Space-time patterns of Late Cretaceous to present magmatism in New Mexico—comparison with Andean volcanism and potential for future volcanism

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Abstract

Space-time plots of more than 3000 K-Ar and $^{40}Ar/^{39}Ar$ radioisotopic ages of Late Cretaceous and Cenozoic volcanic and plutonic rocks are used to evaluate the evolution of magmatism in New Mexico. Several tectonomagmatic subdivisions can be seen in the data. These are: (1) Late Cretaceous to middle Eocene (75–45 Ma) magmatism occurred along and to the south of the northeast-trending Santa Rita lineament which marked the southern boundary of the well-known Laramide magma gap; (2) following the major decrease in Farallon–North America convergence at about 45 Ma, andesitic volcanism engulfed the southwestern quarter of New Mexico to form the intermediate-composition basal one-half to two-thirds of the Mogollon–Datil volcanic field and spread eastward into the Sierra Blanca field; (3) at 37–36 Ma, the ignimbrite "flare-up" began from Trans-Pecos Texas to central Colorado concurrently with a change in mafic volcanism and the first signs of regional extension; (4) the maximum areal extent of magmatism occurred in the Oligocene as activity spread along the nascent Rio Grande rift and in a minor way into the four corners of the state; (5) magmatism waned and the lithosphere cooled during a regional lull between about 21 and 16 Ma in concert with a similar lull throughout much of the western United States; (6) mafic magmatism changed from dominantly basaltic andesite, the Southern Cordilleran Basaltic Andesite (SCORBA) suite, to true basalts following the early Miocene lull as extension along the Rio Grande rift accelerated concurrently with westward expansion of the Great Basin; (7) bimodal basalt–rhyolite volcanism increased at about 10–9 Ma as rotation of the least principal horizontal stress from west-southwest–east-northeast to west-northwest–east-southeast and northwestward expansion of the Great Basin allowed dilation to begin along the northeast-trending Jemez lineament; and (8) a strong pulse of bimodal volcanism began at 5 Ma and continues today with activity confined to the Jemez lineament (dominant) and the Rio Grande rift.

Ignimbrite volcanism during late Eocene and Oligocene (37–23 Ma) occurred in three regionally synchronous pulses (37.5–31.4, 29.3–26.8, 25.1–23.3) from Trans-Pecos Texas to central Colorado, a distance of 1,100 km. Two regional gaps (31.4–29.3 and 26.8–25.1) separate the ignimbrite pulses. Such brief, regionally synchronous episodes of volcanism indicate that changes in far-field forces of tectonic tension and compression are important controls of intraplate magmatism. Trenchward retreat of subducted slabs as indicated by westward younging of linear caldera complexes also reflects plate-margin control of intraplate volcanism.

The tectonomagmatic transitions in New Mexico correlate with changes in plate interactions in the Pacific Basin, again indicating that changes in tectonic tension and compression and the orientation of regional stress fields are felt quickly far inboard of the plate margin. The abrupt decrease in Farallon–North American convergence at about 45 Ma and change in Pacific plate motion at 10–5 Ma had particularly conspicuous effects on volcanism in New Mexico. Also, at approximately 17 Ma, the northwestward retreat of a part of the North American plate margin allowed expansion of the Great Basin, minor clockwise rotation of the Colorado Plateau, and increased spreading along the Rio Grande rift.

Many analogies exist between the extensively studied subduction-related volcanism of the South American Andean arc and the space-time evolution of volcanism in New Mexico. Characteristics of the Andean arc observable in New Mexico include segmentation of the subducting plate into flat and inclined segments, migration of magmatism away from the trench as the angle of slab descent decreases; extinction of volcanism above flat segments, emplacement of major ignimbrite sheets as convergence wanes and slabs roll back toward the trench or fragment and sink, regionally synchronous episodes of volcanism with abrupt on–off behavior; occurrence of major magmatic centers along lineaments transverse to the arc, correlation of ignimbrite volcanism with regional extension and occurrence of alkaline magmatism along the boundary of the volcanic arc with the colder lithosphere of the craton.

The Proterozoic lithosphere of the Southern Rocky Mountains consists of northeast-trending compartments formed by accretion of exotic terranes during continent building. Several magmatic lineaments parallel the accretionary structural grain. The Santa Rita lineament and Colorado Mineral Belt were magmatically active from 75 Ma to approximately 45 Ma during Laramide low-angle to flat subduction. Control of this magmatism must reside in the lithosphere because a tear or other structure in the subducting plate would not be able to maintain a constant location and trend relative to the overlying plate for such a long period. Topographic grooves or ridges on the base of the lithosphere may have controlled asthenosphere–lithosphere contact; differences in hydration and fertility between accreted terranes may also have been a factor as to which lineaments were conducive to magmatism. The Jemez lineament, which is presumed to follow the Mazatzal–Yavapai province boundary, was inactive during the Laramide but became the site of abundant basaltic volcanism from about 10 Ma to present in reaction to northwestward expansion of the Great Basin and clockwise rotation of the Colorado Plateau. Continuation of Jemez volcanism across the Rio Grande rift onto the High Plains indicates fundamental lithospheric control of the mantle anomaly, probably by the Mazatzal–Yavapai province boundary.

The potential for future volcanism in New Mexico is greatest along the Jemez lineament and within the Rio Grande rift. Intersections of transverse lineaments with the Rio Grande rift are especially vulnerable. Two examples are the Jemez and Socorro volcanic centers where geophysical surveys indicate the presence of magmatic activity at depth. Establishment of recurrence intervals of eruptions through geologic mapping and precise radioisotopic dating of volcanic rocks is essential for evaluation of volcanic hazards.

Introduction

Volcanism has been a major component of New Mexico's geological legacy throughout the Late Cretaceous and Cenozoic. New Mexico is a geological "cross roads" that includes portions of the Basin and Range province, Rio Grande rift, Jemez lineament, Colorado Plateau, Southern Rocky Mountains, Great Plains, and the Rocky Mountain alkalic province. Each geologic terrane has added its particular style and composition of volcanic rocks under conditions varying from subduction to rifting to enigmatic volcanic lineaments and isolated pockets of magmatism whose origins are not readily apparent. In this paper we use space-time plots of radioisotopically dated rocks to show how volcanism in New Mexico has evolved since the Late Cretaceous (~ 75 Ma). A lithologically coded histogram shows the episodic nature of the volcanism and how various rock types, such as ignimbrites or basalt flows, have varied with time. Also included area map and a graph that show synchronous pulses of late Eocene and Oligocene ignimbrite volcanism over an 1,100-km, north–northwest-trending segment of the Cordillera, extending from Trans-Pecos Texas to central Colorado (Fig. 1). Using these basic tools, we attempt to relate the patterns of volcanism to particular geologic processes that may have caused them. In particular we focus on the tectonomagmatic transitions between types of volcanism and episodes of magma generation that may reveal the plate tectonic and mantle forces at work.

The paper is organized in sections that begin with the Late Cretaceous and proceed by ten increments through the Cenozoic to the present. Each section discusses the space-time plot and the histogram for that interval and includes an interpretive discussion of what those observations may mean in terms of plate tectonics and theories of magma generation. Because each of the ten time intervals has unique features, we found it more efficient for the writing, and hopefully less confusing for the reader, to discuss the interpretations in each section rather than hold them to the end of the paper as is commonly done. A section on future magmatism addresses the potential for volcanic eruptions with a discussion of the most vulnerable areas based on past patterns. The final section compares space-time patterns of volcanism in New Mexico with similar patterns in the much studied and still active Andean arc of South America.

Methods

Over the past 30 years published, and some unpublished, radioisotopic ages of rocks in New Mexico have been compiled to create a database with more than 3,000 ages. The database was available as an open-file report during its compilation and following computerization was published in 1997 in CD-ROM format (Wilks and Chapin 1997). The database is maintained by Maureen Wilks and many new ages have been added since 1997. The database includes all types of radioisotopic dates, but for this paper we used K-Ar and ^{40}Ar/^{39}Ar ages except for very young rocks for which cosmogenic ^{36}Cl, ^{3}He, and ^{14}C ages were used where available. (To access the database or contribute to it, see the New Mexico Bureau of Geology and Mineral Resources Web site, http://geoinfo.nmt.edu, or contact Maureen Wilks at mwilks@gis.nmt.edu.) The database is searchable by age, latitude and longitude, method used, county, general rock type (such as mafic vs. silicic), and record number.

For this paper space-time plots (Figs. 2A–D, 7A–D, 9A–C) were printed for ten intervals of Late Cretaceous and Cenozoic time plus a summary plot for late Miocene–Present. The plots include all K-Ar and ^{40}Ar/^{39}Ar ages except those with warnings as to reliability or that were known to be significantly in error. The locations of all dated samples for widespread units, such as regional ignimbrites, are shown because they help delineate the geographic extent of a volcanic field. However, dated ash beds from unknown sources, or ashes that were deposited beyond the volcanic field to which they belong, are not shown. Locations of K-Ar ages on evaporites or clays in sedimentary units were also deleted. Some inaccurate K-Ar ages were probably included but they should not obscure the basic patterns.

The histogram (Fig. 3) was prepared with only one data point for each stratigraphic unit or volcanic event and questionable dates were not included. The histogram is an event plot not a volume plot. Some units with a wide range of radioisotopic dates may be underrepresented. These parameters necessitated going through the entire database and making many judgment calls. The histogram is not perfect but we believe that the basic trends are accurate. It was reassuring to compare Figure 3 with a similar histogram that was based upon only 161 K-Ar and fission-track dates and published by Chapin and Seager in 1975. Several of the basic trends are present on both histograms, such as the timing and episodic nature of ignimbrite volcanism, the early (middle) Miocene lull, and the sharp acceleration of bimodal basalt–rhyolite volcanism at about 5 Ma. What made the tedious compilation of Figure 3 possible was the knowledge that W. C. McIntosh had dated and correlated all the ignimbrites in southwestern New Mexico using a combination of ^{40}Ar/^{39}Ar dating and paleomagnetism (see for example McIntosh et al. 1991, 1992; McIntosh and Bryan 2000). This enabled us to ignore (for the histogram) the multitude of duplicating and often conflicting K-Ar dates on the regional ignimbrites. Also, a series of graduate students had completed detailed ^{40}Ar/^{39}Ar geochronology studies of the Rio Puerco (Hallett 1992; Hallett et al. 1997), Taos Plateau (Appelt 1997), Raton–Clayton (Stroud 1997), and Ocate (Olmsted 2000) volcanic fields. Most difficult in construction of Figure 3 was the large number of K-Ar dates in the voluminous and complex Jemez and Latir volcanic fields. A concerted effort was made to avoid biasing the histogram, but it was often difficult to decide which dates to include and which essentially represented the same stratigraphic unit or eruptive event. Some judgment calls on rock types may also have been inaccurate because of lack of uniformity and vagueness in application of lithologic names by those reporting the ages. With these caveats, however, we believe the histogram contains much useful information and raises some intriguing questions that we will address in subsequent sections.

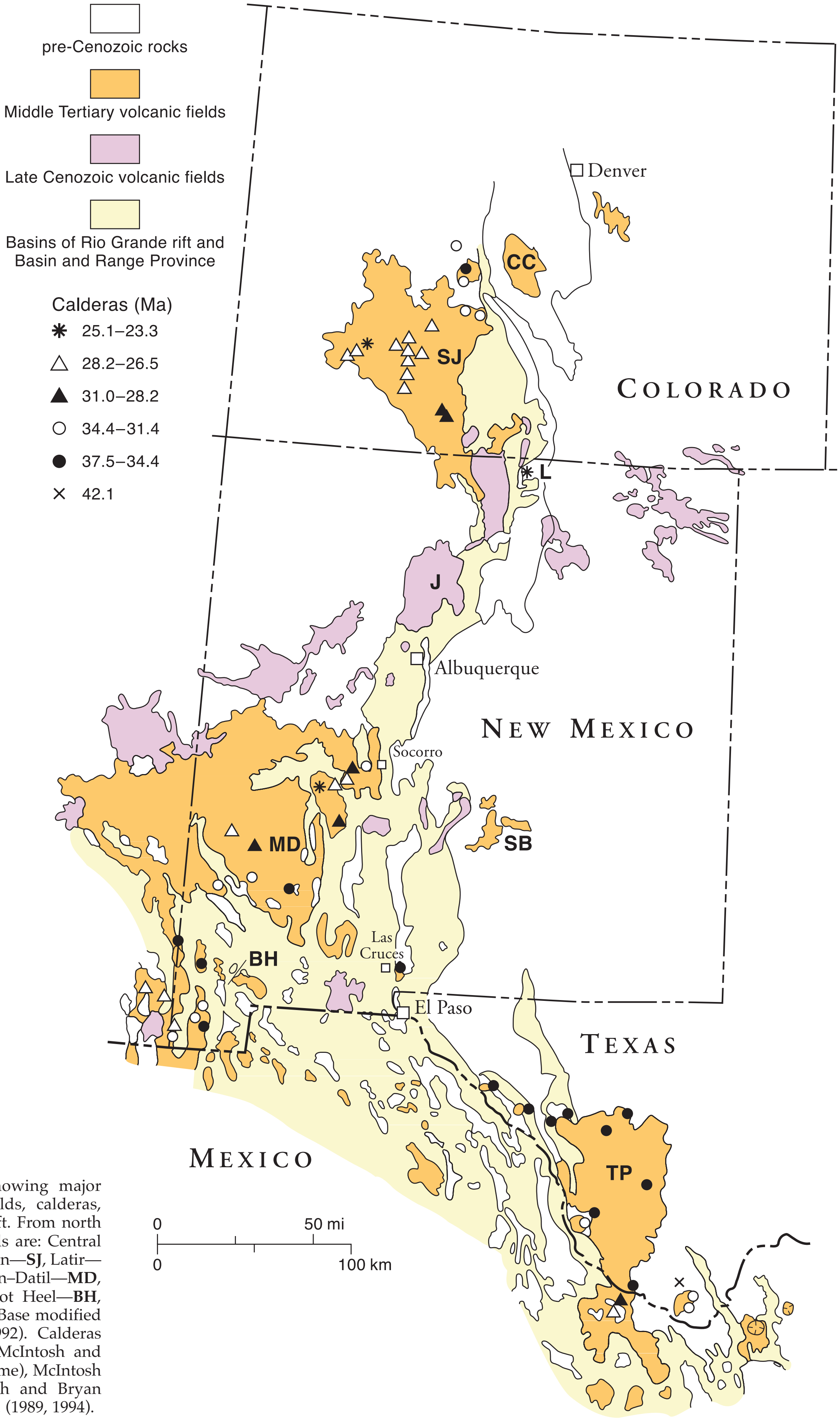


FIGURE 1A—Map showing major Cenozoic volcanic fields, calderas, and the Rio Grande rift. From north to south, volcanic fields are: Central Colorado—**CC**, San Juan—**SJ**, Latir—**L**, Jemez—**J**, Mogollon–Datil—**MD**, Sierra Blanca—**SB**, Boot Heel—**BH**, and Trans-Pecos—**TP**. Base modified from Muehlberger (1992). Calderas from Lipman (2000), McIntosh and Chapin (2004 this volume), McIntosh et al. (1992), McIntosh and Bryan (2000), and Henry et al. (1989, 1994).

