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VOLCANIC AND SEDIMENTARY STRATIGRAPHY OF THE RIO GRANDE GORGE AND THE LATE CENOZOIC GEOLOGIC EVOLUTION OF THE SOUTHERN SAN LUIS VALLEY

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INTRODUCTION

The Taos Plateau volcanic field (TPVF) is one of several dominantly basaltic volcanic fields erupted along the Jemez lineament over the last 10 m.y. These volcanic fields comprise a regional magmatic event that was coincident with regional uplift and tectonic rejuvenation of the Rio Grande rift postdating late Miocene time. TPVF volcanism was dominated by extensive floods of the highly fluid olivine tholeiites (1,500 km³) of the Servilleta Basalt. Andesites and dacites erupted from shields scattered throughout the field are lesser in volume, but coeval with the basalts. The main phase of basaltic and intermediate volcanism (-4.5-3.5 m.y.) was succeeded by a period of low-volume alkalic basalts (>1.8 m.y.).

Post-volcanic erosion by the Rio Grande has cut a canyon up to 180 m deep along the southern edge and northward through the TPVF. Exposures the length of the canyon reveal the interplay between volcanism, sedimentation, and deformation during an approximately one-to-two-million-year period. Earlier history is exposed only along the southeastern margin of the TPVF and in the Tusas Mountains to the west of the study area. The widespread floods of Servilleta Basalts, which appear to have been erupted from vents located along the western margin of the field, record voluminous, short-lived, effusive episodes interspersed with longer intervals during which gravel fans prograded to the west from the Sangre de Cristo Mountains and north—northwest from the Picuris Mountains. Olivine andesites and two-pyroxene dacites erupted from cones both east and west of the Rio Grande and Red River gorges are also locally interlayered with basalts. The entire volcanic section was tilted to the southeast during and following volcanic activity. Deformation during and after volcanism is also recorded by reoccurring movements on intra-rift and rift-boundary faults, differential subsidence of the narrow Velarde and Taos grabens, and local warping of the volcanic units. Local zones of reverse faulting along the eastern segment of the Embudo fault and warping of the plateau surface (Taos graben) demonstrate a shift to local compression late in the evolution of the basin.

REGIONAL SETTING

Crustal extension and related volcanism associated with the inception of the Rio Grande rift are dated at -28-25 m.y. in both the southern (Chapin and Seager, 1975; Seager and others, 1984) and northern (Lipman and Mehnert, 1975) segments of the rift. The volcanism characteristic of the early phase of rifting is in part basaltic, which distinguishes it from the calc-alkaline intermediate rocks of the Oligocene San Juan and Mogollon—Datil volcanic fields that preceded rifting. Large intermediate to silicic centers are an important component of the initial pulse of rift-related volcanism, but these too are distinct from the Oligocene calc-alkaline intermediate volcanism due to the presence of alkali-rich, high SiO rhyolites (e.g., Questa caldera, Lipman, 1983). Recent studies of basins formed in the early phase of rifting indicate a pronounced NW trend to the faults associated with them.

The establishment of N-trending, high-angle faults separating deep, narrow, asymmetric grabens during post-Miocene uplift and faulting contrasts with the NW trends typical of the earlier phase of extension, and clearly indicates a major reorientation of the regional stress field in conjunction with tectonic rejuvenation of the Rio Grande rift. Basaltic volcanism within the axis and on the flanks of the rift became volu-

minous and widespread *after* 10 m.y. and is, therefore, temporally associated with the observed tectonic rejuvenation. The oldest volcanics in all the relevant fields have not been dated, but several did not begin until 7-8 m.y. (Stormer, 1972; O'Niell and Mehnert, 1980) and others initiated activity still more recently.

