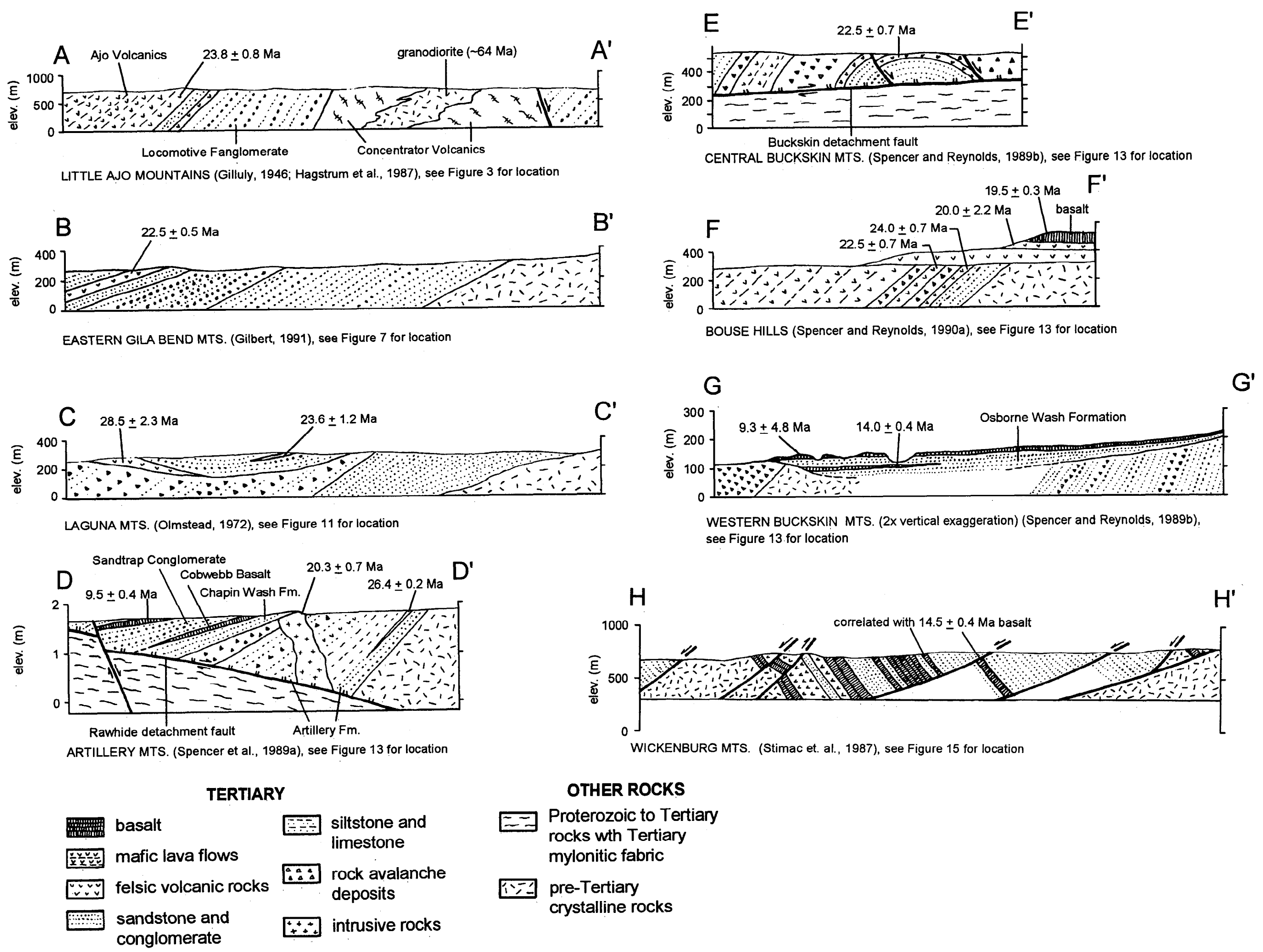


Figure 6. Geologic cross sections of areas where dated rocks constrain the timing of extensional tilting. All are shown without distortion except cross section GG' which is shown with 2x vertical exaggeration. Cross section FF' is somewhat schematic. Figures showing locations of cross sections are indicated.

quence in the subsurface (S.J. Reynolds and D. Okaya, unpublished data, 1994). It seems likely that both areas of exposed prevolcanic sediments were part of a single extensional sedimentary basin. If tilting of basin sediments reflects continued movement on faults that were related to basin genesis, then this basin was probably a southwest tilted half graben.

Volcanic rocks throughout the area of Figure 7 are generally cut by sparse to numerous northwest and north-northwest striking normal faults and are tilted 10°-55° to the southwest or northeast [e.g., *Scott*, 1991; *Gilbert and Skotnicki*, 1993; *Skotnicki*, 1994]. Widespread normal faulting occurred after deposition of these largely 19-21 Ma volcanic rocks and possibly after 17 Ma if the 16.9 and 17.9 Ma dates are accurate. Gently dipping, largely unfaulted basalts that overlap tilted volcanic rocks in some areas [*Peterson et al.*, 1989; *Skotnicki*, 1993a, 1994] are not dated but are lithologically similar to gently dipping, 14-20 Ma basalts in other parts of southwestern Arizona such as the 15 Ma Hot Rock basalt north of the Palo Verde Hills in the southern Belmont Mountains [*Shafiqullah et al.*, 1980].

Summary. Extension in the area of the eastern Gila Bend Mountains began before deposition of 22-23 Ma tuffs, as indicated by coarse clastic, prevolcanic sediments that are inferred to have been deposited in an extensional basin that continued southeastward to the northern Sand Tank Mountains. Available K-Ar data indicate that voluminous, largely mafic volcanism occurred primarily at 19-21 Ma (Figure 2c) and was accompanied or immediately followed by extensional faulting and tilting. Younger, postfaulting basalts are inferred to be 14-20 Ma based on correlation to similar basalts in nearby areas.

Kofa-Eagletail Mountains Area

Magmatism. Voluminous felsic and mafic volcanism in and around the Kofa Mountains produced a volcanic field that extends eastward to the Eagletail and western Gila Bend Mountains and westward across the Trigo Mountains to southeasternmost California. The Kofa volcanic field is comparable in size to the Ajo volcanic field. In the eastern part of the Kofa volcanic field (Figures 9 and 10), volcanic rocks can be divided into four members, as follows (from base to top): (1) mafic lava flows locally interbedded with underlying clastic sedimentary rocks, (2) 20-24 Ma felsic flows, pyroclastic rocks, breccias, domes, and dikes, locally including mafic lava flows that are most abundant around the Eagletail and Kofa mountains, (3) faulted and tilted mafic lava flows (19-22 Ma), and (4) mesa-forming basalt flows

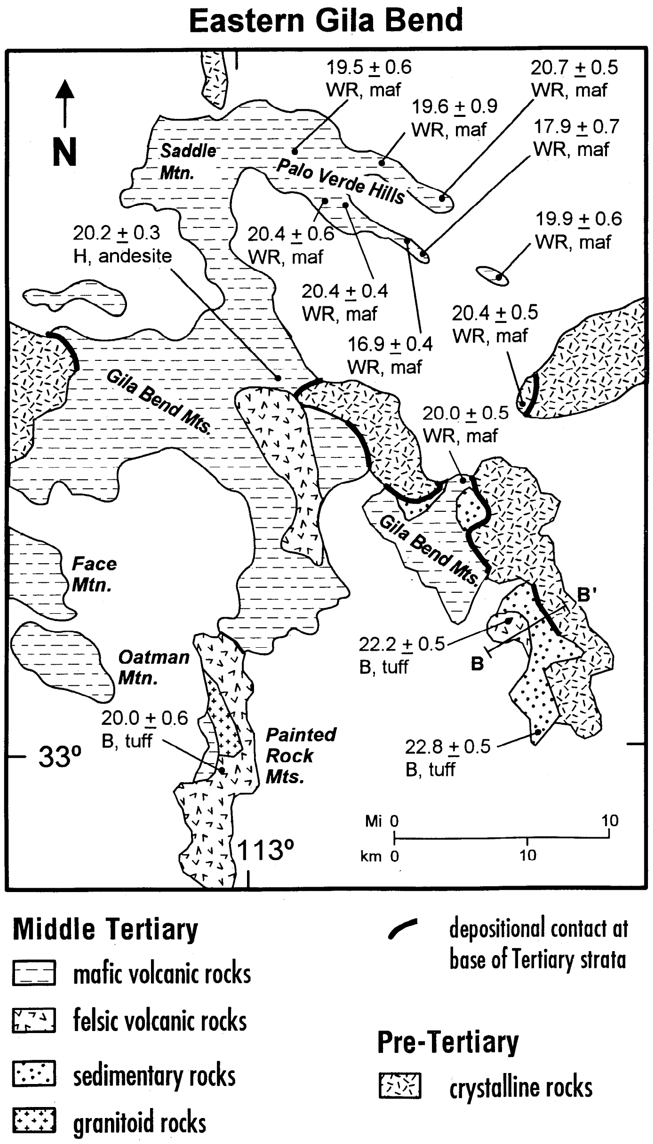


Figure 7. Simplified geologic map of eastern Gila Bend Mountains showing K-Ar dates and locations. K-Ar data from *Shoustra et al.* [1976], *Shafiqullah et al.* [1980], and Table 1.

(17-19 Ma). Mafic lava flows are sparse within the felsic volcanic centers in the Kofa and Eagletail mountains but are common around their margins in the southern Plomosa, New Water, Little Horn, and southeastern Tank Mountains (Figure 9). K-Ar dates from each area indicate that felsic magmatism at the two volcanic centers was approximately synchronous at 19-24 Ma (Figures 2d and 2e) and was accompanied by emplacement of the Columbus Wash granodiorite dated at 22.5±0.4 Ma (mean of two biotite K-Ar dates; Table 1) and a granite in the southern Palomas Mountains dated at 23.2±0.5 Ma by biotite K-Ar [*Bagby et al.*, 1987].

The large felsic volcanic field centered on the Kofa Mountains (western part of Figure 9) includes thick tuff and breccia dated at ≈22 Ma that are interpreted as caldera fill and outflow. The calderas are centered on two large negative Bouguer gravity anomalies that probably represent thick caldera-filling volcanic rocks and possibly underlying related granitoids [*Grubensky and Bagby*, 1990; *Gutmann*, 1981].

Extension. Basal Tertiary volcanic rocks typically rest on pre-Tertiary bedrock or on several to several tens of meters of sedimentary rocks but locally overlie thick sequences of coarse clastic sediments that probably record prevolcanic normal faulting (Figure 9). In the western Gila Bend Mountains and southern Plomosa Mountains, up to perhaps 200-300 m of conglomerate underlies or is interbedded with basal volcanic rocks. Conglomerate clasts in both areas are composed of pre-Tertiary rock types and, locally, minor Tertiary volcanic rocks [*Gilbert et al.*, 1992; *Richard et al.*, 1993; *Richard and Spencer*, 1994]. Tertiary rock avalanche deposits composed of pre-Tertiary rocks locally underlie the Tertiary volcanic rocks in the northeastern Eagletail Mountains [*Spencer et al.*, 1993].

Felsic volcanic rocks are commonly cut and tilted by northwest striking normal faults, although the severity of faulting varies greatly both laterally and vertically. Stratigraphically lower parts of felsic volcanic sequences are tilted moderately to steeply in the western Gila Bend [*Gilbert et al.*, 1992], northeastern Eagletail [*Spencer et al.*, 1993], northern Kofa [*Shafiqullah et al.*, 1980], Little Horn [*Grubensky and Demsey*, 1991], and central Plomosa [*Stoneman*, 1985] Mountains and are gently tilted in the southern Plomosa [*Richard et al.*, 1993], New Water [*Sherrod et al.*, 1990], Little Harquahala [*Spencer et al.*, 1985] and eastern Tank Mountains [*Ferguson et al.*, 1994]. Gently dipping mafic lavas overlie more steeply tilted felsic rocks in the New Water, southern Plomosa, and northern Kofa Mountains.

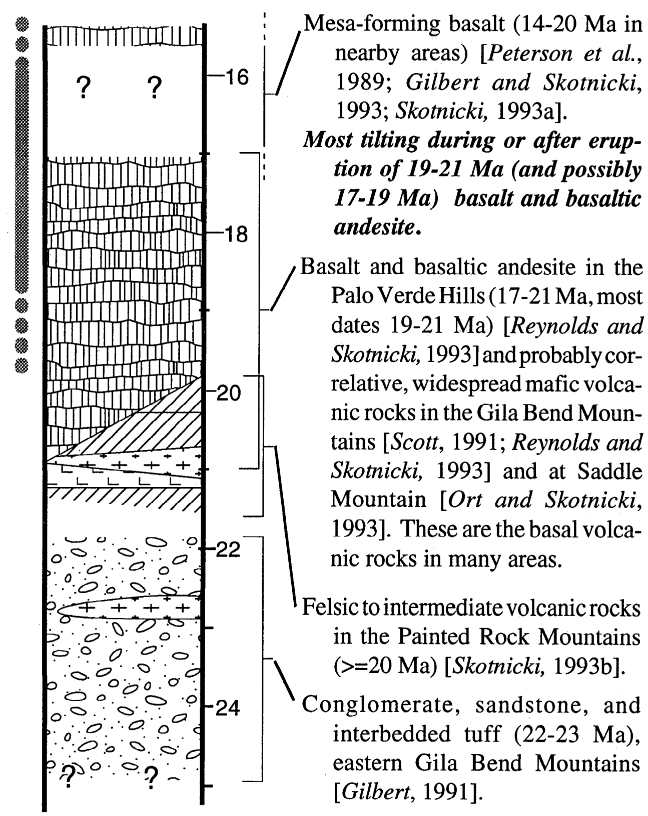


Figure 8. Simplified stratigraphy of the eastern Gila Bend Mountains area.

Summary. Clastic sedimentation began locally before or during early mafic magmatism in the Kofa-Eagletail region, but in most areas, little or no clastic sediment separates pre-Tertiary bedrock from the base of Tertiary volcanic sequences. Voluminous felsic volcanism was accompanied by extensional faulting and tilting in some areas but not in others. Young mafic lava flows in some areas largely or entirely postdate tilting and faulting. In general, extensional faulting and magmatism were broadly synchronous and occurred between about 18 and 24 Ma.

