QUATERNARY VOLCANISM IN NEW MEXICO

NELIA W. DUNBAR

New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NM, 87801

Abstract–Volcanism during the Quaternary has been widespread throughout New Mexico with two main compositions, basaltic and rhyolitic, represented. The basaltic volcanism occurs mainly along the Rio Grande rift or the Jemez lineament, and most occurs in ten distinct fields. The rhyolitic volcanism is focused in the Jemez Mountain volcanic center, which is located at the intersection of the Rio Grande rift and the Jemez lineament, and features two, large-volume, highly explosive eruptions, the deposits of which are widespread throughout the state. A compilation of the ages and geographic distribution of New Mexico Quaternary volcanism suggests no episodicity or systematic variation in geographic location of eruptions, but rather a consistent level of geographically-distributed activity. Despite the frequency of volcanism, the activity would have had little impact on the local climate, although there may have been significant impacts on landscape evolution, particularly through disruption of drainage patterns. Based on the frequency of eruptions over the past 5 Ma, there is a 1% chance of a volcanic event in New Mexico in the next 100 years, and the most likely location of activity would be associated with the geophysically-defined Socorro magma body.

INTRODUCTION

Active volcanism has played a significant role in the geological evolution of New Mexico during the Quaternary. The extensional tectonic setting of New Mexico, together with pre-existing, long-lived zones of crustal weakness, has allowed silicic and mafic magmas to erupt regularly over the past 1.7 million years, producing roughly 350 eruptions over this time period (Limburg, 1990). The mafic eruptions exhibit a wide geographic distribution across the state, and include both explosive and non-explosive events. Young basaltic lava flows, cinder cones, and tuff cones can be observed in many parts of the state. The Quaternary silicic eruptions in New Mexico are all concentrated in the Jemez Mountain Volcanic field, and include two very large eruptions, with a cumulative volume of around 650 km^3 of dense rock (Self et al., 1996). Many of the silicic eruptions from the Jemez Mountain Volcanic field were very explosive, generating ash whose deposits are widespread throughout the state, as well as the thick deposits of pyroclastic flows found in the Jemez Mountains.

This paper will address a number of aspects of Quaternary volcanism in New Mexico. These include background on the tectonic setting of New Mexico, the reasons for and styles of volcanism in this state, followed by a discussion of the location and nature of specific eruptions. Following this, I will discuss the possible climatic and geomorphic effects of Quaternary volcanism in New Mexico, and finally, the likelihood of future volcanic activity in the state.

BACKGROUND ON VOLCANISM IN NEW MEXICO

Tectonic Setting

The tectonic setting and crustal features of New Mexico play a role in controlling the distribution and extent of volcanism. A number of tectonic provinces are represented within New Mexico, including the Colorado Plateau, Great Plains, Southern Rocky Mountains, Basin and Range and Rio Grande Rift. Central New Mexico falls in the Basin and Range province, and is located in an area of active crustal extension. One main focus of crustal extension is the Rio Grande rift (RGR), in which a series of extensional basins run north-south through New Mexico (Fig. 1) (e.g. Chapin, 1979). RGR extension initiated between 32 and 27 million years ago, and continues to present (Chapin, 1979). The area around the RGR has undergone crustal thinning (Olsen et al., 1987) and asthenospheric upwelling along the rift axis (Cordell, 1978), both of which provide conditions favorable for surface volcanism. In fact, significant Quaternary volcanism in New Mexico has been concentrated along the RGR (Fig. 1).

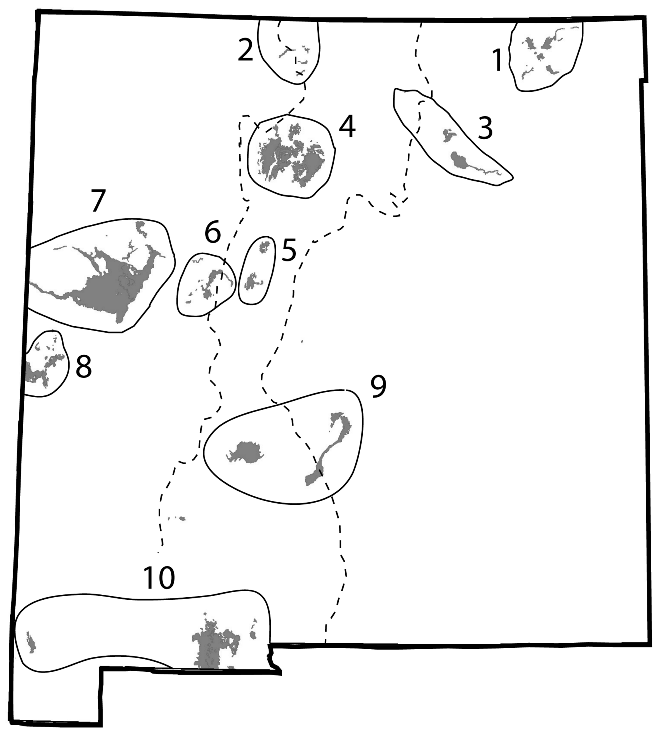

FIGURE 1. Map of surface outcrops of Quaternary volcanism in New Mexico. Outlined areas include: 1) Raton-Clayton volcanic field; 2) Taos Plateau volcanic field and surrounding areas; 3) Ocate-Mora volcanic field; 4) Jemez Mountain volcanic field; 5) Albuquerque-Los Lunas volcanic field; 6) Lucero volcanic field; 7) Zuni-Bandera volcanic field; 8) Quemado volcanic field; 9) Valley of Fires volcanic field; and 10) Potrillo volcanic field and surrounding areas. Naming of the volcanic fields follows Limburg (1990). The approximate location of the Rio Grande Rift is shown by the dashed

A second crustal feature that controls the distribution of volcanism in New Mexico is the Jemez lineament (JL) (Baldridge, 1979). The JL is a long-lived feature that is expressed as a broad NE trending alignment of volcanic features that runs across northern New Mexico and then on into Arizona. The JL is interpreted to be a transverse shear zone (Baldridge, 1979) and may be related to rotation of the Colorado

Plateau (Chamberlin and Anderson, 1989). Alternatively, the JL may have originated as a suture zone in the Precambrian (Aldrich, 1986). The largest Quaternary volcanic feature in New Mexico, the Jemez Mountain volcanic field, is located at the intersection of the RGR and the JL.

Styles of Volcanism

The chemical composition of Quaternary volcanic rocks in New Mexico is mainly either basaltic or rhyolitic, and the eruptive style generally varies with magma composition. There is also a correlation between magma composition and spatial distribution and abundance of vents. All of the major silicic, or rhyolitic, Quaternary volcanism in New Mexico is concentrated in the Jemez Mountain volcanic field, in the northwest part of the state. The rhyolitic eruptions tended to be very explosive, and the volume of rhyolite erupted during the Quaternary is large, but most was erupted during two major eruptions. In contrast, the basaltic eruptions that have occurred in New Mexico during the Quaternary tended to be of relatively low explosivity and low volume. There are many basalt vents, and they are distributed over a wide geographic area.

The most abundant Quaternary volcanism in New Mexico, in terms of number of individual vents and spatial distribution, is mafic, consisting largely of basaltic lava, although similar lava types, such as basanite and basaltic andesite are also represented (Limburg, 1990). The styles of eruption for these lavas are generally of relatively low explosivity, and would have been characterized by gentle fire fountaining or passive effusion from either centralized vents or fissures (e.g. Williams and McBirney, 1979). These styles of eruption generate Hawaiian-style cinder cones and lava flows, such as characterize many of the young basaltic features in New Mexico. However, in the few cases where basaltic lavas interacted with meteoric water during ascent, more explosive eruption styles resulted. This type of eruption may result in deposition of tuff cones, which are low-relief volcanic cones characterized by planar to crossbedded deposits of angular volcanic fragments. Tuff cone deposits may contain accretionary lapilli, which form when wet volcanic ash accretes to a central nucleus, forming a concentrically-layered particle, not unlike a hailstone (e.g., Fisher and Schminke, 1984). Maar craters, which are shallow, low relief, explosion craters, can also result from water-magma interaction (e.g., Williams and McBirney, 1979). Both of these features are represented in the Quaternary volcanic record in New Mexico.

The Quaternary rhyolitic volcanism in New Mexico all occurs in the Jemez Mountain volcanic field. Like volcanism elsewhere in the world, the silicic volcanism in New Mexico tends to be more explosive than the basaltic volcanism, due to the generally higher volatile content and higher viscosity of rhyolitic magma. The large eruptions from the Jemez Mountains are characterized by an initial stage involving generation of fallout tephra (Self et al., 1996). Fallout tephra is generated from a high, sustained eruption column generated by an energetic, explosive eruption (Carey and Sparks, 1986). The deposits produced by fallout ash are well-bedded and well-sorted, and significant deposits of ash from fallout eruptions may be found hundreds of kilometers from the volcanic vent (Sarna-Wojcicki, et al., 1984). At some point during the eruptive cycle, collapse of the eruption column can allow deposition of pyroclastic flows from rapidly travelling clouds of hot gas, ash, pumice and crystals (Fisher and Schmincke, 1984). This stage of the eruption would result in deposition of an ignimbrite, which is characterized by massive texture and overall poor sorting. Interbedded with the poorly-sorted ignimbrite deposits may be thin, planar to crossbedded deposits formed by ash cloud surges, which occur when ash elutriates from the top of a pyroclastic flow, and forms a more dilute cloud that allows bedding to develop.

Some smaller rhyolitic eruptions may also be characterized by initial phases of fallout ash activity, with either associated small-volume pyroclastic flows, or with the most passive style of rhyolitic volcanism, dome growth. In some cases, dome growth may occur without an initial fallout ash phase, or the initial fallout ash may be minor enough to not be well preserved. Depending on cooling and crystallization dynamics, rhyolite domes may either be crystalline, or may be composed of glassy obsidian.

QUATERNARY SILICIC VOLCANISM IN NEW MEXICO

The Jemez Mountain volcanic field (JMVF) has been active for the past 16 Ma, and has produced eruptions with a wide range of compositions (e.g. Self et al., 1996). The initial activity exhibited a wide range of chemical compositions, ranging from basalt to rhyolite, but the activity in the Quaternary has all been rhyolitic. A summary of the chronology and style of Quaternary eruptive events is presented below, and is shown in Table 1.