The Jemez lineament is defined by Plio-Pleistocene volcanic fields extending along a line from central Arizona to northeastern New Mexico. It crosses the rift at a high angle along the Embudo fault zone, the boundary between the San Luis and Espanola Basins. Structural analysis of Proterozoic rocks in the Sangre de Cristo and Picuris Mountains indicates that the lineament is a zone of Precambrian structural weakness (Nielsen and others, 1983). The TPVF lies along the Rio Grande rift axis, but is slightly offset to the north of the Jemez trend. The other major fields of the Jemez lineament, from SW to NE the Springerville, Zuni, Mt. Taylor, Jemez, Ocate, and Raton—Clayton fields, are located partly or entirely on the rift flanks outside the axial depressions. The spacing of Jemez lineament volcanic fields outside the axial region of the rift (measured center-to-center) is 100-140 km. In contrast, the

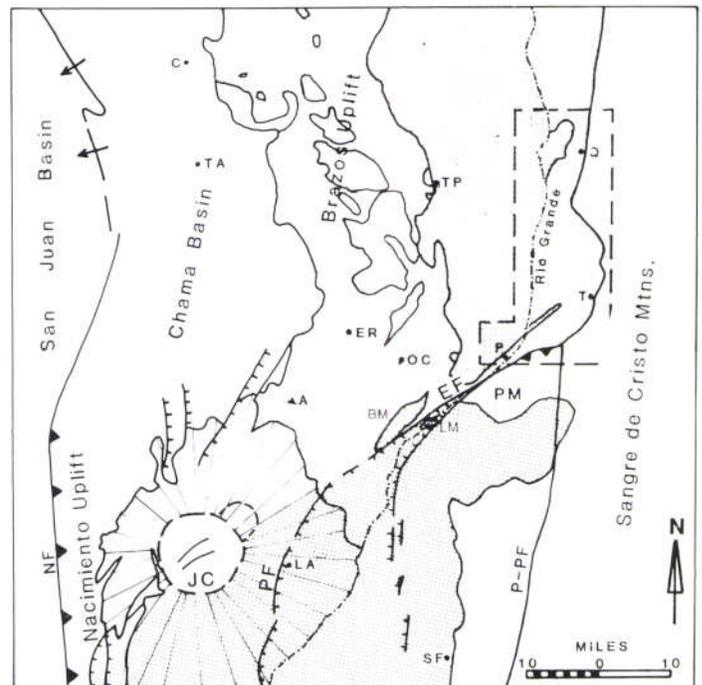


FIGURE 1. Index map of northern New Mexico showing location of study area (region outlined by dashed lines in Figure 2) relative to the San Luis (horizontal ruling) and Espanola (shaded) Basins of the Rio Grande rift and surrounding regional elements. Symbols: TPVF—Taos Plateau volcanic field (vertical ruling); JC—Jemez caldera and its volcanic field (radial patterns); BM—Black Mesa; LM—La Mesita; EF—Embudo fault zone; PM—Picuris Mountains; P—PF—Pecos—Picuris fault; SF—Santa Fe; LA—Los Alamos; A—Abiquiu; ER—El Rito; OC—Ojo Caliente; T—Taos; TP—Tres Piedras; Q—Questa; TA—Tierra Amarilla; C—Chama; NF—Nacimiento fault zone; P—Pilar; unpatterned areas expose pre-rift rocks.

TPVF lies midway between the Jemez and Ocate fields, which are approximately 100 km apart along the Jemez zone. Thus, the position and structural setting of the TPVF is unique among the Jemez zone volcanic fields. Furthermore, the TPVF lies in an actively subsiding basin which buried its older parts. In most other fields along the zone, the inception of volcanism is datable because erosion has accompanied uplift of the rift flanks, leaving the volcanic rocks perched on mesas.