Yuma Area

Magmatism. Tertiary volcanic rocks in the area north and northeast of Yuma in southwestern Arizona and directly adjacent southeastern California form the western half of the Kofa volcanic field. These rocks consist of mafic lava flows overlain primarily by compositionally diverse, 22-24 Ma felsic volcanic rocks that include locally thick, laterally extensive ash flow tuffs commonly interbedded with mafic lavas (Table 2 and Figures 2f, 11, and 12). Thick sections of tuff with associated zones of pyroclastic breccia are interpreted as products of caldera wall collapse; such accumulations have been identified in the northern part of the Arizona Chocolate and Middle Mountains [*Richard*, 1992b, also unpublished data, 1988], the northern Castle Dome Mountains [*Grubensky and Bagby*, 1990], and the Imperial Dam area along the Colorado River [*Richard*, 1992c]. Along the northern margin of the Yuma area, silicic rocks consist dominantly of lavas, associated locally derived tuff and tuffaceous sedimentary rocks, and hypabyssal intrusive rocks. Felsic volcanic rocks are overlain in a few areas by basalt and conglomerate [*Grubensky and Bagby*, 1990; *Richard et al.*, 1992; *Grubensky et al.*, 1993; *D. Sherrod*, written communication, 1993].

Extension. Conglomerate, sandstone, and sedimentary breccia up to 1.2 km thick underlie volcanic rocks along the southern margin of the volcanic field. These strata thicken southward and are bounded on the south by north dipping faults just south of the Gila River [*Olmstead,* 1972; *Lombard,* 1993; *Smith et al.*, 1989; *Pridmore and Craig,* 1982; *Pridmore,* 1983; *Mueller et al.,* 1982]. Although the quality of the data is not good, the dates from tuffs in the Laguna Mountains and from basalt west of Laguna Dam suggest deposition of coarse clastic rocks along the lower Gila River by 24 Ma and perhaps as early as about 28-30 Ma (Figure 6, cross section CC'). The tectonic setting of these rocks is uncertain, but similarity to coarse clastic rocks deposited during early stages of extension in other parts of the region suggests that they too record the onset of normal faulting. If this is the case, extension possibly began earlier in the Yuma area than elsewhere in southwestern Arizona.

Farther north in the Yuma area major tilting of Tertiary strata postdates eruption of 22-24 Ma ash flow tuffs and associated rocks. Gently dipping basalt flows in the southeastern Castle Dome Mountains, dated at 20.4 ± 0.4 Ma, are near older tuffs that dip as steeply as 57° [*Grubensky et al.*, 1993]. In the Middle Mountains and the California Chocolate Mountains, undated conglomerates conformably to unconformably overlie the volcanic rocks and dip greatly decreases up section [*Sherrod and Tosdal*, 1991; *Richard*, 1993b; *Sherrod and Hughes*, 1993].

Summary. Basin formation and deposition of coarse clastic rocks probably related to extension occurred in the southern part of the domain before 24 Ma, and perhaps as early as 28-30 Ma. The basal volcanic rocks in most stratigraphic sections are mafic, but in much of the area Tertiary stratigraphic sequences contain thick silicic ash flow tuffs and lavas erupted between 24 and 22 Ma. Major tilting and extension in areas of volcanism did not begin until after the major period of felsic volcanism, and little volcanism occurred during or after the extension event. Basalt dated at 20.4 ± 0.4 Ma in the Castle Dome Mountains appears to postdate most tilting of Tertiary strata in that range. Minor basaltic volcanism accompanied deposition of synextensional to postextensional conglomerates.

Buckskin Mountains Area

The distribution of Cenozoic rock types in the Buckskin Mountains area is strongly influenced by extreme Miocene extension that was largely accommodated by movement on the regionally northeast-dipping, Buckskin-Rawhide-Bullard detachment fault [*Spencer and Reynolds*, 1991]. Exhumed mylonitic crystalline rocks that form the Harcuvar metamorphic core complex include Tertiary intrusions. The extrusive equivalents of these intrusions, if they exist, are displaced to the northeast relative to footwall intrusions (Figure 13). Volcanism was generally less significant and extension more significant in the Buckskin Mountains area than in the other areas of southwestern Arizona.

Magmatism. The large, partially mylonitic, compositionally diverse Swansea plutonic suite in the central Buckskin Mountains is dated at 21.6 ± 1.5 Ma by the U/Pb zircon method [*Bryant and Wooden*, 1989; *Bryant*, 1992a]. The $^{40}Ar/^{39}Ar$ plateau dates from hornblende from two other locations within the Swansea plutonic suite indicate rapid cooling and probable magma emplacement ages of 29.9 Ma and 26.2 Ma [*Richard et al.*, 1990]. A granitoid pluton in the nearby Bouse Hills is dated at 20.0 ± 0.3 Ma (weighted mean of two K-Ar dates of the pluton and one of a marginal aplitic dike; Table 1 and Figure 13). A K-Ar biotite date of 16.5 ± 0.5 Ma produced in 1973 from a sample of the Bouse Hills pluton [*Shafiqullah et al.*, 1980] is inconsistent with the three dates reported in Table 1 and is disregarded.

Voluminous felsic volcanic rocks in the Buckskin Mountains area are exposed in the Bouse Hills and in the Poachie, Black, and easternmost Harcuvar Mountains. Felsic volcanism began at about 24 Ma and was largely over by about 20 Ma (Figures 13 and 14 and Table 1). The 20 Ma Bouse Hills pluton and possible related, felsic volcanic rocks in the Bouse Hills [*Spencer and Reynolds*, 1990a] represent the end of significant mid-Tertiary felsic magmatism in the Buckskin Mountains area. Widespread thin mafic lava flows are dated in three locations at 19.5-20.2 Ma. Minor mafic volcanism between about 20 and 14 Ma was followed by widespread, dominantly basaltic, bimodal volcanism [*Suneson and Lucchitta*, 1979, 1983; *Grubensky*, 1989b; *Bryant*, 1992b].

Extension. In the Artillery Mountains, which are in the upper plate of the Buckskin-Rawhide detachment fault, Proterozoic crystalline rocks are overlain by the 1-2 km thick Artillery Formation, which consists of sandstone, siltstone, limestone, basalt, conglomerate, rock avalanche deposits, and minor tuff (Figure 6, cross section DD') [*Lasky and Webber*, 1949; *Spencer et al.*, 1989a; *Yarnold*, 1994]. Basal arkosic sandstone and local pebble conglomerate contain a thin tuff, several tens of meters above the base

Table 1. K-Ar Dates

Field Number	Laboratory Number	Latitude	Longitude	Material Dated	Host Rock	K, %	$^{40}Ar_{rad}$, 10^{-10} mol/g	$^{40}Ar_{rad}$, %	Age,* m.y.
				Gila Bend Mountains					
90-WG-330	91-044	33°05.63'	112°46.52'	biotite	dacite	6.438	2.490	59.2	22.2±0.5
90-WG-302C	91-045	32°59.71'	112°45.41'	biotite	dacite	6.422	2.549	63.1	22.8±0.5
92-WG-74	92-011	33°18.12'	113°16.22'	biotite	granitoid	6.939	2.7062	83.92	22.4±0.5
DL 90-117	90-082	33°16.43'	113°17.51'	biotite	granitoid	6.411	2.567	89.1	22.9±0.5
86WAG18		33°12.9±.2'	112°57.3±.7'	hornblende	andesite	1.369	0.4817	73.0	20.2±0.3
2-6-92-5	92-013	33°15.51'	113°15.89'	biotite	gneiss	5.910	117.27	98.79	886.4±20.1
				Painted Rock Mountains					
81m281	83I197	32°59.25'	113°01.33'	biotite	tuff	5.72	1.99	36	20.0±0.6
				Clanton Hills - Cemetery Ridge					
11-6-91-2	92-014	33°16.35'	113°26.90'	biotite	tuff	6.082	2.425	86.4	22.9±0.5
2-6-92-1	92-012	33°18.22'	113°20.84'	plag. conc.	basalt	0.614	0.2121	27.44	19.8±0.6
				Little Horn Mountains					
LHG-26	90-086	33°25.76'	113°42.30'	plag. conc.	basalt of L.H. Mts.	1.028	0.3312	71.2	18.5±0.4
LHG-27	90-087	33°21.45'	113°39.01'	plag. conc.	basalt of Oakland mine	1.708	0.6217	55.9	20.9±0.5
				Eagletail Mountains					
7m9c	87I423	33°27.12'	113°23.38'	biotite	rhyolite	7.172	2.527	65	20.2±0.4
7m61b	91I033	33°26.91'	113°25.90'	biotite	rhyolite	($^{40}Ar/^{39}Ar$ total fusion)			21.8±0.4
6m141	89I581	33°24.81'	113°19.44'	biotite	rhyolite	6.716	2.503	67	21.4±0.4
7m25b	89I544	33°27.00'	113°25.16'	whole rock	bas. and.	0.410	0.1408	40	19.7±0.7
7m51c	89I545	33°23.30'	113°20.06'	whole rock	bas. and.	1.184	0.4474	53	21.7±0.6
				Little Harquahala Mountains					
12-16-88-4	89I524A	33°40.05'	113°40.87'	plag. conc.	basalt	3.084	1.04546	84.0	19.4±0.4
1-15-88-7	89I479A	33°39.42'	113°39.26'	biotite	tuff	7.131	2.67436	64.8	21.5±0.5
1-15-88-7	89I525B	33°39.42'	113°39.26'	feld. conc.	tuff	4.757	1.62850	82.1	19.6±0.4
				Plomosa Mountains					
12-2-90-1	91-043	33°56.89'	114°03.77'	plag. conc.	bas. and.	3.425	1.210	75.9	20.3±0.5
				Bouse Hills					
2-10-85-1	85I494	33°56.07'	113°55.00'	whole rock	basalt	1.1196	0.38053	46.1	19.5±0.3
12-14-88-4	89I489A	33°59.24'	113°54.05'	biotite	dike	6.899	2.37219	59.1	19.7±0.5
12-12-88-5	89I485A	33°55.27'	113°50.92'	biotite	granite	7.239	2.52293	56.4	20.0±0.6
12-14-88-3	89I502A	33°59.88'	113°50.75'	biotite	granite	7.297	2.56823	60.6	20.2±0.5
12-6-84-3	89I522A	33°55.93'	113°55.28'	biotite	tuff	6.923	2.59234	70.9	21.5±0.5
12-6-84-3	89I501A	33°55.93'	113°55.28'	hornblende	tuff	1.159	0.37258	63.4	18.4±0.5
853-11-2	86I076	33°57.37'	113°58.82'	biotite	tuff	7.155	2.80960	49.4	22.5±0.7
853-11-1	86I074	33°57.48'	113°58.75'	biotite	tuff	6.742	2.82649	56.0	24.0±0.7
				Harcuvar Mountains					
11-6-89-1	90-085	34°00.93'	113°06.88'	biotite	tuff	6.261	2.672	78.5	24.4±0.6

Table 1. (continued)

Field Number	Laboratory Number	Latitude	Longitude	Material Dated	Host Rock	K, %	$^{40}Ar_{rad}$, 10^{-10} mol/g	$^{40}Ar_{rad}$, %	Age,* m.y.
				Buckskin Mountains					
BK-DUN	90I243	34°10.88'	114°13.81'	plag. conc.	basalt	2.006	0.34825	63.9	10.0±0.3
BK-IL	90I237	34°11.13'	114°13.74'	plag. conc.	basalt	1.046	0.25159	64.5	13.8±0.4
BK-HL	90I236	34°11.13'	114°13.74'	plag. conc.	basalt	1.125	0.27964	44.5	14.3±0.5
10-28-88-1	89I484A	34°09.99'	113°53.45'	biotite	tuff	6.176	2.49977	67.6	23.2±0.5
				Artillery Mountains					
11-5-88-2	89I523A	34°21.32'	113°33.79'	biotite	tuff	6.774	3.59456	63.6	30.3±0.8
11-5-88-3	89I488A	34°21.47'	113°33.26'	biotite	tuff	6.724	3.95134	66.4	33.6±0.8
5m11	85I722	34°21.52'	113°33.40'	biotite	tuff	7.056	2.828	49	23.0±0.7
5m12	85I446	34°20.13'	113°30.92'	biotite	rhyodacite	6.80	2.403	43	20.3±0.7
9005-2501	90-084	34°18.48'	113°35.14'	plag. conc.	Cobwebb basalt	1.797	0.3472	62.4	11.1±0.3
				Black Mountains - Santa Maria River Area					
WEB169-78	81570	34°19.20'	113°12.66'	biotite	rhyodacite	4.566	1.97150	57.5	24.7±0.2
WEB100-77	81571	34°19.55'	113°05.62'	whole rock	basalt	0.50	0.102447	17.9	11.8±0.6
				Vulture and Wickenburg Mountains					
VG-425	89-103	33°56.21'	112°47.92'	feldspar	rhyolite	4.217	1.2170	49.4	16.6±0.4
VG-432	89-102	33°55.03'	112°53.3'	feld. conc.	dike	3.059	0.9312	60.2	17.5±0.3
VG-409	89-104	33°56.45'	112°47.36'	feldspar	rhyolite	4.943	1.6542	87.0	19.2±0.4
VG-410	89-101	33°56.15'	112°47.9'	feld. conc.	bas. and.	2.405	0.8332	55.0	19.9±0.5
VG-431	90-088	33°53.72'	112°52.11'	sanidine	dike	4.926	1.674	66.5	19.5±0.5
VG-436	90-089	33°56.12'	112°43.31'	sanidine	rhyolite	4.375	1.545	90.3	20.3±0.5
J-78	87-183	33°53.50'	112°39.67'	plag. conc.	basalt	1.185	0.2993	33.8	14.5±0.4
				Hieroglyphic Mountains					
H-70	86-92	33°51.40'	112°14.96'	plag. conc.	basalt	0.985	0.27755	49.8	16.2±0.5
H-68	86-93	33°54.91'	112°19.55'	biotite	latite	6.917	2.096	70.6	17.4±0.6
H-69	86-94	33°51.44'	112°20.25'	feldspar	rhyolite	3.745	2.354	87.2	35.9±0.8
				Big Horn Mountains					
BH-89	85I493	33°41.44'	113°05.68'	plag. conc.	basalt	1.371	0.3851	68.9	16.1±0.2
BHC-211	85I495	33°38.26'	112°54.83'	feldspar	rhyolite	3.312	0.9464	62.7	16.4±0.2
BHC-211	85I496	33°38.26'	112°54.83'	feldspar	rhyolite	3.312	0.9620	67.9	16.7±0.2
BHC-215	85I479	33°44.59'	113°01.88'	biotite	rhyodacite	6.324	2.1612	41.6	19.6±0.2
BHC-212	85I481	33°39.26'	113°05.03'	biotite	rhyolite	6.779	2.3970	52.2	20.3±0.2
BHC-213	85I480	33°43.28'	113°05.31'	biotite	rhyolite	6.212	2.3184	47.1	21.4±0.3
853-26-1A	85I488	33°46.14'	113°03.00'	biotite	granodio.	5.060	6.3324	70.2	70.8±0.5

Error in calculated age determined by method of *Cox and Dalrymple* [1967], assuming a standard deviation of 0.3% for tracer calibration. Error in potassium analysis is either sample standard deviation or 0.5%, whichever is greater. Potassium was measured by flame photometry with a lithium internal standard. Samples with hyphenated laboratory numbers were analyzed at the University of Arizona by M. Shafiqullah. Samples from Black Mountains-Santa Maria River area, incompletely reported by *Brooks* [1985], are reported here (data provided by N. Suneson). All other samples were analyzed at the U.S. Geological Survey in Menlo Park, California, by R.J. Miller or, for dates with "85I" laboratory number from Bouse Hills and Big Horn Mountains, by J.E. Spencer. plag. conc., plagioclase concentrate; L.H. Mts., Little Horn Mountains; Oak., Oakland; feld. conc., feldspar concentrate; bas. and., basaltic andesite; granodio., granodiorite.