Bandelier Tuff

The most dramatic volcanic events that have occurred in New Mexico during the Quaternary are the two major rhyolitic pyroclastic eruptions that occurred at 1.61 and 1.21 million years, the lower and upper members of the Bandelier Tuff, respectively (Spell et al. 1990). A total of 650 km^3 of magma was erupted to produce the two members of the Bandelier Tuff, resulting in a caldera 22 km in diameter, known as the Valles Caldera (Fig. 2) (Self et al., 1996). This dramatic landform is clearly visible in satellite images of New Mexico. Each eruption began with deposition of fallout tephra, with volumes of 20 and 15 km^3 dense rock equivalent (DRE), respectively. Ash from this phase of the eruptions was widely distributed throughout New Mexico, and has been positively identified as far away as Lubbock, Texas (Izett et al., 1972), and probably fell at some distance to the east as well (Self et al., 1996). The fallout tephra from the Bandelier Tuffs were erupted in a number of pulses, some which spread across in different directions away from the vent, depending on the dominant wind at the time of the eruption (Fig. 3 A and B). Thicknesses of up to 3 meters of ash have been measured up to 20 kilometers away from the vent (Fig. 3 A and B, Self et al., 1996), and primary Bandelier tephra up to 10 cm thick has been identified in Socorro, which is around 300 km south of the main vent (Dunbar et al., 1996). Following the eruption of the fallout ash component, activity shifted to ignimbrite deposition. Whereas deposition of the fallout ash component was controlled in part by wind direction at the time of the eruption, the ignimbrite components of the eruption deposited more or less concentrically around the vent (Fig. 2). The maximum thicknesses attained were 180 m for the lower member and 250 m for the upper (Self et al., 1996). Total DRE volumes erupted during the ignimbrite phase of the eruption were about 380 km^3 and 230 km^3 for the upper and lower members, respectively (Self et al., 1996). Together with the Yellowstone and Long Valley volcanic centers, the Valles Caldera is one of the largest Quaternary silicic volcanoes in the U.S., and the upper and lower members of the Bandelier Tuff represent two of the largest eruptions.

Cerro Toledo Rhyolite

Between the eruption of the upper and lower members of Bandelier Tuff, a series of eruptions resulted in emplacement of the Cerro Toledo rhyolites. The Cerro Toledo rhyolites comprise a series of rhyolite domes and lava flows with associated fallout ash deposits (Stix et al., 1988). These domes and fallout ashes were erupted from along the margin of the caldera left by eruption of the lower member of the Bandelier Tuff, and began to erupt within about 100 ka of the lower Bandelier eruption. Domes that are part of the Cerro Toledo rhyolite include Rabbit Mountain, Los Posos, Cerro Toledo and several other small domes. All of these eruptions are small in volume compared to the Bandelier Tuff, and the fallout ash is unlikely to have been deposited as far from source as the larger eruptions. However, the exact size of, and distribution of tephra from, these eruptions has not been rigorously evaluated. Tephra found between Albuquerque and Socorro has been chemically correlated with

TABLE 1. Ages of the Quaternary units in the Jemez Mountains

Unit	Age (Ma)	Technique, reference
Most Recent Activity		
El Cajete	0.06	14-C Wolff and Gardner, 1995
Valle Grande Rhyolite		
La Jara	0.52±0.01	Ar-Ar, Spell and Harrison, 1993
South Mountain	0.52±0.01	Ar-Ar, Spell and Harrison, 1993
San Antonio I and II	0.56±0.004	Ar-Ar, Spell and Harrison, 1993
Santa Rosa II	0.79±0.02	Ar-Ar, Spell and Harrison, 1993
San Luis	0.80±0.003	Ar-Ar, Spell and Harrison, 1993
Seco	0.80±0.005	Ar-Ar, Spell and Harrison, 1993
Santa Rosa I	0.91±0.004	Ar-Ar, Spell and Harrison, 1993
Del Abrigo I-III	0.97±0.1	Ar-Ar, Spell and Harrison, 1993
Del Medio	1.231±0.017	Ar-Ar, Phillips et al., 2003
Redondo Creek	1.24-1.29±0.04	Ar-Ar, Phillips et al., 2003
Deer Canyon	1.26-1.28±0.02	Ar-Ar, Phillips et al., 2003
Upper Bandelier Tuff	1.256±0.009	Ar-Ar, Phillips et al., 2003
Cerro Toledo Rhyolite and Domes		
Fall unit 8/27	1.212±0.006	Ar-Ar, Spell et al., 1996
CT-9	1.212±0.007	Ar-Ar, Spell et al., 1996
CT-6	1.389±0.011	Ar-Ar, Spell et al., 1996
CT-5	1.384±0.008	Ar-Ar, Spell et al., 1996
CT-8	1.459±0.008	Ar-Ar, Spell et al., 1996
CT-7	1.520±0.016	Ar-Ar, Spell et al., 1996
CT-4	1.491±0.009	Ar-Ar, Spell et al., 1996
CT-3	1.542±0.008	Ar-Ar, Spell et al., 1996
CT-2	1.550±0.008	Ar-Ar, Spell et al., 1996
CT-1	1.6521±0.008	Ar-Ar, Spell et al., 1996
Turkey Ridge dome	1.348±0.021	Ar-Ar, Spell et al., 1996
Warm Springs	1.263±0.011	Ar-Ar, Spell et al., 1996
Rabbit Mountain	1.428±0.007	Ar-Ar, Love et al., pers. comm.
Unnamed dome	1.357±0.013	Ar-Ar, Spell et al., 1996
Cerro Trasquilar	1.369±0.011	Ar-Ar, Spell et al., 1996
East Los Posos	1.477±0.009	Ar-Ar, Spell et al., 1996
West Los Posos	1.545±0.016	Ar-Ar, Spell et al., 1996
Lower Bandelier Tuff	1.61±0.01	Ar-Ar, Spell et al., 1990

some Cerro Toledo rhyolite eruptions (Love et al., 2003), but whether this material was a result of primary deposition, or of fluvial reworking, is uncertain. Eruption of Cerro Toledo rhyolites continued on for 400 ka, with the final event indistinguishable in age from the upper member of the Bandelier Tuff (Spell et al., 1990, 1996).

Valle Grande Rhyolites

Following eruption of the upper member of the Bandelier Tuff, a series of rhyolite domes and lava flows were erupted along the margins of the Valles Caldera. The domes and flows are concentrated along an arcuate ring fracture, and there is an age progression in the domes, with the oldest being on the eastern side of the caldera, and becoming progressively younger in a counterclockwise direction. The oldest dome was erupted soon after the upper member of the Bandelier Tuff, at 1.13 $\pm$ 0.11 Ma, and the youngest was erupted at 0.52 $\pm$ 0.01 Ma (Spell et al., 1993). No significant pyroclastic activity associated with dome formation has been reported for the Valles rhyolites.

Most Recent Activity

The most recent eruptive activity in the JMVF is represented by the El Cajete pumice deposit, the Banco Bonito lava, and the Battleship Rock ignimbrite. The El Cajete pumice, the result of fallout ash and surge deposition, has a bulk volume of 1.3 km^3, and is overlain by the Banco Bonito lava (Self et al., 1996). These two deposits are likely to be genetically related (Self et al., 1996), as is the Battleship Rock

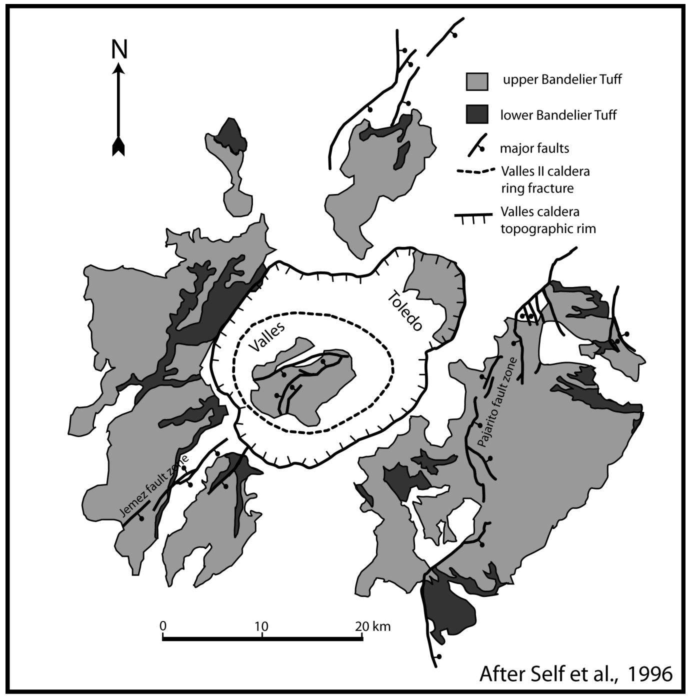

FIGURE 2. Map of distribution of the ignimbrite deposits of the Bandelier Tuff.

ignimbrite, which was erupted from a nearby vent (Self et al., 1991, 1996). These three deposits are chemically distinct from the earlier-erupted Valles rhyolites, and are thought to be part of a distinct batch of new magma (Wolff and Gardner, 1995). These deposits have proven very difficult to date, but Wolff and Gardner (1996) suggest, based on a combination of several dating techniques, that the age of the El Cajete eruption may be as young as 60 ka. They further suggest that the eruption of the El Cajete represents a new phase of activity in the JMVF, and may be a precursor to further eruptive activity.

QUATERNARY BASALTIC VOLCANISM IN NEW MEXICO

Although the most dramatic and volumetrically significant Quaternary volcanism in New Mexico has been silicic, the number of individual basaltic vents, and frequency of basaltic eruptions are much higher. Whereas all silicic volcanism has been concentrated in the JMVF, basaltic volcanism has occurred all along the Rio Grande rift, as well as along the JL (Fig. 1). Basaltic volcanism can be divided into a number of geographically-defined volcanic "fields" (Fig. 1, following Limburg, 1990), each of which will be discussed separately, starting from the northernmost fields and working south.