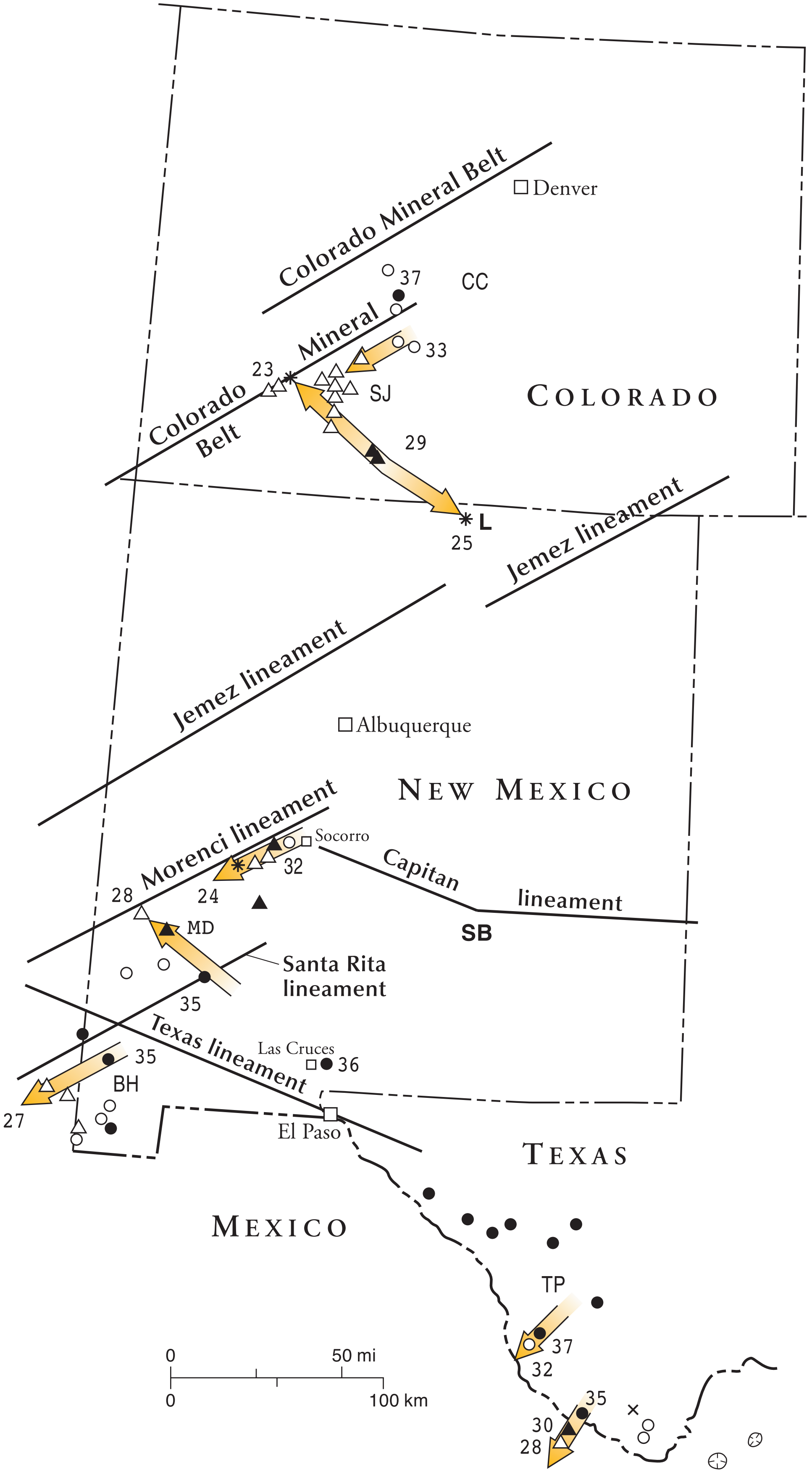
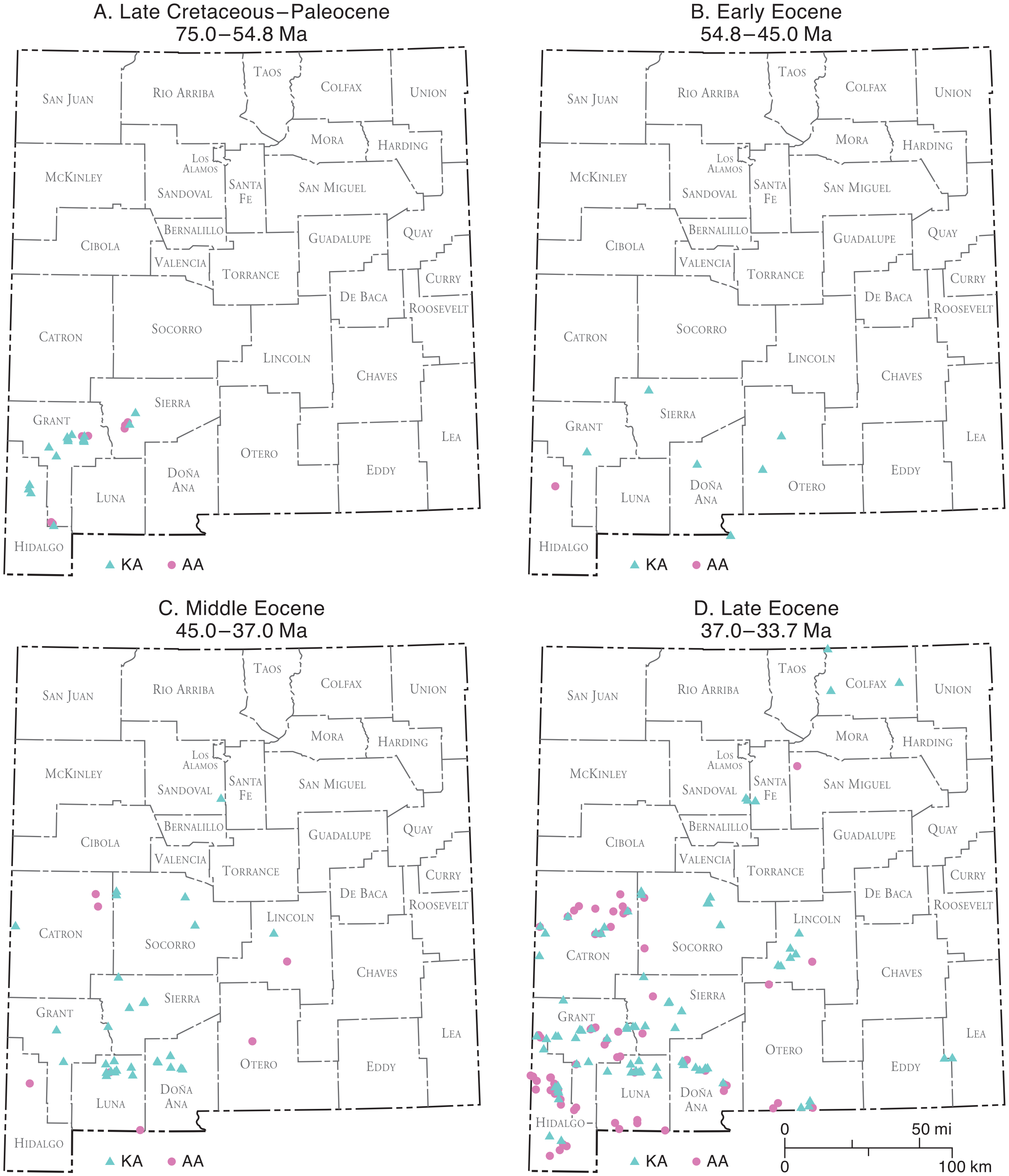


FIGURE 1B—Map showing time–transgressive migration of calderas (arrows) and major lineaments discussed in text. See Fig. 1A for explanation.


A. Late Cretaceous–Paleocene
75.0–54.8 Ma

B. Early Eocene
54.8–45.0 Ma

C. Middle Eocene
45.0–37.0 Ma

D. Late Eocene
37.0–33.7 Ma

FIGURE 2—Space-time plots of magmatism in New Mexico based upon K-Ar (blue triangles) and ^{40}Ar/^{39}Ar (red dots) ages. **A**–Late Cretaceous and Paleocene 75–54.8 Ma; **B**–early Eocene 54.8–45.0 Ma; **C**–middle Eocene 45.0–37.0 Ma; **D**–late Eocene 37.0–33.7 Ma. Data available in Wilks and Chapin (1997) and subsequent revisions to Database DDS–DBI.

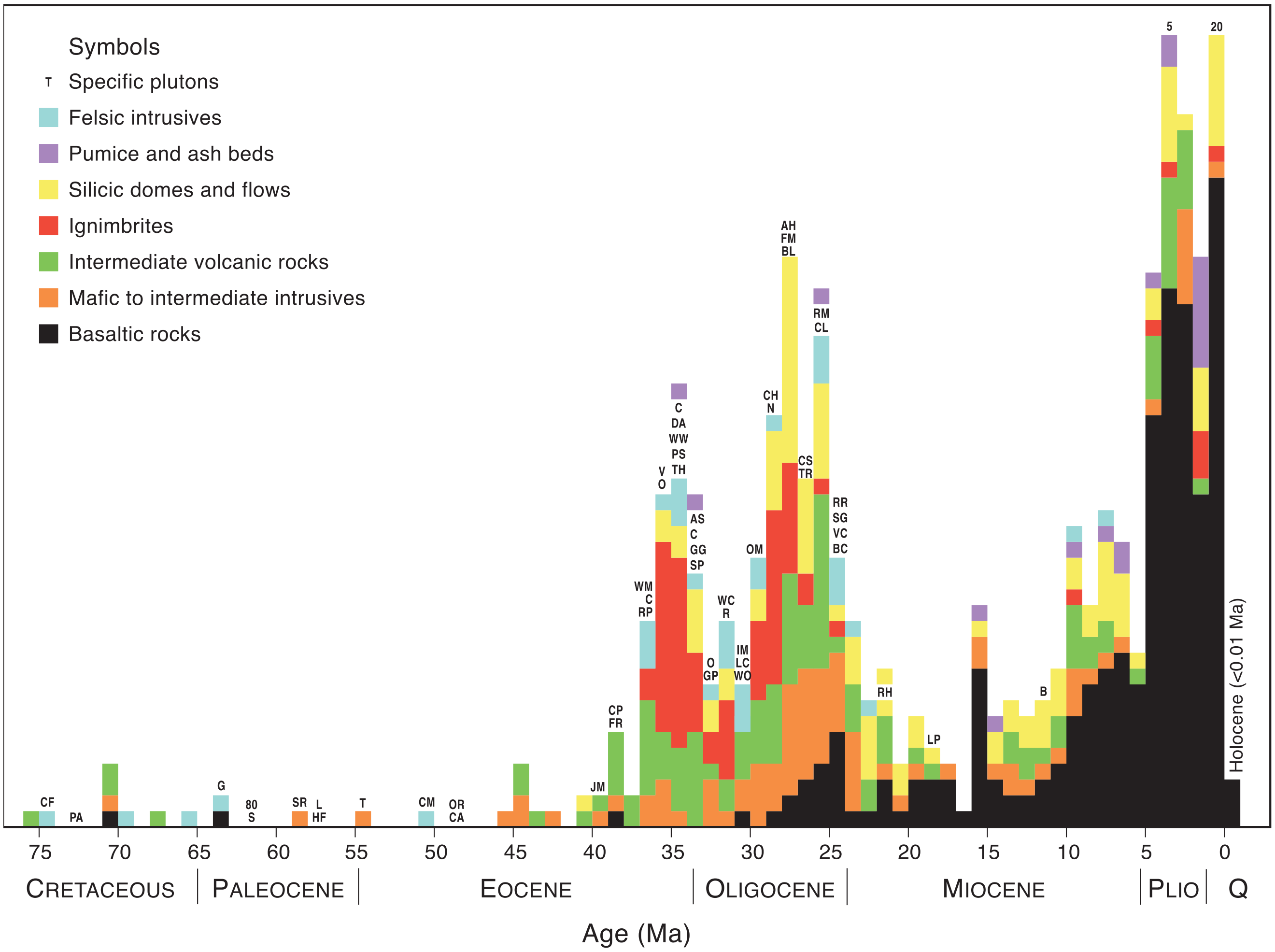


FIGURE 3—Histogram of K-Ar and $^{40}Ar/^{39}Ar$ ages of igneous rocks in New Mexico, Late Cretaceous to present. Only one point plotted for each event or stratigraphic unit, so far as could be ascertained. Dates known or suspected to have significant errors not used. Legend identifies rock types; abbreviations indicate specific plutons. (See Table 1). Numbers in Pliocene and Pleistocene columns indicate number of additional basalts not shown to keep column on the page. Holocene dates shown to right of zero.

Space-time patterns

Late Cretaceous and Paleocene (75–54.8 Ma)

Early Laramide (Late Cretaceous–Paleocene) magmatism (Fig. 2B) in New Mexico was concentrated along and to the south of the Santa Rita lineament (Fig. 1B), which trends about N55°E from the Arizona border in northern Hidalgo County through the Silver City (Grant County) area to the Hillsboro district in western Sierra County. The Santa Rita lineament is one of a series of northeast-trending, complex structural and magmatic zones that cross New Mexico and Colorado (Chapin et al. 1978). The best known are the Colorado Mineral Belt and the Jemez lineament, both of which are approximately parallel to Proterozoic age-province boundaries (Karlstrom and Bowring 1988; Karlstrom and Humphreys 1998). The Continental Dynamics—Rocky Mountain project (CD-ROM) Working Group (2002) recently published a north–south seismic tomographic cross-section of the lithosphere beneath the Southern Rocky Mountains that shows several velocity anomalies that project upward to near Proterozoic crustal boundaries. This suggests that the northeast-trending lineaments may have originated as sutures or subduction zones that formed as Proterozoic land masses were accreted to the Wyoming Archean nucleous. Whatever their origin, these flaws in the lithosphere have provided pathways for the ascent, storage, and differentiation of magmas.

The Laramide of southern New Mexico is difficult to write about because the area is magmatically complex and there are relatively few reliable radioisotopic ages. Many of the K-Ar ages were determined on hornblende, which is notorious for containing excess argon incorporated during crystallization (Harrison and McDougall 1999) and which may result in anomalously old ages. For example, K-Ar ages reported for the Hanover–Fierro stock near Silver City range from 72.2 Ma (hornblende) to 57.6 Ma (biotite). $^{40}Ar/^{39}Ar$ ages of 57.03 ± 0.05 and 57.39 ± 0.07 on potassium feldspar and 57.55 ± 0.07 on biotite indicate that the younger ages are probably more accurate (McLemore et al. 1995). Alternatively, intrusion-related geothermal anomalies greater than 250 °C may have reset the K-Ar and $^{40}Ar/^{39}Ar$ ages of biotite and potassium feldspar as has happened in the Leadville mining district (Bookstrom 1990) and Mount Princeton batholith of Colorado (McIntosh and Chapin 2004 this volume). Another complication is that most radioisotopic ages are on intrusives because of the interest in mineral deposits and the difficulties in dating the intermediate to mafic flows and breccias that lack potassium-rich minerals and are often hydrothermally altered. Extensive cover by middle Tertiary volcanic rocks and basin-fill sediments is also a factor. Thus, sample sites of Late Cretaceous and Paleocene radioisotopically dated volcanic rocks would fill in more of the area of southwesternmost New Mexico in figure 2A if exposures and dates were available.

The histogram of Figure 3 suggests that magmatism occurred sporadically from 75 to 54 Ma. See Table 1 for a list of specific plutons corresponding to the abbreviations used in Figure 3. For additional information use the age and county listed in Table 1 to locate entries for specific plutons in the New Mexico Geochronological Database (Wilks and Chapin 1997).

Interpretation of the Late Cretaceous and Paleocene magmatism requires a review of magmatic patterns in the western U.S. and plate tectonic models. The volcanic arc related to subduction of the Farallon plate beneath North America began to sweep northeastward from its position along the coastal range batholiths of Baja and southern California at about 100 Ma (Fig. 4) and reached southwestern New Mexico by about 70 Ma (Coney and Reynolds 1977; Keith 1978). The inboard migration of the volcanic arc has been interpreted as resulting from flattening of the subducted slab (Fig. 4) due to increased rate of convergence between the Farallon plate and North America (Coney and Reynolds 1977; Keith 1978; Cross and Pilger 1978), or subduction of an oceanic plateau (Livaccari et al. 1981). The subducting Farallon plate consisted of discrete segments that subducted at different rates and angles (Cross and Pilger 1978). The volcanic arc had been continuous along the western margin of the United States but became discontinuous as volcanism migrated into the continent. A Laramide magma gap (~ 75–40 Ma) developed from northern Sierra County, New Mexico, to southern Idaho, within which Laramide magmatism was restricted to the Colorado Mineral Belt, a northeast-trending magmatic belt superimposed on a series of major shear zones (Warner 1978; Tweto and Sims 1963) and mentioned previously as approximately paralleling Proterozoic age-province boundaries.

Two hypotheses have been put forth to explain the Laramide magma gap: (1) very flat subduction that extinguished volcanism and transmitted compressive stresses far inland to buckle the upper crust into the Laramide Southern Rocky Mountains (Cross and Pilger 1978); and (2) transpressional collision of a microplate with the western margin of North America that temporarily prevented subduction beneath the western United States (Maxson and Tikoff 1996). Flat subduction has been a controversial concept in the western United States (for example, Mutschler et al. 1988), but the extensive geological and geophysical documentation of segments of flat subduction in the Andes of South America provides a sound basis for its application to the older, but similar, continental margin volcanism in North America. Papers by Jordan et al. (1983), Jordan and Allmendinger (1986), Soler and Bonhomme (1990) James and Sacks (1999), Gutscher et al. (2000), and Kay and Mpodozis (2001) are particularly informative.