* Age calculation based on decay and abundance constants from *Steiger and Jager* [1977].

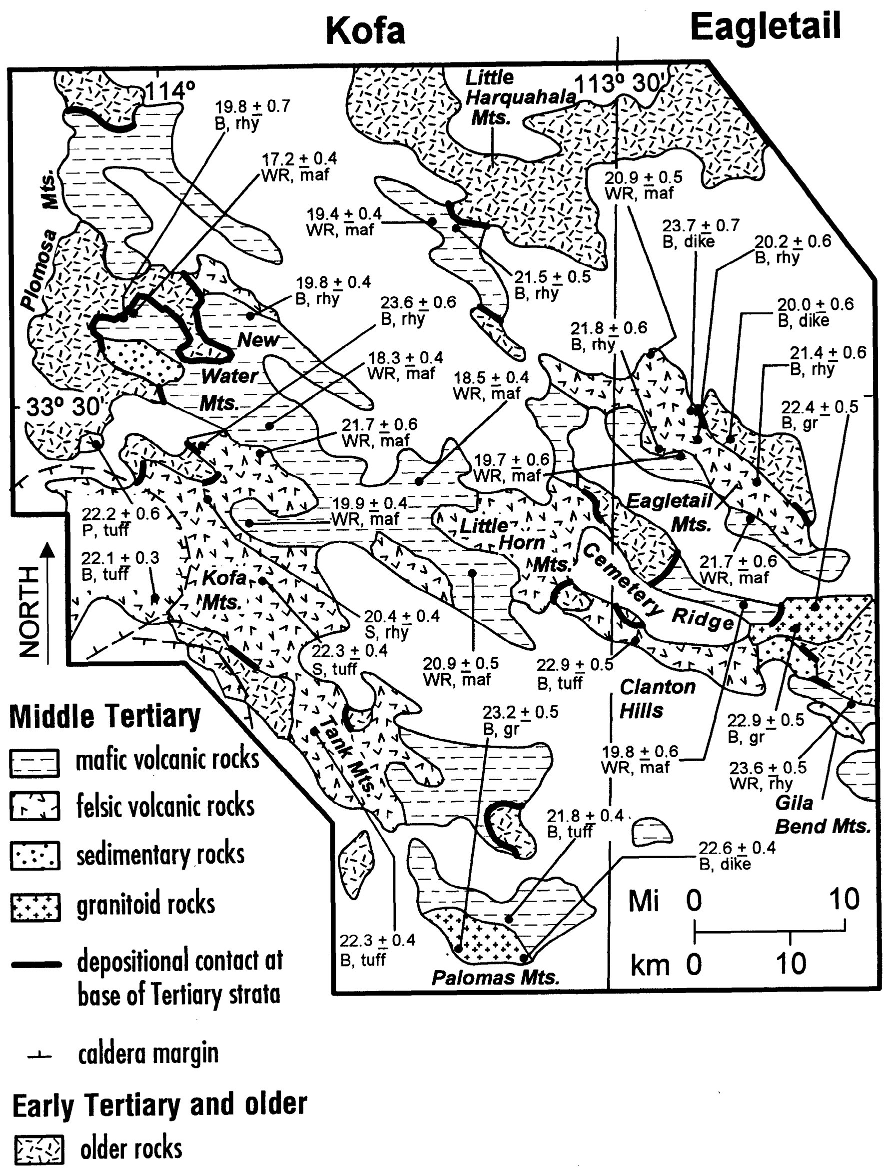
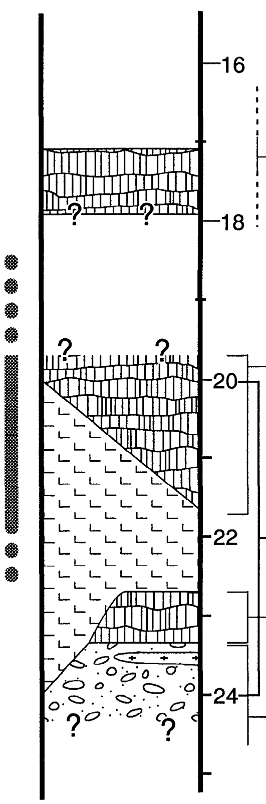


Figure 9. Simplified geologic map of the Kofa-Eagletail mountains area showing K-Ar dates and locations. K-Ar data are from *Miller and McKee* [1971], *Scarborough and Wilt* [1979], *Shafiqullah et al.* [1980], *Bagby et al.* [1987], and Table 1. Date of 19.8±0.7 Ma from felsic lava flows in the southern Plomosa Mountains is error-weighted mean of three dates from *Shafiqullah et al.* [1980] and *Miller and McKee* [1971]. Figure 2d represents dates within "Eagletail" map area that are east of 113°30'W, whereas dates in the "Kofa" map area to the west are represented in Figure 2e.

of the formation, that yielded concordant $^{40}Ar/^{39}Ar$ biotite and sanidine dates with a weighted mean of 26.4±0.2 Ma [*Lucchitta and Suneson*, 1993]. Three K-Ar dates of biotite from this tuff, 23.0, 30.3, and 33.6 Ma (Table 1), are inconsistent with each other and with the concordant $^{40}Ar/^{39}Ar$ biotite and sanidine dates and are considered to be unreliable, possibly because of alteration or the presence of xenocrystic biotite. The Artillery Formation is intruded by the Santa Maria Peak felsite that yielded a biotite K-Ar date of 20.3±0.7 Ma (Table 1). About half of the 40° of tilting that affected the lowermost Artillery Formation (uppermost beds dip ≈20°) occurred during deposition of the Formation [*Spencer et al.*, 1989a, Figure 6]. Basin genesis and syndepositional tilting are interpreted as products of extensional faulting that was underway at 20-27 Ma. Elsewhere, clastic sediments that indicate basin genesis and rock avalanche deposits that indicate probable normal fault scarps are interbedded with tuffs in the Buckskin Mountains (22-23 Ma; Figure 6, cross section EE'), Bouse Hills (22-24 Ma; Figure 6, cross section FF'), Harcuvar Mountains (24 Ma), and northern Plomosa Mountains (>20 Ma).

After the end of significant synextension felsic magmatism at about 20 Ma, faulting and tilting continued in rocks above the Buckskin-Rawhide detachment fault but ended in the Bouse Hills (Figure 6, cross section FF') which are in the footwall of that fault. Mafic lava flows and red sandstone, locally with conglomerate and lacustrine rocks, were deposited during post-20 Ma extension in the Buckskin, Rawhide, and Artillery Mountains [*Spencer and Reynolds*, 1989b]. Included in this group of rocks are moderately



Mesa-forming basalts in the central Gila Bend Mountains [*Gilbert and Skotnicki*, 1993], southern Plomosa Mountains (17.2 Ma basalt of Black Mesa) [*Miller*, 1970; *Richard et al.*, 1993], basalt of Oakland Mine in the Little Horn Mountains [*Grubensky and Demsey*, 1991], and young basalts in the Tank and Palomas Mountains [*Skotnicki and Ferguson*, 1994; *Ferguson et al.*, 1994].

Mafic flows (19.7-21.7 Ma) in the southwestern Eagletail Mountains [*Spencer et al.*, 1992, 1993; *Gilbert et al.*, 1992], basalt of Little Horn Mountains (which is overlain by the rhyolite of Nottbusch Valley) [*Grubensky and Demsey*, 1991], basalt in eastern Cemetery Ridge (19.8 Ma) [*Gilbert et al.*, 1992], mafic flows in the southwestern Little Harquahala Mountains (19.4 Ma) [*Spencer et al.*, 1985].

Tilting and faulting occurred largely during late felsic magmatism and ealy mafic magmatism

Rhyolitic flows, bedded pyroclastic rocks, breccias, dikes, and probable domes in the Eagletail Mountains (20-24 Ma) [*Spencer et al.*, 1992, 1993], basal rhyolite in the Little Harquahala Mountains (21.5 Ma) [*Spencer et al.*, 1985], volcanic rocks of Royal Arch in the Little Horn Mountains [*Grubensky and Demsey*, 1991], compositionally diverse felsic volcanic rocks in the Plomosa Mountains (20 Ma) [*Miller*, 1970; *Richard et al.*, 1993], New Water Mountains (20 Ma) [*Sherrod et al.*, 1990; *Richard and Spencer*, 1994], and Kofa and Tank Mountains (20-24 Ma), including the tuff of Yaqui Tanks and the 22.2 Ma tuff of Ten Ewe Mountain, which are associated with genesis of two inferred calderas [*Bagby et al.*, 1987; *Grubensky and Bagby*, 1990; *Ferguson et al.*, 1994].

Mafic flows that are thick and areally extensive in the central Gila Bend Mountains [*Gilbert and Skotnicki*, 1993], moderately thick in the western Gila Bend Mountains [*Gilbert et al.*, 1992], and thin in the eastern Eagletail Mountains [*Spencer et al.*, 1992] and Clanton Hills [*Gilbert and Spencer*, 1992]. Mafic flows are interbedded with underlying conglomerate in the western Gila Bend Mountains [*Gilbert et al.*, 1992].

Conglomerate and sandstone in the western Gila Bend [*Gilbert et al.*, 1992; *Gilbert and Skotnicki*, 1993], southern Plomosa [*Richard et al*,. 1993], and New Water Mountains [*Richard and Spencer*, 1994] and rock-avalanche deposits in the northeastern Eagletail Mountains [*Spencer et al.*, 1993]. Includes 23.6 Ma interbedded tuff in the western Gila Bend Mountains.

Figure 10. Simplified stratigraphy of the Kofa-Eagletail area (eastern half of the Kofa volcanic field).

tilted basalt dated at 16.0±0.5 Ma (weighted mean of two dates) and interbedded conglomerate in the southeastern Bill Williams Mountains, directly north of the northwestern Buckskin Mountains [*Spencer et al.*, 1989b, c].

Normal faulting ended by 14 Ma in the westernmost Buckskin Mountains where moderately to steeply tilted Tertiary strata are overlain by a flat-lying basalt and fanglomerate dated at 14.0±0.4 Ma (weighted mean of two dates: 13.8±0.4 Ma and 14.3±0.5 Ma; Table 1 and Figure 6, cross section GG'). Faulting apparently continued after this time farther east; feldspar concentrate from the faulted and tilted Cobwebb Basalt in the Artillery Mountains, consisting of fresh plagioclase microlites, less abundant, somewhat altered plagioclase phenocrysts, and groundmass, is dated at 11.1±0.3 Ma (Table 1; this date may be too young due to alteration). The Cobwebb Basalt is overlain by the Sandtrap Conglomerate which contains abundant clasts of mylonitic and chloritic rock derived from the footwall block of the detachment fault and records subareal exposure and continued exhumation of mylonitic footwall rocks. Correlative conglomerate is exposed in klippen in the eastern Buckskin and Rawhide Mountains. In the Artillery Mountains this conglomerate decreases in dip upsection and is nearly flat lying at high stratigraphic levels where it is interbedded with the 9.5 Ma Manganese Mesa basalt (Figure 6, cross section DD').

The chronology of denudational faulting in the Harcuvar complex is also constrained by several thermochronologic studies of lower plate rocks that cooled rapidly as they were exhumed. Biotite from the lower plate in the central and eastern Buckskin Mountains yielded K-Ar dates of 14.8±0.3 Ma and 15.1±0.2 Ma [*Spencer et al.*, 1989c]. A sample from the eastern Buckskin Mountains yielded a biotite $^{40}Ar/^{39}Ar$ total fusion age of 12.7±0.3 Ma [*Bryant et al.*, 1991]. K-feldspar from the same sample yielded an $^{40}Ar/^{39}Ar$ cooling age of 14.0±0.2 Ma for cooling through the lower part of the closure temperature range (mean age calculated from six low-temperature heating steps that yielded 45% of total gas; calculated from data from sample 18 of *Bryant et al.* [1991]). Six of ten fission track zircon dates from samples of lower plate rocks in the eastern Buckskin, Rawhide, and Harcuvar Mountains range from

Table 2. Summary of $^{40}Ar/^{39}Ar$ Dates From Volcanic Rocks in the Yuma Area

Sample ID	Sample Location (Latitude, Longitude)	Mineral Dated, Rock Unit	Mean Age, Ma	N*	Percent of Gas	Isochron Age, Ma	Steps	Initial Ratio
03-25-90-01	33° 13.33', 114° 28.02'	sanidine, lithic tuff	24.1±0.1	7	N/A	24.4±0.1†	All	183±46
03-30-90-09	33° 10.52', 114° 24.97'	sanidine, welded tuff	23.4±0.1	10	N/A	23.3±0.4†	All	297±7
03-90-90-09	33° 10.52', 114° 24.97'	hornblende, welded tuff	22.3±0.1	all	100	22.1±0.1†	All	308±9
04-25-90-04	32° 55.8', 114° 34.4'	plagioclase, near base, ignimbrite of Ferguson Wash	22.7‡	N/A	100	21.6±0.3	3-8	416±25
04-26-90-04	32° 55.2', 114° 30.7'	sanidine, near top, ignimbrite of Ferguson Wash	22.7±0.1	13	N/A	22.6±0.1†	All	317±21
04-26-90-04	32° 55.2', 114° 30.7'	hornblende, near top, ignimbrite of Ferguson Wash	22.2±0.1	2-8	98.6	21.9±0.1†	2-8	315±7

*Number of laser total fusion analyses for sanidine, or steps included in calculated mean age for samples analyzed by step heating in resistance furnace.