Raton-Clayton Volcanic Field

The Raton-Clayton volcanic field is located in the northeast corner of New Mexico (Fig. 1) and is a large and long-lived volcanic field that falls on the JL. The Raton-Clayton volcanic field has been episodically active for the past 9 Ma and significant Quaternary activity has occurred during the last of 3 episodes of activity. This field contains approximately 125 cinder cones, some with associated lava flows, as well as a number of other types of vents. Although a wide range of magmatic compositions are represented in the Raton-Clayton field, volcanism during the Quaternary has been dominantly basaltic, and has mainly produced lava flows and cinder cones. The Raton-Clayton volcanic field covers around 20,000 km^2, and has a low volumetric eruption rate when compared to other major basaltic centers (Aubele and Crumpler, 2001). The Capulin phase, which covers the past 1.68 Ma, has produced at least 16 eruptions. The most recent of these eruptions, at 56 ka, produced the very distinctive landform of Capulin Mountain which is a classic cinder cone, standing 305 m high and having a crater

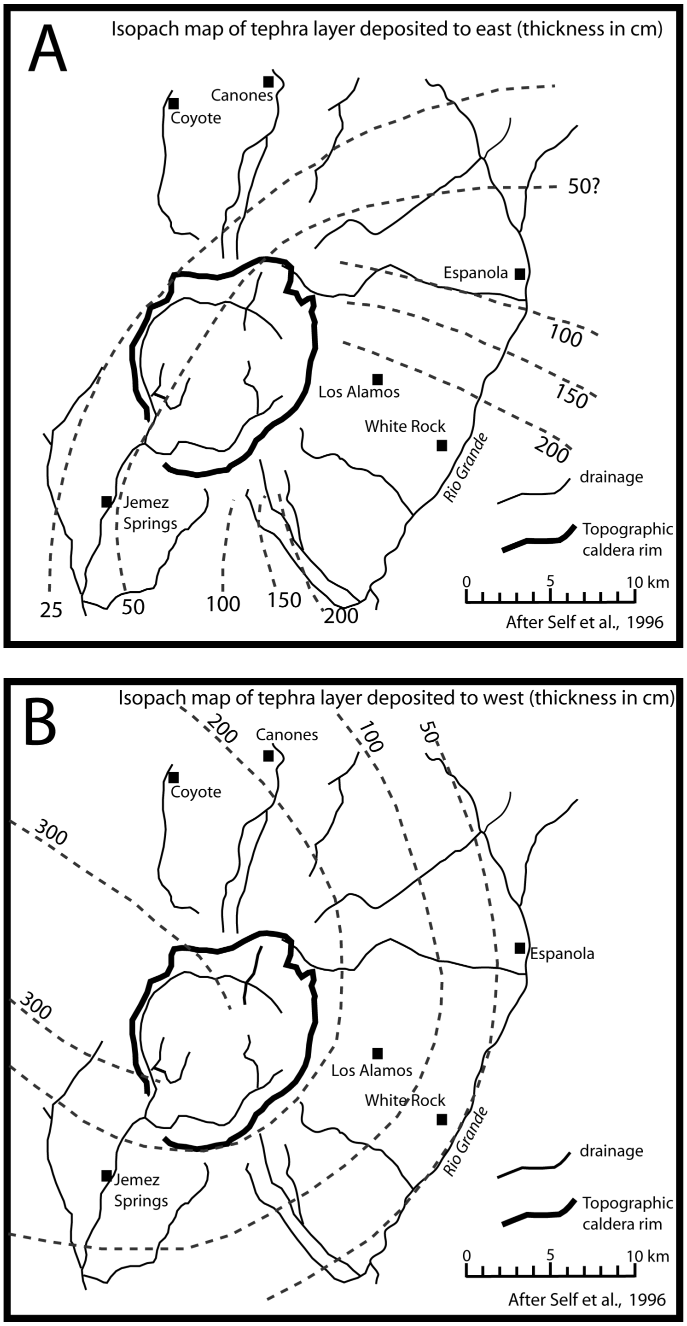

FIGURE 3. Isopach map of the distribution of two plinian fall units that are part of the lower member of the Bandelier Tuff. A). Plinian fall that was deposited in an eastward direction. B). Plinian fall that was deposited in a westward direction.

width of ~1.7 km (Baldridge, 2004; Stroud, 1997) (Table 2). A number of lava flows are associated with the Capulin cone. These appear to have formed during and after the main explosive phase (Aubele and Crumpler, 2001).

An interesting aspect of the Raton-Clayton volcanic field is that it provides insight into landscape evolution of northeastern New Mexico over the past 9 my. The older lava flows in this field are typically found at higher elevations than younger flows, and the interpretation is that the base landscape level was higher when the older flows were erupted than it is today. This characteristic has been used to reconstruct paleotopography and erosion rates in the region (Stroud, 1997).

Taos Plateau and Surrounding Area

The Taos plateau volcanic field, with an aerial extent of around 7000 km^2, is the most voluminous basaltic lava field in the Rio Grande rift. This field is largely composed of basaltic lava flows, and includes at least 35 vents, mainly cinder cones and shield volcanoes. A thick pile of basaltic lava flows make up the bulk of the Taos Plateau. These flows, known as the Servilleta basalts, reach a thickness of ~ 200 m where the Rio Grande cuts down through the basalt at the Taos Gorge, and the total volume of basalt erupted is estimated to be about 200 km^3. In addition to the Servilleta basalts, subordinate amounts of andesite and dacite were also erupted from the Taos Plateau volcanic field (Appelt, 1998). The original forms of the Taos Plateau volcanoes have been largely obscured by erosion. Although most of the Taos Plateau eruptions occurred between 2 and 6 Ma (Appelt, 1998), there is one lava flow erupted at 1.04 Ma, just across the Colorado border from the main part of the Taos Plateau Volcanic field (Appelt, 1998). Furthermore, there are several younger lava flows present in an area west of, but relatively near the Taos Plateau (Fig. 1, Table 2).

Ocate-Mora Volcanic Field

The Ocate-Mora volcanic field is located in the northeast part of New Mexico (Fig. 1), and consists of a large number of basaltic lava flows and cinder cones. The Ocate-Mora field doesn't appear to lie either in the RGR or on the JL, but is geographically close to the JL, and may be related to this zone of crustal weakness. This field is very similar in terms of size, composition and eruptive style to the Raton-Clayton volcanic field. Eruptions in the Ocate-Mora began 8.2 Ma, and the most recent eruption occurred at 0.8 Ma (O'Neill and Mehnert, 1988, Olmsted, 1999). Two major eruptive episodes, between 5.13-4.35 and 3.36-2.85 Ma, produced the largest volume of erupted material, representing 32 and 40 vol. % of the total volcanic field, respectively (Olmsted, 1999). As with the Raton-Clayton volcanic field, erupted lavas are mainly basaltic, although some andesite and dacite are also present. Only two eruptive centers in the Ocate-Mora field have been active during the Quaternary (Table 2). One of these eruptive centers is Maxon Crater, which is a shield volcano with associated scorea vents. This crater produced a lava flow that traveled 90 km along the valley of the Mora river, to the point where it intersects the Canadian river. This long flow can be seen on Figure 1, area 3.

Mount Taylor Volcanic Field

The Mount Taylor volcanic field, which includes the stratovolcano Mt. Taylor, as well as a family of surrounding basaltic vents, volcanic necks, and lava flows, is located on the JL (Fig. 1), and exhibits a wide range of magmatic compositions ranging from rhyolitic to basaltic. Mt. Taylor is the second-largest young volcano in New Mexico, after the Valles Caldera, and retains the distinctive shape of a subdued stratovolcano, with an amphitheater-shaped summit crater, likely the result a late-stage explosive eruption (Crumpler, 1982). Most activity in the Mount Taylor field was between 3.5 and 2.5 Ma (Crumpler, 1982), during which time several hundred eruptions occurred. Activity during the Quaternary has been very limited, with only two documented basaltic eruptions during the Quaternary (Table 2).

Albuquerque-Los Lunas Volcanic Field

The Albuquerque-Los Lunas volcanic field is located within the Rio Grande rift, in central New Mexico (Fig. 1). Many of the volcanic features within the Albuquerque-Los Lunas field are located along fissures, and consist of a number of aligned volcanic features (e.g., Kelley and Kudo, 1978). These include the Albuquerque volcanoes, Wind Mesa/Cat Hills complex, and Los Lunas volcano, all of which have been active in the Quaternary (Table 2). Isleta volcano and Tome Hill are also in the Albuquerque-Los Lunas area, but neither was active during the Quaternary.

The Albuquerque/Los Lunas volcanic field is characterized by

TABLE 2. Ages of selected eruptions in the Quaternary basaltic volcanic fields in New Mexico.

