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VOLCANIC GEOLOGY OF THE RIO PUERCO NECKS

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Abstract—The volcanic necks of the Rio Puerco Valley are among the most concentrated and best preserved examples in the world. They formed by erosion of poorly consolidated pyroclastic material surrounding a more resistant basaltic core. Throughout the valley, necks are preserved over a continuum of erosional stages. A partially exhumed scoria cone near Cerro de Nuestra Senora represents one of the least eroded volcanoes, whereas all that remains of Cabezon Peak is the solidified magma core. Mantle and/or crustal xenoliths occur in about 60% of the necks. Cerros Guadalupe and Negro, in particular, contain an exceptional variety and abundance. A new whole-rock $^{40}Ar/^{39}Ar$ plateau age of 2.658 ± 0.032 Ma for Cabezon Peak is consistent with volcanism on the adjacent Mesa Chivato and Mesa Prieta. The two principal types of volcanic features in the Rio Puerco Valley are (1) subaerial volcanic centers that produced surge and pyroclastic beds, lava flows and intrusive cores or crystallized lava lakes, and (2) wholly intrusive structures, such as dikes, which represent only a small part of the volcanic rocks in the valley. Based on field evidence, two models are given to explain the formation of the necks. In the first, a tuff ring or scoria cone is built around a central vent, then magma ponds in the vent and solidifies. Later, erosion of the outer cone exposes the plug. This model is more consistent with the larger, more symmetrical necks, such as Cabezon Peak and Cerro de Nuestra Senora. In the second model, magma supply rates are lower, the volcanic cone and conduit smaller, and thermal retention lower. The necks form when small pods of magma intrude into overlying volcanic tuffs and breccia near the waning stages of magmatic activity. Those that form by this process display irregular columnar jointing patterns. Most necks in the Rio Puerco Valley are consistent with this latter model.

INTRODUCTION

The volcanic necks in the upper Rio Puerco Valley of west-central New Mexico are among the most numerous and spectacular in the world. They are erosional remnants of volcanic vents from a larger volcanic field that extends from Mount Taylor, east to Mesa Chivato, and across the valley to Mesa Prieta, an area of more than 4000 km^2 (Fig. 1). This paper describes and interprets those volcanic vents that lie between Mesa Chivato and Mesa Prieta, an area of approximately 800 km^2.

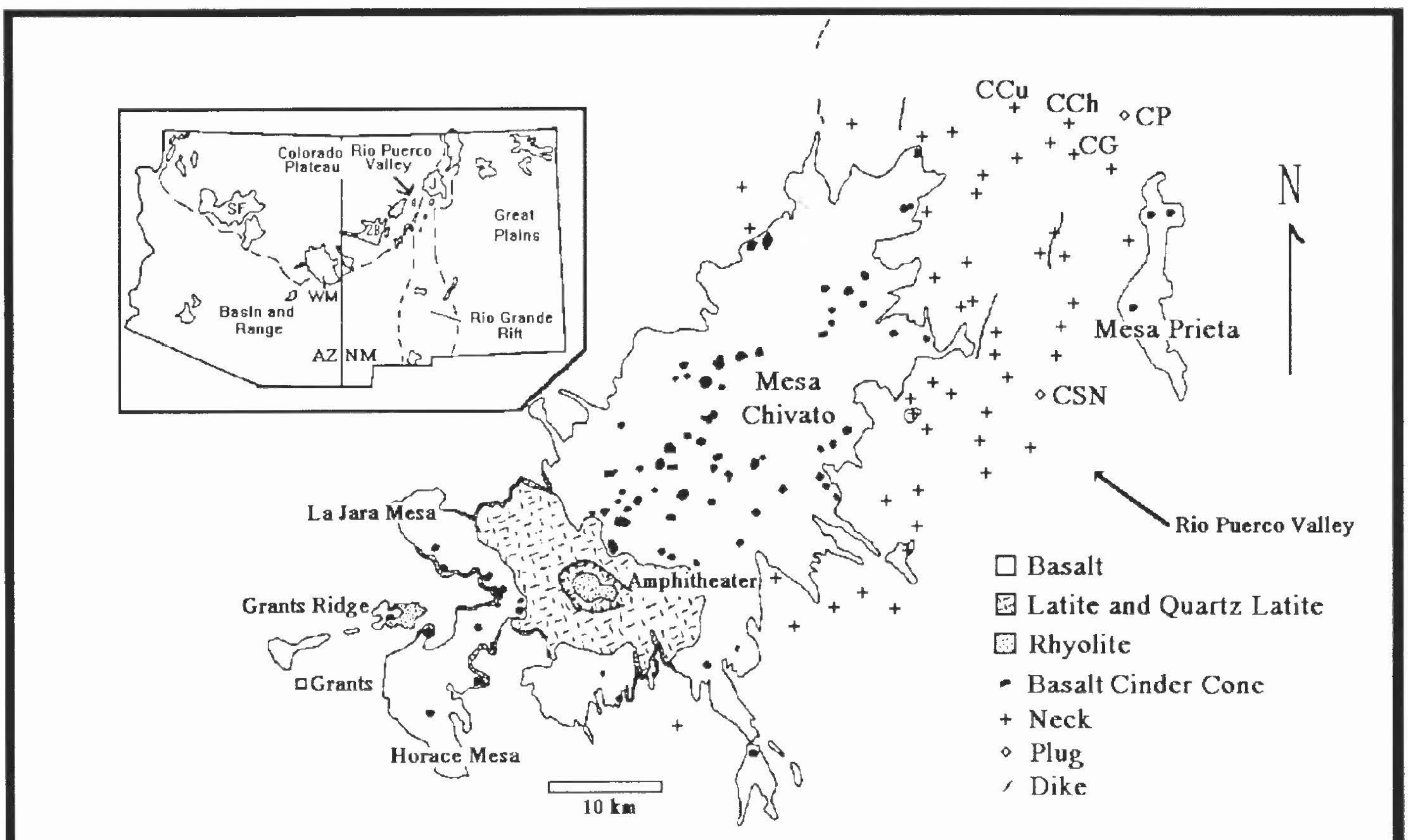

FIGURE 1. Location and generalized geologic map of the Rio Puerco Valley and its necks, plugs and dikes. The San Francisco volcanic field (SF), White Mountains (WM), Zuni-Bandera volcanic field (ZB), Mount Taylor volcanic field and the Jemez volcanic field (J), all arranged along the margin of the Colorado Plateau, are major centers of late Cenozoic volcanism in the area. CP is Cabezon Peak, CCu is Cerro Cuate, CCh is Cerro Chafo, CG is Cerro Guadalupe, and CSN is Cerro de Nuestra Senora. Map modified from Perry et al. (1990).

Erosion and downcutting by the Rio Puerco drainage system over the past 2.5–3.0 Ma has dissected and exposed the interiors of dozens of tuff rings, scoria cones and fissures. Some of these features, such as Cabezon Peak, rise more than 450 m above the present Rio Puerco floor.

The earliest geologic investigation of the Rio Puerco necks was conducted more than a hundred years ago by U.S. Army officer and geologist Major Clarence E. Dutton (1884–85). Photographs taken during his expedition on chemically treated wood are still among the best published images of the necks (e.g., figs. 17–20). Later, Johnson (1907) and Hunt (1937) produced more complete descriptions of individual necks with detailed geologic maps. These early geologists concluded that the "volcanic buttes" were indeed volcanic necks and not remnants of laccoliths or columnar jointed lava sheets.

More recently, geochemical and petrographic studies (Brown, 1969; Aoki and Kudo, 1976) have identified the necks as being composed of alkali basalts, many of which contain mantle (Brunton, 1952; Kudo et al., 1971; Wilshire et al., 1988) and crustal xenoliths. Several geomorphic surfaces have been described in the area, ranging in age from about 2.2 Ma to the present (Slavin, 1991).

Detailed mapping of individual vents will lead to a better understanding of the processes contributing to the formation of volcanic necks and a more specific comprehension of the geomorphic evolution of the upper Rio Puerco Valley. The data and conclusions reached in this paper are part of a larger study of volcanic geology and related geochemical, geochronologic and paleomagnetic characteristics presently being conducted by the author.