† Isochron age concordant with mean age.

‡ Total gas age; error estimate meaningless.

11.1 to 13.8 Ma (2σ ranges from 1.0 to 2.8 Ma) [*Bryant et al.*, 1991]. Two samples from the eastern Buckskin Mountains yielded apatite fission track ages of 13 ± 2 Ma, and one sample from the eastern Harcuvar Mountains yielded an apatite fission track age of 14 ± 2 Ma [*Foster et al.*, 1993].

Fission track apatite data from the lower plate of the Plomosa detachment fault in the northern Plomosa Mountains suggest that rapid cooling related to denudational faulting continued there until approximately 15-16 Ma (dates of 15 ± 3 and 16 ± 2 Ma from the most deeply denuded part of the lower plate [*Foster and Spencer*, 1992]).

Tilting related to normal faulting had ended by 14 Ma in the westernmost Buckskin Mountains, but rapid cooling through argon closure temperatures in biotite and feldspar and fission track annealing temperatures in zircon and apatite occurred in the eastern Buckskin, Rawhide, and Harcuvar Mountains between 15 and approximately 11 Ma. This cooling is not related to igneous activity because very little magmatism occurred in the Harcuvar complex after about 19 Ma except for postextension basalt flows at the north flank of the complex that are mostly 9-13 Ma [e.g., *Suneson and Lucchitta*, 1979]. Erosional denudation is also not a viable mechanism for this cooling because the postextension basalt flows were deposited on a land surface that is at about the same elevation as the modern land surface and is at elevations below exposures of lower plate rocks in many areas [*Spencer and Reynolds*, 1991, Figure 11]. Denudational faulting along the Buckskin-Rawhide-Bullard detachment fault on the northeast flank of the Harcuvar complex is thus the only viable mechanism for rapid cooling at 15-11 Ma.

Summary. Evidence for magmatism before 25 Ma in the Buckskin Mountains area is limited to a thin tuff in the Artillery Mountains dated at 26.4 ± 0.2 Ma and two $^{40}Ar/^{39}Ar$ hornblende plateau dates of 26.2 and 29.9 Ma from the Swansea plutonic suite. The $^{40}Ar/^{39}Ar$ dates are inconsistent with the U/Pb zircon date of 21.6 ± 0.5 Ma from the Swansea plutonic suite, but it is possible that different phases of the suite were intruded over a period of 8-10 Ma. In any case, major felsic magmatism occurred between 25 and 20 Ma over a broad area. Minor mafic volcanism occurred between about 22 and 14 Ma and was followed by largely posttilting basaltic and minor rhyolitic volcanism at 13-9 Ma.

Basins that are interpreted as products of extensional faulting began to form at about 27-24 Ma and by 20 Ma had received thick accumulations of sedimentary and volcanic rocks, including rock avalanche deposits, in the Buckskin,

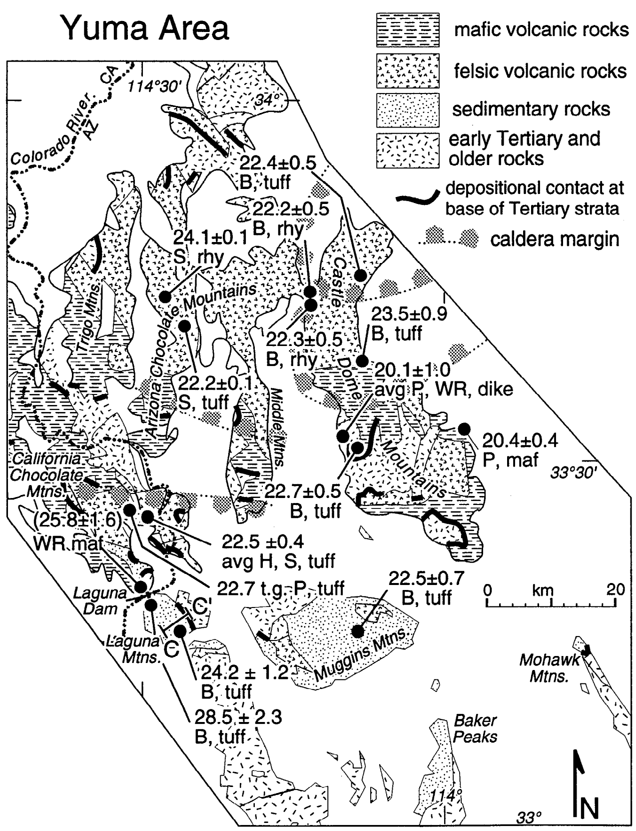


Figure 11. Simplified geologic map of Yuma area showing K-Ar and $^{40}Ar/^{39}Ar$ dates and locations. K-Ar data from *Damon et al.* [1965], *Shafiqullah et al.* [1980], *Gutmann* [1981], *Bagby et al.* [1987], and *Smith et al.* [1989]. The $^{40}Ar/^{39}Ar$ data are from Table 2. Dates with errors greater than 1 m.y. in the southern part of this area were included because no other data are available to constrain the age of these sections.

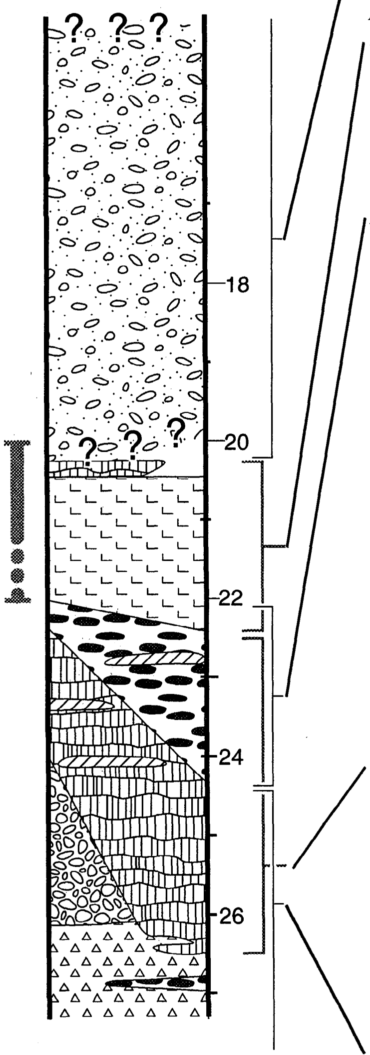


Figure 12. Simplified stratigraphy of the Yuma area (western half of the Kofa volcanic field).

Rawhide, and Artillery Mountains and in the Bouse Hills. By 20 Ma, major tilting had occurred in the Bouse Hills and was underway in the Artillery Mountains. Dated rocks as young as 16 Ma are tilted in the southeastern Bill Williams Mountains. Cooling of mylonitic crystalline rocks in the eastern Buckskin, Rawhide, and Harcuvar Mountains through approximately 300°-100°C occurred at 15-11 Ma and, along with mylonitic debris shed into an active, extensional basin, is interpreted as a consequence of continued exhumation by detachment faulting.

Vulture Mountains Area

Magmatism. Volcanic rocks in the Vulture Mountains area are divisible into the Big Horn, Vulture, and Heiroglyphic volcanic fields (Figure 15) [*Capps et al.*, 1985, 1986; *Kortemeier et al.*, 1986; *Stimac et al.*, 1987; *Grubensky et al.*, 1987; *Grubensky*, 1989a; *Richard*, 1993a]. Volcanic rocks in all three volcanic fields are lithologically similar and are roughly divisible into three major units (Figure 16). (1) Lower mafic lava flows, typically 0-300 m in total thickness, include flows that are commonly interbedded with overlying felsic rocks in the Big Horn Mountains (Tertiary sedimentary rocks are thin or absent at the base of volcanic rock sequences). (2) Overlying felsic flows and massive and bedded pyroclastic rocks, typically 100-1000 m thick, form most of the prominent outcrops and landforms in the ranges. The felsic rocks include the Hells Gate latite in the Heiroglyphic Mountains. (3) Upper basalt is interbedded with rock avalanche deposits, debris flows, and fanglomerate.

Nine of 13 K-Ar dates of rhyolitic and latitic rocks from

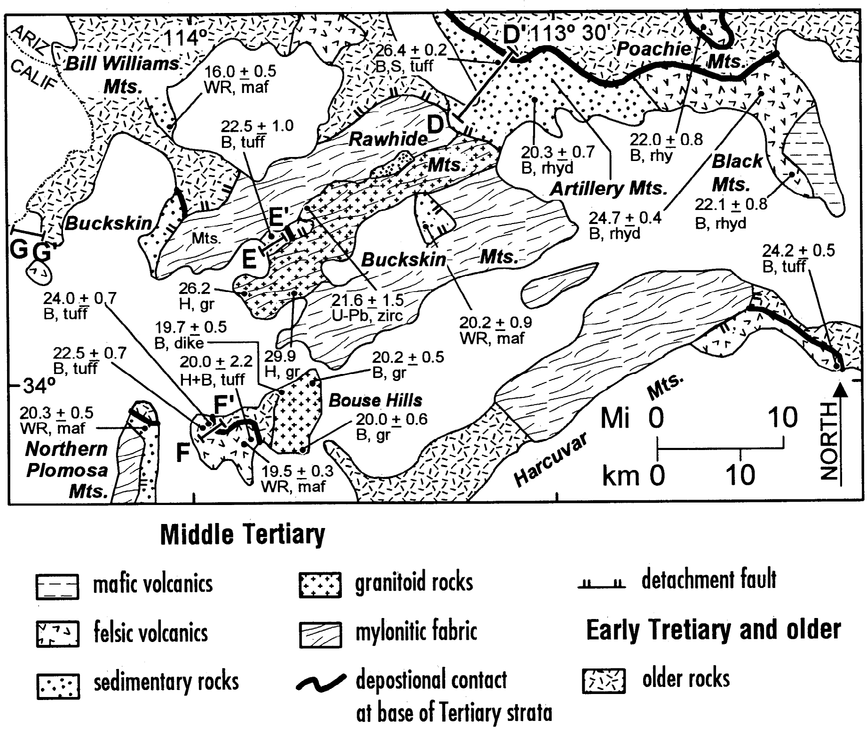


Figure 13. Simplified geologic map of the Buckskin Mountains area showing K-Ar, $^{40}Ar/^{39}Ar$, and U-Pb dates and locations. Geochronologic data from *Brooks* [1985], *Marvin et al.* [1988], *Bryant and Wooden* [1989], *Spencer et al.* [1989c], *Lucchitta and Suneson* [1993], and Table 1. Dates younger than 15 Ma are not plotted.

the middle, felsic part of the volcanic sequences in the three volcanic fields range from 17.4±0.6 Ma to 20.3±0.5 Ma. These 13 dates include seven K-Ar dates from the Vulture Mountains, five of which are within this range, three dates from the Heiroglyphic Mountains, two of which are in this range (Hells Gate latite), and three dates from the Big Horn Mountains, two of which are in this range (Table 1) [*Scarborough and Wilt*, 1979; *Rehrig et al.*, 1980; *Shafiqullah et al.*, 1980]. Dates considered to be unreliable are as follows: A feldspar K-Ar date of 16.6±0.4 from rhyolitic rocks in the Vulture Mountains is probably spurious; the sampled rhyolite directly overlies basalt dated at 19.9±0.4 Ma and is overlain by a thick sequence of rhyolite that, several hundred meters up section, is dated at 19.2±0.4 Ma (Table 1) [*Grubensky*, 1989a]. A biotite K-Ar date of 26.0±0.6 Ma [*Rehrig et al.*, 1980] from the base of the correlative rhyolitic sequence in the adjacent tilt block to the west is also probably erroneous. A biotite K-Ar date of 35.9±0.8 Ma from the stratigraphically lowest rhyolite in the eastern Heiroglyphic Mountains is so different from any other date in the region that it is thought to be spurious (Table 1). A biotite K-Ar date of 21.4±0.3 Ma from a rhyolite in the Big Horn Mountains is also suspected to be slightly too old because the dated rhyolite is stratigraphically above rhyolitic volcanic rocks dated at 20.3±0.2 Ma and 19.6±0.2 Ma (Table 1).

Two granitoid intrusions are probably components of main phase felsic magmatism. A biotite K-Ar date of 19.6±0.5 Ma [*Shafiqullah et al.*, 1980] from a granodiorite in the White Tank Mountains [*Reynolds and Grubensky*, 1993] probably reflects the approximate emplacement age of the granitoid but could reflect cooling due to exhumation by detachment faulting that is younger than granitoid emplacement. A granite in the Belmont Mountains yielded an early Miocene Rb/Sr model age (Tables 3 and 4 and Figure 15).

Nine K-Ar dates of basaltic lavas from all three volcanic fields in the Vulture Mountains area range from 16.6±0.4 Ma to 13.5±0.3 Ma and reflect the age of youngest magmatism. A sequence of gently to moderately tilted basalts and sedimentary rocks overlie pre-Tertiary basement in the western Vulture Mountains [*Grubensky*, 1989a]. Basalt near the base of the sequence has been dated at 20.0±0.4 Ma, and a basalt at the top has been dated at 15.6±0.4 Ma [*Scarborough and Wilt*, 1979]. The age of the youngest basalt is similar to dates from the youngest basalts in surrounding areas. If the older date is accurate, it reflects the age of early mafic volcanism that generally predates felsic volcanism.