The microplate collision (Baja British Columbia hypothesis) was based mainly on discordant paleomagnetic directions of Insular and Intermontane terranes that form the west coast of Canada and southeastern Alaska. As interpreted by Maxson and Tikoff (1996), these terranes were part of a microplate that collided with North America at the latitude of modern Baja California and were subsequently transported northward up to 4,000 km during oblique transpressional convergence of the Kula and North America plates between 94 and 40 Ma. However, more recent paleomagnetic studies, taking into account the effects of compaction shallowing and chemical remagnetization, limit post-mid-Cretaceous northward translation to about 1,000 km (Butler et al. 2001). Paleontologic studies of bivalve rudists suggest that Baja British Columbia was no farther south than 40°N latitude (northern California) in the Late Cretaceous, which limits nortward movement to less than 1,500 km (Kodama and Ward 2001). Thus, passage of a microplate is not consistent with the timing and spatial extent of the Laramide magma gap, nor does it explain the magmatic history of the region. However, the controversy continues as evidenced by the number of presentations on the subject at the 2002 and 2003 Cordilleran Section Geological Society of America meetings (see for example Brandon 2002; and Miller et al. 2002).

To the south of the magma gap, magmatism in the Hillsboro district occurred at least 100 km cratonward (northeast) of the northeast-migrating volcanic arc, a phe-

TABLE 1—Named plutons denoted by abbreviations in Figure 3 and listed in order of decreasing age. Approximate age and county listed to facilitate locating entries in Digital Database DDS–DBI (Wilks and Chapin 1997).

Pluton	Age	County
Copper Flat (CF)	75	Sierra
Pinos Altos (PA)	72	Grant
Gomez (G)	63	Grant
Salado (S)	61	Sierra
Eighty Mountain (80)	61	Grant
Santa Rita (SR)	58	Grant
Lordsburg (L)	57	Hidalgo
Hanover-Fierro (HF)	57	Grant
Tyrone (T)	54	Grant
Cuchillo Mountain (CM)	50	Sierra
Orogrande (OR)	48	Otero
Campus Andesite (CA)	48	Doña Ana
Jicarillo Mountains (JM)	39	Lincoln
Cookes Peak (CP)	39	Luna
Fluorite Ridge (FR)	39	Luna
Wind Mountain (WM)	36	Otero
Cornudas Mountains (C)	36	Otero
Reilly Peak (RP)	36	Sierra
Organ (O)	36	Doña Ana
Victorio Mountains (V)	35	Luna
Cornudas Mountains (C)	35	Otero
Tres Hermanos (TH)	35	Luna
Doña Ana (DA)	35	Doña Ana
Palisades Sill (PS)	35	Colfax
Walnut Wells (WW)	34	Hidalgo
Animas (AS)	34	Hidalgo
Cornudas Mountains (C)	33	Otero
Granite Gap (GG)	33	Hidalgo
Sugarloaf Peak (SP)	33	Doña Ana
Organ (O)	33	Doña Ana
Granite Pass (GP)	33	Hidalgo
Water Canyon (WC)	31	Socorro
Rialto (R)	31	Lincoln
White Oaks (WO)	31	Lincoln
La Cienega (LC)	30	Santa Fe
Iron Mountain (IM)	30	Socorro
Ortiz Mountains (OM)	30	Santa Fe
Nitt (N)	29	Socorro
Cerrillos Hills (CH)	29	Santa Fe
Florida Mountains (FM)	28	Luna
Bonito Lake (BL)	27	Lincoln
Apache Hills (AH)	27	Hidalgo
Three Rivers (TR)	27	Lincoln
Capitan (CS)	27	Lincoln
Rito Del Medio (RM)	25	Taos
Cabresto Lake (CL)	25	Taos
Red River (RR)	25	Taos
Sulfur Gulch (SG)	25	Taos
Virgin Canyon (VC)	25	Taos
Bear Canyon (BC)	24	Taos
Rio Hondo (RH)	21	Taos
Lucero Peak (LP)	19	Taos
Bland (B)	11	Sandoval

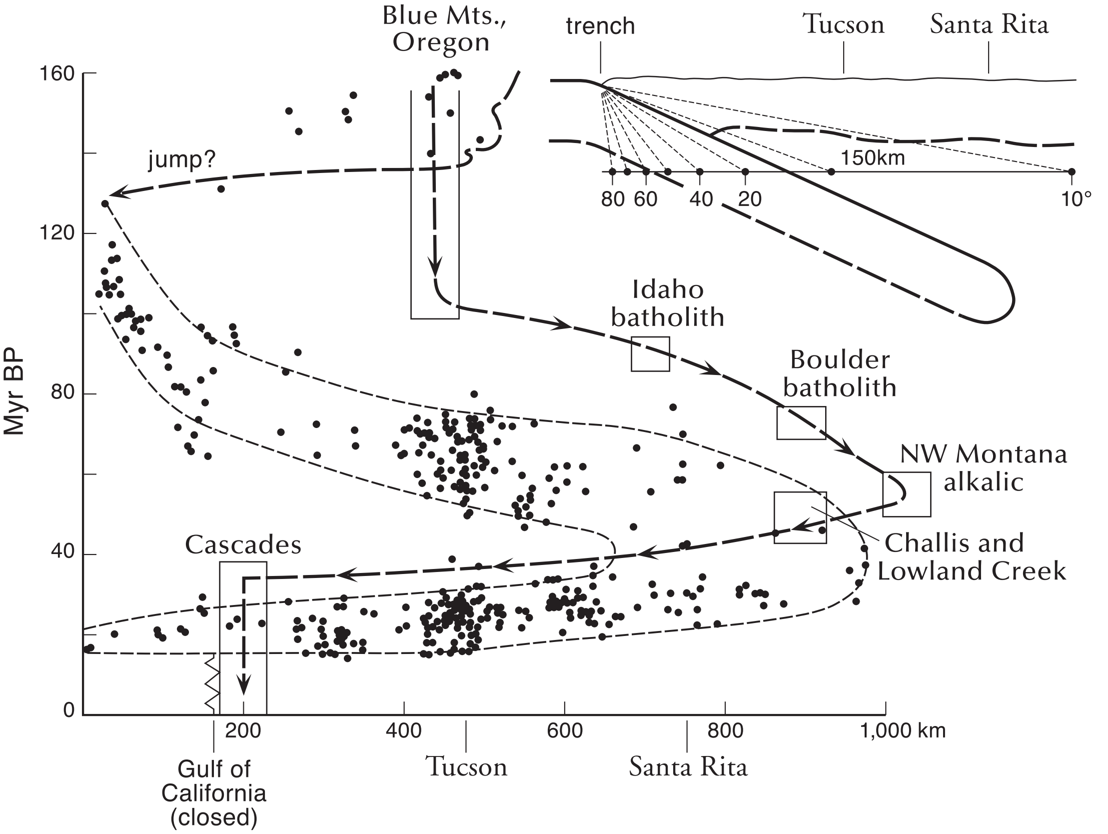


FIGURE 4—Ages of magmatism versus distance from western margin of North American plate. Dots are radiometric ages plotted by Coney and Reynolds (1977). Figure at upper right shows how dip angles of Benioff zones, varying from 80° to 10°, affect distance to intersection of the subducting slab with the 150 km depth line (from Coney and Reynolds 1977). Dashed line with arrows connecting labeled boxes shows trends of magmatism in northern U.S. Cordillera, compiled from multiple sources by Lipman (1992). In both the southern and northern regions, the Late Cretaceous to middle Tertiary eastward sweep of magmatism has been related to flattening of the oceanic slabs being subducted beneath North America. Though the patterns are similar, the timing of eastward migration, followed by rapid westward retreat is not synchronous between the northern and southern regions. Flat slab segment(s) not shown. Figure redrawn from Lipman (1992), with permission of the Geological Society of America.

nomenon observed along transverse lineaments in other volcanic arcs (Carr et al. 1973, 1974; Stoiber and Carr 1973; McBirney et al. 1974; Hughes et al. 1980; Allmendinger et al. 1997; Tosdal and Richards 2001). The position of the volcanic arc at 75 Ma is not well constrained because K-Ar ages of plutons range widely due to the long-lived nature of complex intrusive centers, hydrothermal alteration, and problems inherent in the K-Ar method. Also, McDowell et al. (2001) have recently shown with U-Pb zircon ages that the initiation of volcanism in eastern Sonora, Mexico, began substantially earlier than predicted by geochronology based mainly on plutons. A volcanic pile may be built over a period of several million years before high-level plutons invade it. A similar U-Pb zircon study of Late Cretaceous and early Tertiary volcanic rocks would be useful in southern New Mexico.

Eocene (54.8–33.7 Ma)

The Eocene is a very long epoch (21.1 m.y.) and contains two major tectonomagmatic transitions in the western United States. During the early Eocene (54.8–45 Ma) the Laramide volcanic arc reached as far northeast as the Jarilla Mountains in Otero County of south-central New Mexico (Fig. 2B) where a subeconomic porphyry copper system was emplaced at Orogrande between 48 and 42 Ma (Beane et al. 1975). Mafic to intermediate alkaline dikes and sills in the Sacramento Mountains of Lincoln and Otero Counties, dated by K-Ar and $^{40}Ar/^{39}Ar$ at 44–36 Ma (Asquith 1974; Hutt et al. 1999) were intruded at the very end of the Laramide and during the post-Laramide transition to regional extension. According to Dowe et al. (2002) the high alkali ($K_2O < Na_2O$) nepheline-normative compositions of these intrusives indicate that they may be the easternmost early rift magmas. The northernmost Laramide intrusives in New Mexico are the Cuchillo Mountain stock (50 Ma, K-Ar, hornblende) near Winston in northwestern Sierra County and the Salinas Peak rhyolite sill (49.6 ± 3.8 Ma FT zircon cooling age, Kelley and Chapin 1997) in the San Andres Mountains of northeastern Sierra County. To the north the rest of New Mexico was in the Laramide magma gap caused by flat subduction of segments of the Farallon plate.

At approximately 45 Ma a major change in movement of the Pacific plate from north-northwest to northwest has long been interpreted by the bend in the Hawaii–Emperor seamount chain (Morgan 1972; Clague and Jarrard 1973; Clague and Dalrymple 1989; Atwater 1989). However, Tarduno et al. (2003) have recently questioned this interpretation by determining from paleomagnetism of samples recovered from ocean drilling an age-progressive paleolatitude history for the Emperor seamounts. Thus, it appears that the hot spot moved progressively southward between 81 and 47 Ma, and little or no change in the direction of Pacific plate movement is required. However, based on global plate circuit analysis, the Farallon plate–North American convergence slowed from approximately 11–14 cm/yr to 6–9 cm/yr during this time interval (Stock and Molnar 1988). As convergence slowed the portion of the Farallon plate that had subducted at an increasingly low angle beneath the western U.S. during the 80 to 45 Ma period of rapid convergence began to sink and "roll-back" toward the trench or fall away in pieces (Atwater 1989). Regional compression induced by viscous coupling between the subducting slab and the overriding North American plate was markedly reduced thus ending the Laramide orogeny.

Accurate dating of the end of the Laramide in New Mexico is difficult to establish. After approximately 45 Ma volcanism spread northward into the Laramide magma gap (Fig. 2C), but reliable ages on these rocks are few and far between. Sample localities shown in Figure 2C are mainly around the periphery of the Mogollon–Datil volcanic field because of cover by younger rocks in the central portion of the field. The rocks are a highly variable mix of intermediate to mafic breccias, flows, and volcaniclastic sedimentary rocks that most geologists find difficult to work with. They comprise the basal one-half or more of the Mogollon–Datil, Boot Heel, and Sierra Blanca volcanic fields. Lipman et al. (1970, 1978) estimate that their equivalent in the San Juan volcanic field of Colorado, the Conejos Formation and equivalents, were deposited over more than 25,000 km^2 with an original volume of at least 40,000 km^3 and comprise two-thirds of the volume of that field. In the Mogollon–Datil field, the early intermediate rocks are called the Rubio Peak Formation (Jicha 1954; Elston 1957; Harrison 1986), Palm Park Formation (Kelley and Silver 1952; Seager et al. 1971), and Spears Formation of the lower Datil Group (Tonking 1957; Osburn and Chapin 1983; Cather et al. 1987). K-Ar ages of these rocks range from 44 to 36 Ma with large uncertainties; the oldest ^{40}Ar/^{39}Ar age is 38.7 Ma.

The regional stress field between 45 and 36 Ma was probably a weakly compressional, near-neutral regime. The Farallon plate continued to subduct beneath the North American plate but at a much slower rate. In Colorado an erosion surface of relatively low relief was carved across Laramide uplifts and extended across aggrading basins before eruption of the 36.7 Ma Wall Mountain Tuff (Epis and Chapin 1975). The late Eocene surface (Rocky Mountain surface of Evanoff and Chapin 1994) can be traced southward into northern New Mexico where it forms the exhumed low-relief surface on the Tusas Mountains of Rio Arriba County. The San Juan volcanic field of southwestern Colorado rests upon a comparable late Eocene surface of low relief known as the Telluride surface (Atwood and Mather 1932; Larsen and Cross 1956). In central and southern New Mexico the late Eocene surface is difficult to reconstruct, if present, because andesitic volcanism and minor contractional faulting continued until about 36 Ma (Cather 1990). However, Schmitt (1933) and Livingston et al. (1968) reported that most of the Laramide porphyry copper deposits in southern Arizona and southwestern New Mexico were leached and supergene enriched before burial by volcanic and sedimentary deposits of middle and late Cenozoic age. Cather et al. (2003) have recently identified a low-relief paleoerosion surface in the Chuska Mountains of northwestern New Mexico that post-dates Laramide deformation in the Defiance monocline and underlies the upper Eocene–lower Oligocene Chuska Sandstone.

Tectonic stress plays a major role in determining the style and composition of continental volcanism by controlling the mechanism of ascent of magmas through the crust, which affected the differentiation of the magmas. Eichelberger (1978) concludes that intermediate-composition volcanism is favored by a compressional tectonic environment in which rising rhyolitic diapirs trap basalt and mix convectively to form hybrid magmas. Many studies have reported the presence of basaltic inclusions in intermediate to silicic rocks (for example Sparks et al. 1977; Eichelberger and Gooley 1977; Eichelberger 1978, 1980; Reid et al. 1983; Vernon 1984). The inclusions are often rounded clots with fine-grained, quenched margins. Also common are xenocrysts and zoned phenocrysts totally out of equilibrium with the magma in which they reside (Eichelberger 1978). Banded pumice with alternating silicic and more mafic layers has also been observed in ignimbrites (Sparks et al. 1977; Cas and Wright 1987). Eichelberger (1978, 1980) summarizes the evidence for magma mixing and proposes the following model. Emplacement of basaltic sills in the lower crust causes partial melting with the resultant rhyolite liquids gathering into pluton-size bodies that rise through the crust as diapirs. The rising diapirs are injected with basalt, which causes rapid convection and mixing. The resulting hybrid magmas are the andesites and dacites that dominate the intermediate-composition rock associations of continental volcanic fields and the underlying granodioritic batholiths.

In his study of stress and volcanism in the northern Mogollon–Datil volcanic field, Cather (1990) concluded that tectonic compression during Laramide crustal shortening prevented dike propagation on a regional scale. This left diapirism as the only major mechanism available for ascent of magmas during the early intermediate-composition volcanism that formed the basal one-half of the volcanic field. Cather states that "Because diapirs derive buoyancy from density contrast over a short depth interval, basaltic melts must evolve to at least basaltic andesite composition to penetrate low-density continental crust." Regardless of whether the diapirs began as rhyolitic melts and evolved to andesitic magmas by trapping basalt as suggested by Eichelberger (1978), or evolved through assimilation of wall rocks and fractional crystallization during ascent as diapirs, the result is hybrid, intermediate-composition rocks. Eichelberger's model requires high melt fluid pressures in order for basaltic magmas to rise as dikes and intersect silicic diapirs. The evidence for mixing of silicic and basaltic magmas, however, seems compelling.

More recently, detailed studies of an unusually well exposed, deeply eroded, early Mesozoic arc in New Zealand lead Klepseis et al. (2003) to conclude that development of high melt fluid pressures during melt production caused brittle failure and development of networks of vertical extension fractures that allowed segregation and initial ascent of melt out of the lower crust. Also, their isotopic data (Sr, Nd) suggested that rapid ascent of magmas through fracture networks and shear zones inhibited crustal contamination at shallower levels (Klepseis et al, 2003). Thus, in areas of rapid and voluminous melt production, high melt pressure may trump a weak regional compressive stress field.