DEFINITION OF TERMS

If one looks through the volcanic geology literature (Williams, 1936; Williams and McBirney, 1979) and various geologic dictionaries (AGI Glossary of Geology, Concise Oxford Dictionary of Earth Sciences, McGraw-Hill Dictionary of Earth Sciences, Earth Sciences References) the distinction between a volcanic neck and volcanic plug is ambiguous. Today, the usage of the two terms if often synonymous.

Volcanic necks were originally described by Geikie (1897, 1902) in Scotland as volcanic pipes filled with pyroclastic material or by a volcanic plug or by both. In contrast, Wyatt (1986) defined a volcanic plug as the "solidified magma (as distinct from pyroclastic material) forming either a definite part, or the whole, of a volcanic neck." Therefore, a plug is a type of neck, distinguished only by its lack of pyroclastic material. The usage of plug and neck in this paper will adhere to the early definitions by Geikie. Words synonymous with neck are boss (Wyatt, 1986) and puy (Allaby and Allaby, 1990).

In the Rio Puerco Valley, more than 95% of the volcanic vents are necks; two of the necks, Cabezon Peak and Cerro de Nuestra Senora, classify as plugs. Field investigations suggest that necks are exposed over a continuum of erosional stages. However, either the presence of a neck or a plug may not be entirely a function of erosion. Following a discussion of regional geology, petrology, geochemistry and selected descriptions of necks, two models are presented for the formation of the Rio Puerco necks based on size of the volcanic core, magma supply rate through time and thermal retention.

REGIONAL GEOLOGY

Structure

The Rio Puerco necks lie between the physiographic Colorado Plateau and the Rio Grande rift, an area generally referred to as the transition zone. This zone is concentric about the Colorado Plateau on the southeast, southwest and west, and is "transitional" in its upper crustal structure and lithospheric properties (Thompson and Zoback, 1979; Zoback and Zoback, 1980; Ander, 1981; Baldridge et al., 1983; Aldrich and Laughlin, 1984).

The upper Rio Puerco Valley lies in the Rio Puerco fault zone, a north-northeast-trending belt 15 to 30 km wide and 80 km long (Fig. 2). It is characterized by en echelon faults that formed during the Laramide compressional tectonic episodes and later Rio Grande rift extension (Slack and Campbell, 1976). The older Laramide deformation produced N20°E tensional fractures that resulted from north-trending, right-lateral basement wrench faulting, followed by vertical uplift along the Nacimiento fault (Baltz, 1967). Typical of many Laramide structures in the area, these en echelon faults are of short linear extent, with a predominance of down-to-the-west orientation. Middle Miocene to Holocene extension related to Rio Grande rift development caused renewed

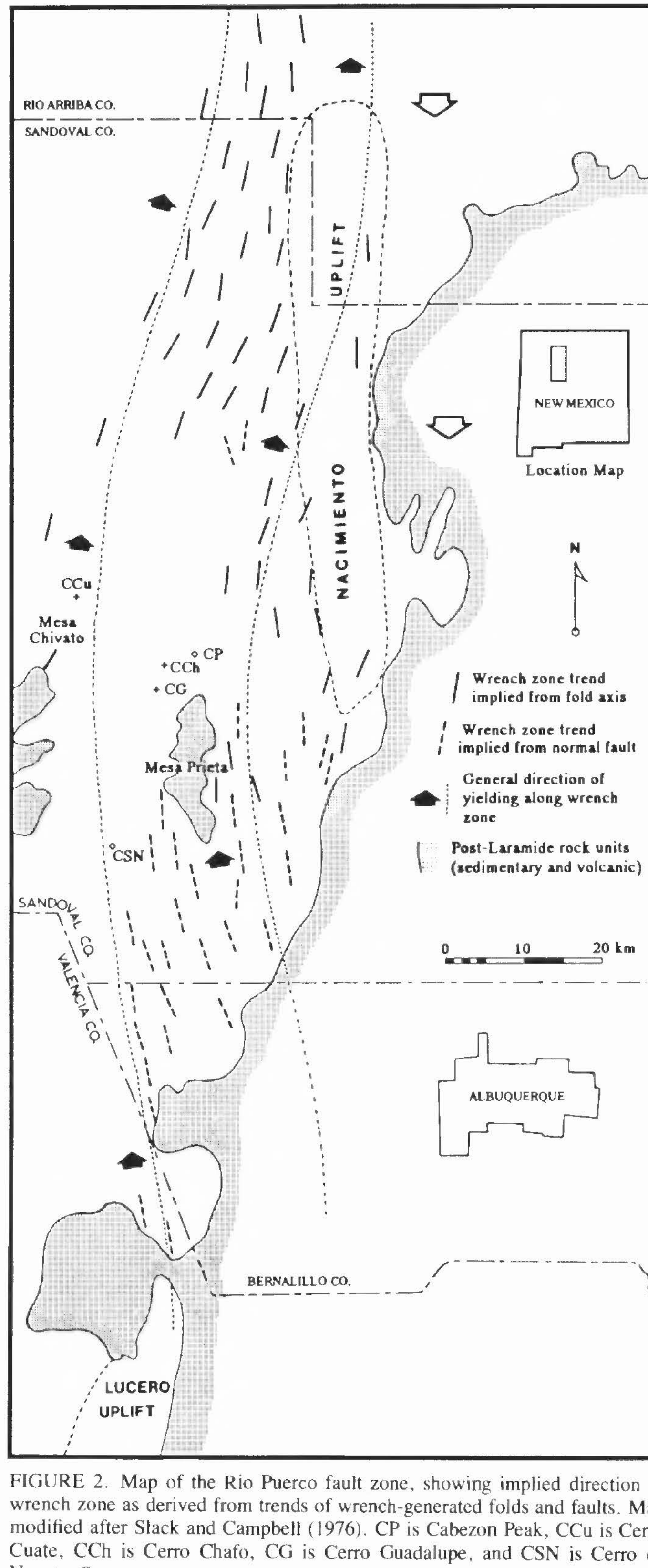

FIGURE 2. Map of the Rio Puerco fault zone, showing implied direction of wrench zone as derived from trends of wrench-generated folds and faults. Map modified after Slack and Campbell (1976). CP is Cabezon Peak, CCu is Cerro Cuate, CCh is Cerro Chafo, CG is Cerro Guadalupe, and CSN is Cerro de Nuestra Senora.

normal faulting and reactivated many older Laramide faults. Displacement was towards the rift axis or down to the east (Slack and Campbell, 1976). Many dikes and elongate necks have similar north-northeast orientations, but few coincide with faults.

Volcanism

With the exception of the Jemez volcanic field and the Lucero area, a majority of the basaltic volcanism in and around the Rio Puerco Valley area has taken place during the past 5 Ma (Fig. 3). Nearby, the Zuni-Bandera volcanic field and Lucero area are dominated by basaltic rocks that cap mesas, and form cinder cones, small shield volcanoes, extensive lava fields and lava tubes. The Mount Taylor volcanic field is dominated by Mount Taylor, a composite latitic-to-rhyolitic volcano; however, a majority of the field is covered with alkali basalts (Perry et al., 1990). These fields along with others (i.e., White Mountains, Jemez Mountains, Taos Plateau, Ocate and Raton-Clayton) form the "Jemez lineament," a N50°E alignment of late Cenozoic volcanic fields (Mayo, 1958). Along this lineament basalts are the most common volcanic rocks, but they do not correlate consistently with tectonic setting as observed in other rifts, such as the East African rift system (Williams, 1970). For example, both tholeiitic and alkalic basalts have erupted within the rift and off the rift axes. And some fields contain both tholeiitic and alkalic basalts erupted within close proximity, as documented for the Lucero area (Baldridge et al., 1987) and the Zuni-Bandera field (Menzies et al., 1991). Geochemical and isotopic interpretations for the origin of contrasting compositions suggest either replacement of thinned lithospheric mantle (source for tholeiitic magma) by an asthenospheric mantle (source for alkalic magmas) with time (Perry et al., 1987), or derivation of alkaline magmas from small-volume melts of the convecting upper mantle or MORB asthenosphere, while tholeiitic basalts may originate from plume-contaminated asthenosphere or stratified lithosphere (Menzies et al., 1991).