The Jemez volcanic field, which began erupting at about 10–13 m.y., is a highly diverse assemblage which includes the entire spectrum from basalt to rhyolite (Ross and others, 1961; Gardner and others, 1984). It is unusual among the Jemez zone volcanic fields in that rhyolite comprises a significant proportion of the eruptives. The remaining fields are dominantly basaltic, with a subordinate component of intermediate rocks (andesites to latites). Pyroclastic deposits and rhyolites are rare, and are altogether absent in several of the volcanic fields. Recent studies, while demonstrating some contrasts among the various volcanic fields, have also served to emphasize similarities (Dungan and others, 1981 b; Dungan and others, 1983a; Condit, 1983; Aubele and Crumpler, 1983; Baldrige and others, 1983).

Each volcanic field embraces some diversity in basaltic-magma types, but the flank eruptives are more alkaline and more diverse. Activity appears to have peaked in the interval 5–3 m.y., during which time tholeiitic to transitional basalts with diktytaxitic groundmass textures were the dominant type. Andesites and more silicic rocks of high-K, calc-alkaline affinity were erupted coevally with basalts of the period of peak activity.

The TPVF lavas were erupted in an actively subsiding basin which underwent internal deformation during and after volcanism. Although volcanism ceased within the San Luis Basin at approximately 1.8–1.5

eruption of basalts continued into the Quaternary on the rift flanks, and evidence for ongoing deformation on the TPVF and elsewhere indicates that the rift remains an active tectonic province. The apparent waning of volcanism beginning at 2–3 m.y., following a regional peak at 5–3 m.y., suggests that the late Cenozoic rejuvenation of activity peaked in the late Pliocene, and that a progressively less active system may be predicted for the future.

PREVIOUS WORK

The geomorphology and general geology of the Taos—Questa area were first described by Lambert (1966). The nomenclature and stratigraphic relationships of Cenozoic sedimentary units in the Espanola Basin and vicinity have been discussed by Galusha and Blick (1971), Manley (1976, 1979), and Steinpress (1980). The Cenozoic tectonic and rifting history has been extensively studied by Kelley (1952, 1954, 1977, 1979) and Manley (1976, 1979). Baltz (1978) presented a summary of the Phanerozoic history of the northern rift.

Analyses of TPVF lavas were published by Wells (1937), Larson and Cross (1956), and Aoki (1967), whose work complemented the study of Ozima and others (1967). The dating and paleomagnetic investigation of Ozima and others demonstrated that at least two magnetic reversals occurred during Servilleta time which ranged from 4.5–3.5 m.y. Lipman and Mehnert (1979) also published a map, chemical analyses of all rock types present in the TPVF, and provided additional dates which are generally consistent with those of Ozima and others. Manley (1979) and Baldrige and others (1980) have published single K—Ar dates of 2.8 m.y. and 4.6 m.y., respectively, on stratigraphically young Servilleta flow units.

Baldrige and others (1980) have criticized the Ozima and others (1967) chronology on two counts. The lack of a mass discrimination correction in the earlier work yields an older and narrower range on ages (5.0–4.5 m.y.) which bring these data into essential agreement with the more recent data. The second point made by Baldrige and others (1980) is that only three, rather than six, magnetic reversals are represented by the volcanic section. This apparent discrepancy could as easily be explained by a lack of eruptions during three of the magnetic intervals as a mismatch between the K—Ar chronology and the magnetic stratigraphy. We argue below that the periods occupied by Servilleta volcanism were short compared to the intervals between eruptive episodes. Clearly, additional dates on the complete stratigraphic section

are needed to satisfactorily resolve these discrepancies. We have continued to use the Lipman and Mehnert/Ozima and other chronology here, because the combined studies span the entire range of activity. However, we acknowledge that these ages may be 20–30% too young.

Zimmerman and Kudo (1979) also studied andesites and dacites, and generated additional major- and trace-element analyses. A select suite of mafic samples was analyzed (including mineral chemistry and some Sr- and Nd-isotopic analyses) by Dungan and others (1981a). Recent major-element, trace-element, mineral-chemistry analyses plus isotopic analyses and petrologic modeling by Dungan and co-workers (Dungan and others, 1983a, b, c; McMillan and Dungan, 1982; McMillan and Williams, 1983; Williams and Murthy, 1979; McMillan and others, 1983; Moorbath and others, 1983; Thompson and Dungan, 1982) have greatly expanded the analytical data base.