Extension. The central and eastern Vulture Mountains and western Heiroglyphic Mountains are perhaps the most severely extended tilt block array in Arizona. Numerous, moderately to gently southwest dipping normal faults cut and displace moderately to steeply northeast dipping Tertiary stratigraphic sequences and underlying pre-Tertiary crystalline rocks [*Rehrig et al.*, 1980; *Stimac et al.*, 1987; *Grubensky et al.*, 1987; *Grubensky*, 1989a]. Locally, beds are vertical or overturned, and some normal faults are so tilted by younger, crosscutting normal faults that they have apparent reverse displacement. Conglomerate and interbedded basalt at uppermost levels in the mid-Tertiary stratigraphic sequences commonly have fanning dips so that stratigraphically higher beds dip less steeply than lower

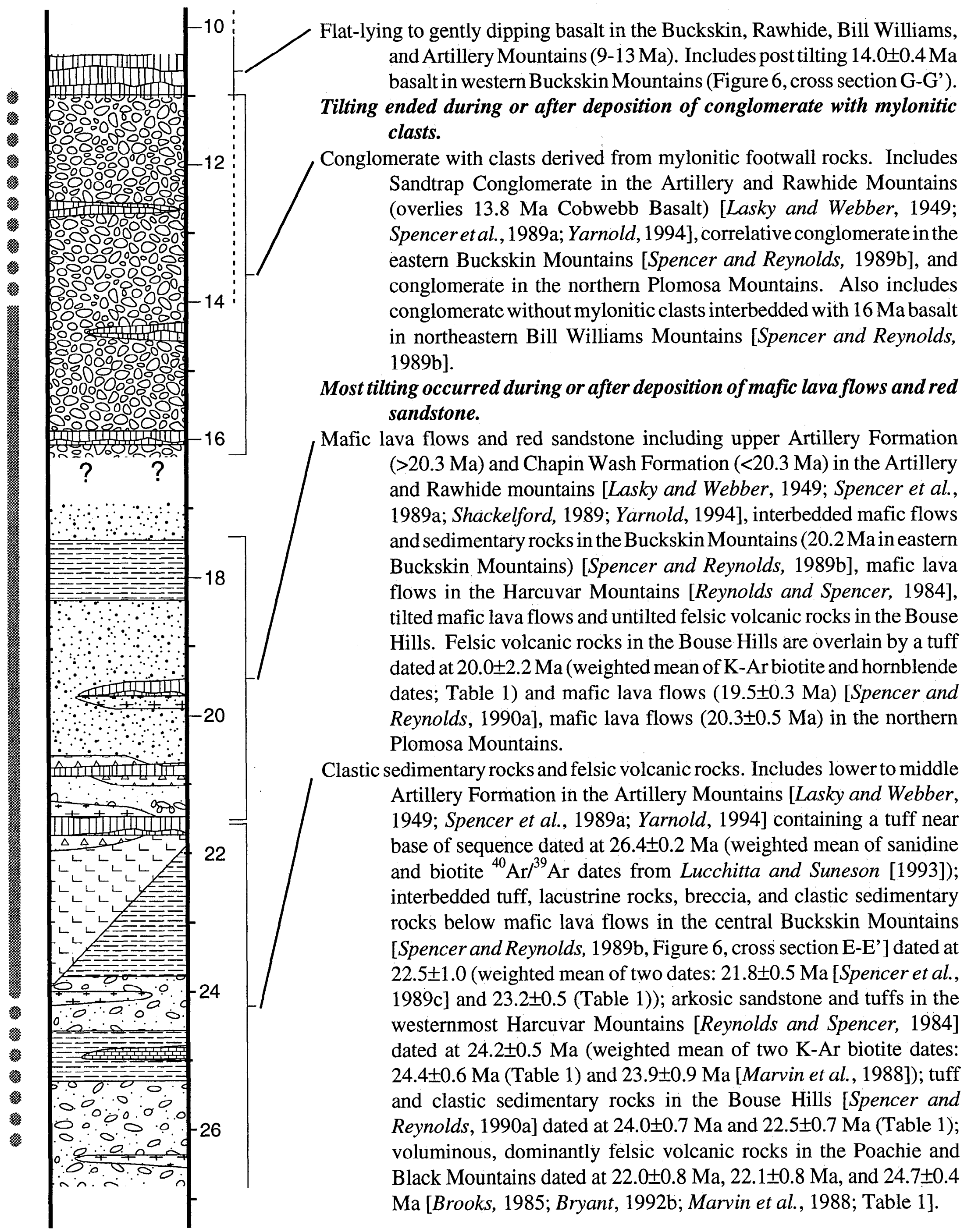


Figure 14. Simplified stratigraphy of the Buckskin Mountains area.

beds. Fanning dip sequences were likely deposited in half grabens during faulting, and debris flows and rock avalanche deposits that form part of these sequences are interpreted as indicative of active basin tilting and faulting at the margins of the basins [e.g., *Dickinson*, 1991, Figure 28].

A basalt flow dated at 14.5±0.4 Ma (Table 1) in the western Heiroglyphic Mountains overlies debris flows that dip 30°-40° and is overlain by fanglomerate that dips approximately 10° [*Grubensky et al.*, 1987]. Approximately 5 km to the northeast in the adjacent tilt block, probably correlative basalt and overlying fanglomerate dip 25°-55° and are cut by normal faults (Figure 6, cross section HH') [*Stimac et al.*, 1987]. Approximately 10 km to the north of the dated basalt, similar basalt and overlying fanglomerate are tilted 40° at one location and are vertical in another [*Grubensky et al.*, 1987]. Similar basalt about 10 km to the southwest in the Vulture Mountains dips 20° [*Grubensky*, 1989a] and is dated at 14.5±0.2 Ma [*Shafiqullah et al.*, 1980]. Basalt in the northern Vulture Mountains dated at 13.5±0.3 Ma locally dips approximately 13° [*Rehrig et al.*, 1980] but is regionally distributed as if it were untilted [*Reynolds and Grubensky*, 1993]. These K-Ar dates and field relationships indicate that tilting was underway at 15-14 Ma and ended at about 14-13 Ma.

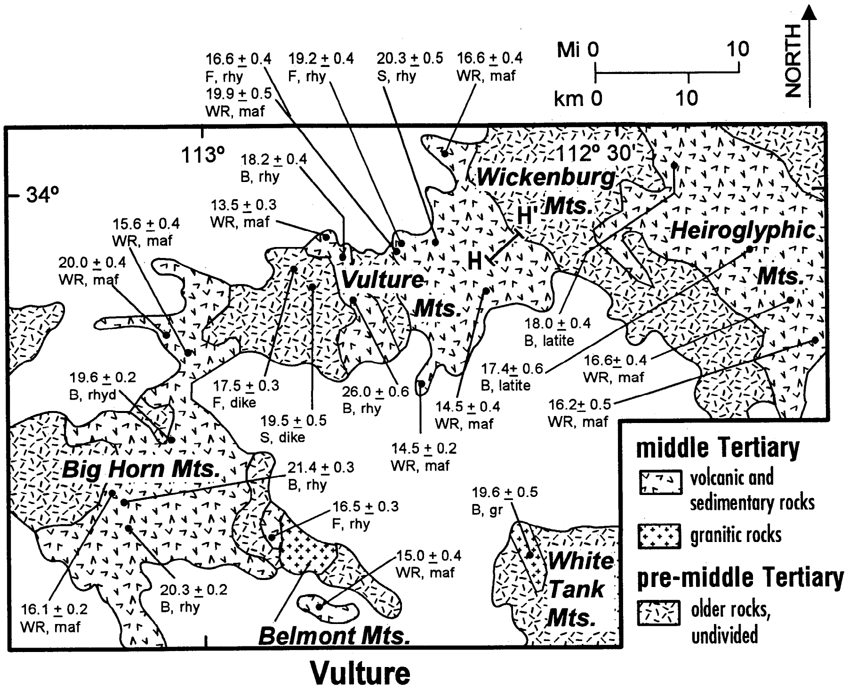
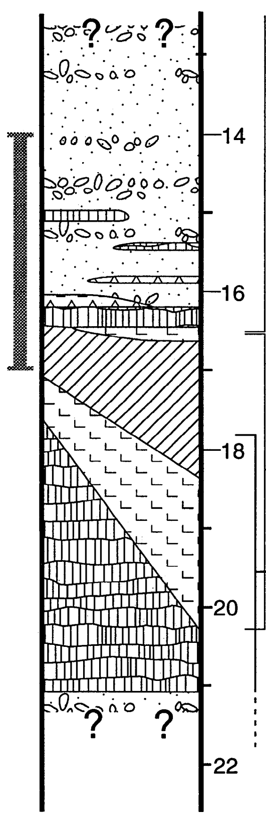


Figure 15. Simplified geologic map of the Vulture Mountains area showing K-Ar dates and locations. K-Ar data from *Scarborough and Wilt* [1979], *Rehrig et al.* [1980], *Shafiqullah et al.* [1980], and Table 1. Due to complex and intense faulting and tilting, Tertiary rocks are not divided into mafic and felsic components and depositional contacts at base of Tertiary sequences are not shown.



Basalt and interbedded fanglomerate, debris flows, and rock avalanche deposits (9 K-Ar dates of 13.5-16.6 Ma). Includes the 16.5±0.3 Ma Beer Bottle rhyolite and the mostly andesitic Burnt Mountain volcanics in the Big Horn Mountains (Table 1; *Capps et al.* [1985]; *Stimac et al., 1994*). K-Ar dates include four from the Vulture volcanic field (13.5-16.6 Ma) and two from the Heiroglyphic Mountains (16.6±0.4 Ma and 16.2±0.5 Ma; Table 1; *Shafiqullah et al.* [1980]; *Rehrig et al.* [1980]; *Scarborough and Wilt* [1979]). Three dates from basalts at or near the stratigraphic top of Big Horn volcanic field range from 16.1±0.2 Ma to 15.0±0.4 Ma (Table 1; *Scarborough and Wilt* [1979]; *Shafiqullah et al.* [1980]).

Tilting occurred after felsic magmatism and during deposition of overlying basalt and clastic rocks at 14-17 Ma.

Felsic, massive to bedded lava flows and pyroclastic rocks, typically 100 to 1000 meters thick (17.4-20.3 Ma). Includes interbedded mafic lava flows of the Dead Horse volcanics in the Big Horn Mountains and the Hells Gate latite in the Heiroglyphic Mountains.

Mafic lava flows in the Heiroglyphic Mountains (up to 300 m thick), Vulture Mountains (0-150 m thick), and sparse flows in the Big Horn Mountains [*Capps et al.*, 1985, 1986; *Kortemeier et al.*, 1986; *Stimac et al.*, 1987; *Grubensky et al.*, 1987; *Grubensky*, 1989a; *Richard*, 1993a].

Figure 16. Simplified stratigraphy of the Vulture Mountains area.

Table 3. Rb/Sr Data for Belmont Granite

	Value
Rb ppm	174.6
Sr ppm	5.69
$^{87}Rb/^{86}Sr$	88.93
$^{87}Sr/^{86}Sr$	0.73368

Sample of Belmont granite, sample number UAKA 85-405. Sample location 33° 38'N, 112° 53'W, Belmont Mountains, Maricopa County, Arizona. Uncertainties are not reported.

The basal mafic and middle felsic parts of the mid-Tertiary stratigraphic sequence in the eastern Heiroglyphic Mountains typically dip 30°-60° to the northeast. Dips of overlying basalts and interbedded conglomerate and rock avalanche deposits are typically less and in some areas are progressively less up section [*Capps et al.*, 1986]. A basalt flow dated at 16.6±0.4 Ma dips 20°-30° [*Scarborough and Wilt*, 1979], and a flow dated at 16.2±0.5 (Table 1) is subhorizontal. Basalt that is apparently correlative with the 16.2 Ma basalt, located approximately 2 km to the northeast of the dated sample area, dips 20° and is cut by normal faults [*Reynolds and Grubensky*, 1993]. Farther east (outside the are of Figure 15), at the Black Canyon Shooting Range, sedimentary rocks and capping basalt dated at 15.4±0.4 Ma dip 25° to the northeast [*Scarborough and Wilt*, 1979; *Jagiello*, 1987]. Approximately 10 km northeast of this location at Pyramid Peak, mafic volcanic rocks dipping 20°-25° to the northeast are dated at 17.7±0.4 Ma [*Scarborough and Wilt*, 1979; *Reynolds and Grubensky*, 1993]. These K-Ar dates and field relationships indicate that tilting was underway at 17-15 Ma and ended at about 15 Ma.

Moderately to steeply tilted, dominantly felsic volcanic rocks in the Big Horn Mountains have yielded K-Ar dates as young as 18.5±0.6 Ma (R. Miller, unpublished data, 1991) and are unconformably overlain by slightly to moderately tilted and faulted Beer Bottle rhyolite [*Capps et al.*, 1985] that is dated at 16.5±0.3 (weighted mean of two dates; Table 1). Slightly tilted, stratigraphically higher basalts are dated at 16.1±0.2 Ma (Table 1). The gently dipping Hot Rock basalt at the southern edge of the Big Horn Mountains is dated at 15.0±0.4 Ma. These K-Ar dates and field relationships indicate that tilting began after about 18.5 Ma, was underway at 16-18 Ma, and ended at about 15-16 Ma.

Summary. Voluminous, dominantly felsic volcanism occurred in the Vulture Mountains area at approximately 17-20 Ma. Igneous rocks related to this magmatic epoch include typically hundreds of meters of rhyolitic flows, pyroclastic rocks, and shallow level intrusions in three volcanic fields. Two granitoids are also suspected to be representative of this magmatic epoch. Mafic volcanic rocks underlie the felsic volcanic rocks in the Vulture and eastern Heiroglyphic volcanic fields and are extensively interbedded with felsic volcanic rocks in the Big Horn Mountains. Basaltic volcanism followed felsic magmatism, occurred at approximately 14-17, and was accompanied by generally moderate to extreme normal faulting and tilting.

South Mountains Area

The South Mountains metamorphic core complex, located on the south flank of the Phoenix metropolitan area (Figure 1), consist of Proterozoic crystalline rocks intruded by Tertiary granite and granodiorite in the eastern half of the range [*Reynolds and Rehrig*, 1980; *Reynolds*, 1985]. The granodiorite intrusion yielded a U-Pb zircon date of 22.0±4.1 Ma and an Rb/Sr whole rock isochron date of 24.9±3.0 Ma [*Reynolds et al.*, 1986a]. In the eastern half of the range the rocks are overprinted by a gently dipping mylonitic fabric with a northeast trending lineation and top-to-the-northeast shear-sense indicators [*Reynolds*, 1985]. Local exposures of a detachment fault and widespread overprinting of the mylonitic carapace by brittle deformation features typically associated with detachment faults indicate that a detachment fault succeeded the earlier mylonitic shear zone as the rocks cooled.