Volcanism in the Zuni-Bandera field is among the youngest in the area, 1.38 Ma to A.D. 400 (Maxwell, 1986). Both tholeiitic and alkaline basalts extruded through fissures, cinder and spatter cones, small shields, maars and collapse pits (Ander et al., 1981). Many of these features are aligned in a north-northeast direction (Maxwell, 1986), an orientation common to many vents and dikes erupted and emplaced during the past 5 Ma. Some 30 cinder cones range in height from 1 to 170 m and many are more than 1 km in diameter (Maxwell, 1982).

To the east of the Zuni-Bandera field, late Cenozoic basaltic volcanism in the Lucero area began 8.3 Ma and has continued episodically to the Holocene (Baldridge et al., 1987). This area is characterized by basalt-capped mesas in which lavas were extruded mainly from broad, low shield volcanoes. Other volcanic features include cinder cones, maars, tuff rings and several plugs. Similar to the Zuni-Bandera field, the Lucero area has produced both tholeiitic and alkalic basalts, tending towards larger volumes of tholeiitic and increasing bimodal distribution between alkalic and tholeiitic with time (Baldridge et al., 1987).

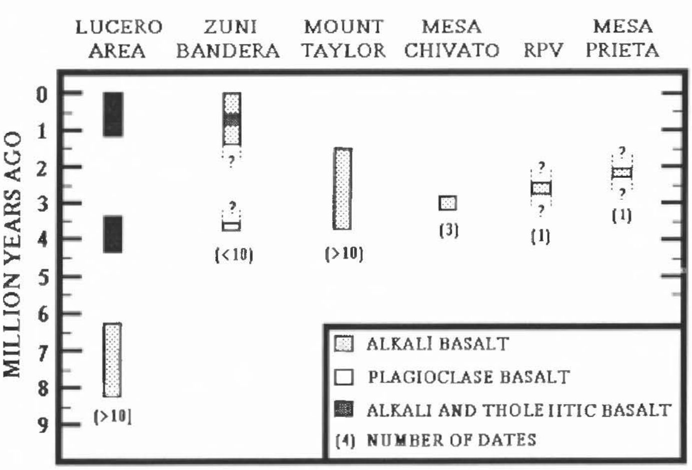

FIGURE 3. Timing and composition of basaltic volcanism in volcanic fields along the southeastern Colorado Plateau in New Mexico. Data from Armstrong et al. (1976), Bachman and Mehnert (1978), Ander et al. (1981), Maxwell (1986), Baldridge et al. (1987), and Perry et al. (1990).

The Mount Taylor volcanic field is dominated by Mount Taylor, a composite volcano constructed of latite and quartz latite flows and rhyolite ignimbrites. However, the volcano itself comprises only about 20% of the volcanic field; the remainder consists of extensive basalt-capped measas whose lavas were extruded from numerous vents along the periphery of the main volcano. The area covered by these flows today may represent only a fraction of their original extent. Volcanism in the area occurred from about 3.8 to 1.5 Ma (Perry et al., 1990). Basalts were extruded throughout this period and became more voluminous with time. However, they are chemically different in that no tholeiitic basalts are associated with Mount Taylor volcanism when compared to other volcanic fields in the transition zone. Features associated with basaltic magmatism include about 100 cinder and spatter cones, trachyte flow-domes, maars, and pit craters, the bulk of which occur on Mesa Chivato. Erosion of these features is minimal, although some cinder cones are partially dissected and some maars are filled with alluvial and lacustrine sediments (Crumpler, 1980).

PETROGRAPHY

With the exception of dikes, the petrography from neck to neck is amazingly consistent. All have similar mineralogy and many of the same textures. Flows are similar in mineral composition to their associated necks.

Necks

The necks are composed of fine-grained, porphyritic basalts that contain 4–20% phenocrysts, with olivine > clinopyroxene > plagioclase > magnetite. Most necks have an intergranular to trachytic groundmass containing microlites of plagioclase, clinopyroxene, olivine and magnetite. Plagioclase compositions range from andesine to labradorite (An_{46}–An_{64}). Olivine phenocrysts often have an embayed texture and rarely show growth zonations.

Flows

Flows associated with individual necks are holocrystalline, fine-grained, porphyritic basalt. Mineralogically, the flows (e.g., Fig. 4a) are similar to their corresponding neck basalt. Phenocryst phases include olivine and orthopyroxene. Flows associated with individual necks are restricted in their areal extent and often confined to the vent area. Thicknesses rarely exceed several tens of meters and are commonly interbedded with pyroclastic-fall material.

Dikes

Dikes are fine- to medium-grained, hypocrystalline basalts. Again, they are very similar in their mineral assemblage and mineral proportions, with the exception of a glassy matrix, to the necks and flows. Alteration of phenocryst phases is common, with olivine being replaced by chlorite and calcite. Groundmass plagioclase, clinopyroxene and magnetite remain relatively unaffected.

Xenoliths

Approximately 70% of the necks in the Rio Puerco Valley contain mantle and/or crustal xenoliths. Ultramafic varieties are by far the most common and include peridotites, websterites, dunites, harzburgites, clinopyroxenites and orthopyroxenites (Kudo et al., 1971; Wilshire et al., 1988). Crystal size varies from coarse- to medium-grained, although clinopyroxenites and dunites are most commonly medium grained. Individual crystals are arranged in an equigranular texture and show undulose extinction. Red spinel is a common accessory phase, especially in peridotites. The spinel is typically anhedral and occurs along grain boundaries or in interstices (Fig. 4b). Little (<0.1 mm) or no reaction rim exists between xenolith and host basalt. Additional petrographic descriptions of xenoliths can be found in Brunton (1952), Brown (1969), Kudo et al. (1971) and Wilshire et al. (1988).

In contrast, crustal xenoliths are less common. Only about 10% of the necks contain them. Very little is known about their mineralogy or origin, but most appear to be felsic granulite to granite in composition.

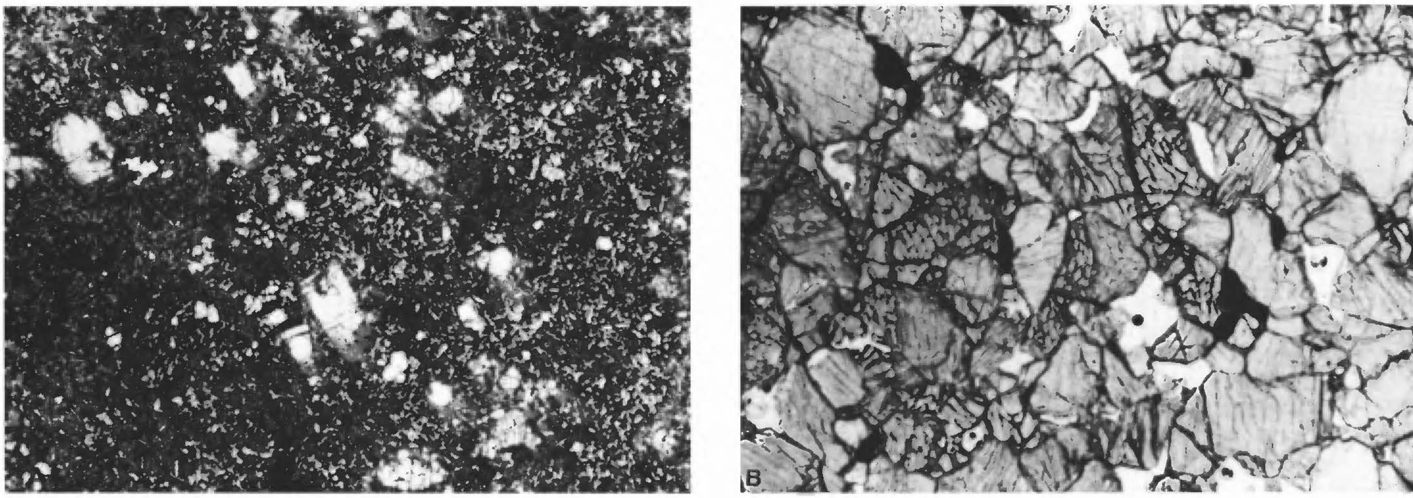

FIGURE 4. Photomicrographs. A, porphyritic alkali basalt flow at Cerro Chafo. Olivine is the dominant phenocryst phase (some are partially embayed), and groundmass consists of plagioclase, olivine, clinopyroxene and magnetite. B, spinel pyroxenite from Cerro Negro. A medium- to coarse-grained, equigranular texture is common, with nearly all crystals showing undulose extinction. Exsolution in clinopyroxene crystals is seen at higher magnification. Bottom width of photo is 3.6 mm.