Unit	Age (Ma)	Technique, reference	Age (Ma)	Technique, reference	Age (Ma)	Technique, reference
Raton-Clayton						
Twin Mountain basalt flow	0.048±0.014	Ar-Ar Stroud, 1997				
Capulin Mountain cinder cone	0.056±0.008	Ar-Ar Stroud, 1997	0.059±0.006	^{36}Cl Sayre et al., 1995		
Capulin Mountain 5th basalt flow	0.056±0.008	Ar-Ar Stroud, 1997				
"The Crater" basalt flow	0.124±0.03	Ar-Ar Stroud, 1997				
Trinchera creek basalt flow	0.13±0.05	Ar-Ar Stroud, 1997				
Capulin Mountain 3rd basalt flow	0.225±0.058	Ar-Ar Stroud, 1997				
Horseshoe Crater basalt flow	0.44±0.08	Ar-Ar Stroud, 1997				
Purvine Hills basalt flow	0.52±0.2	Ar-Ar Stroud, 1997				
Las Maetas basalt flow	0.64±0.14	Ar-Ar Stroud, 1997				
E. Eagle Mountain basalt flow	0.98±0.01	Ar-Ar Stroud, 1997				
S. of Red Mtn basalt flow	1.14±0.12	Ar-Ar Stroud, 1997				
Yankee volcano basalt flow	1.14±0.16	Ar-Ar Stroud, 1997				
Blosser mesa basalt flow	1.25±0.08	Ar-Ar Stroud, 1997				
S. of Red Mtn basalt flow	1.28±0.06	Ar-Ar Stroud, 1997				
Chaco Arroyo basalt flow	1.44±0.18	Ar-Ar Stroud, 1997				
Carr Mtn basalt flow	1.68±0.13	Ar-Ar Stroud, 1997				
Taos and Surrounding areas						
Tierra Amarilla flow	0.25±0.06	K-Ar Lipman and Mehnert, 1975				
Upper Brazos Canyon flow	0.25±0.14	K-Ar Lipman and Mehnert, 1975				
unnamed basalt	0.81±0.05	K-Ar Scott and Marvin, 1985				
unnamed basaltic andesite	0.96±0.03	K-Ar Scott and Marvin, 1986				
unnamed basaltic andesite	1.1±0.04	K-Ar Scott and Marvin, 1987				
Mesita vent	1.03±0.01	Ar-Ar Appelt, 1998				
Ocate-Mora						
Cerro del Oro	0.81± 0.14	K-Ar O'Neill and Mehnert, 1988				
Maxon Crater	1.58± 0.16	Ar-Ar Olmsted, 2000	1.37± 0.15	K-Ar O'Neill and Mehnert, 1988		
Mount Taylor						
High mesa E side of Mt. Taylor	1.52± 0.18	K-Ar Crumpler, 1982				
unnamed basalt flow	1.56± 0.17	K-Ar Lipman and Mehnert				
Lucero						
Suwanee flow, Cerro Verde	0.278±0.302	K-Ar Leavy and Shafiqullah				
Suwanee flow	0.328±0.2	K-Ar Bachman and Mehnert, 1978				
Badger Butte	0.5±0.1	K-Ar Baldridge et al., 1987				
Mush Mountain	0.7±0.1	K-Ar Baldridge et al., 1987				
Volcano Hill flow	0.8±0.1	K-Ar Baldridge et al., 1987				
Albuquerque-Los Lunas						
Cat Hills	0.144±0.038	K-Ar Kudo et al., 1977				
Albuquerque volcanoes	0.195±0.04	K-Ar Bachman and Mehnert, 1978	0.155±0.047	Geissman et al., 1989		
Albuquerque volcanoes	0.12	Ar-Ar McIntosh pers. comm.				
Los Lunas volcano phase 2	1.25±0.02	Ar-Ar Dunbar et al., 2001				
Zuni-Bandera						
McCartys flow	0.0039±0.0012	^{36}Cl Dunbar and Phillips, 2004	0.0032±0.001	^{14}C, Laughlin et al., 1994	2.45±1.2	^{3}He, Laughlin et al., 1994
Bandera flow	0.0112±0.006	^{36}Cl Dunbar and Phillips, 2004	0.0107-0.0126±0.0666	^{14}C, Laughlin et al., 1994	11.2±1.1	^{3}He, Laughlin et al., 1994
Paxton Springs S	0.015±0.0010	^{36}Cl Dunbar and Phillips, 2004				
Twin Craters flow	0.018±0.001	^{36}Cl Dunbar and Phillips, 2004	0.0169-0.019	^{14}C, Laughlin and Woldegabriel, 1997		
Paxton Springs N flow	0.0207±0.0022	^{36}Cl Dunbar and Phillips, 2004				
Laguna flow	0.054±0.05	K-Ar Laughlin et al., 1993				
Bluewater flow	0.057±0.006	^{3}He, Laughlin et al., 1994				
Cerro Brillante cinder cone	0.94±0.4	K-Ar Anders et al., 1981				
Fence Lake flow	1.38± 0.29	K-Ar Crumpler et al., 1982				
Cerro Alto cinder cone	1.5± 0.3	K-Ar Anders et al., 1981				

Table 2 cntd.

Unit	Age (Ma)	Technique, reference	Age (Ma)	Technique, reference	Age (Ma)	Technique, reference
Quemado						
Red Hill	0.071± 0.012	Ar-Ar McIntosh and Cather, 1994				
Zuni Salt Lake	0.086± 0.031	Ar-Ar McIntosh and Cather, 1994				
Flow NE of Blaines Lake	0.206± 0.034	Ar-Ar McIntosh and Cather, 1994				
Cerro Pomo basalt	0.5±0.19	K-Ar Minier et al., 1988				
Apache Springs	0.9±0.2	K-Ar Bikerman, 1972	1.0±0.1	K-Ar Ratte et al., 1984		
Flow E of Blaines Lake	0.970± 0.014	Ar-Ar McIntosh and Cather, 1994				
Cerro Pomo basaltic andesite	1.35±0.21	K-Ar Minier et al., 1988				
Flow SE of Blaines Lake	1.51± 0.01	Ar-Ar McIntosh and Cather, 1994				
Lava in Quemado Crater	1.55± 0.01	Ar-Ar McIntosh and Cather, 1994				
Valley of Fires/Socorro						
Carrizozo lava flows (upper &lower)	0.0052± 0.0007	^{36}Cl Dunbar, 1999	0.0043± 0.001	^{3}He Anthony et al., 1998		
Broken Back Craters	0.02-0.05	geomorphology, Lindburg, 1990				
Jornada del Muerto	0.78± 0.1	K-Ar Bachman and Mehnert, 1978				
Potrillo and surrounding areas						
unnamed basalt flow	0.0082±0.00022	^{36}Cl Leavy, 1987				
unnamed basalt flow	0.0108±0.0007	^{36}Cl Leavy, 1987				
Hunt's Hole	0.016±0.007	^{3}He Williams and Poths, 1994	<0.05	geomorphology, Stuart, 1981		
Aden Crater	0.022±0.004	^{3}He Williams and Poths, 1994				
Kilbourne Hole	0.028	^{3}He Williams, 1999	0.024	soil, Gile, 1990		
unnamed basalt flow	0.0444±0.0037	^{36}Cl Leavy, 1987				
Potrillo post-maar flow #1	0.070±0.006	^{3}He Williams and Poths, 1994				
Black Mountain flow 1	0.079±0.007	^{3}He Williams and Poths, 1994				
Potrillo post-maar flow #2	0.082±0.006	^{3}He Williams and Poths, 1994				
Black Mountain flow 2	0.098±0.005	^{3}He Williams and Poths, 1994				
Afton flow #1	0.103±0.005	^{3}He Williams and Poths, 1994				
Afton flow #2	0.114±0.007	^{3}He Williams and Poths, 1994				
Little Black Mountain flow	0.117±0.009	^{3}He Williams and Poths, 1994				
unnamed basalt flow	0.1603±0.0016	^{36}Cl Leavy, 1987				
Potrillo maar flow	0.18±0.03	K-Ar Seager et al., 1984				
unnamed basalt flow	0.2508±0.0224	^{36}Cl Leavy, 1987				
San Miguel flow	0.49± 0.03	K-Ar Seager et al., 1984	~0.2	soil, Gile, 1990		
Aden-Afton flow	0.53±0.03	K-Ar Seager et al., 1984				
unnamed basalt flow	0.53±0.04	K-Ar Seager et al., 1984				
Animas basalt flow	0.544±0.05	K-Ar Lynch, 1978				
Santo Tomas #2 flow	0.55± 0.03	K-Ar Seager et al., 1984				
pre-Potrillo maar flow	1.2±0.06	K-Ar Seager et al., 1984				

cinder cones, spatter cones, and lava flows. The chemical composition of these volcanic features is generally basaltic, although the Los Lunas volcano represents more evolved lava compositions (Dunbar et al., 2001). The Isleta volcano includes a tuff cone feature, whose bedded deposits are visible in roadcuts on I-25 near Isleta. The Los Lunas volcano forms a distinctive landmark on the west side of I-25 near the town of Los Lunas. The volcano is geometrically complex, and shows evidence of pyroclastic activity, lava flows, and lava ponding. Detailed ^{40}Ar/^{39}Ar dating (Dunbar et al., 2001) has shown the Los Lunas volcano to be polygenetic. One part of the volcano was erupted around 3.8 Ma, and the second formed at 1.25 Ma.

The Albuquerque volcanoes consist of at least 15 vents, 5 of which fall along a very distinct 10 km long fissure (Smith, 1999). These spatter vents produced a number of lava flows which form the cliffs and terraces 25 m above the modern Rio Grande flood plain on the west side of Albuquerque (Baldridge, 2004). The early flows are the most widespread, and the later flows accumulated nearer the vent (Crumpler, 1999), giving the whole fissure system a broad, shield-like appearance. The largest cone of the Albuquerque volcanoes contained a lava pond in its central crater (Crumpler, 1999).

Lucero Volcanic Field

The Lucero volcanic field is located southeast of Mt. Taylor (Fig. 1), and consists mainly of lava flows, cinder cones and small shield vents dominated by tholeiite basalts (Baldridge et al., 1987). These volcanic features occur mainly as isolated outcrops spread over an area of around 2000 km^3. The total volume of the Lucero volcanic field is estimated to be 7.3 km^3 (Baldridge, 2004). The Lucero field has been active for the past 8 Ma, and has undergone three main phases of activity (Baldridge, 2004), including a number of events dated in the Quaternary (Table 2). Several of the youngest vents are mainly pyroclastic. A Quaternary feature of the Lucero field, the small Cerro Verde shield, produced a 42 km long lava flow that flowed along a drainage (Fig. 1, area 6). As with the Raton-Clayton and Ocate-Mora volcanic fields, the oldest lavas in the Lucero field are at the highest elevations, and the more recent flows occur near the modern land surface, recording landscape evolution in this area.

Zuni-Bandera Volcanic Field

The Zuni-Bandera volcanic field (ZBVF) (Fig. 1) is one of the most striking examples of basaltic volcanism in New Mexico, and has been active mainly during the Quaternary. This volcanic field, which contains at least 100 vents (Luedke and Smith, 1978) consists of a sequence of mafic lavas flows and cinder cones erupted over the past 0.7 Ma (Laughlin et al., 1993). The extensive field covers an area of 2,460 km^2. Combined flow thickness is as great as 145 m in some places, and the total volume of all flows is at least 74 km^3 (Laughlin et al, 1993). The ZBVF is located on the JL, and lavas are thought to be derived from the mantle (Laughlin et al, 1972; Perry et al., 1987; Menzies et al., 1991). Perry et al. (1987), suggest that late Cenozoic basaltic rocks from the Colorado Plateau-Basin and Range transition area show isotopic characteristics of both enriched and depleted mantle, and may come from the boundary between these two mantle types. Menzies et al. (1991) also suggest that, although the chemical composition of the Zuni-Bandera lavas is typical of intraplate volcanisim, with a distinctive mantle signature. Geochemical compositions include tholeiitic and alkaline basalts, as well as minor basaltic andesites and one basanite (Menzies et al., 1991).

Cinder cones, including the well-known Bandera Crater, and lava fields including a'a and pahoehoe, are the dominant features of the ZBVF. Extensive lava tube systems are present, as well as a number of other features of Hawaiian volcanism. Nichols (1946) mapped and catalogued the geomorphic features of the apparently-young McCartys basalt flow and recognized many features of Hawaiian-style volcanism, including pahoehoe flow patterns, small spatter cones, gas cavities, large wedge-shaped cracks, collapse depressions, large pressure ridges and tumescences. These types of features are also present in other, apparently older flows, although in some cases they are obscured by erosion.