Fission track analyses of apatite from four samples from the Sierra Estrella, located approximately 10 km to the southwest of the South Mountains (Figure 1), indicate that rapid cooling occurred at 24.7±0.4 Ma [*Fitzgerald et al.*, 1994]. This is interpreted to reflect early extension and exhumation in the breakaway region of the South Mountains detachment fault. A hornblende $^{40}Ar/^{39}Ar$ date of 20.7±0.4 Ma from the South Mountains granodiorite and biotite K-Ar dates of 20.5±0.4 Ma, 20.2±0.4 Ma, and 19.2±0.4 Ma indicate that rapid cooling was occurring at 21-19 Ma and that extension-related mylonitization of exposed rocks ended at about 19 Ma [*Reynolds et al.*, 1986a; *Fitzgerald et al.*, 1994]. Continued cooling through the apatite fission track annealing temperature at 17.5±1.0 Ma (weighted mean of 17 analyzed samples from *Fitzgerald et al.* [1994]) is interpreted as a consequence of late stage detachment faulting and exhumation.

Seven kilometers northeast of exposed mylonitic rocks in the South Mountains a sequence of Tertiary sedimentary and volcanic rocks, tilted to the southwest, disconformably overlie Proterozoic crystalline rocks in the Tempe Butte and Papago Buttes area [*Péwé et al.*, 1986] and are interpreted as part of the upper plate of the South Mountains detachment fault [*Reynolds*, 1985]. The lowest Tertiary unit consists of coarse sedimentary breccia and rock avalanche deposits that grade upward into sandstone and siltstone with a corresponding decrease in stratal dip from 50° to 30° or less. The sedimentary rocks are overlain by tilted, intermediate lava flows that yielded a whole rock K-Ar date of 17.6±0.4 Ma [*Scarborough and Wilt*, 1979]. The thick clastic sequence

Table 4. Calculated Model Ages for Several Assumed Initial $^{87}Sr/^{86}Sr$ Ratios

Assumed Initial Ratio	Apparent Age, Ma
0.703	24.82
0.706	22.39
0.709	19.97
0.712	17.54

Uncertainty in apparent ages due to 0.1% uncertainty in both measured ratios is 0.6 Ma (1σ).

is interpreted as evidence of prevolcanic normal faulting and tilting, and the 17.6 Ma K-Ar date is interpreted to indicate that tilting related to movement on the South Mountains detachment fault continued after 17.6 Ma.

Summary. Apatite fission track dates from the Sierra Estrella indicate that exhumation and rapid cooling of the lower plate of the South Mountains detachment shear zone began by about 25 Ma. Granitoid intrusion in the South Mountains was followed by extension-related mylonitization that occurred before 19-20 Ma. Continued rapid cooling of lower plate rocks through fission track apatite annealing temperatures at 17-18 Ma indicates continued tectonic denudation. Tilting of upper plate rocks, inferred to be related to continued extension, occurred both before and after 17.5 Ma. The age of prevolcanic basin genesis and clastic sedimentation is poorly constrained but could extend as far back as the initiation of cooling in the Sierra Estrella at 25 Ma.

Summary and Discussion

Magmatism

Mid-Cenozoic volcanism in southwestern Arizona commonly produced a three-part sequence of early mafic to intermediate lava flows overlain by felsic to intermediate lava flows and pyroclastic rocks in turn overlain by basaltic and andesitic lava flows (Figures 17 and 18). In some areas, basal mafic rocks are absent and in others they are overlain by mesa-forming basalts without intervening felsic rocks. The upper basaltic and andesitic lavas can be divided into 13-20 Ma mafic lavas that were erupted immediately after felsic magmatism and appear to be related to it, and <13 Ma basalt, such as in the Buckskin Mountains area, that are not associated with the volcanic fields defined by earlier volcanism.

Voluminous felsic magmatism began between 25 and 22 Ma in five of the eight areas represented by the histograms in figure 2 (Figures 2b and 2d-2g). In the Organ Pipe and Vulture areas voluminous felsic magmatism began largely at about 20 Ma (Figures 2a and 2h). In the eastern Gila Bend Mountains, felsic magmatism was fairly minor, and voluminous mafic magmatism occurred at 19-21 Ma (Figure 2c). Only six dates out of 166 plotted are older than 25.0 Ma; two of these are from thin tuffs interbedded within voluminous clastic sedimentary rocks and another is probably spurious. Two others are problematic because they conflict with a U-Pb zircon date. Felsic magmatism ended at 19-20 Ma in most areas (Figures 2b-2e and 2g), at about 22 Ma in the Yuma area (Figure 2f), and at 15-17 Ma in the Vulture Mountains and Organ Pipe areas (Figures 2a and 2h). The duration of voluminous felsic magmatism in each area was about 3-6 Ma.

The most extensive areas of volcanic rocks in southwestern Arizona form the Kofa and Ajo volcanic fields (Figure 19). Two calderas inferred at the center of the Kofa volcanic field correspond to residual Bouguer gravity lows [*Grubensky and Bagby*, 1990]. The only other large residual Bouguer gravity anomaly in southwestern Arizona is under the Ajo volcanic field (Figures 4 and 19; *Lysonski*

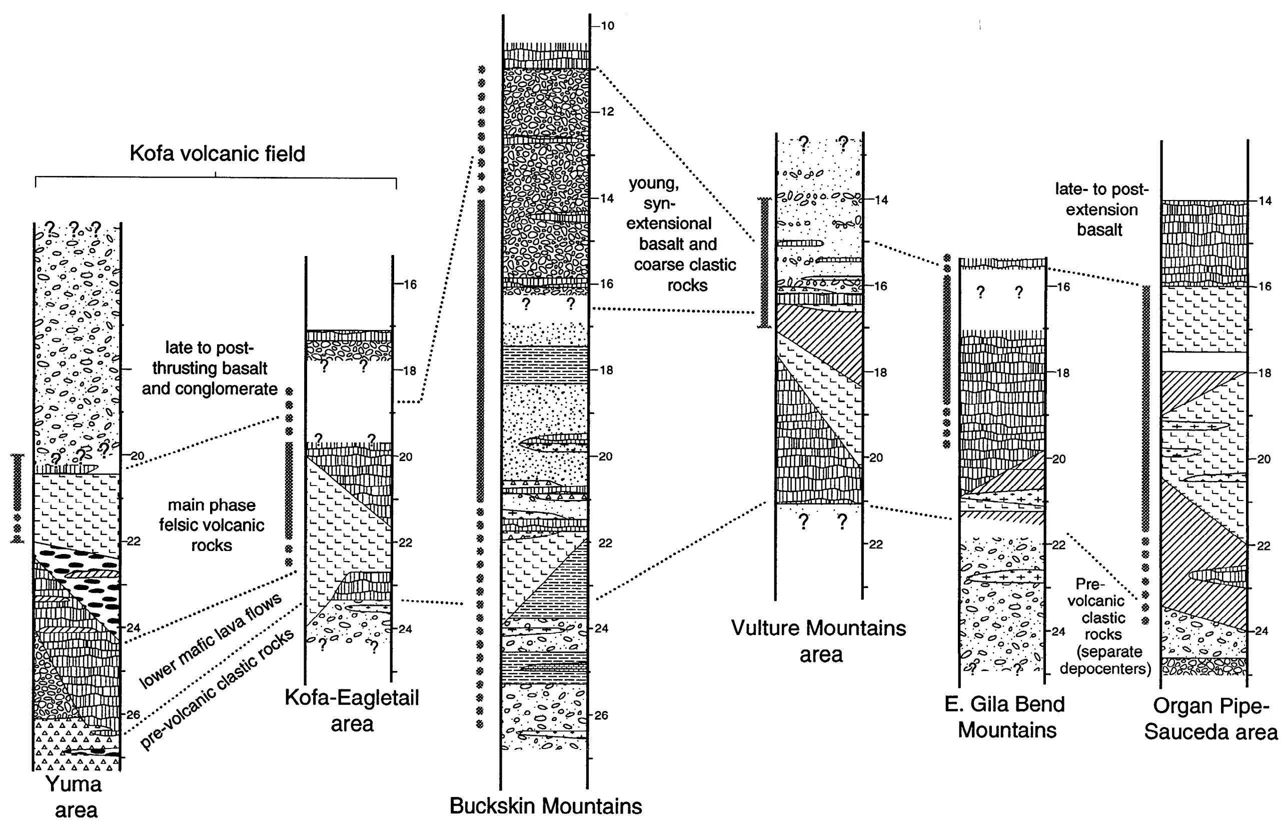


Figure 17. Time-stratigraphic columns from Figures 5, 8, 10, 12, 14, and 16 showing correlation of assemblages and timing of tilting. Vertical scale in Ma. Deposition of major assemblages and timing of tilting are diachronous, but each area contains a crudely similar sequence of strata and chronology of tilting. See Figure 5 for explanation of patterns.

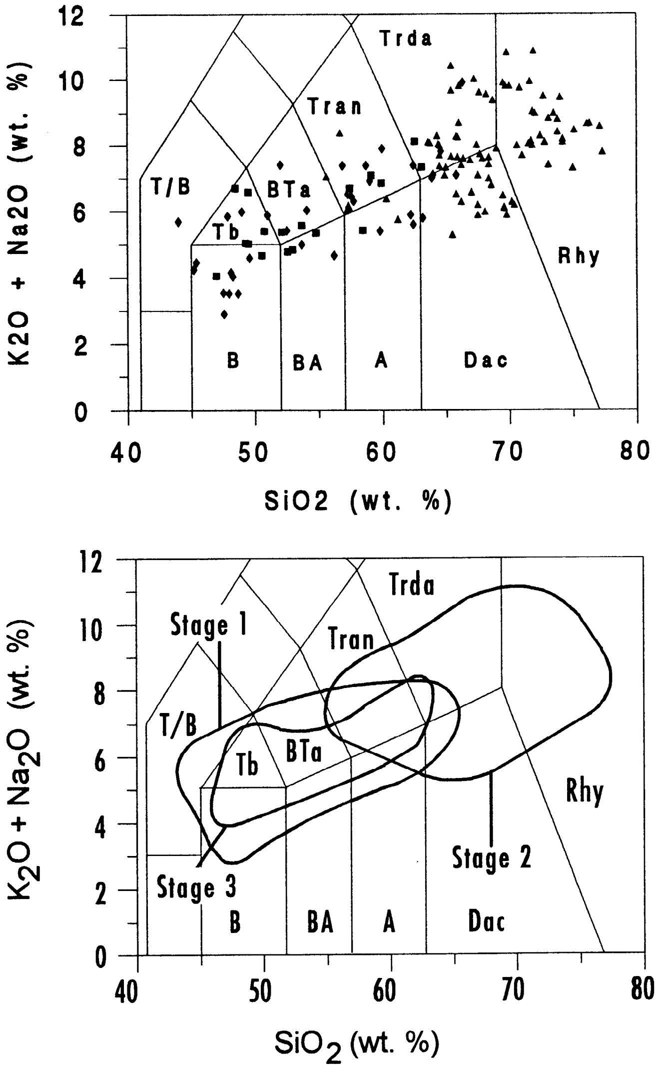


Figure 18. Weight percent SiO_2 versus total alkalies for rocks in southwestern Arizona. (top) Individual analyses with symbols as follows: diamonds, stage 1 mafic rocks; triangles, stage 2 felsic to intermediate rocks; squares, stage 3 basaltic to andesitic rocks (includes two samples of trachydacite). (bottom) Areas representing each of the three stages of magmatism as defined by the points in the top part. Data (140 analyses) from *Gilbert and Skotnicki* [1993], *Kortemeier et al.* [1986], *Gray et al.* [1985a], *Crowe* [1978], *Crowe et al.* [1979], *Dillon* [1975], *Grubensky et al.* [1993], *Gilluly* [1946], *Roddy et al.* [1988], *Davis* [1985], *R. Miller* [unpublished data, 1991], and *S. Richard* [unpublished data, 1994]. Samples with K_2O/Na_2O > 3 were rejected due to K metasomatism [e.g. *Roddy et al.*, 1988]. Classification from *Le Bas et al.* [1986]. T/B, tephrite/basanite; Tb, basalt; B, basalt; BA, basaltic andesite; A, andesite; Dac, dacite; Rhy, rhyolite; Trda, trachydacite; Tran, trachyandesite; BTa, basaltic trachyandesite.

et al. [1980]). Based on the voluminous felsic volcanic rocks in the Ajo volcanic field, it seems likely that this gravity anomaly also represents buried, low-density, mid-Tertiary granitoids or intracaldera fill.

Mafic volcanism was widespread during late felsic magmatism and immediately following it. These mafic volcanic rocks commonly consist of basalt and the youngest flows within this assemblage commonly form mesas. Significant mafic volcanism typically began during later felsic volcanism and outlasted it by 1-3 Ma.

Basaltic and locally bimodal volcanic rocks in the Buckskin Mountains area that are younger than about 13 Ma represent part of a suite of largely postextension volcanic rocks that are widely exposed in central Arizona and are locally exposed over much of the southwestern United States [*Scarborough*, 1985; *Lynch*, 1989]. This late Cenozoic suite of basaltic to bimodal, commonly alkalic volcanic rocks is geochemically distinct from the mid-Tertiary, calc-alkaline, compositionally diverse volcanic rocks [*Nealy and Sheridan*, 1989]. In Arizona, initial $^{87}Sr/^{86}/Sr$ of the basaltic to bimodal suite rocks is consistently <0.7055, whereas older mid-Tertiary volcanic rocks are characterized by $^{87}Sr/^{86}Sr$ >0.7055 (Figure 2 of *Spencer and Reynolds* [1989a]).

Extension

Earliest extension in southwestern Arizona is indicated by largely prevolcanic clastic sedimentary rocks deposited in four depocenters (Figure 19) and possibly by several other areas with prevolcanic sedimentary rocks. Dated volcanic rocks interbedded with clastic sedimentary rocks in the Artillery depocenter indicate that sediment deposition began at 26-27 Ma and had produced a thick sequence of volcanic and sedimentary rocks, with decreasing upsection dip, by 20 Ma. Volcanic rocks within the coarse clastic sequence in the Laguna Mountains of the Yuma depocenter are dated at 24.2 ± 1.2 Ma and 28.5 ± 2.3 Ma. Rock avalanche deposits and debris flows in both depocenters indicate that cliffs and steep slopes were present, and we infer that active faulting was occurring at the basin margins. The Artillery depocenter formed the tapered end of the upper plate of the active Buckskin-Rawhide detachment fault, and its genesis and history seem firmly linked to detachment faulting. Similarly, the Yuma depocenter, active by 28.5 ± 2.3 Ma and still active at 22.5 ± 0.7 Ma, is bounded to the southeast by the Baker Peaks and Mohawk detachment faults [*Mueller et al.*, 1982; *Pridmore and Craig*, 1982], and it seems likely that its genesis and history are intimately linked to extension. The coarse, prevolcanic sedimentary rocks northeast of the South Mountains possibly represent an old ($\approx$20-25 Ma) depocenter related to early detachment fault displacement. The Ajo and Gila Bend depocenters contain 20-24 Ma volcanic rocks and were receiving coarse clastic debris before and during early volcanism. These basins are not known to be associated with detachment faults, but probably also reflect an extensional tectonic setting.