GEOCHEMISTRY

Samples suitable for geochemical analyses were collected from dikes, flows and necks. Classification (Fig. 5), is based on total alkali versus silica (Le Bas et al., 1986). The rocks range in composition from basanite to trachybasalt to basalt. With the exception of one dike, all samples are *ne*-normative.

The necks display a geographical distribution of composition (Fig. 5). In the northern and central part of the area, basalts and trachybasalts dominate. Necks in the southern part tend to have lower SiO_2 and higher total alkalis but do not consistently correspond to high MgO, Cr and Ni, as might be expected with more primitive basalts. 85% of the flows sampled are basalts and trachybasalts and similar in major element composition to their associated neck basalt. The dikes, as a group, are lower in SiO_2 and classified as basanite to slightly trachybasalt. However, most dikes in the Rio Puerco Valley contain altered groundmass and phenocryst assemblages, and therefore total alkali content may not indicate their original unaltered composition.

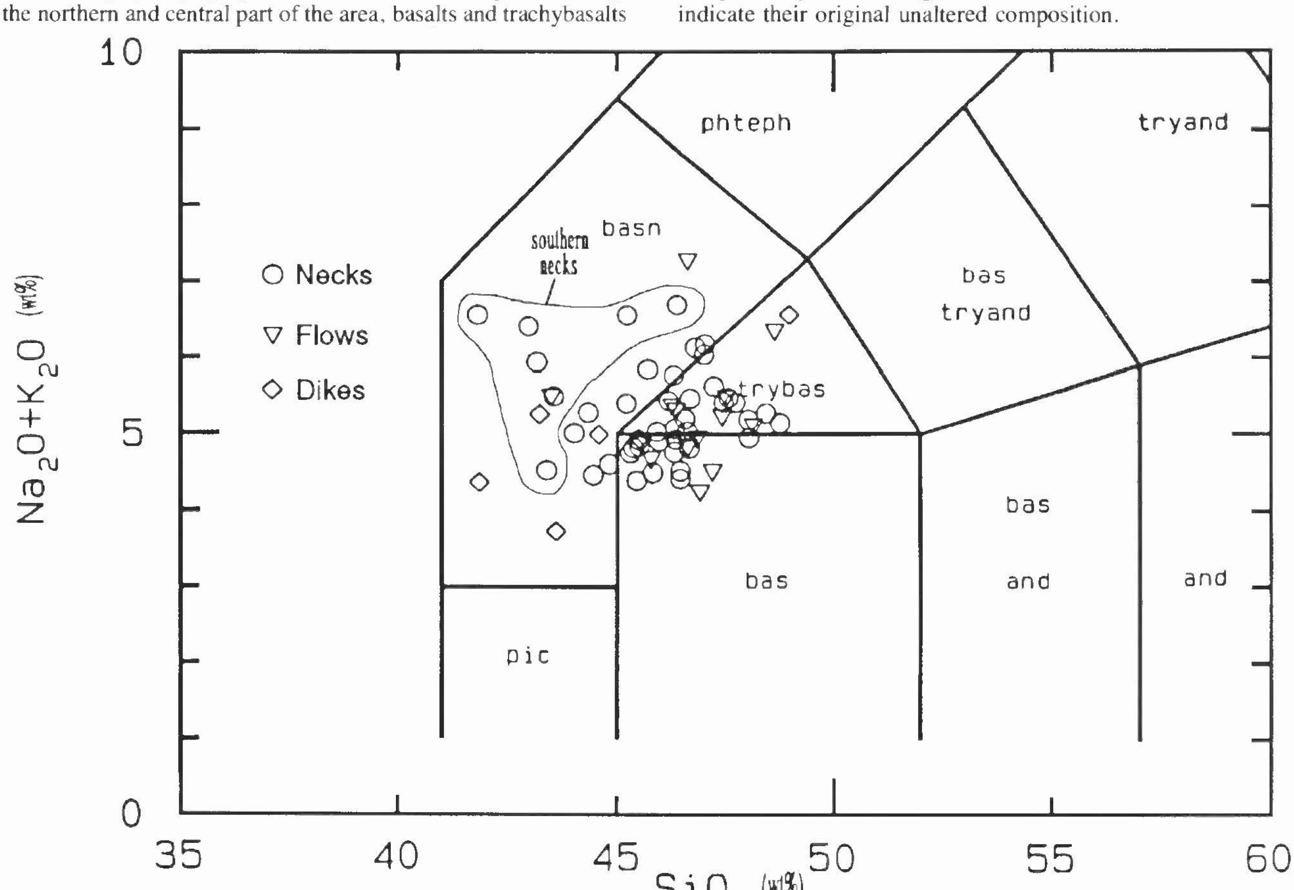

FIGURE 5. TAS diagram (total alkali vs. silica) after Le Bas et al. (1986). *Pic* is picrite, *basn* is basanite, *phteph* is phonotephrite, *bas* is basalt, *trybas* is trachybasalt, *bas tryand* is basaltic trachyandesite, *bas and* is basaltic andesite, *and* is andesite, *tryand* is trachyandesite. Necks in the southern part of the field area are grouped together.

TABLE 1. $^{40}Ar/^{39}Ar$ data for Cabezon Peak. The data is preceded by sample number, location name, sample weight (grams), irradition batch number, irradiation parameter (J), measured discrimination of atmospheric argon, and detector type (electron multiplier). Columns of data give temperature of incremental heating steps, ratios of Ar isotopes (^{40}Ar = initial and radiogenic, ^{39}Ar = potassium-derived, ^{37}Ar = calcium-derived, ^{36}Ar = initial), % of total ^{39}Ar in heating step, moles of potassium derived ^{39}Ar, K/Ca ratio calculated from $^{37}Ar/^{39}Ar$ ratio, age and 1 sigma error. Lines following each data step show total gas, K/Ca, total gas age, plateau temperature range, percent ^{39}Ar on the plateau, plateau age, and its error (method of Fleck et al., 1977).

	temp (C)	40Ar/39Ar	37Ar/39Ar	36Ar/39Ar	%39Ar	moles 39	K/Ca	age(Ma)	1 sigma
wr nm783									
Cabezon Peak	1050	2.292	0.759	6.30e-03	23.6	3.945e-13	1.317	2.67	0.07
wt=423.4	1150	2.932	1.227	8.43e-03	25.8	4.317e-13	0.815	2.74	0.07
RD79	1250	1.553	1.289	3.80e-03	15.7	2.633e-13	0.776	2.67	0.08
J=0.003442	1350	2.110	5.682	5.72e-03	14.0	2.344e-13	0.176	2.61	0.05
disc=299.1	1450	3.023	8.314	8.66e-03	21.0	3.511e-13	0.120	2.87	0.11
multiplier	total gas						0.300	2.72	0.06
	plateau	1050-1450			100.1			2.658	0.032

VOLCANIC GEOLOGY

In the following section detailed descriptions of the volcanic successions at the more interesting necks and plugs will be described, in order to arrive at conclusions about their relationship to the timing of regional volcanism and mode of formation.

Age of volcanism

Volcanism throughout the Rio Puerco Valley region appears to have occurred over the past 3.2 Ma, or 4 Ma if Mount Taylor is included (Perry et al., 1990). With the exception of one new $^{40}Ar/^{39}Ar$ date, no radiometric dates have been determined for the Rio Puerco necks, but several K-Ar dates are available for Mesa Chivato and Mesa Prieta. Three dates obtained on basalt samples from the north and east sides of Mesa Chivato range from 3.22 ± 0.20 Ma to 2.68 ± 0.30 Ma (Bachman and Mehnert, 1978; Lipman and Mehnert, 1979). Across the valley, a basalt flow on Mesa Prieta has a K-Ar age of 2.2 ± 0.3 Ma. A new whole-rock $^{40}Ar/^{39}Ar$ plateau age obtained on an alkali-olivine basalt from Cabezon Peak is 2.658 ± 0.032 Ma (Fig. 6; Table 1) This age is slightly younger than volcanism of Mesa Chivato but older than Mesa Prieta. It appears that the time of volcanism is progressively younger to the east.