Three distinct pulses of activity have been recognized in the ZBVF. The first between 0.7 and 0.6 Ma, the second between 0.2 and 0.11 Ma, and a third, youngest pulse occurring over the past 50 ka (Laughlin et al., 1993; Dunbar and Phillips, 2004). The Zuni-Bandera volcanic field hosts most of the youngest volcanic activity in New Mexico, including the McCartys flow and the Bandera Crater flow, dated at 3.9 $\pm$ 1.2 and 11.2 $\pm$ 0.6 ka, respectively (Dunbar and Phillips, 2004). The names and ages of the best-dated flows are shown in Table 2.

Quemado Volcanic Field

The Quemado volcanic field is located in the western part of New Mexico (Fig. 1), and is almost continuous with the Springerville volcanic field of eastern Arizona. The Quemado volcanic field contains a large number of basaltic volcanic features, including cinder cones, lava flows and maars (Limburg, 1990). A total of 32 vents have been identified in the Quemado volcanic field, some of which have been dated by McIntosh and Cather (1994), and others of which have not been studied (Callender et al., 1983). The youngest volcanism identified in the Quemado field is a very young-looking feature, Zuni Salt Lake, which has been dated using ^{14}C analysis of diatoms, to an age of 23,000 $\pm$ 1400 years (Bradbury, 1966), but more recent $^{40}Ar/^{39}Ar$ dating suggests an age of 86,000 $\pm$ 31,000 years (McIntosh and Cather, 1994). Zuni Salt Lake is a maar volcano, and spectacular surge bedding is present in the deposits associated with this eruption. Limburg (1990) suggests that much of the field may be younger than 20 ka, based on the lack of soil development in the field, so the field may have experienced significant Quaternary activity beyond the eruptions listed in Table 2. Other volcanism in the Quemado field is as old as 7.9 Ma (McIntosh and Cather, 1994). The associated Springerville volcanic field also was active during the Quaternary (Condit et al., 1989).

Valley of Fires Volcanic Field

The lava flows and cinder cones found in the area here called Valley of Fires are located in south-central New Mexico (Fig. 1), and are the only Quaternary volcanic features in New Mexico linked to neither the RGR or JL. The vents for these features follow on the Capitan lineament, a zone of crustal weakness that extends across eastern New Mexico (Allen, 1991). The Capitan lineament is interpreted as a deeply penetrating zone of crustal weakness along which magmas have been able to rise and erupt (Chapin et al., 1978).

Two main areas of Quaternary activity are present in the Valley of Fires area: Broken Back Craters, which consist of two large cinder cones and associated lava flows (Limburg, 1990), and the very young and well-studied Carrizozo Malpais lava flow. The total eruptive volume of the Carrizozo lava flows is estimated to be between 2.8 and 4.3 km^3 (Allen, 1952); thickness averages 10-15 m, and the total length of the flow field is 75 km (Keszthelyi and Pieri, 1993). The flows are interpreted to be tube-fed (Keszthelyi and Pieri, 1993), and are characterized by pahoehoe textures, such as ropey flow tops, smooth lava sheets, toes, tumuli, and pressure ridges. The flow top of the lava is very well-preserved, and in some places even retains an iridescent appearance, typical of young lava flows. Two distinct lava flows have been identified in the Carrizozo field (Renault, 1970). The lower flow extends for the full 75 km length. The central part of the flow is narrow, whereas the lower part spreads to a width of nearly 8 km. The upper flow extends approximately 25 km from the vent and is wider, on average, than the lower flow and, where both flows can be observed, is typically thicker (Weber, 1964). The contact between the upper and lower flows is brecciated, but shows no evidence of erosion or soil development (Faris, 1980), suggesting that the time between eruption of the two flows was relatively short.

The apparently-young Carrizozo lava flows have proven very difficult to date. No carbon suitable for ^{14}C analysis has been found under the Carrizozo flows. Allen (1952) estimated, based on visual observation, that the flows are less than 1000 years old, and Weber (1964) estimated the age as 1500 yrs old. These ages may have been influenced by age estimates for the geomorphically-similar and nearby McCartys lava flow that was estimated to have erupted roughly 1000 yrs ago, based on Acoma Indian legend, and an apparent stratigraphic relationship with Pueblo I artifacts (Nichols et al., 1946). Since then, Salyards (1991) estimated an age of approximately 5000 yrs, based on secular variation magnetostratigraphy. He notes, however, that there are potential problems with the confidence of this age determination, and that an independent age determination would be necessary to confirm his age interpretation.

Based on recent cosmogenic ^{36}Cl dating (Dunbar, 1999), my preferred eruption date for the Carrizozo malpais is 5200 ± 700 yrs ago. This age is in good agreement with secular variation magnetostratigraphy and ^{3}He ages (Anthony et al., 1998), but is much older than ages based on visual observations of the flow surface morphology. The age of the Carrizozo lava flows are geomorphically-consistent with the age of the well-dated McCartys flow. There is no apparent age difference between the upper and lower Carrizozo flows, suggesting that these two flows were formed by as an essentially single eruptive event.

Potrillo Volcanic Field and Associated Areas

The Potrillo volcanic field, located in southwestern New Mexico (Fig. 1), is located in the southern portion of the RGR, near the eastern margin of the Basin and Range Province. This field, together with a few associated areas, has been extremely active during the Quaternary. The Potrillo field contains a total of several hundred young lava flows, cinder cones and maar craters, covering a total area of 4,600 km^2 (Williams, 1999). The erupted material in this field is dominantly alkali olivine basalt and basanite (Hoffer, 2001). The West Potrillo field alone includes 124 cinder or spatter cones, two maar volcanoes and a number of lava flows (Hoffer, 2001). Landsat imagery indicates that these features were erupted over an extended period of time, but probably all during the Quaternary (Hoffer, 2001). The Potrillo field is well-known for well developed and well exposed maar volcanoes, of which the best-known is Kilbourne Hole, a maar known for its abundance of mantle xenoliths (Padovani, 1987). Several other well-exposed maar craters are also present in the Potrillo field, including Hunts Hole and Potrillo maar. Potrillo maar and its associated explosive deposits cover an area of around 13 km^2, and exhibit three phases of activity. The first is characterized by pre-maar effusive basaltic volcanism, followed by the very explosive maar formation, followed by moderately explosive formation of cinder and spatter cones. Another well-known feature of the Potrillo field, Aden crater, sits atop a broad shield. The 1.6 km diameter crater shows evidence of a lava lake which overflowed the crater rim. Post-shield spatter cones are found inside the crater, as well as on the flanks of the shield (Hoffer, 1976)

A number of dating techniques have been used to determine the age of the volcanic features in the Potrillo volcanic field, as well as other nearby volcanic features. These include conventional K-Ar dating, $^{40}Ar/^{39}Ar$ dating, as well as cosmogenic techniques, such as ^{36}Cl (Leavy, 1987) and ^{3}He (Williams, 1999) and soil development methods (Gile, 1987) (Table 2).

EPISODICITY OF VOLCANISM

As discussed in the previous sections, volcanism occurred in numerous areas of New Mexico during the Quaternary. When considered as a whole, there does not appear to be any spatial or temporal pattern to Quaternary volcanism in New Mexico (Fig. 4). Rather, it appears that there has been more-or-less continuous volcanic activity throughout the Quaternary, and throughout different geographic regions of the state. The most recent activity has been concentrated in three areas, the Zuni-Bandera volcanic field, the Carrizozo lava flows, and the Potrillo volcanic field, which are widely spaced around the state. So, there does not appear to be any significant episodicity to, or systematic geographic migration of, volcanic activity during the Quaternary.

CLIMATIC IMPACT OF VOLCANISM

Volcanic eruptions can have a wide range of impacts on climate and weather. Volcanic ash associated with explosive eruptions, though sometimes voluminous and very visible, typically has minimal impact on weather or climate. The ash component of an eruption falls out within minutes to weeks in the troposphere (Robock, 2000). A small amount of ash may persist in the stratosphere for up to a few months, but will only have small climatic impact.

In addition to the ash component, explosive volcanic eruptions produce abundant quantities of gas. The dominant gases emitted are H_2O, N_2 and CO_2. Both H_2O and CO_2 are greenhouse gases, but their background atmospheric concentrations are large enough that the effect of a single eruption is likely to be negligible (Robock, 2000). However, another component of volcanic gas, sulfur species, mainly SO_2, has the potential to be much more climatically significant (Rampino and Self, 1984). The reaction of SO_2 with atmospheric H_2O and OH can form the compound H_2SO_4, which has the effect of absorbing solar radiation. If significant H_2SO_4 forms in the stratosphere following a volcanic eruption, the result can be stratospheric warming and related tropospheric cooling (e.g., Robock, 2000). Two moderate-sized, sulfur-rich eruptions, Mt.Pinatubo and Mt. Agung, each caused tropospheric coolings of 0.4^{o}C (Mills, 2000). A period of dramatic cooling in Europe, the "year without a summer" in 1816, resulted from the very large eruption of Mt. Tambora (Mills, 2000), probably due to S emission from this eruption (Rampino and Self, 1982). The residence time of H_2SO_4 in the stratosphere may be up to three years, and this is the time period over which significant cooling may persist (Robock, 2000).

A second effect of volcanism on the atmosphere is the reduction of stratospheric ozone levels (Robock, 2000). As is the case for climate cooling, ozone depletion resulting from volcanic eruptions is largely related to volcanic S introduced to the stratosphere. The sulfate aerosols in the stratosphere following an explosive eruption can provide surfaces for the heterogeneous chemical reactions that destroy ozone (Robock, 2000). A generalized mid-latitude ozone depletion of 5% was observed as a result of the eruption of Mt. Pinatubo (e.g. Robock, 2000) with ozone depletion in the vicinity of the volcanic cloud reaching 20% (Grant et al., 1992). However, depletion of stratospheric ozone will not necessarily affect climate.

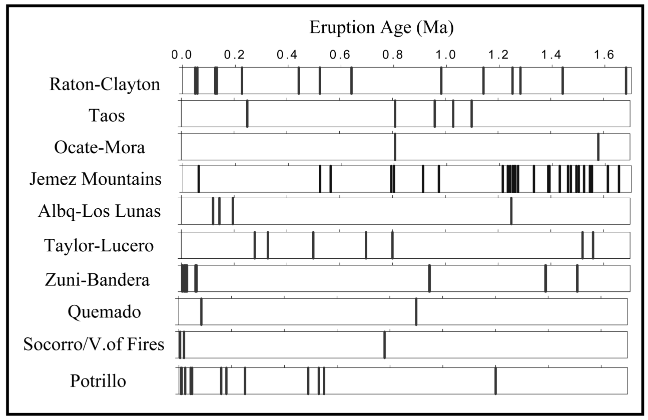

FIGURE 4. Integrated ages of Quaternary volcanism in New Mexico. Data compiled from Tables 1 and 2.