The second Eocene tectonomagmatic transition was marked at 37–36 Ma by the beginning of regional extension and the eruption of large-volume ignimbrites (Figs. 3,5). This began the well-known ignimbrite "flare up" involving the entire southwestern quarter of New Mexico (Fig. 2D) and neighboring Basin and Range province. The transition from Laramide compression to middle Tertiary extension in the Mogollon–Datil field (Cather 1990) is indicated by (1) displacement reversal across fault zones in the Baca Basin of west-central New Mexico, (2) initial foundering and burial of Laramide uplifts beneath what would later become basins of the Rio Grande rift, and (3) the change from early intermediate composition volcanism of the lower Datil Group to bimodal basaltic andesite–silicic ignimbrite volcanism of the upper Datil Group. [Note: in Figure 3 many dark-colored, mafic lavas of late Eocene–early Oligocene

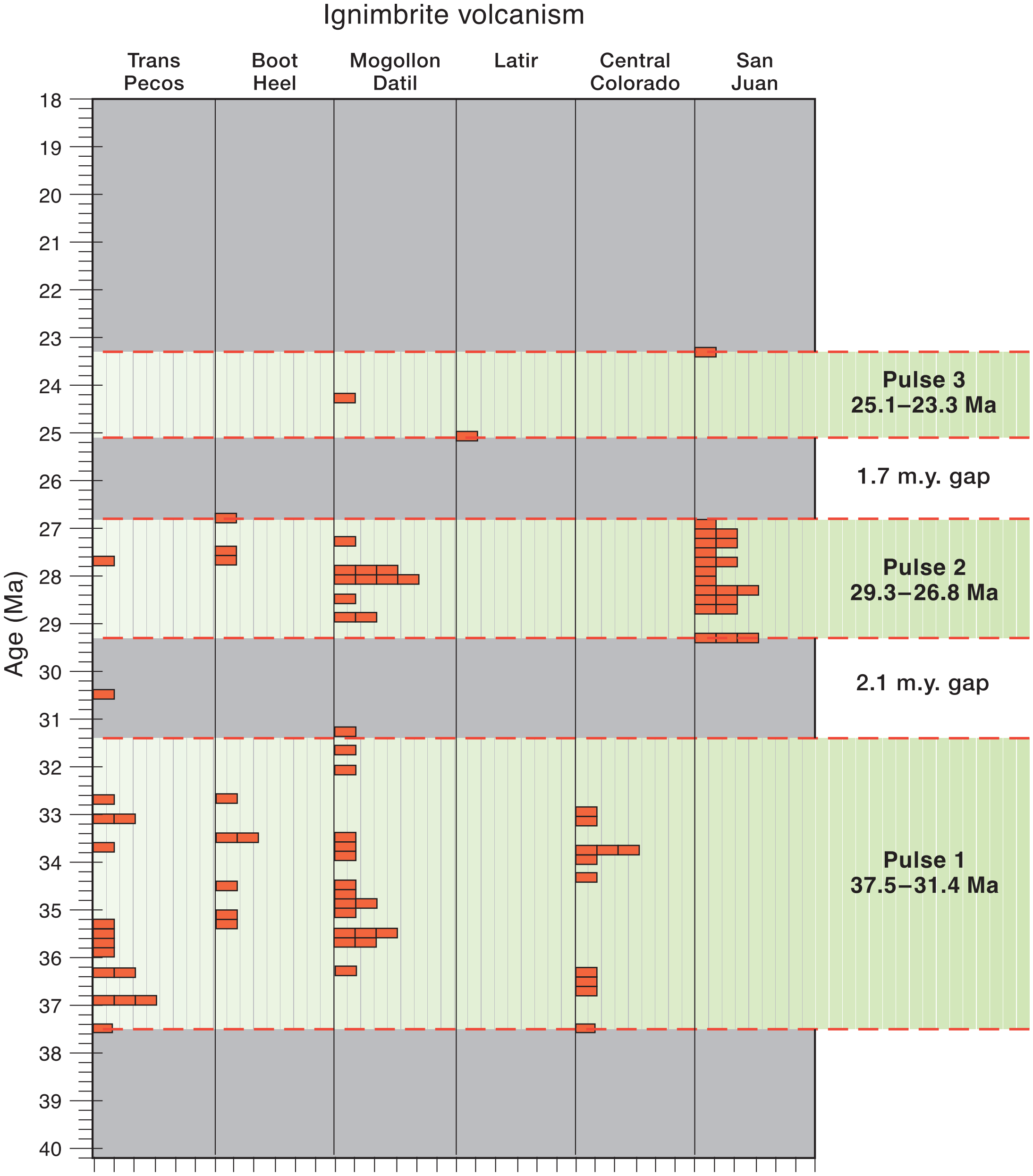


FIGURE 5—Graph showing episodic ignimbrite volcanism in New Mexico, Colorado, and Trans-Pecos Texas (includes two ignimbrites from adjacent calderas in Mexico).

age, classified as intermediate in early reports and lacking chemical data, could be considered basaltic.] Additional evidence is present in the Las Cruces area where subsidence of the Goodsight–Cedar Hills half-graben and accumulation within it of six ignimbrite outflow sheets erupted elsewhere indicates that basin subsidence was tectonic rather than magmatic in origin (Mack et al. 1994; McMillan et al. 2000). The oldest of these tuffs were erupted from the nearby Organ cauldron between 36.2 and 35.7 Ma (McIntosh et al. 1991).

Sparks et al. (1977) proposed that injection of basic magma into silicic magma chambers causes superheating, vigorous convection, and vesiculation, which may fracture the volcanic edifice and trigger an explosive eruption. Cather (1990) pointed out that basaltic andesite melts, which were more dense than upper continental crust, were able to ascend via diking because dikes derive buoyancy over a large vertical extent with "roots" in the dense upper mantle or lower crust. The change from intermediate-composition volcanism to bimodal basaltic andesite and silicic ignimbrite volcanism coincided with the onset of regional extension. Regional extension provides the missing link in cross-sectional models of how the crust changes during the switch from intermediate-composition to bimodal volcanism. The abrupt formation of very large, shallow batholiths (see Lipman et al. 1978; Lipman 1988), compositionally zoned from granite to granodiorite or quartz monzonite and containing basaltic inclusions is a bit mysterious without the change in tectonic stress that expedites rapid ascent of both silicic and mafic melts.

Ignimbrite volcanism in New Mexico and neighboring areas of Colorado and Trans-Pecos Texas was episodic beginning at approximately 37–36 Ma, largely ended by 26.8 Ma but had three last gasps between 25.1 and 23.3 Ma (Fig. 5). Two gaps, or lulls, in ignimbrite volcanism are conspicuous throughout the area. The first occurred between approximately 31.4 and 29.3 Ma and the second between approximately 26.8 and 25.1 Ma (Fig. 5). Only one ignimbrite is known to have been erupted within these two intervals, and nearly all regional ignimbrites within this area have now been dated by $^{40}Ar/^{39}Ar$. The two gaps are quite remarkable in light of the 86 regional ignimbrites emplaced with a total volume of at least 30,000 km^3.

The common element along the 1,100-km Trans-Pecos Texas–Colorado segment of the Cordillera is a subducted Farallon plate that began to roll back or sink deeper into the mantle, perhaps as several large pieces, after convergence slowed at about 45 Ma. This allowed asthenospheric mantle to flow into the growing wedge above the subducted plate and heat the overlying continental mantle lithosphere that had previously been enriched in fluids and trace elements by subduction processes. Several authors, such as Kempton et al. (1991) and Davis et al. (1993), have argued on isotopic grounds that enrichment of the lithospheric mantle must have occurred long ago, probably during Proterozoic assembly of the continent. As upwelling asthenosphere heated the lithospheric mantle, melting generated magmas enriched in large-ion-lithophile elements (Ba, Rb, Sr) and light-rare-earth elements (La, Ce, Nd, Sm) that are more soluble in fluids than high-field-strength elements (Nd, Ta) that tend to be retained in dehydrating slabs (Davis et al. 1993; Davis and Hawkesworth 1995; McMillan et al. 2000). Isotopic and trace element studies of middle Tertiary volcanic rocks in southwest New Mexico by these authors indicate that the parental magmas were derived from enriched lithospheric mantle in contrast to late Cenozoic rift-related rocks (< 9 Ma) whose compositions reveal derivation from the asthenosphere.

Magmatic evolution of the middle Tertiary volcanic fields began with intrusion of basaltic melts from the lithospheric mantle, partial melting of the lower crust, and generation of hybrid blends of fractionated basalt and crustal melts. These magmas rose as diapirs to feed central volcanoes and small subvolcanic plutons. Eruption of intermediate-composition lavas and breccias from these volcanoes and the coalescence of complex volcaniclastic aprons surrounding the volcanoes formed the basal one-half to two-thirds of the volcanic fields. Magmas erupted during this early intermediate phase were highly variable, ranging from basaltic andesite to rhyolite, but were mostly andesitic to dacitic. The capping phase of the large, middle Cenozoic volcanic fields in New Mexico and Colorado involved a major flux of basaltic magma into a crust that had been heated by magma of the early intermediate phase. The density of the lower crust had been increased by the addition of mafic sills (Glazner and Ussler 1988; Johnson 1991) that, in combination with high heat flow, expedited the ascent of magmas to higher levels in the crust. Also expediting magma ascent was the beginning of regional extension that permitted rapid ascent by diking and less hybridization of magmas. The result was coalescing of numerous intermediate to silicic magma bodies to form large batholiths of probable laccolithic shape (Lipman 1988; Petford 1996) at shallow crustal levels. Johnson (1991) estimates from neodymium isotopic analyses that the ignimbrites erupted from these batholiths contain a major, often dominant, mantle component. He concludes that, whereas the largest volumes of mafic lavas were erupted after caldera-related magmatism, the largest fluxes of basaltic magma into the crust occurred during the ignimbrite magmatism (see also Perry et al. 1993).

The synchronous ignimbrite eruptive episodes and gaps extending from Trans-Pecos Texas to central Colorado require a regional mechanism. The abrupt turning on and off of the eruptive pulses requires a means of preventing eruptions from continuing and then of starting them up again. But can magmas ascend rapidly enough through the mantle and crust to provide the quick reaction time required for the abrupt on–off behavior? Several lines of evidence indicate that magmas rise surprisingly fast. Basaltic melts originating at depths of about 100 km beneath island arcs acquire excess U^{238} from aqueous fluids given off by the subducting plate. Uranium-thorium isotopic disequilibria has been used to estimate transit times between release of the fluids and arrival of lavas at the surface (Turner et al. 2001). Preservation of excess concentrations of radium–226 (half-life 1,600 yrs) in island arc lavas indicates a transit time from slab to surface of only a few hundred to a few thousand years, which yields an average melt velocity of approximately 1,000 m per yr (Turner et al. 2001). Hall and Kincaid (2001) studied the rise of diapirs in a scale-model subduction zone and observed that where multiple diapirs of strongly buoyant fluid form a network of diapir trails, subsequent diapirs encountering this network rise to the surface in 104 to 106 yrs. This is ample time to preserve the high degrees of U-Th disequilibrium observed in island arcs. Turning to silicic magmas, Petford (1996) calculates ascent rates of ~ 10^{-2} m/s for granitic melts in dikes compared to 10^{-10}–10^{-7} m/s for granitic diapirs. He proposes a model in which batholiths are formed by coalescence of tabular sills or laccoliths fed by granitic feeder dikes. Petford (1996) suggests that batholith assembly may be dominated by long periods of inactivity interrupted by rapid bursts of activity with melts arriving via dikes. The rate-limiting step in pluton formation is how fast and how much melt is produced in the source region at any one time (Hanson and Glazner 1995; Petford 1996). In Petford's model, space is created by a combination of faulting, inflation, and surface uplift.

Lawton and McMillan (1999) derived a three-phase tectonic model (Fig. 6) for creation of passive continental rifts above foundering subducted slabs by comparing the Jurassic–Early Cretaceous Mexican Borderland rift and the Cenozoic Rio Grande rift. During phase one thick accumulations of andesitic to dacitic rocks preceded both rifts and had high La/Ta ratios and low ε Nd consistent with partial melting of subcontinental lithosphere. Mafic lavas were rare or absent due to their inability to penetrate low-density crust under neutral to compressive stress and/or because they were captured by silicic magma bodies. Phase two (Fig. 6) begins with concurrent regional extension and eruption of a bimodal suite of silicic ignimbrites and mafic lavas. Spatial correlation of rifting with the inboard extent of the preceding volcanic arc suggests to Lawton and McMillan (1999) that ascent of arc magmas and resultant thermal weakening of the crust controls the locus and orientation of brittle upper crustal extension as slabs begin to roll back. Phase three (Fig. 6) begins when slab retreat and return flow of asthenosphere above the sinking slab has proceeded far enough to allow decompression partial melting of asthenospheric mantle and resultant eruption of basalts with chemical signatures similar to ocean island basalts (low La/Ta, high ε Nd).

Correlation of the ignimbrite flare up with the change of regional stress from compression to tension seems firm on both theoretical grounds and field and petrologic relationships. However, determining the beginning of regional extension is often difficult and not without controversy. For example in the Socorro area the beginning of extension could be picked at 36 Ma based on Cather's evidence for the change to bimodal volcanism and a change from reverse to normal faulting, or approximately 29 Ma based on the beginning of domino-style normal faulting at Socorro (Chamberlin 1983; Cather et al. 1994), or approximately 27–26 Ma based on the oldest sediments preserved in a rift basin (Osburn and Chapin 1983), or approximately 16 Ma

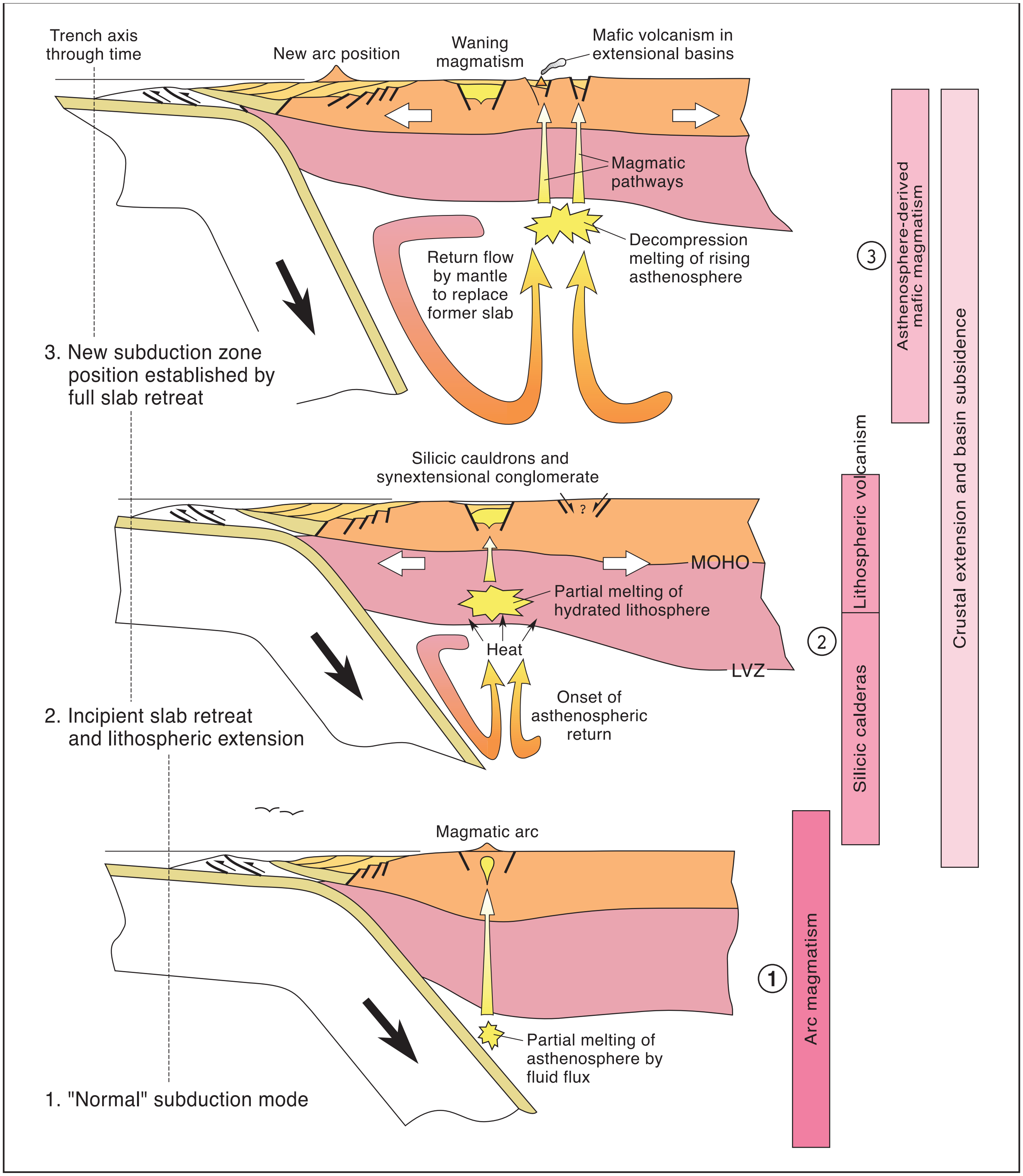


FIGURE 6—Tectonic model for creation of passive continental rift above foundering subducted slab. Redrawn from Lawton and McMillan (1999) with permission of the Geological Society of America.

based on the onset of rapid subsidence of rift basins (Cather et al. 1994). Similar opportunities for disagreement exist elsewhere. Aldrich et al. (1986) picked 32 Ma for the beginning of extension based on a study of the orientation of K-Ar-dated dikes in New Mexico. Henry et al. (1991) and James and Henry (1991) also picked 32–31 Ma as the change to regional extension in Trans-Pecos Texas based on dike and vein orientations and changes in magma chemistry from arc-like to bimodal alkali basalt-rhyolite. However, ignimbrite volcanism began in Trans-Pecos Texas about 37 Ma (Fig. 5). It appears that regional extension began rather haltingly as the subducted Farallon slab began to roll back, perhaps in pieces. Bimodal silicic ignimbrite–mafic lava volcanism began several million years before extension was strong enough for normal faulting and basin subsidence to become conspicuous.