Xenolith localities

Ultramafic and crustal xenoliths are found in about 70% of the neck localities. Table 2 gives the distribution and relative abundance of xenoliths found at each locality. Ultramafic varieties consist of two main types, peridotites and websterites, although dunites, harzburgites, clinopyroxenites and orthopyroxenites are also present. The xenoliths are hosted in alkali basalt, commonly subangular to subrounded in shape, and range in size from 2–5 cm. However, some xenoliths as large as 20 cm in the longest dimension are found at Cerro de Guadalupe and Cerro Negro. Xenoliths of crustal origin are far less common. They are commonly found in cored volcanic bombs and are felsic granulite and granitic in composition. Several studies give chemical and isotopic data for mantle xenoliths from Cerro de Guadalupe and Cerro Negro, but a petrologic and geochemical study of the complete xenolith population in the Rio Puerco Valley is lacking.

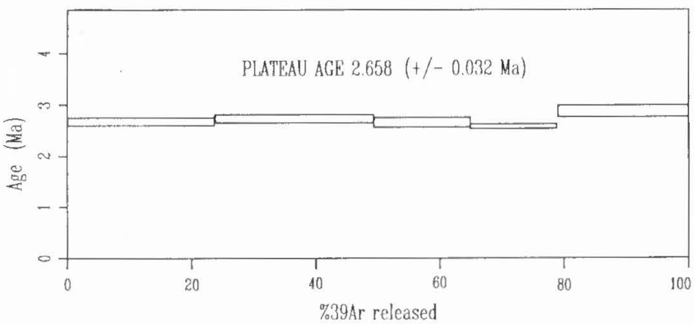

FIGURE 6. Apparent age vs. %^{39}Ar released, plateau-age spectra diagram. Each step is determined by incremental heating, the error in each is proportional to the thickness of individual bars. Additional data on age is found in Table 1.

Igneous features

A field description of every individual neck is not possible here. Instead, descriptions of the more accessible necks with good outcrop exposures, easily recognizable volcanic features (such as columnar jointing), and nearly complete preservation of volcanic sequences are given below. The field context of the necks is crucial to the models presented later concerning the formation of necks and plugs.

Cabezon Peak

Cabezon Peak is a volcanic plug located in the northeastern portion of the field area (Fig. 1). It has an elevation of 2373 m and stands approximately 240 m above the surrounding Cretaceous sediments. It is one of only two plugs (the other is Cerro de Nuestra Senora) that rise above the elevation of Mesa Prieta, although neither rises above

TABLE 2. Location and distribution of xenoliths. X, present; XX, abundant. Unnamed locations are labeled Hill, followed by latitude and longitude in parentheses.

Location	sedimentary	metamorphic	ultramafic
Hill 6793 (35 36N;107 19W)	---	---	---
Cerro Parido	X	---	---
Cerro del Ojo Frio	X	---	---
Cerro del Ojo de las Yeguas	X	---	X
Cerro Cuate	X	---	X
Cerro Chafo	X	X	X
Cabezon Peak	---	X	X
Cerro de Santa Clara	---	---	XX
Cerro de Guadalupe	X	---	XX
Cerro Cochino	X	---	---
Cerro Chamisa Losa	X	X	X
Cerro Salado	---	---	X
Cerrito Cochino	---	---	X
Canyon Jara Losa	---	---	---
Cerro de Nuestra Senora	X	X	X
Cerro Santa Rosa	X	X	XX
Cerro de Jacobo	X	---	---
Cerro Chato	---	X	---
Santa Rosa Peak north	X	X	XX
Cerro Vacio	---	X	X
Cerrito Negro	X	X	X
Hill 7264 (35 14N;107 20W)	X	---	---
Hill 7652 (35 14N;107 21W)	---	---	---
Hill 6283 (35 12N;107 19W)	X	---	---
Cerro Negro	X	---	XX
Cerro Seboyeta	X	---	X
Seboyeta Canyon	X	---	---
Picacho Peak	X	---	---

the mean elevation of Mesa Chivato (Johnson, 1907). Cabezon is nearly cyclindrical in shape, with a basal diameter of just under 0.5 km that tapers upwards to 0.15 km. It exhibits a columnar jointed pattern that is nearly vertical at the top and flairs outward at 30–45° near the base. The columns are composed of non-vesiculated, fine-grained, slightly porphyritic olivine basalt, and range in size from 0.5–2.5 m in diameter. The top of Cabezon is capped with scoriaceous basalt that is remnant from the original cone.

Unlike other necks in the area, Cabezon has few outcrops of pyroclastic material. Volcanic breccia located on its west face is composed of fine-grained, vesiculated bombs and lapilli. The contact with the denser basalt is welded. Some breccia shows crude bedding defined by color change and size of pyroclast, with the beds dipping back into the plug. Basaltic talus lies in the low relief areas surrounding the plug, but above the Cretaceous sediments. There are no lava flows found on Cabezon today; that is not to say, however, that they did not at one time exist. The surrounding country rocks are Cretaceous sandstones and shales of the Mesaverde Group. Their beds dip gently (<5°) north-northwest and lack physical evidence of deformation or baking of sediments caused by volcanic activity. Several questionable horizontal contacts between sediments and pyroclastic material suggest the paleosurface was between 2130 and 2135 m at the time of eruption.

Cerro de Nuestra Senora

Nuestra Senora is a plug located in the middle of the study area (Fig. 1) and is second in size only to Cabezon Peak. It is 2230 m in elevation and rises approximately 500 m above the valley floor. It is roughly cylindrical in shape with a lower diameter of approximately 0.25 km but is not as symmetrical as Cabezon. Columnar jointing observed in Nuestra Senora is similar to that seen at Cabezon. Individual columns are on average smaller in diameter, flare out near the base, and become vertical near the top. The peak is capped with welded scoriaceous basalt. The plug consists of a non-vesicular, porphyritic olivine basalt. Associated pyroclastic material is minor but similar in compositon. Talus surrounds Nuestra Senora and spreads outwards for approximately 80 m in all directions. No contact between pyroclastic breccia and Cretaceous sediments has been found. As at Cabezon, the surrounding sedimentary rocks are neither structurally disturbed nor have they undergone contact metamorphism.

Cerro de Guadalupe

Guadalupe is a neck located in the northern portion of the study area (Fig. 1) about 5.5 km southeast of Cabezon Peak. It stands 2086 m in elevation and is one of the most irregularly shaped necks in the field. Guadalupe is composed of basalt, variably welded pyroclastic breccia, and several feeder dikes to the south that trend north-northeast. These dikes are less than 1 m wide and all contain small (<2 cm) baked sandstone xenoliths. A 1-m-thick cone sheet extends 450 m south of the neck. Several late stage dikes intrude obliquely through columnar jointed basalt and pyroclastic breccia in the main neck (Johnson, 1907, fig. 6). Columnar jointed basalt constitutes about 50% of the outcrop area but is rather irregularly developed. For example, near-vertical columns can be seen at the peak as well as on the side but as a rule they are curved and form concave and convex, half-moon structures. Pyroclastic breccia constitutes the remaining 50% of Guadalupe. It is composed of welded spatter and scoriaceous bombs, sedimentary clasts (<5% of total volume) and basalt-coated ultramafic xenoliths. The welded contact relationship between the pyroclastic breccia and denser basalt, common to many necks, is clearly exposed (Fig. 7). Outcrops such as these provide strong evidence that subaerial volcanic activity built a cone prior to intrusion of the neck basalt.

Guadalupe is one of two necks that contain a large and varied abundance of ultramafic xenoliths. Cr-diopside peridotites are most common and can be as large as 20 cm. Cr-diopside websterite, Al-augite pyroxenites, wehrlites and dunites are also found (Wilshire et al., 1988). Gneissic granulites are present but rare.

FIGURE 7. Welded contact between pyroclastic breccia (Tp) and neck basalt (Ti) on the northeast side of Cerro de Guadalupe.