Another possible climatic impact of volcanism is a recently-noted link between episodes of volcanism and El Niño climatic events. A relationship between volcanism and El Niño was noted by Hirono (1988) then discounted by Robock (2000), and then suggested again by Adams et al. (2003) based on a more complete dataset. Although there does appear to be a correlation, the cause-and-effect relationship between volcanic eruptions and El Niño is not clear. Adams et al. (2003) do not suggest that volcanic eruptions directly trigger El Niño events. They speculate, rather, that explosive tropical eruptions may move the atmosphere towards a condition that is favorable for El Niño climatic patterns to prevail.

Volcanic eruptions that produce large amounts of Fe-rich ash that is deposited into the ocean may affect global climate (Sarmiento, 1992). The reason for this is that introduction of Fe into Fe-poor ocean water may trigger major biotic activity, thereby removing CO_2 from the atmosphere and sequestering it on the seafloor as the organisms die. The removal of CO_2, a greenhouse gas, from the atmosphere, can result in global cooling.

Although large-volume volcanism has occurred in New Mexico during the Quaternary, none is likely to have had a significant impact on climate. Many basaltic events have taken place during the past 1.7 million years, and most are likely to have released significant S to the atmosphere. However, the low explosivity of these eruptions would not have allowed the S released during the eruptions to penetrate into the stratosphere, where it would have the greatest climatic effect. Therefore, these basaltic eruptions probably had no impact on climate.

The eruptions that would have been explosive enough to reach the stratosphere, the eruption of the upper and lower members of the Bandelier Tuff, probably did not emit much S. This is based on measurement of very low S contents in melt inclusions from these eruptions, suggesting that little S was dissolved in the melt (Dunbar and Hervig, 1992). A low-S melt cannot degas large quantities of S, and therefore would probably have introduced little S to the stratosphere. However, Wallace et al. (2003) suggests that petrological estimates of S degassing for large silicic eruptions based on determination of the amount of S dissolved in the melt may underestimate the total amount of S emitted by these eruptions. This admits the possibility that eruption of the Bandelier Tuff emitted some amount of S, but at this point, it would be impossible to quantify the amount in order to assess the climate impact. The best estimates that we have, based on measured values of S, suggest that the emissions, and therefore the climatic impact, would have been low.

IMPACT OF VOLCANISM ON LANDSCAPE EVOLUTION

Because of the great abundance of young volcanoes in New Mexico, the landscape in many areas of the state has been formed by past volcanic activity. The black, barren, lunar-landscape of the very young basalt flows, as well as the prominent cinder cones around Grants and Carrizozo are a distinctive volcanic landscape and the basalt-capped mesas around Albuquerque and Santa Fe are volcanically-formed. Some of the state's most distinctive landforms, Mt. Taylor, the Jemez Mountains, Capulin Peak, Shiprock and Cabezon Peak are all volcanoes or volcanic remnants. So, at the most basic level, Quaternary volcanism has had a significant impact on the landscape of New Mexico.

In addition to creating distinctive, eruptive landforms, large volcanic eruptions may result in dramatic modifications of the landscape around the vent areas, and can also affect sedimentary processes at a distance from the vent. In the case of basaltic eruptions, lava flows can fill low-lying areas and disrupt drainages. In the case of explosive silicic eruptions, pyroclastic material may create new landscapes over 10^4 km^2, resulting in burial of existing topography and drainages by hundreds of meters of pyroclastic material (Manville, 2002). Once this burial has occurred, re-establishment of drainages involves mobilization and transport of huge volumes of volcanic material. This process has been studied in modern eruptions of Mount St. Helens (Major et al., 2000) and Mt. Pinatubo (Pierson et al., 1992) as well as in eruptions preserved in the geological record. The extreme overloading of depositional systems near the locations of volcanic eruptions results in major changes in lithofacies types, fluvial styles, depositional environments and sedimentation rates (e.g., Manville, 2002). The suspended sediment loads in streams following the 1980 eruption of Mount St. Helens were 500 times above background just following the eruption, and even 20 years after the eruption, sediment loads were still 100 times above background (Major et al., 2000). The disruption of fluvial systems by volcanic eruptions presents a significant hazard to surrounding communities, one that endures long after the actual eruption has ceased.

Significant disruption of drainage patterns in New Mexico occurred as a result of the eruption of the upper and lower members of the Bandelier Tuff (Cather and McIntosh, 1990; Mack et al., 1996). Pumice from these eruptions has been found hundreds of kilometers south of the Valles Caldera, interbedded with ancestral Rio Grande sediments. These pumices are interpreted to have been deposited from flood events that occurred in response to the Rio Grande becoming dammed by pyroclastic deposits. The downstream transport of these deposits may have been very rapid, on the order of a few days to weeks, based on the high abundance of pumice in the deposits (Mack et al., 1996).

In addition to fluvially transported pumice, fine ash was widely deposited around New Mexico during the eruption of the Bandelier Tuff (Figs. 2-3). Primary deposits of volcanic ash up to 10 cm thick from eruptions from the Valles Caldera have been found as far south as Socorro, almost 300 km south of the vent (Dunbar et al., 1996). So, even drainage systems hundreds of kilometers from vent may have felt the effect of these large eruptions.

As well as pyroclastic deposits from large, silicic eruptions, basaltic eruptions also have the potential to modify landscape and drainage patterns, although these modifications would all take place relatively close to the volcanic vent. Basaltic lava flows provide a cap rock that covers underlying sediment, modifying erosion patterns and leading to the mesa and butte topography characteristic of the arid Southwest. The ages of lava flow cap rocks provide time markers that can be used to estimate erosion rates (Stroud, 1997). Erosion rates can be estimated in areas where more than one generation of lava flow caprock is present, and the different flows are at different elevations. By assuming that the elevation of the lava flow represents the ground surface at the time of that eruption, the combined differences in age and elevation of two different flows can yield an erosion rate.

Basaltic lava flows may also affect river behavior, if the flows travel down the river bed. Damming of the Colorado River by basaltic lava flows may have occurred repeatedly in the Grand Canyon area (Hamblin, 1994; Fenton et al., 2004). These authors suggest that a number of damming events have occurred on the Colorado River over the past 500 ka, as a result of basaltic lava blocking the narrow river channel. The damming caused upstream lakes to form, which resulted in catastrophic floods when the dams failed (Fenton et al., 2004). This same type of damming/flood cycles may have taken place in New Mexico during the Quaternary. One location where this may have occurred would be in the Ocate-Mora volcanic field (Fig. 1, area 3), where a basaltic lava flowed for 96 km in the Mora River valley (Olmsted, 2000). The Mora River appears to have rapidly eroded down through the basaltic lava (Olmsted, 2000) so any disruption in drainage patterns would have been short-lived. Some older flows in the Ocate-Mora area, however, appear to have blocked river drainages for long enough time periods to significantly change sedimentation patterns (Olmsted, 2000).

VOLCANIC HAZARDS IN NEW MEXICO

With the possible exception of the Jemez Mountains (Wolff and Gardner, 1995), none of the New Mexico volcanoes that have erupted in the Quaternary are ever likely to erupt again. However, a large magma body underlies an area stretching from just south of Albuquerque to near Socorro (Balch et al., 1997). The magma body is located at a depth of 19 km in the crust, and many small earthquakes associated with the magma body have been detected using seismometers (Sanford et al., 1995). Although there is no evidence for any imminent eruption from this magma body, it would be a likely location for future volcanism in New Mexico.

But, how likely is an eruption to actually occur in New Mexico in the near future? Study of the ages of volcanism in New Mexico indicates that there have been more than 700 volcanic eruptions in New Mexico in the last 5 million years (Limburg, 1990). Based on this information, Limburg (1990) estimates that there is roughly a 1% chance that some type of volcanic eruption could occur somewhere in New Mexico in the next 100 years, and a 10% chance that an eruption will occur in the next 1000 years. Approximately 100 eruptions will occur in the next million years. Widespread seismic monitoring around the state would help provide forewarning, and predict where an eruptive event might take place.

CONCLUSIONS

Volcanism has been temporally common and geographically widespread throughout the Quaternary in New Mexico. Two main types of volcanism have occurred during the Quaternary in New Mexico, one consisting of relatively small, geographically distributed basaltic events, and a second characterized by a concentration of small to large volume silicic events from the Jemez Mountain Volcanic Center. Much of the volcanic activity during this time period has been focused along the Rio Grande rift, or the Jemez lineament, although one set of centers falls along the Capitan lineament. The effect of Quaternary volcanism on climate in New Mexico was probably negligible. However, the effect on landscape evolution, particularly through formation of landscapes and disruption of drainage patterns, may have been significant.

ACKNOWLEDGMENTS

This work was supported by the NMBGMR (NMIMT, Peter Scholle, Director and State Geologist). Thanks to Bill McIntosh, Dave Love, Philip Kyle, and Jane Aubele for useful advice, reviews and discussion.

REFERENCES

Aldrich, M. J., Jr., 1986, Tectonics of the Jemez Lineament in the Jemez Mountains and Rio Grande rift, *in* Heiken, G., ed., Workshop on Recent research in the Valles Caldera, American Geophysical Union, p. 1753-1762.

Allen, J. E., 1952, The Carrizozo Malpais: Roswell Geological Society Guidebook, p. 9-11.

Allen, M. S., and McLemore, V. T., 1991, The geology and petrogenesis of the Capitan Pluton, New Mexico: New Mexico Geological Society, Guidebook 42, p. 115-127.

Anders, M., Heiken, G., Eichelberger, J., Laughlin, A., and Huestis, S., 1981, Geologic and geophysical investigations of the Zuni-Bandera volcanic field, New Mexico: Los Alamos National Laboratory Report LA 8827-MS.

Anthony, E., Hoffer, J., Williams, W., Poths, J., and Penn, B., 1998, Geochemistry and geochronology of Quaternary mafic volcanic rocks in the vicinity of Carrizozo, New Mexico: New Mexico Geological Society, Guidebook 49, p. 116-122.