As discussed earlier with regard to the paper by Klepeis et al. (2003), basaltic melt production in the mantle may increase melt pressure in the lower crust sufficient to overcome a weakly compressive regional stress field. High-volume magmatic "nodes" may result and exhibit evidence of extensional strain independent of weak regional compression. This may be responsible for some of the divergent opinions as to the beginning of regional extension in the New Mexico region.

If retreat or roll back of the subducted Farallon plate was a major factor in causing the middle Cenozoic volcanism in New Mexico and vicinity, perhaps how it retreated may also be important. Coney and Reynolds (1977) envisaged a rapid retreat of volcanism west–southwestward toward the trench as the dip of the Farallon plate increased. Atwater (1989) suggested that the slab may have broken up and fallen away in pieces. Humphreys (1995) proposed that the subducted Farallon plate separated by tearing or necking near the northern and southern boundaries of the United States and buckled downward along an east-west trending axis at the latitude of southern Nevada–northern Arizona. Movement of the separated edges toward the central axis of downwelling, accompanied by asthenospheric upwelling behind the trailing edges, explains the southward progression of east–west belts of volcanism from Idaho to southern Nevada from approximately 54 to 21 Ma, concurrently with northwestward retreat of volcanism from southern Arizona toward the axis of buckling (Humphreys 1995). However, Humphreys' map of volcanic belts shows a single, sinuous, north-trending belt from the Mogollon–Datil field through central Colorado labeled 37 Ma without explanation as to how an implied westward retreat of the subducted slab beneath the Southern Rocky Mountains could occur perpendicular to the proposed east–northeast-trending axis of buckling beneath the Great Basin. Is it possible that the apparent conflict in directions of buckling could have caused alternating episodes of compression and tension as first one direction then another dominated? If so, individual east-west-trending volcanic belts in the Great Basin may also exhibit synchronous along-strike pulses of ignimbrite volcanism.

Inboard of the Great Basin magmatism also spread eastward in late Eocene as lamprophyre dikes (34.8–34.4 Ma, K-Ar, whole rock) were injected into Permian evaporites in southeastern New Mexico (Brookins 1980), and both alkaline and calc-alkaline intrusions perforated the Otero Plateau and the Hueco Mountains on the New Mexico–Texas border between 36.8 and 33.0 Ma (K-Ar, biotite; Barker et al. 1977; Henry et al. 1986). Recent ^{40}Ar/^{39}Ar ages (McLemore 2002) range from 36.32 ± 0.15 Ma (Wind Mountain, hornblende) to 34.48 ± 0.34 Ma (Red Hills syenite, biotite). These intrusions are part of the Trans-Pecos magmatic belt and the Rocky Mountain alkalic province (RMAP), which follows the Rocky Mountains–Great Plains boundary from Mexico to Canada (Mutschler et al. 1985, 1991; Wooley 1987; McLemore 1996). Magmatism became more alkaline as the depth of magma generation increased toward the boundary with the colder and thicker lithosphere beneath the Great Plains (Lipman et al. 1971; Keith 1978). Other Eocene rocks of the RMAP are present at Orogrande in Otero County; the Jicarilla and Alamogordo areas of the Sacramento Mountains; the Lincoln County porphyry belt; the Cerrillos, San Pedro, and Ortiz districts of Santa Fe and Sandoval Counties; and in the Laughlin Peak–Chico Hills area of Colfax County in northeastern New Mexico.

As evident in Figures 7A–D, alkaline magmatism continued to occur sporadically along the RMAP in Oligocene through Pleistocene time. The Oligocene and early Miocene alkaline magmatism in Colfax and Mora counties is overshadowed by the younger, prolific basaltic volcanism of the Jemez lineament. Gold mineralization and breccia pipes are frequently associated with alkaline intrusions of the RMAP (with Cripple Creek, Colorado, the best-known example). Examples in New Mexico are the White Oaks and Nogal–Bonito districts in the Lincoln County porphyry belt, the Ortiz–San Pedro districts in Santa Fe County, and the Elizabethtown–Baldy district of Colfax County.

Oligocene (33.7–23.8 Ma)

The Oligocene is a relatively short epoch (9.9 m.y.) but it is prominent in New Mexico's magmatic history. Especially prominent are the many large-volume ignimbrites and associated basaltic andesite lava fields that spread over vast areas of southwestern New Mexico and adjacent areas of Arizona and Chihuahua, Mexico. Impressive swarms of mafic dikes were also injected outward from the Mogollon–Datil and San Juan volcanic fields for many tens of kilometers into the Colorado Plateau and eastward toward the Great Plains (Chamberlin et al. 2002). Magmatism spread to all four corners of New Mexico (Fig. 7A) as relatively localized volcanism developed in many areas, including the diatremes of Ship Rock (26.4 Ma) and Mitten Rock (24.3 Ma). Magmatism also spread northward along the nascent Rio Grande rift. Several new or expanded volcanic fields developed in the Oligocene, including the Sierra Blanca, Ortiz, and Latir fields. Many felsic plutons were intruded, some associated with calderas and others as single bodies or independent complexes. Extrusion of silicic domes and flows was also widespread, including the very large Taylor Creek rhyolite field on the border of Catron and Sierra Counties.

Ignimbrite volcanism continued to be conspicuously episodic. (Note: Some of the ages cited below are slightly different from the published ages because they have been corrected to a Fish Canyon Tuff monitor age of 27.84 Ma.) The Oligocene epoch began during a 1.4 m.y. gap (33.5–32.1 Ma) in ignimbrite volcanism in the Mogollon–Datil field (Fig. 5) that followed the first pulse of ignimbrite eruptions of late Eocene age. After a brief (32.1–31.4 Ma) pulse that involved only three regional ignimbrites in the Mogollon–Datil field, major pyroclastic volcanism became nearly extinct between 31.4 and 29.3 Ma (Fig. 5) throughout the Southern Rocky Mountains and adjoining areas (Chapin and McIntosh 1990). The climax of ignimbrite volcanism began at about 28.9 Ma in the Mogollon–Datil field (McIntosh et al. 1992), 27.6 Ma in the Boot Heel field (McIntosh and Bryan 2000), and 29.3 Ma in the San Juan volcanic field of Colorado (Lipman 2000). In the Mogollon–Datil field, eleven major ignimbrites with a total volume in excess of 6,000 km^3 were emplaced during the brief interval 28.9–27.4 Ma (McIntosh et al. 1992). In the San Juan field, 20 large-volume ignimbrites were erupted during the interval 29.3–27.0 Ma with a volume of at least 8,000 to 10,000 km^3 (Lipman 2000). In both the Datil–Mogollon and San Juan fields one last large-volume ignimbrite was erupted almost as a synchronized "last gasp" after gaps of 3.0 m.y. and 3.6 m.y., respectively. These were the tuff of Turkey Springs (24.3 Ma, Ferguson 1986; McIntosh et al. 1992) from the Bear Trap Canyon caldera in the San Mateo Range southwest of Socorro and the Sunshine Peak Tuff (23.3 Ma) from the Lake City caldera in the San Juan field (Steven and Lipman 1976; Hon 1987).

The earliest calderas in central Colorado are aligned along the west flank of the Rio Grande rift (Fig. 1). From north to south, the calderas are Grizzly Peak, 34.3 Ma; Wall Mountain Tuff caldera, 36.7 Ma, obliterated by intrusion of the Mount Princeton batholith and subsequent erosion;

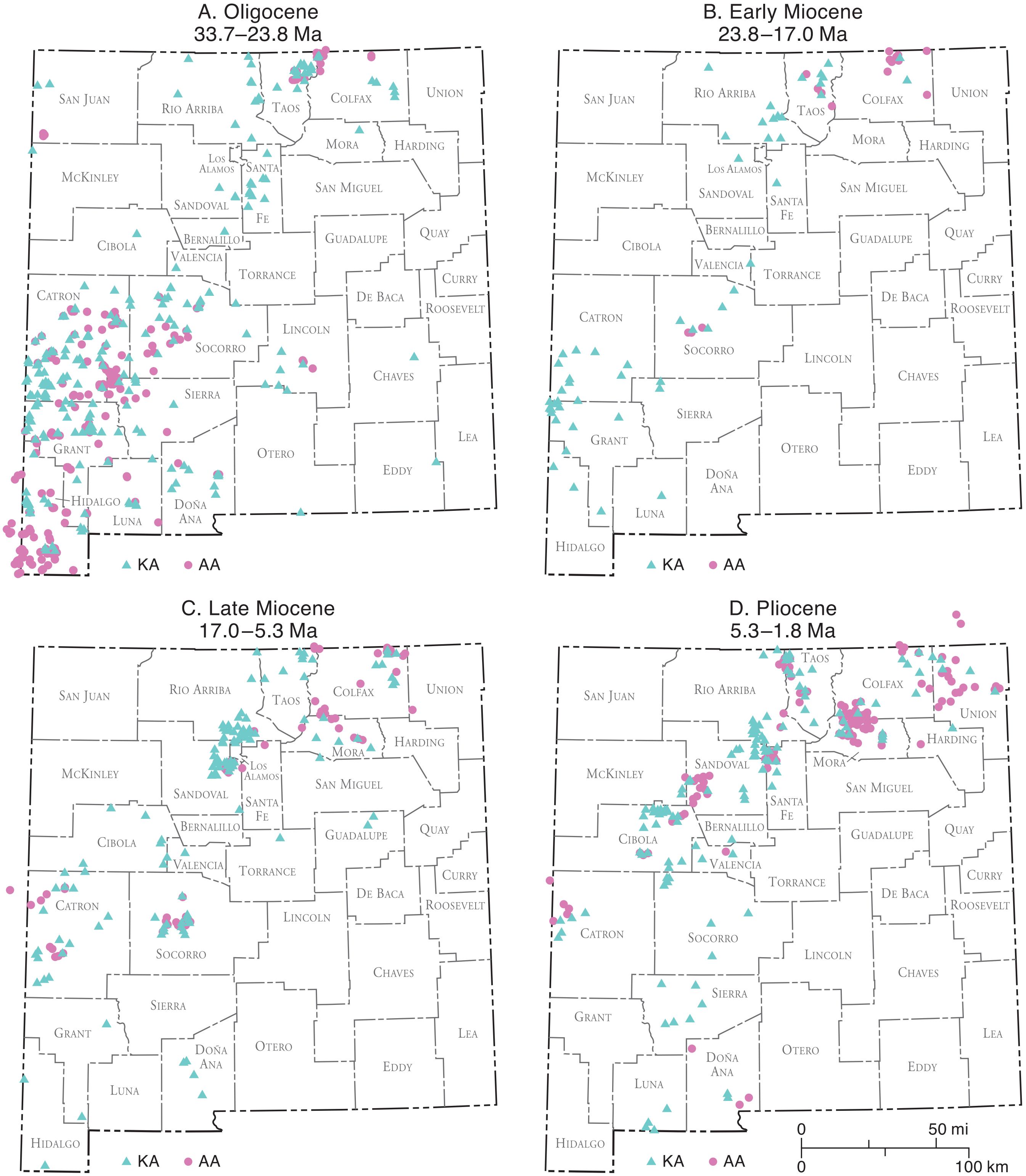


FIGURE 7—Space-time plots of magmatism in New Mexico based upon K-Ar (blue triangles) and ^{40}Ar/^{39} (red dots) ages: **A**–Oligocene (33.7–23.8 Ma), **B**–early Miocene (23.8–17.0 Ma), **C**–late Miocene (17.0–5.3 Ma), and **D**–Pliocene (5.3–1.8 Ma). Data available in Wilks and Chapin (1997) and subsequent revisions to Database DDS–DBI.

Mount Aetna, 33.8 Ma; Marshall Creek, 33.6 Ma; and Bonanza, 32.9 Ma (McIntosh and Chapin 2004 this volume). The second pulse of ignimbrite volcanism in Colorado also began along the west flank of the Rio Grande rift at Platoro, 29.3–28.4 Ma (Lipman 2000). Caldera volcanism fired up shortly thereafter in both the western San Juan Mountains, 28.6–27.8 Ma, and in the huge central caldera cluster around Creede, 28.6–27.0 Ma (Lipman 2000). Ignimbrite volcanism then shifted to the Questa caldera (Taos County) on the east flank of the Rio Grande rift at 25.1 Ma (Smith et al. 2002; Miggins 2002) before shifting back to the Lake City caldera in the western San Juan field at 23.3 Ma (Lipman 2000). Looking at Figure 5, one wonders why the San Juan volcanic field was so late in developing caldera volcanism. Perhaps regional extension was slow to encroach on the Colorado Plateau microplate that escaped much of the Cenozoic volcanism, or melts from the mantle found it more difficult to penetrate the Plateau lithosphere.

In New Mexico the earliest caldera collapsed within what would later become the Rio Grande rift with eruption of tuffs from the Organ caldera (36.2–35.5, McIntosh et al. 1991). Ignimbrite volcanism then migrated 220 km northwestward (Fig. 1B) into the west-central Mogollon–Datil volcanic field (McIntosh et al. 1992). However, caldera sources for several ignimbrites in the northern Mogollon–Datil field with ages ranging from 35.6 to 33.7 Ma are unknown and may never be found due to burial by younger units. At the northeast corner of the Mogollon–Datil field the earliest caldera formed at Socorro within the Rio Grande rift in response to eruption of the Hells Mesa Tuff (32.1 Ma McIntosh et al. 1992; 31.9 Ma, Chamberlin et al. 2004 this volume). A series of five overlapping calderas (Fig. 1) then formed at progressively younger ages over a distance of 60 km to the southwest (28.8–24.3 Ma; McIntosh et al. 1992; Chamberlin et al. 2004 this volume). In the Boot Heel volcanic field of extreme southwestern New Mexico and southeastern Arizona, the earliest caldera (Muir, 35.2 Ma) is farthest northeast and the youngest caldera (Turkey Creek, 26.8 Ma) is farthest southwest (McIntosh and Bryan 2000). In each of the above examples except for Questa, ignimbrite volcanism younged to the west. Lawton and McMillan (1999) and McMillan et al. (2000) discuss the role of slab roll back in passive continental rifting. The variations in younging directions of calderas, northwest versus southwest, and the comparatively early caldera formation in the Boot Heel field may indicate that the slab was breaking up as suggested by Atwater (1989).

The Oligocene ignimbrites are commonly interlayered with, and capped by, basaltic andesite flows, which have trace-element and isotopic signatures characteristic of orogenic (arc) rocks (Cameron et al. 1989; McMillan et al. 2000) and higher silica contents (52–57% SiO_2) than true basalts (< 52 wt% SiO_2). Cameron et al. (1989) have called these mafic lavas the Southern Cordilleran Basaltic Andesite (SCORBA) suite and suggest that they may be the most extensive Cenozoic basaltic suite in North America. In New Mexico they became abundant at about 29 Ma (Fig. 3) and are particularly voluminous between 27 and 24 Ma, after which they diminish in abundance until about 16 Ma. True basalts are the dominant mafic rocks after the early Miocene lull (20–16 Ma, Fig. 3). According to Cameron et al. (1989) the SCORBA suite was erupted in a more extensional tectonic environment than the preceding intermediate-composition rocks of the volcanic arc. By reaching the surface more quickly and directly than most pre-SCORBA magmas, the SCORBA melts experienced less differentiation (see also Cather 1990 and McMillan et al. 2000). Cameron et al. (1989) hypothesize that the SCORBA melts were erupted in a weaker extensional environment than true basalts based on their eruption from central vents rather than major fissures. This is only partly true because whereas the SCORBA magmas did form imposing central vent complexes, such as the line of andesitic volcanoes along the south side of the San Agustin Plains, they also were injected along with more mafic magmas in major dike swarms extending for tens of kilometers onto the Colorado Plateau from both the Mogollon–Datil and San Juan volcanic fields. The arc-like trace element and isotopic signatures and higher silica contents than true basalts may be due to some combination of mantle metasomatism, depth of magma generation, and crustal contamination influenced by a rising thermal gradient in the crust. An in-depth coverage of this topic is available in McMillan (1998) and McMillan et al. (2000).