Cerro Cuate

Cuate, located 7 km west of Cabezon Peak, is an elongate, dike-like intrusion of basalt. It trends N26°E, and is about 360 m long and 150 m wide. Local highs at the north and south ends are separated by a saddle. A narrow dike can be traced northward from the main body for 4 km, but no dike is observed to the south. This neck may represent an expanded part of the dike that locally broke through the surface in a fissure style eruption. There is no offset in the underlying Mancos Shale and therefore Cuate is not believed to be fault controlled. Conversely, a dike near Gonzales Canyon (35°29′N lat., 107°8′W long.) has several intrusions of explosion breccia that appear to never have reached the surface but are controlled by a normal fault with <2 m of down-to-the-east displacement.

With the exception of a small remnant on the north end, Cuate is composed entirely of columnar jointed basalt. Columnar jointing at the south peak occurs in pods similar to those at Guadalupe. Individual pods are 5–20 m in diameter and have a similar joint geometry throughout, but are unlike those of its neighbor. It is possible that each pod represents an individual intrusion of magma and that they may have grown in a way similar to pillow basalts. On the north peak, jointing is more regular but dips in towards the neck. The breccia at the north end is similar to other pyroclastic breccias already discussed, except that it contains a gypsum cement of unknown origin.

Cerro Cuate is not the only neck in the Rio Puerco Valley that shows dike-like elongation. Others include Cerrito Cochino and Cerros Cochino, Parido, Seboyeta and Negro, and Picacho Peak. However none of these necks are as elongate as Cuate.

Some volcanic centers in the Rio Puerco Valley are composed entirely of pyroclastic fall or flow material and have undergone comparatively little erosion. Most are tuff cones typically composed of a lower bedded-pyroclastic deposit overlain by thin (<5 m) lava flows that are restricted in areal extent to the top of the cone. The pyroclastic rocks contain non-welded scoria and variably welded basaltic lapilli and bombs. Interestingly, most of these marginally eroded tuff cones are within several kilometers of Mesa Chivato. Their preservation may be a function of age, or Mesa Chivato may be protecting them from erosion.

MODE OF FORMATION

Aside from early reconnaissance work (Dutton, 1884–1885; Johnson, 1907; Hunt, 1937) the mode of formation of the Rio Puerco necks has received surprisingly little attention. In this study, detailed field mapping and comparison of both intrusive and extrusive features allow two end-member models to explain their formation. Factors governing neck formation are size of the volcanic cone, magma supply rate through time and thermal retention.

The formation of a small volcanic neck can be illustrated by a series of idealized cross sections through a volcano (Fig. 8). Initially, when the vent forms and the eruption becomes subaerial, the diameter of the vent is exceedingly small, magma supply rate is relatively low, and initial deposits consist of pyroclastic rocks and accidental country rock (Fig. 8B). Continued eruption enlarges the vent by detaching successive sedimentary blocks from the conduit. Small and repeated enlargements over time are favored over large catastrophic eruptions because surrounding sediments remain undisturbed (Johnson, 1907). From time to time lava spills over the edge of the vent and becomes interbedded with the pyroclastic breccia. The volume of magma extruded is relatively small, leading to the development of a small volcano. As the magma supply wanes and the vent becomes plugged with breccia and lava flows, individual pods of magma are intruded into overlying pyroclastic deposits (Fig. 8C). Or, alternatively, a lava pond may form in the conduit but due to the small size and structural weakness of the cone, the pond may collapse on itself, forcing pods of molten lava into the wall of the cone. When the pods crystallize, columnar joints form in a variety of patterns perpendicular to the cooling surface; jointing is a product of thermal stresses encountered during the cooling of the intrusion (Spry, 1962). Possibly, these pods grow and advance in a way similar to pillow lavas. Figure 8D illustrates what is seen today in the valley, after a couple million years of erosion. This model is consistent with the formation of most necks in the Rio Puerco Valley for several reasons: (1) the erupted volume of magma is small, leading to the formation of a small cinder cone or tuff ring; (2) as a consequence of its small size, the volcano is a poor insulator of heat and magma tends to intrude in small pods rather than crystallize as one large lava pond; and (3) irregular columnar jointing patterns supports the small pod-of-magma intrusion theory.

The formation of a larger volcanic neck is shown in Fig. 9. The formation of the vent and cone (Fig. 9B) are similar to the processes previously described (Fig. 8B) but larger in size. Once a structurally

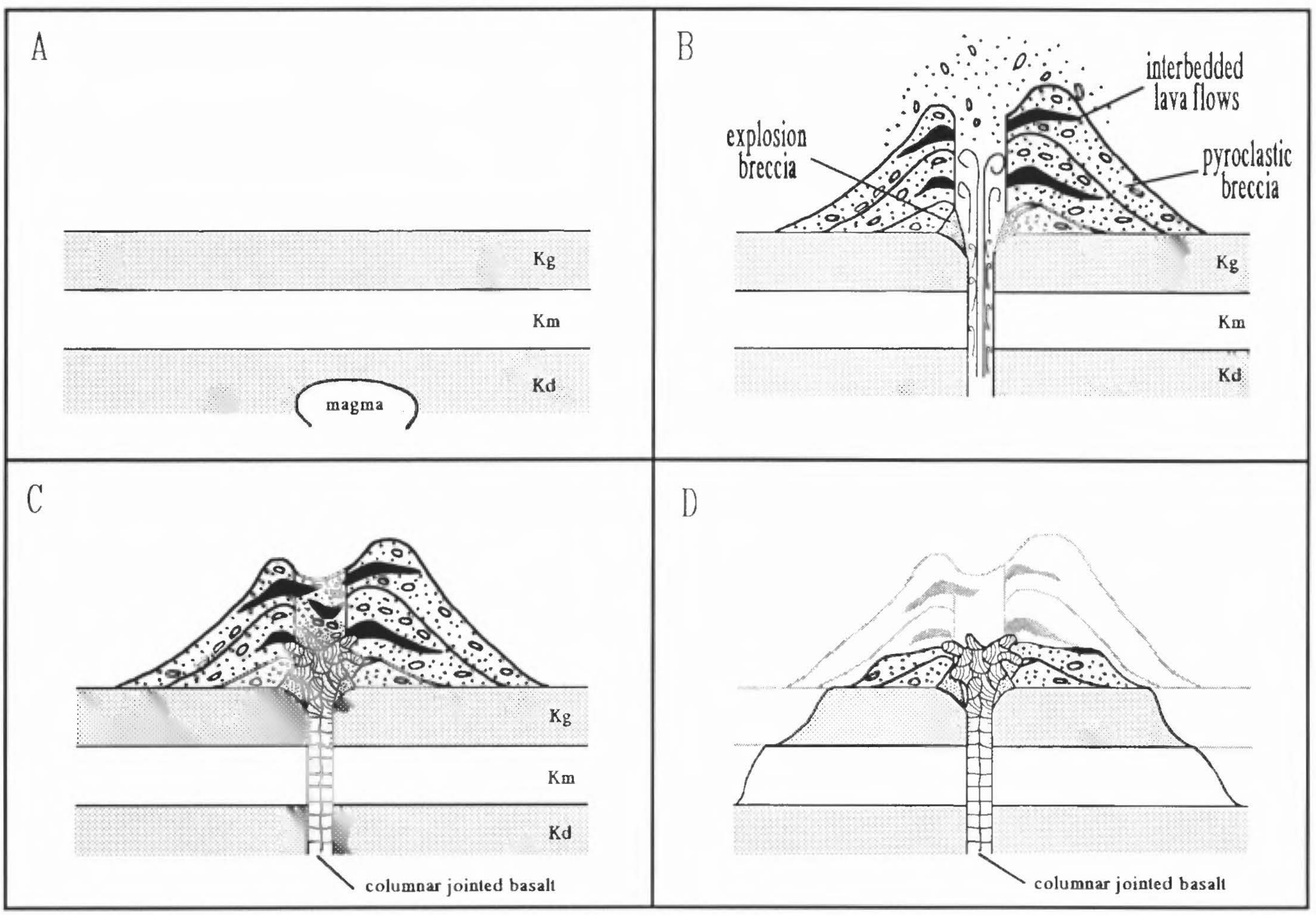

FIGURE 8. Idealized cross sections that explain the formation of a volcanic neck. A, prior to eruption; Kg is Cretaceous Gallup Sandstone, Km is Cretaceous Mancos Shale, Kd is Cretaceous Dakota Sandstone. B, initial volcanic explosion and formation of composite cone. C, conduit becomes closed by welded pyroclastic breccia and localized lava flows, magma intrudes as small pods into surrounding volcanic deposits at the lower levels of the conduit and upon cooling forms erratic columnar jointing. D, after erosion, individual columnar jointed pods are exposed with pyroclastic breccia.