Appelt, R. M., 1998, $^{40}Ar/^{39}Ar$ geochronology and volcanic evolution of the Taos Plateau volcanic field, northern New Mexico and southern Colorado [Master's thesis]: Socorro, New Mexico Institute of Mining and Technology, 149 p.

Aubele, J. C., and Crumpler, L. S., 2001, Raton-Clayton and Ocate volcanic fields, New Mexico Geological Society, Guidebook 52, p. 69-76.

Bachman, G. O., and Mehnert, H. H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America Bulletin, v. 89, p. 283-292.

Balch, R., Hartse, H., Sanford, A., and Lin, K., 1997, A new map of the geographic extent of the Socorro mid-crustal magma body: Bulletin of the Seismological Society of America, v. 87, p. 174-182.

Baldridge, W. S., 1979, Petrology and petrogenesis of Plio-Pleistocene basaltic rocks from the central Rio Grande rift, New Mexico, and their relation to rift structure, *in* Riecker, R. E., ed., Rio Grande rift; Tectonics and magmatism: Washington, DC, American Geophysical Union, p. 323-354.

Baldridge, W. S., 2004, Pliocene-Quaternary volcanism in New Mexico and a model for genesis of magmas in continental extension, *in* Mack, G. H., Giles, K.A., ed., The Geology of New Mexico: Socorro, New Mexico Geological Society, Special Publication 11, p. 312-330.

Baldridge, W. S., Perry, F. V., and Shafiqullah, M., 1987, Late Cenozoic volcanism of the southeastern Colorado Plateau; I, Volcanic geology of the Lucero area, New Mexico: Geological Society of America Bulletin, v. 99, p. 463-470.

Callender, J., Seager, W., and Swanberg, C., 1983, Late Tertiary and Quaternary tectonics and volcanism, scale 1:500,000. New Mexico State University Energy Institute Scientific Map Series, in Geothermal Resources of New Mexico.

Carey, S., and Sparks, R. S. J., 1986, Quantative models of the fallout and dispersal of tephra from volcanic eruption columns: Bulletin of Volcanology, v. 48, p. 109-125.

Cather, S. M., and McIntosh, W. C., 1990, Volcanogenic flood deposits near San Antonio, New Mexico; depositional processes and implications: International Sedimentological Congress, Program and Abstracts, v. 13, p. 80.

Chamberlin, R. M., and Anderson, O. J., 1989, The southern margin of the Colorado Plateau; a ragged edge bounded by Neogene domains; of crustal extension: New Mexico Geological Society, Guidebook 40, p. 37-38.

Chapin, C. E., 1979, Evolution of the Rio Grande rift; a summary, *in* Riecker, R. E., ed., Rio Grande Rift; tectonics and magmatism: Rio Grande rift; tectonics and magmatism: Washington, DC, American Geophysical Union, p. 1-5.

Condit, C. D., Crumpler, L. S., Aubele, J. C., and Elston, W. E., 1989, Patterns of volcanism along the southern margin of the Colorado Plateau; the Springerville Field, *in* Leeman, W. P., and Fitton, J. G., eds., American Geophysical Union 1987 fall meeting symposium on Magmatism associated with lithospheric extension, American Geophysical Union, p. 7975-7986.

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

Crumpler, L. S., 1982, Volcanism in the Mt. Taylor Region: New Mexico Geological Society, Guidebook 33, p. 291-298.

Crumpler, L. S., 1999, Ascent and eruption at the Albuquerque volcanoes; a physical volcanology perspective, New Mexico Geological Society, Guidebook 50, p. 221-234.

Crumpler, L. S., 2001, Volcanism in New Mexico; an overview: New Mexico Museum of Natural History and Science, Bulletin 18, p. 17-29.

Dunbar, N., 1999, Cosmogenic ^{36}Cl-determined age of the Carrizozo lava flows, south-central New Mexico: New Mexico Geology, v. 21, p. 25-29.

Dunbar, N., and Phillips, F., 2004, Cosmogenic ^{36}Cl ages of lava flows in the Zuni-Bandera volcanic field, north-central New Mexico, USA: New Mexico Bureau of Mines and Mineral Resources, Bulletin 160, p. 51-59.

Dunbar, N. W., and Hervig, R. L., 1992, Volatile and trace element composition of melt inclusions from the Lower Bandelier Tuff: Implications for eruptive style and magma chamber processes: Journal of Geophysical Research, v. 97, p. 15151-15170.

Dunbar, N. W., McIntosh, W. C., Cather, S. M., Chamberlin, R. M., Harrison, B., and Kyle, P. R., 1996, Distal tephras from the Jemez volcanic center as potential time-stratigraphic markers in the ancestral Rio Grande sediments from the Socorro area: New Mexico Geological Society, Guidebook 47, 69-70.

Dunbar, N. W., McIntosh, W. C., and Love, D., 2001, Dating basalts using the $^{40}Ar/^{39}Ar$ method: Improvements based on electron microprobe evaluation of samples: EOS, Transactions of the American Geophysical Union, v. 82, no. 47, p. F1321.

Faris, K. B., 1980, A geochemical model for the magmatic history of the Carrizozo basalt field, south central New Mexico [MS thesis]: Socorro, New Mexico Institute of Mining and Technology, 168 p.

Fenton, C., Poreda, R., Nash, B., Webb, R., and Cerling, T., 2004, Geochemical discrimination of five pleistocene lava-dam outburst flood deposits, western Grand Canyon, Arizona: Journal of Geology, v. 112, p. 91-110.

Fisher, R. V., and Schmincke, H. U., 1984, Pyroclastic Rocks: New York, Springer-Verlag, 472 p.

Geissman, J. W., Harlan, S. S., Brown, L., Turrin, B. D., and McFadden, L. D., 1989, Bruhnes Chron geomagnetic excursion recorded during the late Pleistocene, Albuquerque Volcanoes, New Mexico, U.S.A, *in* Lowes, F. J., Collinson, D. W., Parry, J. H., Runcorn, S. K., Tozer, D. C., and Soward, A. M., eds., Proceedings of the NATO Advanced Study Institute on Geomagnetism and paleomagnetism, D. Reidel Publishing Company, p. 123-126.

Gile, L. H., 1987, A Pedogenic Chronology For Kilbourne Hole ; southern New-Mexico .1. Soils in the Tuff: Soil Science Society of America Journal, v. 51, p. 746-751.

Grant, W., Fishman, J., Browell, E., Brackett, V., Nganga, D., Minga, A., Cros, B., Veiga, R., Butler, C., Fenn, M., and Nowicki, G., 1992, Observations of reduced ozone concentrations in the tropical stratosphere after the eruption of Mt. Pinatubo: Geophysical Research Letters, v. 19, p. 1109-1112.

Hamblin, W. K., 1994, Late Cenozoic lava dams in the western Grand Canyon: Geological Society of America Memoir 183, 138 p.

Hirono, M., 1988, On the trigger of El NiZo-Southern Oscillation by the forcing of early El Chichon volcanic aerosols: Journal of Geophysical Research, v. 93, p. 5365-5384.

Hoffer, J. M., 1976, The Potrillo basalt field, South-central New Mexico: New Mexico Geological Society, Special Publication 5, p. 89-92.

Hoffer, J. M., 2001, Geology of the west Potrillo Mountains, Volcanology in New Mexico, New Mexico Museum of Natural History and Science, Bulletin 18, p. 141-145.

Izett, G. A., Obradovich, J. D., Naeser, C. W., and Gebula, G. T., 1978, K-Ar and fission-track zircon ages of Cerro Toledo rhyolite tephra units in the Jemez Mountains, north-central New Mexico: United States Geological Survey, Professional Paper, 1199-D, p. 37-41.

Izett, G. A., Wilcox, R. E., and Borchardt, G. A., 1972, Correlation of a volcanic ash bed in Pleistocene deposits near Mount Blanco, Texas, with the Guaje Pumice Bed of the Jemez Mountains, New Mexico: Quaternary Research, v. 2, p. 554-578.

Kelley, V. C., and Kudo, A. M., 1978, Volcanoes and related basalts of Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 156, 30 p.

Keszthelyi, L. P., and Pieri, D. C., 1993, Emplacement of the 75-km-long Carrizozo lava flow field, south central New Mexico: Journal of Volcanology and Geothermal Research, v. 59, p. 59-75.

Kudo, A. M., Kelley, V., Damon, P., and Shafiqullah, M., 1977, K-Ar ages of basalt flows at Canjilon Hill, Isleta Volcano, and the Cat Hills volcanic field, Albuquerque-Belen basin, central New Mexico: Isochron West, v. 18, p. 15-16.

Laughlin, A. W., Brookins, D. G., and Causey, J. D., 1972, Late Cenozoic basalts from the Bandera lava field, Valencia County, New Mexico: Geological Society of America Bulletin, v. 83, p. 1543-1551.

Laughlin, A. W., Charles, R. W., Reid, K., and White, C., 1993, Field-trip guide to the geochronology of the El Malpais National Monument and the Zuni-Bandera volcanic field, New Mexico, New Mexico Bureau of Mines and Mineral Resources, Bulletin 149, 23 p.

Laughlin, A. W., Perry, F. V., Damon, P. E., Shafiqullah, M., Harrington, C. D., Wells, S. G., and Drake, P., 1993, Geochronology of the Mount Taylor, Cebollita Mesa, and Zuni-Bandera volcanic fields, Cibola County, New Mexico: New Mexico Geology, v. 15, p. 81-92.

Laughlin, A. W., Poths, J., Healey, H. A., Reneau, S., and WoldeGabriel, G., 1994, Dating of Quaternary basalts using the cosmogenic ^{3}He and ^{14}C methods with implications for excess ^{40}Ar: Geology, v. 22, p. 135-138.

Laughlin, A. W., and WoldeGabriel, G., 1997, Dating the Zuni-Bandera volcanic field, Natural history of El Malpais National Monument, New Mexico Bureau of Mines & Mineral Resources, Bulletin 156, p. 25-30.

Leavy, B. D., 1987, Surface-exposure dating of young volcanic rocks using in situ buildup of cosmogenic isotopes: [Ph.D. dissertation]: Socorro, New Mexico Institute of Mining and Technology, 167 p.

Leavy, B. D., and Shafiqullah, M., 1987, New K-Ar analyses of basalts from Southern California and central New Mexico: Isochron West, v. 48, p. 19-20.

Limburg, E., 1990, Recent and potential volcanism of New Mexico [MS thesis]: Socorro, New Mexico Institute of Mining and Technology, 149 p.