Rhyolitic lavas and domes were also a conspicuous component of middle to late Oligocene volcanism especially during the interval 28–26 Ma (Fig. 3). It is no doubt significant that both basaltic andesite lavas and rhyolitic lavas and domes were most abundant during the 29–26 Ma climax of ignimbrite volcanism. The two rock types form a truly bimodal suite typical of regional extension. Best known of the rhyolite fields is the Taylor Creek Rhyolite in the southern Black Range where at least 20 lava domes and flows were erupted from individual vents over a 20 by 50 km area in approximately 100,000 yrs (Duffield and Dalrymple 1990; Eggleston 1987). Apparently, the Taylor Creek Rhyolite was erupted from a single magma reservoir, which never became sufficiently volatile rich to produce a major pyroclastic eruption and caldera collapse but leaked repeatedly to feed the domes and flows (Duffield and Dalrymple 1990).

Ascent of magma bodies to high levels in the crust was another characteristic of the Oligocene in New Mexico. Some were volatile rich and erupted violently giving rise to ignimbrite sheets and caldera complexes. Others produced lavas, domes, breccias, and small-volume pyroclastic deposits, eventually rising to intrude their own ejecta. And some magma bodies were trapped at shallow levels in the crust as small stocks, laccoliths, or thick dike-like masses that probably never erupted. Note that very few plutons are identified after the Oligocene. The lack of exposed plutons may be partly because of erosion having not yet cut deep enough to expose them, but more likely it is caused by the post-Oligocene preponderance of basalt flows fed by dikes that seldom develop longer-lived shallow magma reservoirs.

Dike injection was more widespread in New Mexico during the Oligocene than at any other time, probably because of a combination of high heat flow and tensional stress. Compositions ranged over the full spectrum with mafic to intermediate being most common (Fig. 3). Pervasive hydrothermal alteration commonly interfers with both geochronology and geochemistry, so detailed studies are scarce. The largest dike swarm fans from northwest to southeast for more than 100 km away from the Socorro–Magdalena area, which was a major center of basaltic andesite (SCORBA) volcanism during the interval 29–24 Ma; available K-Ar dates show a similar age range for the dikes. Some dikes in this swarm (for example, the Jones dike on the Capitan lineament and one of the Riley dikes north of Magdalena) are quite thick and exhibit compositional zoning from monzonite or diorite cores to mafic, fine-grained margins. An analogous dike swarm projects southward from the San Juan volcanic field as much as 75 km onto the Colorado Plateau through the Dulce area (Rio Arriba County) of the Jicarilla Apache Reservation. Available K-Ar dates range from 27 to 24 Ma, which is similar to the peak of San Juan volcanism (Lipman 1989, 2000).

Price and Henry (1984) and Henry et al. (1991) compiled dike and vein trends for Texas, northern Mexico, and adjoin-

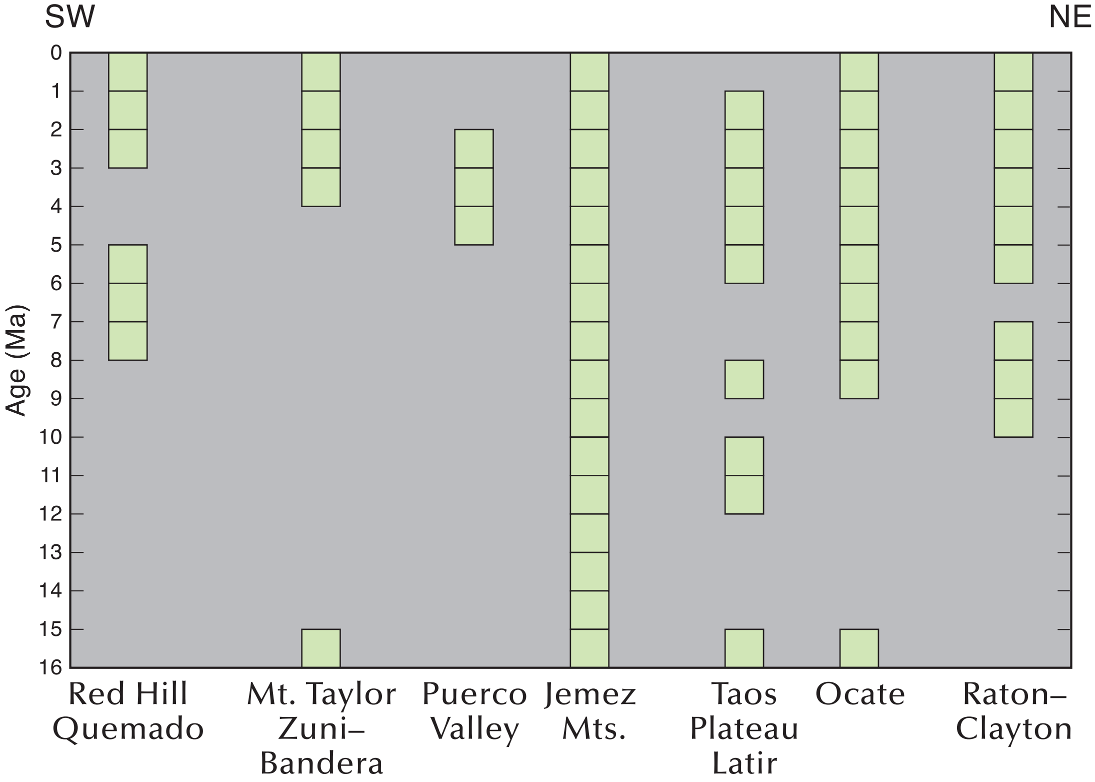


FIGURE 8—Histogram showing timing and range of volcanism in different segments of the Jemez lineament as indicated by K-Ar and $^{40}Ar/^{39}Ar$ ages.

ing parts of the southwestern United States. The authors concluded from east–northeast-trending dikes and veins that regional compression continued until approximately 31 Ma with the least principal horizontal stress (LPHS) oriented north–northwest. After approximately 31 Ma regional extension took over with the LPHS oriented east–northeast and the dominant trend of dikes, veins, and faults north–northwest, essentially perpendicular to the pre-31 Ma dike and vein trends. These changes in paleostress indicators are well documented and appear to conflict with our correlation of the ignimbrite flare up with the beginning of regional tension. Note in figure 5 how well the Trans-Pecos regional ignimbrites fit the temporal pattern of ignimbrite episodes in New Mexico and Colorado. Price and Henry (1984) report that Laramide shortening ended before silicic volcanism began during late Eocene. At issue is the nature of the transition from late Cretaceous–middle Tertiary subduction-related regional compression to middle and late Tertiary regional extension. The 38–32 Ma main period of volcanism in West Texas may have occurred in a near-neutral stress field because of its distance from the trench and the decreased convergence rate after 45 Ma. In New Mexico and Colorado strong rift-related normal faulting lagged the beginning of bimodal silicic ignimbrite–mafic lava volcanism by as much as 7 m.y. More work is needed to resolve the apparent conflict between petrogenetic and structural paleostress indicators during a transition from regional compression to tectonic tension that apparently occurred episodically over a period of several million years. As suggested earlier, rapid and voluminous melt production may result in local areas of tensional stress superimposed upon a weakly compressional stress field, thus complicating efforts to decipher the timing of a tectonic transition.

Miocene (23.7–5.3 Ma)

The Miocene is also a long epoch (18.3 m.y.) like the Eocene, and it too contains two tectonomagmatic transitions. The first occured in conjunction with the early Miocene lull in volcanism, which is so apparent in figure 3 between approximately 20 and 16 Ma. The lull is present over much of the western United States. McKee et al. (1970) first pointed out its existence in the Great Basin between 20 and 17 Ma. A similar early Miocene lull (called middle Miocene before changes in the Oligocene–Miocene and Miocene–Pliocene boundaries) was recognized by Damon (1971) for the Basin and Range province, by McBirney (1978) and McBirney et al. (1974) for the Cascade Range, and by Marvin et al. (1974) for Colorado. Chapin and Seager (1975) published a histogram of 161 K-Ar and fission-track ages of late Eocene to Holocene volcanic rocks in New Mexico, which shows a "middle" Miocene lull between 20 and 16 Ma within a broader lull between 20 and 11 Ma.

Several recent studies have clarified the significance of the early Miocene lull in magmatism. Perry et al. (1993) concluded from changes in the neodynium isotopic composition of 12 large-volume rhyolite systems located throughout the western United States that assimilation of crustal wall rocks decreased from the Oligocene to the Miocene because of regional cooling of the lower crust and that rhyolite systems younger than 20 Ma are dominated by mantle components. Kelly et al. (1992) showed that the peak of apatite fission-track (AFT) cooling ages in New Mexico and Colorado occurred between approximately 23 and 17 Ma more or less coincident with the 20 to 16 Ma lull in volcanism seen in Figure 3. The 17–16-Ma time coincides with major tectonic changes in the western United States caused by changes in Pacific–North America plate interactions that generated space for the Great Basin to expand westward. The Garlock fault which forms the southern boundary of the Great Basin underwent up to 80 km of left-lateral offset that coincided with clockwise rotation of the Transverse Ranges and extensional splaying of the Mojave block (Atwater 1989). The westward expansion of the Great Basin also correlates with eruption of at least 90% of the 174,000 km^3 Columbia River flood basalts in only 1.7 m.y. between 17.2 and 15.5 Ma (Swanson et al. 1989; Tolan et al. 1989; Baksi 1989). Cather et al. (1994) document an interval of rapid extension along the Rio Grande rift between approximately 16 and 10 Ma that induced rapid tilting of half grabens and development of unconformities in many rift basins. Thus, the effects of the 17-Ma beginning of expansion of the Great Basin were felt quickly in New Mexico as the Rio Grande rift began rapid extension and decompression melting of upwelling asthenosphere began to generate basaltic magmas (Davis et al. 1993).

An update of plate reconstruction since 33 Ma (chron 13) by Atwater and Stock (1998) documents changes in Pacific–Farallon–North American plate interactions that made possible the westward expansion of the Great Basin and increased spreading in the Rio Grande rift. As the East Pacific Rise approached the trench off southern California at approximately 28 Ma the intervening narrow section of the Farallon plate between the Pioneer and Murray fracture zones abruptly broke into two small plates, the Monterey and Arguello microplates (Atwater 1989; Atwater and Stock 1998). After the breakup the two microplates continued to subduct very slowly beneath North America, but at approximately 18 Ma (chron 5E) the last remnant was captured by the Pacific plate, and the Pacific–North American plate boundary was complete from Cape Mendocino for 700 km to the south (Atwater and Stock 1998). Motion of the Pacific plate at this time was approximately N60°W at a rate of about 33 mm/yr (Atwater and Stock 1998). Without an intervening spreading ridge the segment of North America adjoining the Pacific plate was able to follow the Pacific plate westward. Wernicke et al. (1988) and Wernicke and Snow (1998) have calculated more than 300 km of extension between the Colorado Plateau and the Sierra Nevada across the Basin and Range province near the latitude of Las Vegas, Nevada, since 16 Ma. The response in New Mexico was an approximately 1.5° clockwise rotation of the Colorado Plateau microplate (Chapin and Cather 1994), sharply increased extension across the Rio Grande rift, and the beginning of volcanism in the Jemez Mountains and along the northeast-trending Jemez lineament (Fig. 1). The Jemez lineament in New Mexico consists of seven volcanically active segments separated by gaps with relatively few eruptions (Fig. 7D). From southwest to northeast, the segments are Red Hill–Quemado, Mt. Taylor–Zuni Bandera, Puerco Valley, Jemez Mountains, Taos Plateau–Latir volcanic field, Ocate volcanic field, and Raton–Clayton volcanic field. The post-16 Ma volcanic histories of these segments are compared in the histogram of Figure 8. The Jemez volcanic field at the intersection of the Jemez zone and the Rio Grande rift stands out for its nearly continuous (but episodic in detail) volcanism from about 15 Ma to present. Its location at a major structural intersection aided the ascent, storage, and differentiation of mantle-derived melts, resulting in the most complex volcanic field in the southwestern United States for this time period (Smith and Luedke 1980). Three other segments (Red Hill–Quemado, Ocate, and Raton–Clayton) began long-term eruptive histories at 8–10 Ma and by approximately 5 Ma volcanism was occurring in all segments of the Jemez lineament. The eruptive products are dominantly basaltic, but minor volumes of more silicic differentiates are present in several segments. The Jemez volcanic field is anomalous for its large volumes of rhyolitic products including the 600 km^3 Bandelier Tuff.

Aldrich and Laughlin (1984) and Aldrich et al. (1986) have published the most detailed descriptions and interpretation of the part of the Jemez lineament west of the Rio Grande rift. Their key observations bearing on the origin of the lineament are: (1) the lineament is approximately 50-km wide as measured by two parallel lines that enclose most of the vents; (2) the trend is N52°E; (3) faults and vent alignments within the lineament display a N25°E en echelon pattern, not a N52°E lineament-parallel pattern; (4) joint intensity measured in Cretaceous sandstones within the lineament near Grants in Cibola County, is more than twice that of adjacent areas outside the lineament; (5) the lineament is the locus of high seismicity between Grants and the Jemez Mountains; (6) basalts with low ^{87}Sr/^{86}Sr ratios and mantle derived xenoliths have been found at several localities along the lineament; and (7) changes in Permian limestones and the distribution of porphyry copper deposits and metamorphic core complexes across a southwestward projection of the Jemez lineament in Arizona suggest a long history of differential movements across the Jemez lineament.

Aldrich and Laughlin (1984) also compiled orientations of the least-principal horizontal stress (LPHS) including contemporary measurements of in-situ stress, earthquake focal mechanism solutions, and geologic features less than 5 m.y. old, such as dike trends, alignment of cinder cones, and slip directions on faults. By plotting 93 stress indicators on a map of the Jemez zone and adjacent areas they found that the LPHS in the interior of the Colorado Plateau is oriented about N40°E, whereas in the southern Basin and Range province the LPHS is oriented east-west to west-northwest–east-southeast. The transition zone between these two stress provinces coincides with the Jemez lineament and marks the present geophysical boundary of the Colorado Plateau. Magnetotelluric and gravity studies (Ander 1980) indicate that the lithosphere immediately south of the Jemez lineament is geophysically similar to that of the Basin and Range province in contrast to the lithosphere immediately north of the Jemez lineament, which is geophysically similar to the interior of the Colorado Plateau.

Aldrich and Laughlin (1984) propose the following model: (1) late Laramide N45°E directed compression was resolved into left slip along the Proterozoic province boundary beneath the Jemez lineament resulting in a north-northeast–trending en echelon set of fractures; and (2) between 7 and 4 Ma, the direction of spreading in the northern Great Basin and Southern Rocky Mountains rotated to west-northwest or northwest (Zoback and Thompson 1978; Eaton 1979), which caused additional minor clockwise rotation of the Colorado Plateau, increased extension across the Jemez lineament, and opened the north-northeast-trending en echelon faults enabling them to act as conduits for magma. However, the en echelon fractures may have formed during the clockwise rotation of the Colorado Plateau rather than during the Laramide. This would agree with Aldrich's and Laughlin's observation number 4 above.

The spreading history of the Basin and Range province is key to solving the mystery of why the Jemez lineament began erupting basaltic magmas in late Miocene and accelerated this activity between approximately 10 to 5 Ma, whereas other northeast-trending lineaments in New Mexico and Colorado remained dormant. Between 17 and 10 Ma the LPHS was oriented east-northeast–west-southwest, approximately perpendicular to the NNW trend of the Pacific–North American plate margin (Zoback et al. 1981) and was remarkably uniform over most of the southwestern United States. The trend of the northern Nevada rift and the feeder dikes for the Columbia Plateau flood basalts reflect this orientation. But between approximately 10 and 5 Ma the LPHS rotated about 45° clockwise as pointed out by several authors (Zoback and Thompson 1978; Eaton 1979; Zoback et al. 1981). This brought the LPHS into near perpendicularity with the N25°E orientation of en echelon faults formed along the Jemez lineament. Northwestward expansion of the Great Basin permitted approximately 1.5° clockwise rotation of the Colorado Plateau (Chapin and Cather 1994) which lead to incipient development of a new southeastern Plateau boundary along the Jemez lineament (Aldrich and Laughlin 1984).