STRUCTURAL EVOLUTION OF THE SOUTHERN SAN LUIS VALLEY

The Taos Plateau volcanic rocks and associated sediments (see map in Lipman and Mehnert, 1979) lie at the southern end of the San Luis Basin (SLB), one of the major axial grabens of the Rio Grande rift. The SLB is terminated at its south end by the Embudo fault zone, which separates the east-tilted SLB from the west-tilted Espanola Basin and from the upthrown Picuris Mountain block. Although the Abiquiu embayment is topographically part of the Espanola Basin, it exhibits the same east tilt as the SLB. This is demonstrated by the succession of broad, east-sloping terraces of the El Rito River drainage, between Abiquiu and El Rito.

These similar tilts suggest that the Abiquiu embayment is a western extension of the SLB. However, the structural relationship is complicated by the outcrop of Precambrian quartzite at Cerro Azul (west of the map area, see map in Lipman and Mehnert, 1979). Gravity data in Cordell (1976) indicate that Cerro Azul is the surface expression of an E—W basement ridge north of the Embudo fault which at least in part separates the SLB from the Abiquiu embayment. Like the Abiquiu region, the Tusas Mountains to the north are east-tilted sediments and interbedded volcanics which were deposited within an earlier, broader rift basin. The uplifted Tusas Mountains are now the topographic margin of the southern SLB, but are not separated from it by a major fault. The seismically active boundary between the San Juan and Chama Basins (Cash and others, 1983) is probably the hinge of the broad, east-tilted region that is bounded on the east by the Taos fault.

North-trending, down-to-the-east faults and monoclines that parallel the Rio Grande define the western border of the main downthrown graben block (Taos graben) which lies between the Sangre de Cristo Mountains on the east and a major intra-rift horst on the west. Although the horst lies largely in the subsurface (Cordell, 1978), it is exposed in two places west of the Rio Grande on the Taos Plateau (Brushy Mountain and Timber Mountain) and extensively in southern Colorado as the San Luis Hills. Rocks exposed on the horst are early Miocene intrusions, lavas, and pyroclastic rocks associated with the early phase of rifting (Lipman and Mehnert, 1979; Thompson and Dungan, 1982). Much of the Sangre de Cristo Mountain front has no Quaternary fault scarp along it within the study area, yet it marks the position of the main border fault (Taos fault) of the SLB (and the Taos graben) on the eastern margin of the Taos Plateau. The northwest-trending frontal segment of the mountain front and the Red River fault zone (Fig. 2) may be a reactivation of a northwest-trending fault system present in the Questa caldera (Lipman, 1983).

The Embudo zone is seismically active (Cash and others, 1983), and there is a sag in a leveling line along U.S. Highway 84 where it crosses the fault southwest of Black Mesa. Post-Pliocene movements are demonstrated by the fault scarps along the base of the Picuris Mountains, in the paleodepression tilted by Servilleta Basalts at La Mesita and Black Mesa where they straddle the fault zone (and are displaced by it), and in the extra thickness of the Chamita Formation under Black Mesa.