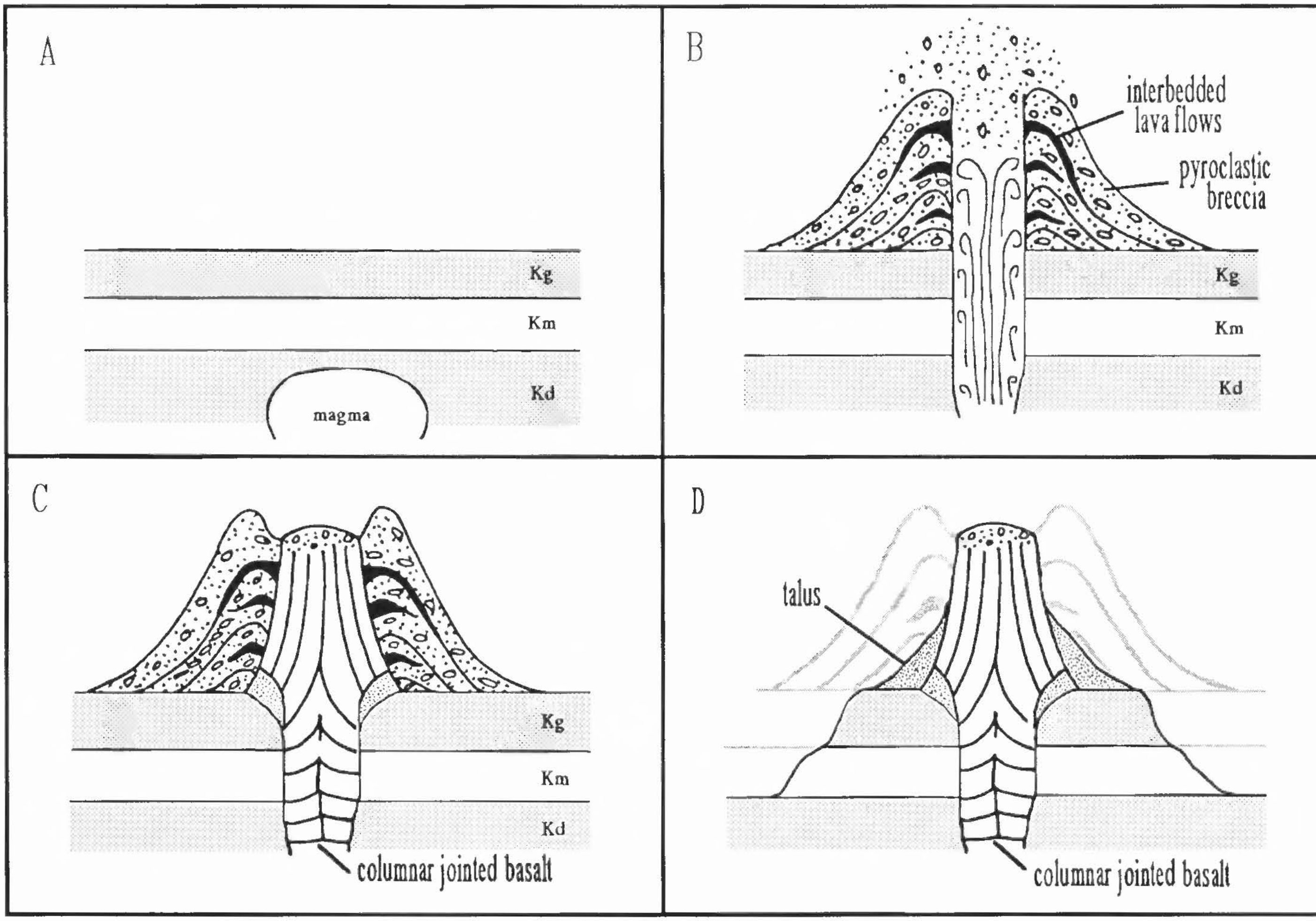

FIGURE 9. Idealized cross sections that explain the formation of a volcanic plug. A, prior to eruption; Kg is Cretaceous Gallup Sandstone, Km is Cretaceous Mancos Shale, Kd is Cretaceous Dakota Sandstone. B, initial volcanic explosion and formation of composite cone. C, conduit becomes filled with lava pond. D, after erosion of the less resistant cone, the plug is exposed.

sound cone has formed and the volcano is able to retain its own eruptive thermal energy by insulation, it is possible, when magma supply rates diminish, to fill and crystallize a conduit full of molten lava (Fig. 9C). Vertical columnar jointing will form in the upper regions of the conduit as heat is lost through the top of the volcano. Columns will flare out towards horizontal attitudes near the base of the cone and below the pre-eruption surface because the sedimentary rocks are cool. After a couple million years of erosion, part or all of the surrounding volcanic cone is removed, exposing the frozen lava pond (Fig. 9D). Only two features in the Rio Puerco Valley fit this model, Cabezon Peak and Cerro de Nuestra Senora, and both are volcanic plugs based on the previous definition.

REGIONAL VOLCANIC PERSPECTIVE

The basalt stocks that dot the Rio Puerco Valley have been regarded as true volcanic necks since they were first described by Dutton (1884–1885). They are similar in physical appearance to the necks described by Williams (1936) in the Hopi Buttes volcanic field, 350 km due west in Arizona. However, rocks of the Hopi Buttes have a distinctly different chemistry and a controversial mode of emplacement involving eruption through a lake. Hopi Buttes rocks are classified as monchiquites and lamprophyres and are extremely silica-undersaturated basalts with high water, TiO_2 and P_2O_5 contents. They were erupted into the late Miocene–early Pliocene Hopi Lake. The eruptions may have become phreatic by interaction of magma with water-saturated rocks beneath the lake (Sutton, 1974). An alternative interpretation suggests the violent eruptions were caused by exsolution of magmatic gas as magma ascended through the crust (Shoemaker et al., 1962). Whatever the mode of formation, necks vary from location to location and may depend not only on depth of erosion but on magma composition, supply rate, volatile content, and local geology and tectonic stresses.

The $^{40}Ar/^{39}Ar$ date for Cabezon Peak of 2.658 ± 0.032 Ma confirms the belief that volcanism was coincident with activity on Mesa Chivato and Mesa Prieta (Dutton, 1884–85; Johnson, 1907; Hunt, 1937; Crumpler, 1980). Although two different dating methods have been used (K-Ar and $^{40}Ar/^{39}Ar$), volcanic activity appears to become younger towards the rift. Perhaps the most useful lessons that can be learned from the volcanic necks is how they compare to their noneroded equivalents on Mesa Chivato.

Volcanic landforms on Mesa Chivato include maars, cinder and spatter cones, and north-northeast-trending fissures (Crumpler, 1980). It seems intuitive that these fissures would correlate to the dike-like, elongate features down in the valley, such as Cerro Cuate, Cerro Cochino and Cerrito Cochino. However, correlation of other features requires detailed mapping to reconstruct what erosion has removed. By definition, maar volcanoes have floors below the surrounding ground surface. Therefore, their recognition requires that the paleosurface has not been eroded away. Based on current work, no maars exist in the Rio Puerco Valley. Instead, most of the necks were originally tuff rings or scoria cones, built above the ground surface. Calcite- and palagonite-cemented, highly fragmented, and well-sorted pyroclastic breccias are evidence that some eruptions may initially have been phreatomagmatic (see description of Cerro Chafo, Hallett, this volume). Other eruptions were more magmatic and produced scoria and spatter cones; Cabezon Peak, Guadalupe and Nuestra Senora are examples.

CONCLUSIONS

1. Volcanism in the Rio Puerco Valley area is intermediate in age between activity on Mesa Chivato and Mesa Prieta. This is consistent with volcanism becoming younger towards the east.

2. Volcanic features display a continuum of erosional stages. Scoria cones that have suffered little erosion occur within several kilometers of the edge of Mesa Chivato. More eroded features occur in the river valley.