Additional insight into the timing and cause of magmatism along the Jemez lineament has come from several studies of late Miocene changes in Pacific plate motion and its effects on adjoining plates. Cox and Engebretsen (1985) concluded from a change in the trend of the Hawaiian chain of volcanoes that motion of the Pacific plate changed to a more northerly direction 5 m.y. ago possibly preceded by a smaller change at about 8.5 Ma. They also cited evidence for intense deformation and uplift along the San Andreas fault beginning at approximately 5 Ma and two major shifts in rotation poles at 8.5 and 5.0 Ma across the Juan de Fuca–Pacific spreading center. More recently Atwater and Stock (1998) calculated a 20–25° clockwise change in Pacific–North American relative plate motion at approximately 8 Ma from Pacific–Antarctica relative plate motion projected via a global plate circuit. Cande and Kent (1995) had previously concluded from Pacific–Antarctica relative motion that the late Neogene change of Pacific motion consisted of an abrupt 8° change near 5.9 Ma, added to a gradual change that started near 12 Ma. Argus and Gordon (2001) using geodetic results from very long baseline interferometry (VLBI), satellite positioning (GPS), and satellite laser ranging (SLR) estimated current angular velocities between the Pacific plate, Sierra Nevada microplate, and the North American plate. Plate reconstructions using these velocities indicate that the Sierran microplate changed motion relative to North America at approximatelyt 8–6 Ma in concert with changes in Pacific plate motion and that deformation in the Basin and Range must also have changed at this time. Wessel and Kroenke (2000) summarized changes in tectonism within and around the borders of the Pacific plate and derived a model for the absolute motion of the Pacific plate ,which includes synchronous changes in all Pacific spreading ridges at 6 Ma. The cause Wessel and Kroenke proposed was jamming of the subduction zone along the northern margin of the Australian plate by the very large and buoyant Ontong Java Plateau.

Whereas the above studies differ somewhat in timing and proposed causes, they provide abundant evidence around the Pacific Basin for a major change in plate interactions between approximately 10 and 5 Ma. The chain reactions in western North America included increased convergence and transpressive deformation along the San Andreas fault, transfer of Baja California to the Pacific plate, more northerly movement of the Sierran microplate, expansion of the Great Basin to the northwest, rotation of the LPHS from west–southwest to west–northwest, or northwest, clockwise rotation of the Colorado Plateau and dilation of north–northeast-trending fractures along the Jemez lineament resulting in a sharp increase in basaltic volcanism. Considered in this wider context, magmatism along the Jemez lineament becomes much less enigmatic. However, if increased volcanism along the Jemez lineament represents an attempt by the Colorado Plateau to break a new southeastern boundary, why does the lineament cross the Rio Grande rift and continue to erupt basaltic magmas as far as southeastern Colorado (Fig. 9C)? The Mazatzal–Yavapai Proterozoic province boundary must be the fundamental lithospheric control.

Pliocene (5.3–1.8 Ma) and Pleistocene (1.8–0.01 Ma)

Because their magmatic patterns are so similar, the Pliocene and Pleistocene are combined for discussion purposes. The acceleration of bimodal basalt-rhyolite volcanism beginning at about 5 Ma, as seen on the space-time plots of Figures 7D and 9a and the histograms of Figures 3 and 8, is especially dramatic when one considers that the combined Pliocene–Pleistocene interval is only about 5.3 m.y. compared to 11.6 m.y. for the preceding late Miocene plot (Fig. 7C). The Pliocene and Pleistocene space-time plots also show that the volcanism was confined almost entirely to the Jemez lineament and the Rio Grande rift with the Jemez lineament by far the dominant trend.

By 5 Ma all segments of the Jemez lineament were volcanically active (Fig. 8). Volcanism in the Mt. Taylor–Zuni Bandera, Puerco Valley, and Taos Plateau–Latir segments filled in gaps in the late Miocene Jemez lineament making it a more dramatic lineament in the Pliocene (Fig. 7D). Pliocene eruptions also greatly expanded the Ocate and Raton–Clayton volcanic fields. Student theses at New Mexico Tech by Hallett (1992, Puerco Valley), Appelt (1997, Taos Plateau), Stroud (1997 Raton–Clayton), and Olmsted (2000, Ocate) provided a large number of ^{40}Ar/^{39}Ar dates for these largely Pliocene volcanic fields.

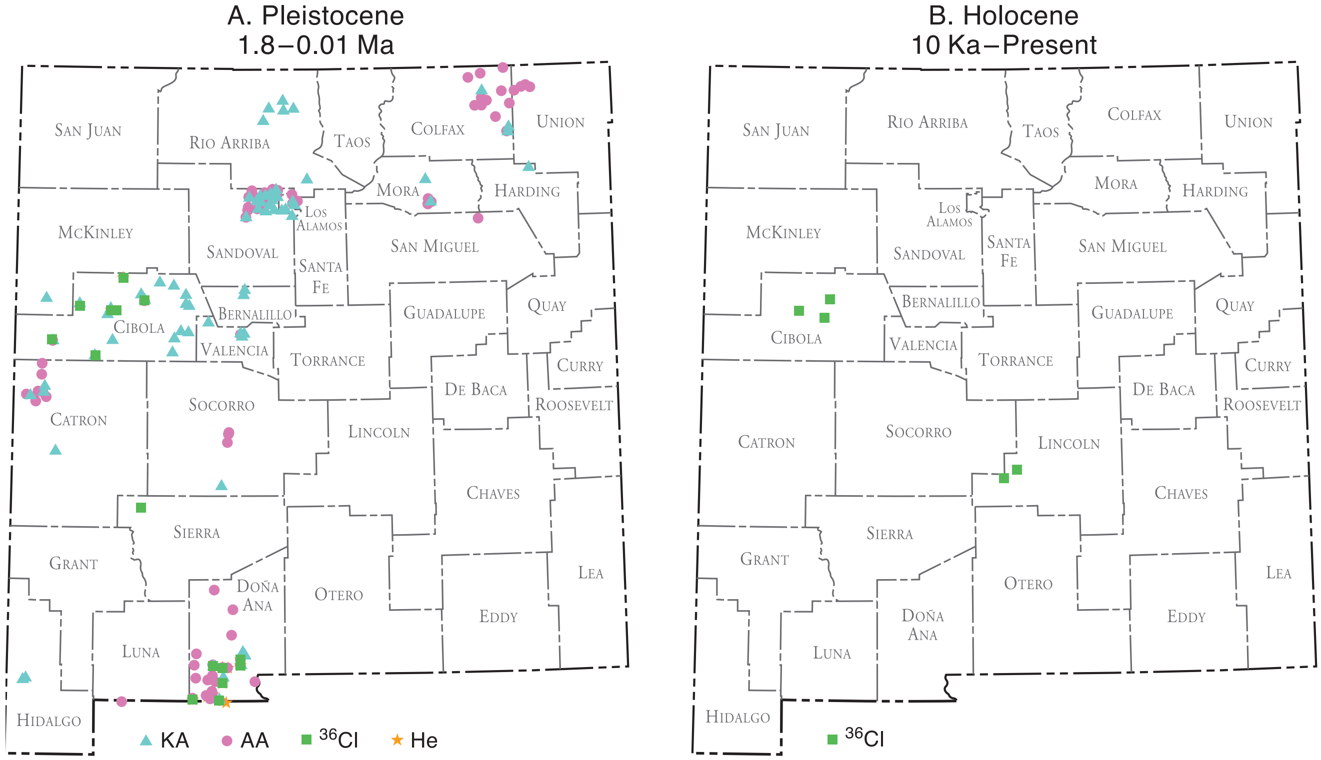
In southern New Mexico, more than 200 small-volume basaltic eruptions formed the Potrillo volcanic field between about 900 Ka and 40 Ka (Williams 1999). A combination of ^{40}Ar/^{39}Ar and ^{3}He surface-exposure dating (Fig. 9a) has provided fresh insight into this formerly difficult-to-date field (Williams 1999).

Holocene (0.01 Ma–Present)

Volcanism in the Holocene followed the pattern of the past 9 m.y. by being confined to the Jemez lineament and the Rio Grande rift (Fig. 9C). Two large-volume basaltic eruptions occurred: the McCartys flow (Cibola County) in the Zuni–Bandera volcanic field and the lower and upper Carrizozo flows (Lincoln County) in the Tularosa Basin of the Rio Grande rift (Fig. 9B). The McCartys flow has been dated at about 3.2 ka (average of four ^{14}C dates, Laughlin et al. 1994) and at 3.9 ± 1.2 ka by the ^{36}Cl surface-exposure method (Dunbar and Phillips 1994; 2004 this volume); the Carrizozo flows were dated at 5.2 ± 0.7 ka by the ^{36}Cl method (Dunbar 1999). Previous visual estimates of the age of these flows (McCartys, >1,000 yrs, Allen 1952; Carrizozo, 1,500 yrs, Weber 1964) based on geomorphology and Indian artifacts were shown to be too young. The older ages of these flows are corroborated by ^{3}He dates for the McCartys flow (Laughlin et al. 1994) and by ^{3}He (Anthony et al. 1998) and secular variation magnetostratigraphy (Salyards 1991) for the Carrizozo flows.

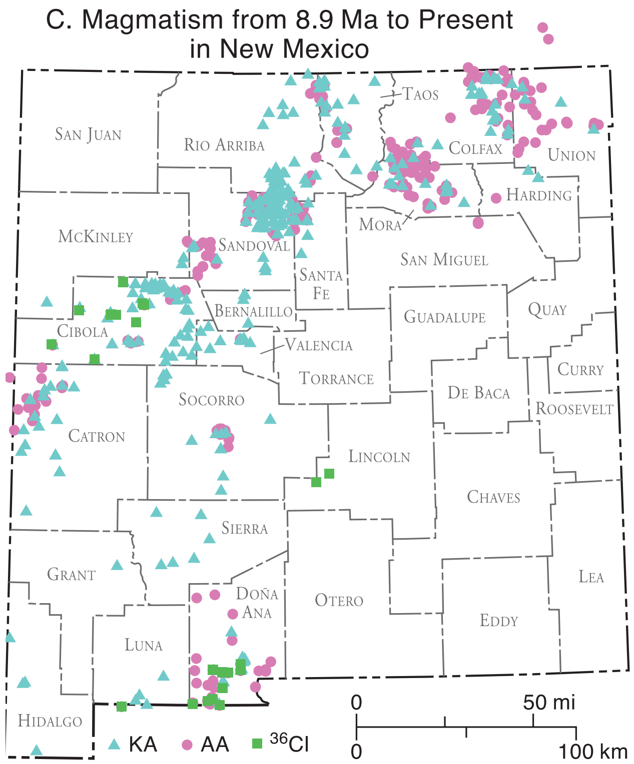
The erupted volume of the Carrizozo flows has been estimated at 2.8–4.3 km^{3} (Allen 1952) with an average thickness of 10–15 m. The vents for the Carrizozo flows and nearby Broken Back Crater flows (Pleistocene) occur at the intersection of north-trending rift-related faults with the Capitan lineament (Fig. 1B), a major east–west to west–northwest-trending basement flaw (Chapin et al. 1978) that also localized the Capitan stock in Lincoln County (28.8 Ma, Dunbar et al. 1996), the Railroad dikes in Chavez County, and Jones dike in Socorro County (27.9 Ma, Aldrich et al. 1986) during middle Oligocene. The lower Carrizozo flow traveled 75 km down the Tularosa Basin as a tube-fed pahoehoe system. Keszthelyi and Pieri (1993) estimate that effusion rates were 5.3 m^{3} per second, and the eruption duration was three decades. The Carrizozo eruptions are surprisingly voluminous considering the lack of previous volcanism in the area and the inactivity of the Capitan lineament since about 26 Ma.

In contrast the Zuni–Bandera volcanic field has a long and complex eruptive history spanning the past 0.7 m.y.



A. Pleistocene 1.8–0.01 Ma

B. Holocene 10 Ka–Present



C. Magmatism from 8.9 Ma to Present in New Mexico

FIGURE 9—Space-time plots of magmatism in New Mexico based upon K-Ar (blue triangles), ^{40}Ar/^{39}Ar (red dots), and ^{36}Cl or ^{3}He surface exposure (green squares and orange stars, respectively) ages: **A**–Pleistocene (1.8 Ma–10 ka), **B**–Holocene (10 ka–present), and **C**–summary plot of magmatism from 8.9 Ma to present. Data available in Wilks and Chapin (1997) and subsequent revisions to Database DDS–DBI.

(Laughlin et al. 1993a,b). At least 100 vents have been recognized in the volcanic field (Luedke and Smith 1978) which has an areal extent of at least 2,460 km^2. Laughlin et al. (1993b) recognize three pulses of basaltic eruptions: (1) 0.7–0.6 Ma, (2) 0.2–0.11 Ma, and (3) a young pulse difficult to date. The Bandera flow in the Zuni–Bandera field is almost Holocene in age. Laughlin et al. (1994) report an average age of 11 ka based on both ^{3}He and ^{14}C dates.

Future magmatism

If magmatism follows the pattern of the past 9 m.y., future eruptions are most likely to occur within the Rio Grande rift and along the Jemez lineament (Fig. 9C). Limburg (1990) estimates that New Mexico has experienced almost 700 volcanic events over the past 5 m.y. She calculates an average eruption probability of ~ 10^{-4} per yr, equivalent to 100 eruptions over the next million years. The combined areal extent of the Jemez lineament and the Rio Grande rift is very large, but some localities have a higher probability than others. Intersections of the Rio Grande rift with cross-cutting lineaments (Fig. 1B) are likely prospects for future magmatic activity because the deeply penetrating mosaic of intersecting fractures aids the ascent, storage, and differentiation of magmas. Examples are the Jemez volcanic field at the intersection of the Jemez lineament and Rio Grande rift; the Socorro volcanic field at the intersection of the Morenci and Capitan lineaments (Fig. 1B) with the rift (Chapin et al. 1978); the Potrillo volcanic field (Doña Ana County) located where the Texas lineament crosses the rift; the Elephant Butte area (Sierra County) where the Santa Rita lineament intersects the rift; and the area northwest of Carrizozo in Lincoln County where north-trending rift faults cut the Capitan lineament. Several of these intersections have experienced Quaternary volcanism or are modern geothermal areas.

Socorro area

The Socorro area is of particular interest because of unusual earthquake activity, high heat flow, and seismological evidence for contemporary magma bodies in the subsurface. Earthquake activity is the highest of any area along the Rio Grande rift in both numbers and strength and occurs primarily in swarms (Sanford et al. 1977, 1983). Research on the earthquake activity by Allan Sanford and others since the early 1960s led to the recognition of magma bodies in the 1970s (Sanford et al. 1973, 1977). Strong reflected phases on microearthquake seismograms were used to map the extent of an elliptical, sill-like, mid-crustal magma body present at depths near 19 km (Sanford et al. 1977; Rinehart et al. 1979). Recent remapping of the Socorro magma body by Balch et al. (1997) using 5,455 reflected phases on seismograms of 1,181 microearthquakes indicates that the deep, sill-like magma chamber covers an area of at least 3,400 km^2 with a north–south dimension of approximately 80 km (from north of Bernardo to south of San Antonio, New Mexico) and with a maximum east–west dimension of aproximately 50 km. The upper surface of the magma body shows no regional dip and has a maximum relief of about 0.5 km (Balch et al. 1997). Ake and Sanford (1988) estimate that the total thickness of the magma body is less than 150 m.