The history of motion on the Embudo fault zone is complex. Left

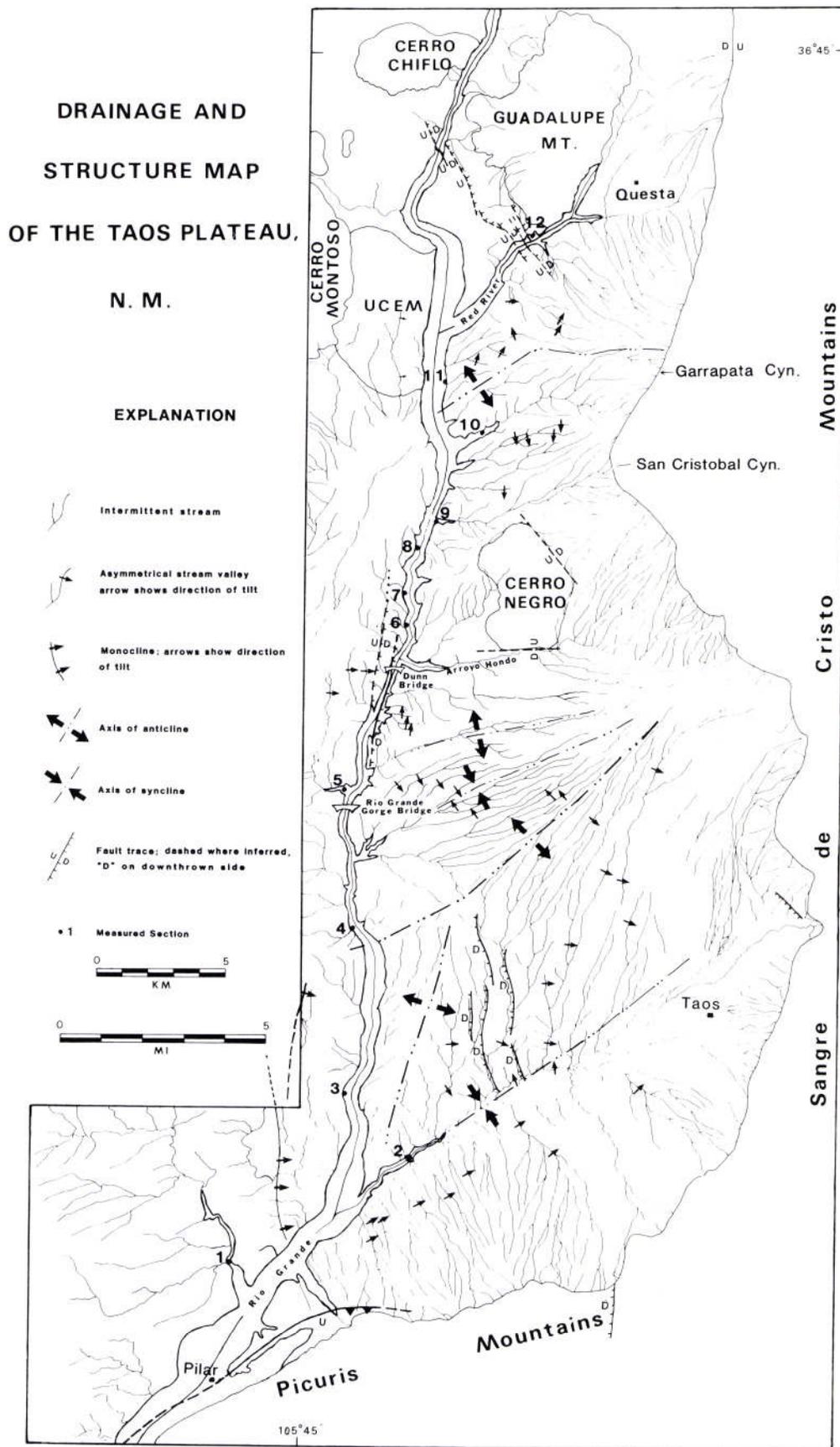


FIGURE 2. Drainage and structure map of the Taos Plateau. Location of measured sections of Figure 7 shown by numbers. Modified from Peterson (1981).