At dozens of widely distributed locations in southwestern Arizona, mid-Tertiary volcanic strata rest disconformably on pre-Tertiary plutonic or metamorphic rocks or on several to several tens of meters of coarse clastic debris that in turn rest on bedrock. Thus the four depocenters discussed above were areally restricted and were surrounded by bedrock when volcanism began (five depocenters if the South Mountains area is included). The general absence of clastic strata beneath the volcanic sequences in other areas is interpreted to indicate that extensional faulting was not widespread before magmatism and only significantly predated it at four or five depocenters. Initial extensional faulting may have produced some basins that simply deflected preexisting drainages and did not accumulate sediments,

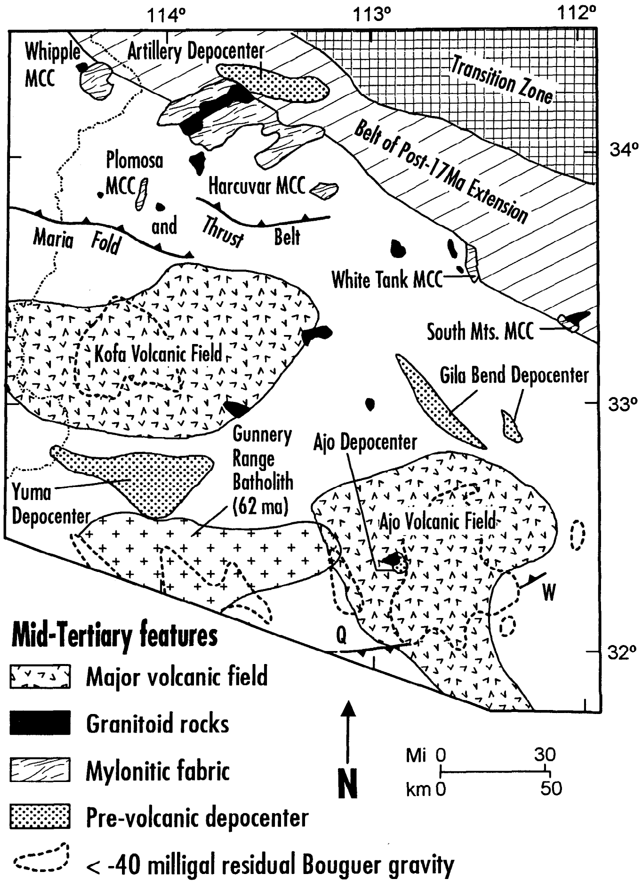


Figure 19. Map of major mid-Tertiary tectonic and magmatic features and late Cretaceous to earliest Tertiary thrust faults and Gunnery Range batholith. Area shown is same as in Figure 1. Outlines of major volcanic fields are highly simplified. MCC, metamorphic core complex; Q, Quitobaquito thrust; W, Window Mountain Well thrust.

at least initially. Such basins would not leave a record of prevolcanic sedimentary rocks but were probably insignificant in southwestern Arizona because most areas blanketed by volcanic rocks are not very extended and thus probably never underwent significant extensional faulting. Even basins that are externally drained generally accumulate coarse clastic debris adjacent to active basin-bounding faults and thus contain some record of extension [e.g., *DiGuiseppi and Bartley*, 1991], especially if such basins were blanketed by volcanic rocks during faulting.

Low-volume magmatism occurred during early clastic sedimentation at the largely prevolcanic depocenters. The second oldest date in the entire Ajo volcanic field, 23.8 ± 0.8 Ma, is from volcanic rocks interbedded with the upper part of the Locomotive fanglomerate (Figure 5). The oldest date from the combined Kofa volcanic field and Yuma depocenter, 28.5 ± 2.3 Ma, is from a tuff within the thickest exposed part of the Yuma area clastic sequence. The oldest date from volcanic rocks in the Buckskin Mountains area is from a tuff (26.4 ± 0.2 Ma) near the base of the Artillery Formation. Restoration of displacement on the Buckskin-Rawhide detachment fault places the Artillery depocenter above granitoids of the Swansea plutonic suite dated at 29.9 Ma and 26.2 Ma. We conclude that extension began only locally before 23-24 Ma, occurred primarily if not entirely within the areas of the prevolcanic depocenters, and was associated with local, low-volume magmatism.

In most areas, extension and magmatism were broadly synchronous. In the Sauceda-Organ Pipe, Gila Bend, Eagletail-Kofa, and Yuma areas, stratigraphically lower volcanic rocks (20-25 Ma) are slightly to moderately tilted and cut by northwest striking faults, whereas younger (15-20 Ma), dominantly mafic volcanic rocks are less tilted or are untilted. In some areas, however, extension continued after magmatism had largely ended. In the Buckskin Mountains area, extension-related tilting during deposition of upper plate volcanic and sedimentary rocks at 26-20 Ma produced fanning dips in Artillery Formation. Continued tilting after this time produced fanning dips in overlying sedimentary rocks that contain only a single basalt unit. Fission track cooling ages from lower plate crystalline rocks indicate that tectonic exhumation in this area may have continued until 11 Ma with very little associated magmatism. Extreme extension and tilting in the Vulture Mountains area, located between the Buckskin and South Mountains areas, occurred at 17-14 Ma and outlasted all but the youngest basaltic volcanism.

Extension in southwestern Arizona began locally before 25 Ma and was widespread between about 20 and 25 Ma. In southern and western areas, extension ended between about 16 and 20 Ma, did not generally cause tilting of more than about 50°, and did not uncover mylonitic crystalline rocks in metamorphic core complexes. In a northwest trending belt that extends from Phoenix northwestward to the northeast flank of the Harcuvar metamorphic core complex and beyond, extended rocks are commonly highly tilted and slivered by faulting and detachment faults uncovered mylonitic crystalline rocks. Extension did not end until after 17 Ma in the South Mountains area, about 14 Ma in the Vulture Mountains area, and about 11-12 Ma in the Buckskin area (Figure 20). Within this belt extension outlasted mid-Tertiary volcanism and was transitional into a younger period of deep basin development that has been attributed to a distinctly different period of postsubduction high-angle normal faulting and basaltic to bimodal, commonly alkalic volcanism [*Eberly and Stanley*, 1978; *Menges and Pearthree*, 1989].

Tectonic Implications

Magmatism. Within southwestern Arizona magmatism was superimposed on crust that had different tectonic histories in different areas. The late Cretaceous Maria fold-and-thrust belt in west central Arizona and adjacent southeastern California is spatially associated with mid-Tertiary uplift of the Harcuvar metamorphic core complex, and buoyancy forces associated with the crustal welt produced by thrusting were a major factor driving core complex uplift [*Spencer and Reynolds*, 1990b]. If Cenozoic magmatism was caused by radiogenic heating of overthickened crust, as proposed by *Glazner and Bartley* [1985], intense magmatism should have occurred in the Buckskin Mountains area to the north of the surface trace of the regionally north dipping thrusts of the Maria fold and thrust belt. In fact, magmatism here was somewhat subdued, whereas voluminous magmatism occurred to the south in the Kofa volcanic field where volcanic rocks locally rest on clastic sedimentary rocks deposited in the foredeep of the thrust belt (Figure 19)

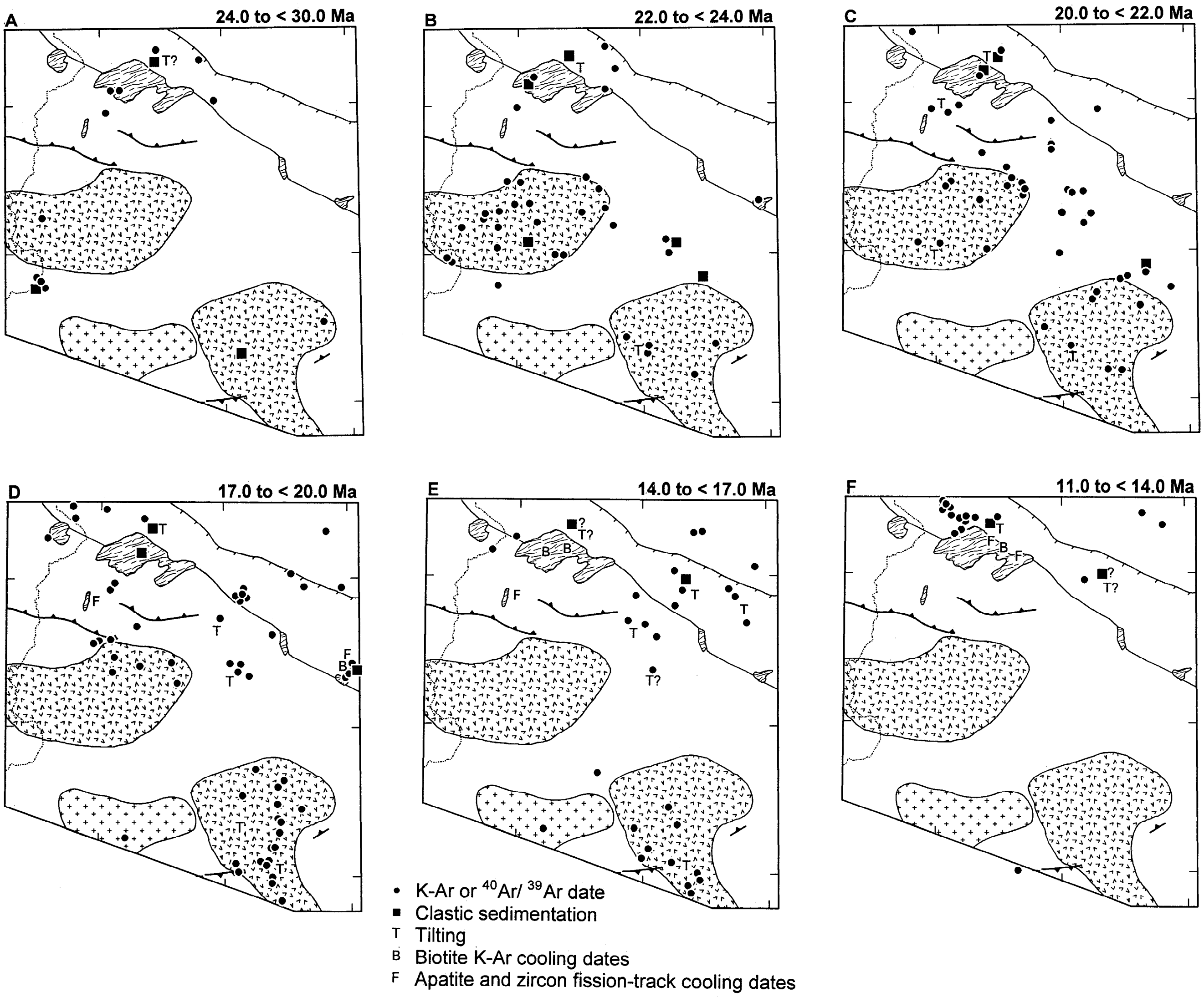


Figure 20. All of the dates that reflect the timing of mid-Tertiary magmatism and extension are plotted in these six maps, each of which represents a segment of time, as indicated. Also shown are locations of tilted fault blocks where timing of tilting is constrained. It is apparent from this diagram that widely distributed magmatism and extension did not migrate systematically within southwestern Arizona except that youngest extension occurred primarily near the Transition Zone province. Dates plotted at the north edge of Figure 20f reflect young basaltic magmatism that is chemically distinct from earlier, compositionally diverse magmatism and that represents a style of volcanism that has continued in Arizona to the Quaternary. Other features shown are labeled in Figure 19.

[*Tosdal and Stone*, 1994]. Similarly, a region of thrust faulting in south central Arizona contains early Tertiary two-mica garnet granites that are thought to be the product of anatectic melting within overthickened crust, but this area is not greatly affected by mid-Tertiary volcanism [*Wright and Haxel*, 1982; *Haxel et al.*, 1984; *Farmer and DePaolo*, 1984]. In addition, mid-Tertiary metaluminous (biotite-hornblende) granitoids in southwestern Arizona are dissimilar to the early Tertiary anatectic peraluminous granitoids and were probably derived in part from the mantle. The nearly synchronous initiation of magmatism across southwestern Arizona (Figure 20), lack of a relationship between mid-Tertiary magmatism and areas of earlier crustal thickening, and the metaluminous character of mid-Tertiary granitoids are all inconsistent with theories that relate magmatism to radiogenic heating of overthickened crust.