Lipman, P. W., and Mehnert, H. H., 1979, The Taos Plateau volcanic field, northern Rio Grande rift, New Mexico, *in* Riecker, R. E., ed., International symposium on the Rio Grande rift: Rio Grande Rift; tectonics and magmatism: Washington, DC, American Geophysical Union.

Love, D. W., Dunbar,N. W., McIntosh, W. C., Sorrell, J., and Pierce, D., 2003, Volcanic debris from the Jemez Mountains constrain the age, sediment-source history, and deformation of fluvial facies of the Ancestral Rio Grande (Upper Santa Fe Group), central Albuquerque Basin, New Mexico: Geological Society of America Rocky Mountain Section Meeting Abstracts with Program.

Luedke, R. G., and Smith, R., 1978, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Arizona and New Mexico: U. S. Geological Survey Map I-1091-A.

Lynch, D. J., 1978, The San Bernadino volcanic field of southeastern Arizona.: New Mexico Geological Society, Guidebook 29, p. 261-268.

Mack, G. H., McIntosh, W. C., Leeder, M. R., and Monger, H. C., 1996, Plio-Pleistocene pumice floods in the ancestral Rio Grande, southern Rio Grande Rift, USA: Sedimentary Geology, v. 103, p. 1-8.

Major, J. J., Pierson, T. C., Dinehart, R. L., and Costa, J. E., 2000, Sediment yield following severe volcanic disturbance; a two-decade perspective from Mount St. Helens: Geology, v. 28, p. 819-822.

Manville, V., 2002, Sedimentary and geomorphic responses to ignimbrite emplacement: Readjustment of the Waikato River after the AD 181 Taupo Eruption, New Zealand: Journal of Geology, v. 110, p. 519-541.

McIntosh, W. C., 1994, ^{40}Ar/^{39}Ar geochronology of basaltic rocks and constraints on late Cenozoic stratigraphy and landscape development in the Red Hill-Quemado area, New Mexico: New Mexico Geological Society, Guidebook 45, p. 209-224.

Menzies, M. A., Kyle, P. R., Jones, M., and Ingram, G., 1991, Enriched and depleted source components for tholeiitic and alkaline lavas from Zuni-Bandera, New Mexico: Inferences about intraplate processes and stratified lithosphere: Journal of Geophysical Research, v. 96, p. 13645-13671.

Mills, M. J., 2000, Volcanic aerosol and global atmospheric effects, *in* Sigurdsson, H., Houghton, B. F., McNutt, S. R., Rymer, H., Stix, J., and Ballard, R. D., eds., Encyclopedia of volcanoes: San Diego, CA, p. 931-943.

Minier, J., Reiter, M., Shafiqullah, M., and Damon, P. E., 1988, Geothermal studies in the Quemado area, New Mexico: Geothermics, v. 17, p. 735-755.

Nichols, R. L., 1946, McCartys basalt flow, Valencia County, New Mexico: Geological Society of America Bulletin, v. 57, p. 1049-1086.

Olmsted, B. W., 2000, ^{40}Ar/^{39}Ar Investigations of the Ocate Volcanic Field, North-Central New Mexico [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 194 p.

Olsen, K. H., Baldridge, W. S., and Callender, J. F., 1987, Rio Grande Rift; an overview, *in* Ramberg, I. B., Milanovsky, E. E., and Qvale, G., eds., Symposium on Rifts of the continents and oceans, a part of the 27th international congress, Amsterdam, Elsevier, p. 119-139.

O'Neill, J., and Mehnert, H., 1988, Petrology and physiographic evolution of the Ocate Volcanic Field, North-Central New Mexico: U. S. Geological Survey Professional Paper 1478A, p. 1-30.

Padovani, E. R., 1987, The ground truth from crustal xenoliths; a multifaceted approach, *in* Noller, J. S., Kirby, S. H., and Nielson-Pike, J. E., eds., Geophysics and petrology of the deep crust and upper mantle, Washington, D.C., U. S. Geological Survey, p. 40-43.

Perry, F. V., Baldridge, W. S., and DePaulo, D. J., 1987, Role of asthenosphere and lithosphere in the genesis of late Cenozoic basaltic rocks from the Rio Grande rift and adjacent regions of the Southwestern United States: Journal of Geophysical Research, v. 92, p. 9193-9213.

Phillips, E., Goff, F., Kyle, P., and McIntosh, W., 2003, Collapse and resurgence of the Valles Caldera, Jemez Mountains, New Mexico: Field relationships and ^{40}Ar/^{39}Ar ages of megabreccia blocks and constraints on the timing of resurgence: New Mexico Geology, v. 25, p. 46-47.

Pierson, T. C., Janda, R. J., Umbal, J. V., and Daag, A. S., 1992, Immediate and long-term hazards from lahars and excess sedimentation in rivers draining Mount Pinatubo, Philippines: U. S. Geological Survey, Water Resources Investigation Report 92-4039, 183-203.

Rampino, M. R., and Self, S., 1984, Sulfur-rich volcanic eruptions and stratospheric aerosols: Nature, v. 310, p. 677-679.

Ratté, J. C., Marvin, R. F., and Naeser, C. W., 1984, Calderas and ash flow tuffs of the Mogollon Mountains, southwestern New Mexico: Journal of Geophysical Research, v. 89, p. 8713-8732.

Robock, A., 2000, Volcanic eruptions and climate: Reviews of Geophysics, v. 38, no. 2, p. 191-219.

Salyards, S. L., 1991, A possible mid-holocene age of the Carrizozo Malpais from paleomagnetics using secular variation magnetostratigraphy: New Mexico Geological Society, Guidebook, 42, p. 153-157.

Sanford, A., Balch, R., and Lin, K., 1995, A seismic anomaly in the Rio Grande rift near Socorro, New Mexico: Seismological Research Letters (abstract), v. 66, no. 2, p. 44.

Sarmiento, J. L., 1993, Carbon cycle; atmospheric CO_2 stalled: Nature, v. 365, no. 6448, p. 697-698.

Sarna-Wojcicki, A. M., Bowman, H. R., Meyer, C. E., Russell, P. C., Woodward, M. J., McCoy, G., Rowe, J. J., Jr., Baedecker, P. A., Asaro, F., and Michael, H., 1984, Chemical analyses, correlations, and ages of upper Pliocene and Pleistocene ash layers of east-central and Southern California: United States Geological Survey, Professional Paper 1293, 40 p.

Scott, G. R., and Marvin, R. F., 1985, Geologic map of surficial deposits and basaltic rocks near the Rio Chama, Rio Arriba County, New Mexico: U. S. Geological Survey, scale 1:50,000.

Seager, W. R., Shafiqullah, M., Hawley, J. W., and Marvin, R. F., 1984, New K-Ar dates from basalts and the evolution of the southern Rio Grande Rift: Geological Society of America Bulletin, v. 95, no. 1, p. 89-99.

Self, S., Heiken, G., Sykes, M. L., Woheltz, K., Fisher, R. V., and Dethier, D. P., 1996, Field excursions to the Jemez Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 134, 72 p.

Self, S., Wolff, J. A., Spell, T. L., Skuba, C. E., and Morrissey, M. M., 1991, Revisions to the stratigraphy and volcanology of the post-0.5 Ma units and the volcanic serction of the VC-1 core hole, Valles caldera, New Mexico: Journal of Geophysical Research, v. 96, p. 4107-4116.

Smith, G. A., Florence, P. S., Castrounis, A. D., Luongo, M., Moore, J. D., Throne, J., and Zelley, K., 1999, Basaltic near-vent facies of Vulcan Cone, Albuquerque volcanoes, New Mexico: New Mexico Geological Society, Guidebook 50, p. 211-220.

Spell, T. L., and Harrison, T. M., 1993, ^{40}Ar/^{39}Ar geochronology of post-Valles caldera rhyolites, Jemez Volcanic Field, New Mexico: Journal of Geophysical Research, v. 98, p. 8031-8052.

Spell, T. L., Harrison, T. M., and Wolff, J. A., 1990, ^{40}Ar/^{39}Ar dating of the Bandelier Tuff and San Diego Canyon ignimbrites, Jemez Mountains, New Mexico—temporal constraints on magmatic evolution: Journal of Volcanology and Geothermal Research, v. 43, p. 175-193.

Spell, T. L., Kyle, P. R., and Baker, J., 1996, Geochronology and geochemistry of the Cerro Toledo Rhyolite, New Mexico Geological Society, Guidebook 47, p. 263-268.

Stix, J., Goff, F., Gorton, M. P., Heiken, G., and Garcia, S. R., 1988, Restoration of compostional zonation in the Bandelier silicic magma chamber between two caldera-forming eruptions: Geochemistry and origin of the Cerro Toledo rhyolite, Jemez Mountains, New Mexico: Journal of Geophysical Research, v. 93, p. 6129-6147.

Stroud, J. R., 1997, Geochronology of the Raton-Clayton volcanic field, with implications for volcanic history and landscape evolution [MS thesis]: Socorro, New Mexico Institute of Mining and Technology, 116 p.

Stuart, C., 1981, Hunt's Hole maar volcano, DoZa Ana County, south-central New Mexico: Geology of the Border, El Paso Geological Society Field Trip Guidebook, p. 64-72.

Wallace, P., Carn, S., Rose, W., Bluth, G. J. S., and Gerlach, T., 2003, Integrated petrologic and remote sensing perspectives on magmatic volatiles and volcanic degassing: EOS, Transactions of the American Geophysical Union, v. 84, p. 441-446.

Weber, R. H., 1964, Geology of the Carrizozo Quadrangle, New Mexico: New Mexico Geological Society, Guidebook 15, p. 100-109.

Williams, H., and McBirney, A. R., 1979, Volcanology: San Francisco, Freeman Cooper and Co., 397 p.

Williams, W. J. W., 1999, Evolution of Quaternary intraplate mafic lavas detailed using ^{3}He surface exposure and ^{40}Ar/^{39}Ar dating, and elemental and He, Sr, Nd and Pb isotopic signatures; Potrillo volcanic field, New Mexico, U.S.A. and San Quintin volcanic field, Baja California Norte, Mexico [Ph.D. dissertation]: El Paso, University of Texas, 195 p.

Williams, W. J. W., and Poths, J., 1994, The Potrillo volcanic field, southern Rio Grande Rift; ^{3}He surface exposure dates and petrogenetic considerations: New Mexico Geology, v. 16, p. 81.

Wolff, J. A., and Gardner, J. N., 1995, Is the Valles caldera entering a new cycle of activity? Geology, v. 23, p. 411-414.