Small, relatively shallow magma bodies (possibly silicic) may be present above the southern end of the Socorro magma body as indicated by: (1) screening of SV waves (Shuleski 1976; Sanford et al. 1977); (2) anomalously high values of Poisson's ratio (Caravella 1976); and (3) the spatial distribution of microearthquake hypocenters (Shuleski et al. 1977; Sanford et al. 1977). The geophysical techniques used to detect shallow magma bodies do not permit precise determination of their location, shape or volume. The inferred shallow magma bodies are located along the Socorro accommodation zone (SAZ), a northeast-trending boundary between two domains in which domino-style fault blocks are tilted in opposite directions with stratal dips as high as 60–70° (Chapin et al. 1978; Chapin 1989). The SAZ formed early in rifting as the Morenci lineament (Fig. 1B), a preexisting crustal flaw, provided a natural break between systems of normal faults developing concurrently to the north and south. The Morenci lineament and the subsidiary SAZ have leaked magmas episodically since at least 32 Ma; the youngest eruption generated the basalt of Socorro Canyon dated by ^{40}Ar/^{39}Ar at 3.73 ± 0.1 Ma (R. Chamberlin unpublished data). A compilation of radioisotopic ages of igneous rocks emplaced along the SAZ (Chapin 1989; R. Chamberlin unpublished data) reveals that, before the present 3.7 m.y. gap in volcanism, the longest gap since 18.45 Ma was 2.35 m.y., and the average recurrence interval was 0.81 m.y. (Newell 1997; Chamberlin unpublished data). Dated silicic events outnumbered basaltic events 19–11, but this is partly because of the easier dating of silicic rocks and the relatively large number of small silicic domes and flows. It appears, however, that we are overdue for an eruption somewhere along the SAZ. The hazard to humans depends greatly on whether the magma is basaltic (moderate risk) or silicic (major risk). We have no way at present to answer this question.

Geophysical and geomorphological measurements indicate that the Socorro magma body is a young feature that is currently being supplied with new magma from a deeper source. The earthquake swarms occurring above the magma body at depths of 2–10 km have been recognized in volcanic areas elsewhere as being associated with active magmatic intrusion (Sanford and Einarsson 1982). Releveling of survey lines by Reilinger et al. (1980) and Larsen et al. (1986) indicate that the ground surface above the Socorro magma body is being uplifted at a rate of approximately 2 mm/yr. Uplifted stream terraces and a bulge in the long profile of the Rio Grande (Bachman and Mehnert 1978; Ouchi 1983), while less quantitative, may also indicate uplift over the Socorro magma body. Recent INSAR interferograms covering the time period 1992–1999 indicate uplift of the ground surface above the Socorro magma body at an average rate of 2-4 mm/yr during this period (Fialko and Simons 2001).

Using teleseismic signals from distant earthquakes propagating through the crustal volume containing the Socorro magma body, Schlue et al. (1996) identified a compressional to shear wave conversion they interpret to be a partially molten lower crustal root to the Socorro magma body. Finite element modeling of this anomaly suggests that the intrusion of mantle magmas responsible for the ongoing inflation of the Socorro magma body is occurring via a steeply east-dipping conduit located beneath the western margin of the southern Albuquerque Basin (Schlue et al. 1996). Larsen et al. (1986) estimate magma injection of approximately 4–6 km^3/100 yr into a large sill-like magma body at a depth of 19 km would produce the observed surface uplift.

Sill-like basaltic magma bodies have been inferred elsewhere in the western United States from horizons producing strong shear-wave reflections, regions of anomalously slow compressional (P) waves, or as seismic-reflection bright spots (Glazner and Ussler 1988). The upper boundaries of these inferred magma bodies generally occur at midcrustal depths marked by prominent increases in P-wave velocity (Glazner and Ussler 1988). These authors point out that crustal density profiles calculated from measured P-wave velocity profiles indicate that basaltic magmas near their liquidus should be less dense than crustal rocks below the midcrustal velocity discontinuities and more dense than rocks above them. Thus, rising basaltic magmas may be trapped as they lose buoyancy at the midcrustal discontinuities. Glazner and Ussler (1988) also suggest that trapping of ascending basaltic magmas at midcrustal density discontinuities may result in generation of silicic magma systems.

Jemez area

The Jemez volcanic field occurs at another major intersection, that of the Jemez lineament and the Rio Grande rift (Fig. 1A,B). Episodic volcanism over the past 15 m.y. built the Jemez volcanic pile, the longest, most voluminous, and most continuous activity of any site on the Jemez lineament (Fig. 8). The largest eruptions were the lower and upper Bandelier Tuff; precise ^{40}Ar/^{39}Ar dating by Spell et al. (1996) indicates the eruptions occurred at 1.608 ± 0.010 Ma and 1.225 ± 0.008 Ma, respectively, with a repose interval of 380 ± 20 kyr between caldera collapse events. Following collapse of the Valles caldera (upper Bandelier Tuff) small rhyolite domes and flows were emplaced at 973–915 ka, 800–787 ka, and 557–521 ka as indicated by ^{40}Ar/^{39}Ar dating of sanidine (Spell and Harrison 1993). Thus, quiescent intervals between clusters of silicic eruptions ranged from 115 kyr to 230 kyr. Spell and Harrison (1993) also attempted to date the youngest eruptive events, El Cajete and Battleship Rock, but found that biotite from the youngest rocks contained excess argon that resulted in erroneously old ages (205 ka). Subsequently, Toyoda et al. (1995) obtained eruptive ages of 45–73 ka by electron spin resonance dating of quartz grains from the El Cajete and Battleship Rock units of the moat rhyolites. ^{14}C dates on carbonized logs (> 58 ka) and thermoluminescence dating (< 60 ka) of paleosols beneath the El Cajete pumice-fall deposits are consistent with the much younger ages of these units (Reneau et al. 1996). Wolff and Gardner (1995) point out that these eruptions represent the first activity in nearly half a million years in the Valles caldera and may indicate a new cycle of silicic magma generation induced by intrusion of mafic magma at depth.

Seismic studies using travel times from local earthquakes and explosions (Ankeny et al. 1986), teleseismic studies (Roberts et al. 1991; Lutter et al. 1995; Steck et al. 1998), seismic reflection imaging (Aprea et al. 2002), and gravity and electromagnetic data have resulted in a comprehensive picture of heterogeneities in the crust and uppermost mantle beneath the Jemez Mountains. Of particular interest is a 10 x 14 km low-velocity (- 23%) zone at depths between approximately 5 and 15.5 km beneath the geothermally active western part of the Valles caldera and interpreted as containing at least 10% melt (Steck et al. 1998). Lutter et al. (1995) and Steck et al. (1998) also identified a low-velocity zone near the crust–mantle boundary that is consistent with the presence of partial melt in the lower crust, perhaps a result of underplating by mafic melts from the mantle.

The precise ^{40}Ar/^{39}Ar dating of volcanic rocks and tephra in the Socorro and Jemez areas provides some perspective on recurrence intervals in complex volcanic fields with both mafic and silicic magmatism. The cosmogenic ^{36}Cl ages by Dunbar and Phillips (1994) for basaltic flows in the Zuni–Bandera volcanic field reveal that during the past 25 kyr, basaltic eruptions occurred at about 20.7, 18.0, 15.0, 11.2, and 3.9 ka. The ^{40}Ar/^{39}Ar dating by Olmsted and McIntosh (2004 this volume) for basalt flows in the Ocate volcanic field provides recurrence intervals for a major long-lasting basaltic field whose activity lasted about 8 m.y. All these recurrence intervals are long in terms of human life spans. Still, it would be prudent to continue the mapping and precise dating of volcanic fields and to monitor the localities judged most likely to host future eruptions. The estimated 700 volcanic events during the past 5 m.y., the wide variation in recurrence intervals between localities and type of volcanism, the lack of knowledge of how much time is on the "clock" for most vent areas, and the very large areal extent of volcanism in New Mexico make prediction difficult.

Discussion

Comparison of the magmatic history of New Mexico with that of the western margin of South America reveals many similarities and helps resolve questions of interpretation, particularly the issue of flat subduction. Extensive studies of the Andean volcanic arc since the early 1980s have made it the "type locality" for continental-margin, subduction-related volcanism. The literature is too voluminous to review here but readers will find the following papers particularly helpful: Jordan et al. (1983), Isacks (1988), Hildreth and Moorbath (1988), Soler and Bonhomme (1990), Allmendinger et al. (1990), Sébrier and Soler (1991), Kay et al. (1991), Whitman et al. (1996), Kay and Abbruzzi (1996), Allmendinger et al. (1997), James and Sacks (1999), Kay et al. (1999), Gutscher et al. (2000), Tosdal and Richards (2001), Kay and Mpodozis (2001), and Beck and Zandt (2002). Some important observations and interpretations synthesized from these papers are: (1) the Andean arc is segmented with alternating segments of flat and normal subduction; (2) volcanism migrates away from the trench as the angle of subduction decreases and ceases when the asthenospheric wedge between the subducting slab and the lithospheric mantle becomes too thin or too dehydrated; (3) during flat subduction, the slab dips at a normal angle (30° for the Andes) to a depth of about 100 km and then follows the base of the lithospheric mantle because, not having gone through the basalt to eclogite phase change, the slab is less dense than the asthenospheric mantle; (4) widespread melting of both lithospheric mantle and crust, accompanied by large-volume ignimbrite eruptions, occurs during a transition from flat subduction to normal subduction as asthenospheric mantle intrudes above the slab as it sinks or rolls back; (5) volcanism is episodic with regionally synchronous magmatic activity interspersed with magmatic quiescence, or lulls; (6) tectonic shortening of the overriding plate thickens the ductile lower crust and, together with tectonic wedging and magmatic additions, produces a plateau uplift; (7) dewatering of the subducting slab and hydration of the asthenospheric wedge and overriding lithosphere induces melting and magmatism; (8) magma compositions are determined by blending of subcrustal and deep-crustal magmas in zones of melting, assimilation, storage, and homogenization (MASH, Hildreth and Moorbath 1988) within the mantle-crust transition; (9) fluids for mineralization are released as the crust thickens and hydrous lower crustal amphibole-bearing mineral assemblages break down to drier, garnet-bearing assemblages; and (10) porphyry copper deposits form in environments where the magmatic arc is in a nearly neutral stress regime, usually during transitions in or out of flat-slab subduction.

Characteristics of the magmatic history of New Mexico and adjacent areas that have analogs in the Andes are: (1) migration of Laramide volcanism away from the trench, presumably with flattening of the subducting slab; (2) thickening of the crust to 50 km, or more, presumably accompanied by uplift of an orogenic plateau; (3) segmentation of the volcanic arc with a segment of flat subduction that caused the Laramide magma gap and segments in which a shallowing angle of subduction caused the volcanic arc to migrate eastward with time; (4) westward migration of volcanism accompanied by a major ignimbrite flare up as the low-angle slab segments began to roll back or disintegrate beginning in middle Eocene; (5) regionally synchronous episodic volcanism, especially conspicuous during brief pulses of ignimbrite volcanism; (6) increasing potassium content of magmas toward the craton with alkaline varieties farthest east; (7) magmatism and porphyry copper deposits along a lineament transverse to the arc; and (8) tectonomagmatic transitions in amount and composition of volcanism correlative with changes in rates and directions of plate convergence.

Some differences exist, however, between the Late Cretaceous and Cenozoic volcanism in New Mexico and the evolution of volcanic activity in the Andes. Convergence between the South American and Nazca plates continues today and the volcanic arc is still active in contrast to the southwestern United States where development of a transform boundary (the San Andreas fault) ended subduction in middle Oligocene (30–26 Ma). The early Cenozoic volcanic arc in the southwestern U.S. became much broader east–west (~ 1,000 km) than in the Andes (50–400 km) and the flat-slab configuration persisted longer (~ 40 m.y. versus

13–25 m.y.). Dips of the subducting slabs along the North American continental margin were steep (50–75°, Keith 1978) before and after the low-angle excursions that swept the volcanic arc ~ 1,000 km eastward, whereas the slabs beneath the "normal" segments of the Andean arc descend at angles of about 30°. A major, and as yet unexplained, difference is that crustal thickening and high topography in the southwestern U.S. extended far inboard of the volcanic arc to beneath the High Plains. The timing and causes of crustal thickening and regional uplift in the western United States are hotly debated topics. Keller et al. (2002) have recently suggested that the 50-km-thick crust of the Rocky Mountain–High Plains region may have been inherited from the Proterozoic based on recent data from Baltica.

Another subject of considerable controversy is the nature of volcanic lineaments and the causes of their differing magmatic histories. The Santa Rita lineament and the Colorado Mineral Belt (Fig. 1B) were magmatically active during the Late Cretaceous and Paleocene when they were approximately parallel to the convergence direction of the subducting Farallon or Kula plates (Cross and Pilger 1978; Lipman 1980; Bookstrom 1990). The Santa Rita magmatic zone formed along the southeastern edge of the Laramide magma gap. Asthenospheric mantle set in motion by reduction of the wedge-shaped opening between a flat-slab segment to the northwest and an inclined but shallowing slab segment to the southeast may have heated the slab edges and the base of the mantle lithosphere with resultant melt generation. This might also explain why the Copper Flat porphyry (75 Ma) near Hillsboro in Sierra County was emplaced earlier than plutons of the northeast-sweeping volcanic arc. Magmatism along the Colorado Mineral Belt occurred concurrently with that of the Santa Rita lineament but near the center of the Laramide magma gap. The question of why the Colorado lineament became magmatically active while the parallel Jemez zone remained dormant until the Miocene provokes the following discussion.

The Jemez, Santa Rita, Morenci, and Colorado lineaments (Fig. 1B) are part of a northeast-trending series of parallel, magmatically defined lineaments that cut across Colorado and New Mexico at spacings of 70–170 km (Chapin et al. 1978). None of the lineaments show an along-strike progression of ages, so they are not plume tracks. Structural controls of the lineaments are seldom obvious. The Jemez lineament coincides approximately with the Yavapai–Mazatzal province boundary which separates Proterozoic rocks older than 1,700 m.y. to the north from younger rocks to the south (Karlstrom and Bowring 1988; Karlstrom and Humphreys 1998). The Colorado lineament appears to be at least partially controlled by major northeast-trending shear zones in Proterozoic rocks (Tweto and Sims 1963; Warner 1978) and also parallels a nearby Proterozoic age-province boundary. Structural controls of the other northeast-trending lineaments are obscure, but may be related to transcurrent faults and boundaries of Proterozoic rock masses added to North America as the continent accreted southward from the Wyoming Archean province (Karlstrom and Bowring 1988). The seismic tomographic profile of the CD-ROM Working Group (2002) that crosses the Proterozoic structural grain of the Southern Rocky Mountains from northeastern New Mexico to southern Wyoming provides a valuable perspective on the northeast-trending lineaments. Several steeply dipping velocity anomalies on the profile project up to overlying Proterozoic crustal boundaries. The CD-ROM Working Group interprets these crust and mantle features as signatures of Proterozoic paleosubduction zones.

A major enigma concerning northeast-trending lineaments magmatically active during Laramide low-angle subduction is how the magmatism maintained its position on the North American plate while both it and the underlying Farallon plate were moving in different directions. Neither direction nor velocity was constant for either plate during the 75–45 Ma interval (Engebretsen et al. 1985). Therefore, it seems highly unlikely that a feature on the Farallon plate could have maintained a constant trend and location relative to the overlying North American plate. This means that whatever is controlling magmatism along the lineament has to reside in the North American lithosphere. The segmented nature of the Southern Rocky Mountain lithosphere, essentially compartmentalized by northeast-trending Proterozoic paleosubduction zones and shear zones between accreted terranes, may mean that there is a northeast-trending topographic grain on the base of the lithosphere. A convex-upward groove on the base of the lithosphere could retain asthenospheric mantle between the lithosphere and the flatly subducted Farallon plate. Conversely, a convex-downward protrusion on the base of the lithosphere might stretch the flat slab sufficiently to allow asthenospheric mantle to penetrate it. Also, Livaccari et al. (1981) and Saleeby (2003) make a good case for subduction of the Hess–Shatsky oceanic plateau as the cause of flat subduction of a segment of the Farallon plate and the resultant Laramide orogeny. Interaction of irregularities on the subducting plateau with the base of the lithosphere could also be involved. Another factor may be differences in hydration or fertility for magma generation between different segments of the Southern Rocky Mountain lithosphere. Perhaps geochemical and isotopic studies can narrow the possibilities.

Limburg's 1990 estimate of 700 volcanic events over the past 5 m.y., at least half of which occurred in the last 2 m.y., and an average eruption probability of 0.01% per yr, or 1% over the next 100 yrs, indicates that New Mexico has a low, but significant, risk to people and infrastructure from future volcanic activity. If magmatism follows the pattern of the last 9 m.y., future eruptions are most likely to occur along the Jemez lineament (dominant) and the Rio Grande rift. Areas where the Rio Grande rift intersects cross-cutting lineaments, such as the Jemez Mountains and Socorro area, are most vulnerable. The presence of a very large, sill-like magma body at a depth of 19 km in the Socorro area with accompanying seismic activity, domal uplift, and geophysical characteristics suggestive of shallow magma bodies indicates vulnerability, but also a natural laboratory for study of rift magmatism. The availability of precise $^{40}Ar/^{39}Ar$ dating and surface-exposure dating for young rocks makes it possible to establish accurate recurrence intervals for eruptions, an important step in evaluating volcanic hazards.

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