We infer a similar cause of mid-Tertiary magmatism in southwestern Arizona and in other large volcanic fields around the Colorado Plateau on the basis of four observations, as follows: (1) The three-part volcanic succession of mafic-felsic-mafic that characterizes the Oligocene-Miocene volcanic rocks of southwestern Arizona is typical of many other mid-Cenozoic volcanic fields in the western United States [e.g., *Lipman*, 1992], including the San Juan volcanic field of Colorado and the Mogollon-Datil volcanic field of southwestern New Mexico [*Lipman et al.*, 1978; *Elston and Bornhorst*, 1979]. (2) Major element chemistry of volcanic and shallow intrusive rocks is similar (Figure 21). (3)

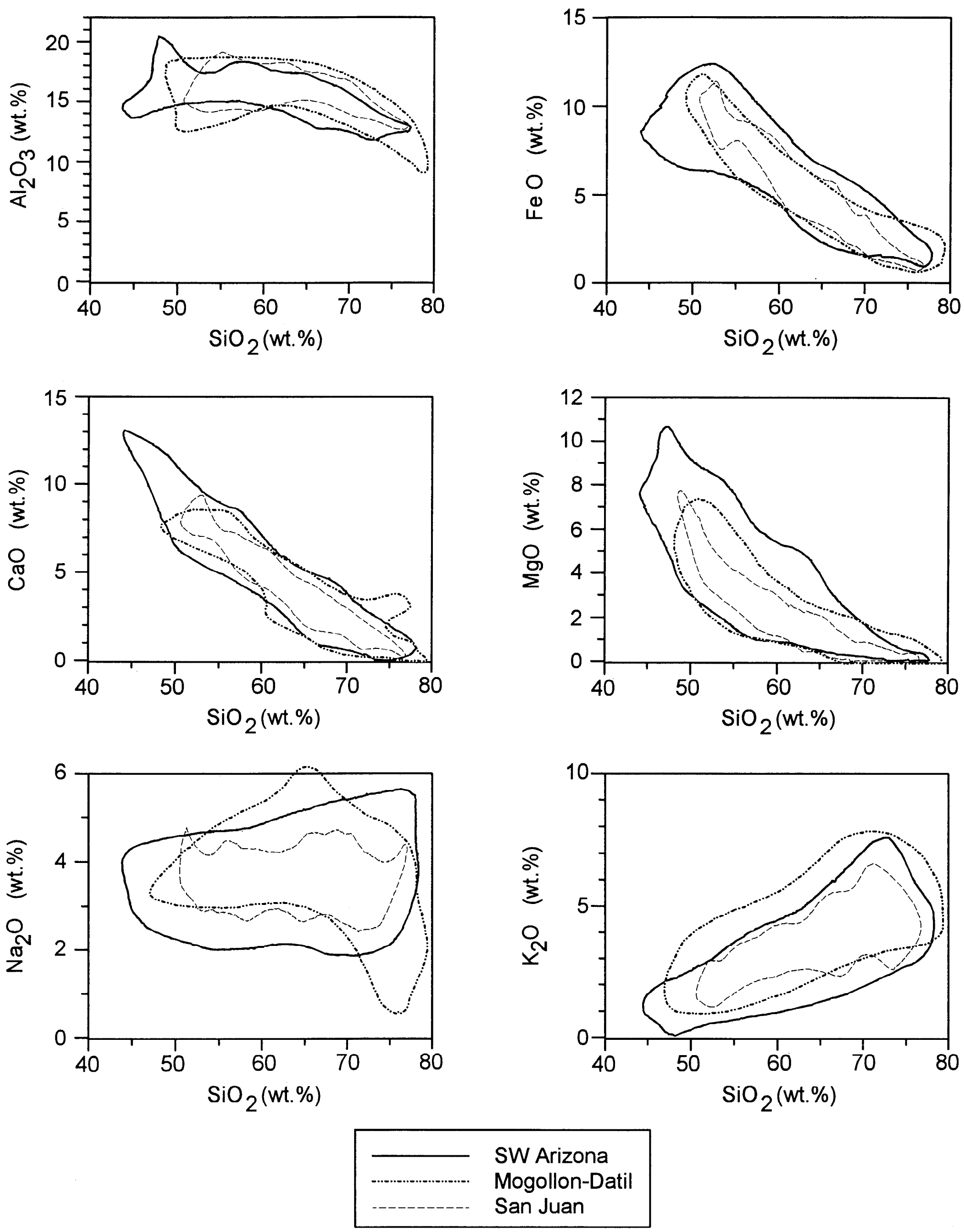


Figure 21. Major element oxides versus silica for southwestern Arizona (140 analyses represented in Figure 18), Mogollon-Datil volcanic field of southwestern New Mexico (146 analyses from *Elston et al.* [1976]), and San Juan volcanic field in southwestern Colorado (117 analyses from *Lipman* [1975]).

Volcanism in southwestern Arizona occurred as part of a broad east to west migration of middle Cenozoic magmatism that began in Colorado and New Mexico at 30-35 Ma [*Lipman et al.*, 1978; *Marvin et al.*, 1987; *McIntosh et al.*, 1991], in southeastern Arizona and southern Utah largely at 25-30 Ma [*Steven et al.*, 1979; *Rowley et al.*, 1994; *Dickinson and Shafiqullah*, 1989; *Nelson et al.*, 1992], and in southwestern Arizona at 20-25 Ma [*Spencer and Reynolds*, 1989a]. All of these fields were erupted following a lull in magmatic activity that followed Laramide tectonism and represent a westward return sweep of the locus of magmatism to near the continental margin following the eastward sweep that occurred in the late Cretaceous. (4) Within each of these areas, magmatism was roughly synchronous and subregional migration patterns are not apparent. These other fields, including the Marysvale field in south central Utah, are built on the edges of the Colorado Plateau where neither earlier crustal thickening nor mid-Tertiary extension can be easily invoked as mechanisms that triggered magmatism.

Magmatism in southwestern Arizona is part of a regional westward sweep of petrologically similar magmatism that occurred within crust with diverse geologic histories. As have many others, we infer that magmatism was triggered by subduction and that regional westward migration occurred as subducted oceanic lithosphere became progressively younger and weaker, and was consequently less able to laterally penetrate the asthenosphere beneath North America [e.g., *Severinghaus and Atwater,* 1990; *Spencer*, 1994]. Features that complicate inferences of a subduction origin for magmatism include simultaneous magmatism over large areas such as southwestern Arizona or the Mogollon-Datil volcanic field, subregional migration patterns such as the northward migration of magmatism from southwestern Arizona to the Lake Mead and Death Valley areas after 20 Ma, and enormous areal variations in the volume of volcanic rocks produced. Even with these poorly understood complications, the plate tectonic context of magmatism and lack of convincing alternatives point to a subduction origin for all but the latest basaltic magmatism.

Extension. Subduction ended along the continental margin adjacent to southwestern Arizona at about the time of initial felsic magmatism and extension [*Atwater*, 1989]. Extension initiation in the southern Basin and Range province has been attributed to changes in plate boundary tectonics at this time [*Ingersoll*, 1982]. Cenozoic extension occurred before subduction termination in most other areas of western North America, including Mexico [*Henry and Aranda-Gomez*, 1992], the northern Great Basin [*Gans et al.*, 1989], and the northwestern United States and adjacent Canada [*Armstrong and Ward*, 1991]. Extension in these other areas produced metamorphic core complexes and low- and high-angle normal faults, was associated with post-Laramide magmatism [e.g., *Sawyer et al.*, 1994], and was generally similar in character and structural style to extension in southwestern Arizona. These similarities suggest that extension in all these areas was caused by the same mechanisms, that magmatic heating of the lithosphere was possibly the primary trigger for extension, and that subduction termination was not a significant cause of mid-Tertiary extension. In some large areas of the Great Basin, however, magmatism and extension were diachronous or magmatism was insignificant [e.g. *Best and Christiansen*, 1991; *Axen et al.*, 1993], which suggest that other factors such as plate boundary stresses played an important role in controlling extension.

The chronology and distribution of extension and magmatism in southwestern Arizona place constraints on theories of relationships between the two. Minor magmatism occurred during localized, largely prevolcanic extension and was followed by voluminous mafic and felsic magmatism and approximately synchronous faulting and tilting. Most commonly, extension-related tilting occurred after the beginning of voluminous felsic magmatism and before the end of younger mafic magmatism. Extension outlasted magmatism by several million years only in a northwest trending belt adjacent to the Transition Zone. These relationships are consistent with the concept that subduction-related magmas heated and weakened the lithosphere and triggered extension that was driven largely by gravitational potential energy inherited from earlier crustal thickening. Possibly earliest magmas did not reach the Earth's surface but could have initiated local prevolcanic extension. The 30 Ma $^{40}Ar/^{39}Ar$ date from the Swansea plutonic suite may reflect such prevolcanic igneous activity.

The belt of youngest extension is directly adjacent to the Transition Zone, which is structurally contiguous with the Colorado Plateau. Both the Transition Zone and plateau escaped significant upper crustal extension. The Transition Zone slopes regionally southwestward, from elevations of slightly over 2000 m to around 500-700 m. This southwestward slope developed during the early to middle Miocene and was associated with drainage reversal [*Peirce et al.*, 1979]. This change has been attributed to expulsion of middle to lower crust from beneath the Transition Zone during mid-Tertiary extension. Progressively more rock was expelled from southwestern areas, leading to progressively greater subsidence toward the southwest [*Spencer and Reynolds*, 1989a; see also *Wernicke*, 1985]. The gravitational potential energy of the elevated plateau and Transition Zone became a driving force for expulsion of deep crust. Extensional forces associated with topography were so great that extension continued by this expulsion process for several million years after it had ended elsewhere in southwestern Arizona and after magmatism had largely ended. The existence of a belt of young extension adjacent to an areally extensive topographic high supports the hypothesis that extension was driven by gravitational potential energy stored in topographic highs and crustal roots [e.g., *Coney and Harms*, 1984; *Molnar and Lyon-Caen*, 1988]. The exceptionally long duration (26-11 Ma) of extension and the highly effective exhumation of areally extensive midcrustal mylonites in the Harcuvar metamorphic core complex are inferred consequences of extension driven by gravitational potential energy associated with both the crustal roots of the Maria fold and thrust belt and the elevated Transition Zone physiographic province. No other part of southwestern Arizona was extended under conditions where so much potential energy was available for extension.

Several hypotheses have been proposed for relationships between magmatism and extension that are not consistent with geologic relationships in southwestern Arizona, as follows:

1. *Leeman and Harry* [1993] proposed that, during extension in the Basin and Range province, decompression melting of basaltic rocks within the mantle lithosphere caused mid-Tertiary magmatism. Two problems with application of this hypothesis to southwestern Arizona are (1) initial widespread and voluminous magmatism occurred before significant extension, and (2) young extension continued adjacent to the Transition Zone largely without magmatism. In addition, major element geochemistry and the mafic-felsic-mafic stratigraphy of volcanic rocks resembles large volcanic fields in adjacent states that are built on crust that is not significantly extended.

2. *Wernicke et al.* [1987] proposed that the time interval between late Cretaceous to early Tertiary magmatism and mid-Tertiary extension was controlled by the thermal state of the lithosphere, which was strongly influenced by the severity of earlier magmatism. According to this hypothesis, areas of substantial Laramide magmatism were hotter and extended earlier than areas less affected by magmatic heating. The 62±4 Ma (unpublished U/Pb zircon date from R.M. Tosdal (written communication, 1994)) Gunnery Range batholith is by far the largest post-Jurassic granitoid in southwestern Arizona (Figure 19), and according to the hypothesis of *Wernicke et al.* [1987] this area should have been hottest and extended earlier than adjacent areas. The Gunnery Range batholith is broken into six northwest trending basin and range pairs that reflect minor to moderate extension [*Gray et al.*, 1988; *Reynolds*, 1988]. At the north end of two of these ranges a regionally north dipping detachment fault has been broken and uplifted by the

younger range-bounding faults [*Mueller et al.*, 1982; *Pridmore and Craig*, 1982]. This detachment fault is north of the batholith, dips away from it, and thus did not extend into its presumably hot roots. There are no other early extension faults known in the area of the Gunnery Range batholith, and we are thus unable to support the hypothesis of *Wernicke et al.* [1987]. Furthermore, there is very little Tertiary volcanic rock in this area (as with the Sierra Nevada and Peninsular Range batholiths), which suggests that heating associated with earlier batholith emplacement did not promote mid-Tertiary magmatism.

3. *Glazner and Supplee* [1982] and *Glazner and Bartley* [1984] proposed that mid-Tertiary magmatism and extension migrated northward in Arizona due to northward movement of the southern edge of the subducted Farallon/Vancouver plate. Our data and analysis of southwestern Arizona do not reveal a northward migration of magmatism and extension. Both occurred approximately synchronously over all of southwestern Arizona. Earliest extension and magmatism occurred locally before 25 Ma in the Buckskin-Artillery mountains area in the north and in the Laguna Mountains in the southwest, but the great burst of magmatism and extension began at 20-25 Ma over almost all of southwestern Arizona with no discernable pattern of migration (Figure 20). A belt of young extension adjacent to the Transition Zone represents the only significant departure from nearly synchronous extension and magmatism, and this can be explained by topographically driven expulsion of midcrust from beneath the Transition Zone.

4. *Rehrig and Reynolds* [1980] and *Lister and Baldwin* [1993] proposed that large-magnitude extension and denudation of midcrustal mylonites in metamorphic core complexes occurred in areas of intense magmatism, possibly because core complex uplift was driven by magmatic buoyancy. In southwestern Arizona, however, the extensive Ajo and Kofa volcanic fields are only slightly to moderately extended. The metamorphic core complexes contain scattered Tertiary intrusions, but in large areas, such as the Harcuvar and Harquahala Mountains, Tertiary igneous rocks are limited to volumetrically insignificant dikes, and even these are generally absent in the mylonitic rocks in these ranges. Upper plate Tertiary sections adjacent to the core complexes include volcanic rocks, but these are generally not particularly thick and are dominated by sedimentary rocks. All of the dated igneous rocks in the core complexes are older than about 20 Ma and predate much or most of the extension, denudation, and cooling. There is thus no correlation between local magnitude of extension and intensity of igneous activity. Indeed, there is a suggestion of an anticorrelation [see also *Sawyer et al.*, 1994]. We conclude that hypotheses that relate core complex genesis to localized upper crustal magma injection are not important in southwestern Arizona.

Conclusion

Mid-Tertiary volcanic rocks in southwestern Arizona are geochemically and stratigraphically similar to many other Cenozoic volcanic fields in the western United States and were produced within the same plate tectonic setting. Regional migration patterns of magmatism are somewhat complex but generally westward, and include southwestern Arizona. Mafic to felsic magmatism that precedes fundamentally basaltic, locally bimodal volcanism has been related to low-angle subduction [e.g., *Lipman et al.*, 1972; *Severinghaus and Atwater*, 1990]. Younger basaltic and bimodal volcanism appears to be related to late extension and the termination of subduction [*Christiansen and Lipman*, 1972]. Evidence for alternative origins and migration patterns of Tertiary magmatism was not recognized in this study.

Initial magmatism and extension were closely associated in southwestern Arizona. Normal faulting and associated sedimentation locally preceded voluminous magmatism, but even these areas contain evidence of minor, synchronous magmatism. Earlier thermal and structural history did not influenced the timing of extension initiation. The local magnitude and duration of extension were determined by the amount of earlier crustal thickening and by topography rather than by magmatic inflation of the crust or magmatic buoyancy forces. These relationships support the theory that stresses generated by topography and buoyant crustal roots played the dominant role in driving extension and that magmatism triggered extension by regional heating and weakening of the lithosphere.

Dozens of field and geochronologic studies of southwestern Arizona completed over the past 15 years provide a wealth of new information concerning the chronology of magmatism and extension and temporal and spatial relationships between them. These studies provide constraints on theories for the forces and processes that caused magmatism and extension in at least one part of the Basin and Range province and elucidate general processes involved in extensional tectonism. It should be remembered, however, that even within different parts of the Basin and Range province styles and magnitudes of extension and magmatism, and relationships between them, vary greatly [e.g., *Axen et al.*, 1993]. The significance and even existence of these variations are still not well understood.

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