3. The formation of volcanic necks and plugs may not be solely a function of erosion, but also the size of the volcanic cone, magma supply rate and thermal retention.

4. Volcanic necks in the Rio Puerco Valley are smaller than the plugs and contain irregular columnar jointing caused by intrusion and crystallization of small pods of magma. Most remnants of vents are necks.

5. Volcanic plugs in the Rio Puerco Valley have vertical columnar jointing and form when conduits fill with magma. The volcano is larger and retains heat better than those volcanoes that form necks.

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REFERENCES

Aldrich, M. J. and Laughlin, A. W., 1984, A model for the tectonic development of the southern Colorado Plateau boundary: Journal of Geophysical Research, v. 89, p. 10,207–10,218.

Allaby, A. and Allaby, M., 1990, The concise Oxford dictionary of earth sciences: New York, Oxford University Press, p. 300, 397.

Ander, M. E., 1981, Geophysical study of the crust and upper mantle beneath the central Rio Grande rift and adjacent Great Plains and Colorado Plateau: Los Alamos National Laboratory Report LA-8676-T, 218 p.

Ander, M. E., Heiken, G., Eichelberger, J., Laughlin, A. W. and Huestis, S., 1981, Geologic and geophysical investigation of the Zuni-Bandera volcanic field, New Mexico: Los Alamos National Laboratory, Report LA-88270-MS, 39 p.

Aoki, K. and Kudo, A. M., 1976, Major-element variations of late Cenozoic basalts of New Mexico: New Mexico Geological Society, Special Publication 5, p. 82–88.

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.

Baldridge, W. S., Bartov, Y. and Kron, A., 1983, Geologic map of the Rio Grande rift and southeastern Colorado Plateau, New Mexico and Arizona: American Geophysical Union, Washington, D.C., scale 1:500,000.

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.

Baltz, E. H., 1967, Stratigraphy and regional tectonic implications of part of Upper Cretaceous and Tertiary rocks, east-central San Juan Basin, New Mexico: U.S. Geoogical Survey, Professional Paper 552, 101 p.

Bates, R. L. and Jackson, J. A., 1980, Glossary of Geology: Second edition, American Geological Institute, Falls Church, Virginia, p. 419, 484.

Brown, 1969, Igneous geology of the Puerco Necks [M.S. thesis]: Albuquerque, University of New Mexico, 89 p.

Brunton, G. D., 1952, The study of an unusual augite near Cabezon Peak, Sandoval County, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 40 p.

Crumpler, L. S., 1980, An alkali-basalt through trachyte suite, Mesa Chivato–Mount Taylor volcanic field, New Mexico: Geologic Society of America Bulletin, part II, v. 91, p. 1293–1331.

Dane, C. H. and Bachman, G. O., 1957, Preliminary geologic map of the northwestern part of New Mexico: U.S. Geological Survey, Miscellaneous Geologic Investigation Map I-224, scale 1:380,160.

Dutton, C. E., 1884–1885, Mount Taylor and the Zuni plateau: Sixth Annual Report, U.S. Geological Survey, p. 106–198.

Fleck, R. J., Sutter, J. F. and Elliot, D. H., 1977, Interpretations of discordant $^{40}Ar/^{39}Ar$ age-spectra of Mesozoic tholeiites from Antarctica: Geochimica et Cosmochimica Acta, v. 41, p. 15–32.

Gawell, M. J. and Laughlin, A. W., 1975, Chemical and petrographic variations in the Cerro Negro–Cerrito Arizona cinder cone lineation, Valencia County, New Mexico: Geological Society of America, Abstracts with Programs, v. 7, p. 1084.

Geikie, A., 1897, Ancient volcanoes of Great Britain: 2 vol., London, Macmillan, 969 p.

Geikie, A., 1902, The geology of East Fife: Memoir, Geological Survey of Scotland, p. 200–283.

Hunt, C. B., 1937, Igneous geology and structure of the Mount Taylor volcanic field, New Mexico: U.S. Geological Survey, Professional Paper 189-B, p. 51–80.

Johnson, D. W., 1907, Volcanic necks of the Mount Taylor region, New Mexico: Geological Society of America Bulletin, v. 18, p. 303–324.

Kudo, A. M., Aoki, K. and Brookins, D. G., 1971, The origin of Pliocene-Holocene basalts of New Mexico in the light of Sr-isotopic and major-element abundances: Earth and Planetary Science Letters, v. 13, p. 200–204.

Laughlin, A. W., Brookins, D. G., Kudo, A. M. and Causey, J. D., 1971, Chemical and strontium isotopic investigations of ultramafic inclusions and basalts, Bandera Crater, New Mexico: Geochimica et Cosmochimica Acta, v. 35, p. 107–113.

Le Bas, M. J., Le Maitre, R. W., Streckeisen, A. and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745–750.

Lipman, P. W. and Mehnert, H. H., 1979, Potassium-argon ages from the Mount Taylor volcanic field, New Mexico: U.S. Geological Survey, Professional Paper 1124-B, 8 p.

Maxwell, C. H., 1982, El Malpais: New Mexico Geological Society, Guidebook 33, p. 299–301.

Maxwell, C. H., 1986, Geologic map of El Malpais lava field and surrounding areas, Cibola County, New Mexico: U.S. Geological Survey, Miscellaneous Investigations Map I-1595, scale 1:62,500.

Mayo, E. G., 1958, Lineament tectonics and some ore districts of the Southwest: American Institute of Mining Engineers, Transaction, v. 10, p. 1169–1175.

McNeil, M., 1991, Earth Sciences Reference: Lake San Marcos, California, Flamingo Press, p. 377, 601.

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. 13,645–13,671.

Parker, S. P., 1984, McGraw-Hill Dictionary of Earth Sciences: New York, McGraw-Hill, p. 553, 561.

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

Perry, F. V., Baldridge, W. S., DePaolo, D. J. and Shafiqullah, M., 1990, Evolution of a magmatic system during continental extension: the Mount Taylor volcanic field, New Mexico: Journal of Geophysical Research, v. 95, p. 19,327–19,348.

Thompson, G. A. and Zoback, M. L., 1979, Regional geophysics of the Colorado Plateau: Tectonophysics, v. 61, p. 149–181.

Shoemaker, E. M., Roach, C. H. and Byers, F. M., 1962, Diatremes and uranium deposits in the Hopi Buttes, Arizona; *in* Petrologic studies—a volume in honor of A. F. Buddington: New York, Geological Society of America, p. 327–355.

Slack, P. B. and Campbell, J. A., 1976, Structural geology of the Rio Puerco fault zone and its relationship to central New Mexico tectonics: New Mexico Geological Society Special Publication, v. 6, p. 46–52.

Slavin, P. J., 1991, Summary of recent work on the geomorphology of the upper Rio Puerco: New Mexico Bureau of Mines and Mineral Resources, Bulletin 137, p. 171–172.

Spry, A., 1962, The origin of columnar jointing, particularly in basalt flows: Journal of the Geological Society of Australia, v. 8, p. 191–216.

Sutton, R. L., 1974, The geology of Hopi Buttes, Arizona: Geological Society of America, Rocky Mountain Section, Guidebook 27, p. 647–671.

Williams, H., 1936, Pliocene volcanoes of the Navajo-Hopi Country: Geological Society of America Bulletin, v. 47, p. 111–172.
Williams, H. and McBirney, A. R., 1979, Volcanology: San Francisco, Freeman, Cooper and Co., 397 p.
Williams, L. A. J., 1970, The volcanics of the Gregory Rift Valley, East Africa: Bulletin of Volcanology, v. 34, p. 439–465.
Wilshire, H. G., Meyer, C. E., Nakata, J. K., Calk, L. C., Shervais, J. W., Nielson, J. E. and Schwarzman, E. C., 1988, Mafic and ultramafic xenoliths from volcanic rocks of the western United States: U.S. Geological Survey, Professional Paper 443.
Wyatt, A., 1986, Challinor's Dictionary of Geology: Sixth edition, New York, Oxford University Press, p. 336.
Zoback, M. L. and Zoback, M., 1980, State of stress in the conterminous United States: Journal of Geophysical Research, v. 85, p. 6113–6156.