slip along the Embudo is required by the opening of the San Luis and Espanola Basins. Early Santa Fe sedimentary rocks of the Bradley conglomerate are broken by a conjugate fracture system which suggests left-lateral wrenching with transcurrent movement oriented N 60° E, parallel to the Embudo fault trend (Leininger, 1982). Left-lateral slip along the Embudo fault is a late development in the history of the rift. Early rifting was dominated by simple extension and dip-slip motion. The transcurrent motion began during the Pliocene and is synchronous with the major uplift of the Picuris Mountains in that epoch. The Embudo fault at present has a hinge point near Pilar. East of Pilar the south side is moving up and over the north (Taos Plateau) side. Analysis of the fractured Bradley conglomerate clasts plus the microfaulted and sheared Ojo Caliente dunes in the Pilar area support a late compressive (reverse faulting) and strike-slip stage (left-lateral offset) (Muehlberger, 1979; Leininger, 1982). West of Pilar the movement is slightly divergent, resulting in a narrow, downthrown fault block that opens south-westward into the Espanola Basin. The north boundary fault crosses the Rio Grande and appears to split into two branches. One apparently continues S 60° W through the crestal graben of the Jemez caldera (i.e., along trend of the Jemez lineament), and the other turns southward as the Pajarito fault (Golombek, 1983; Los Alamos fault zone of Kelley, 1954) that marks the west side of the Velarde graben (Manley, 1979). The south boundary fault of the narrow downthrown block turns southward through Espanola and marks the east side of the Velarde graben.

Active subsidence of the Velarde graben is asymmetrical with a sense opposite to that characterizing the SLB. Strata within the Velarde graben are tilted to the west and movement is dominantly along the Pajarito fault. Thus, the Velarde graben is the counterpart of the Taos graben in its structural position across the Embudo fault zone which can be regarded as an intracontinental transform (Muehlberger, 1979) connecting two narrow zones of active extension.

The Pajarito fault scarp exhibits a large magnitude of displacement (100 m in 1.1 m.y.) which is comparable to the rate determined by Lipman and Mehnert (1979) for San Pedro Mesa (500 m in 3 m.y.). Although movements along most of the Taos fault (and the Sangre de Cristo frontal fault in general) are difficult to assess quantitatively, we infer similar large displacements throughout its entire length. The highest scarp within the Taos Plateau proper is along the Dunn Bridge fault (35 m in 3.5 m.y.) which probably marks the structurally lowest point in the Taos graben. Its total length is but a small fraction of the Pajarito or Taos faults. All other fault scarps in the region are short, with generally low displacements (meters to a few tens of meters).

Volcanism in the Espanola Basin straddles the Velarde graben. The relatively small Cerros del Rio field (Baldrige, 1979) lies to the east of the Pajarito fault; the much larger Jemez volcanic field lies to the west of the Pajarito. Additional basaltic volcanic centers lie to the south along the offset to the Albuquerque Basin (San Felipe Mesa). Vents in the Taos Plateau volcanic field are scattered throughout the southern San Luis Basin. None of the post-Miocene vents lie to the east of the Taos fault, although the coeval Ocate volcanic field lies 40 km to the east on the boundary between the Sangre de Cristo Mountains and the High Plains. The crestal graben of the resurgent dome of the Valles caldera lies along the Jemez trend, suggesting some Jemez trend control. However, there is very little indication that the structures which define boundaries between major structural blocks on the Taos Plateau play a role in controlling the locations of vents.

MID- TO LATE CENOZOIC SEDIMENTATION HISTORY

Thick sections of pre- and early-rift volcanic rocks and early-rift alluvial deposits west of the Taos Plateau, and in the Questa volcanic center to the east, indicate that the early phase of rifting (>20 m.y.) was not accompanied by uplift of the region (Lipman and Mehnert, 1979). Although the early-rift volcanoclastic deposits are not exposed in the study area, the Picuris Formation, a late Oligocene (to early Miocene?) tuffaceous sand and gravel deposit, has been mapped to the east along the northern Picuris Mountain border (Montgomery, 1953), and the Abiquiu Formation, which thickens southward into the Abiquiu region (Smith, 1938), occurs to the west.

Gravity data indicate that the greatest subsidence (7-8 km) occurred in the deep Taos graben along the eastern edge of the southern SLB (Cordell, 1978; Lipman and Mehnert, 1979). Five kilometers of alluvial sediments shed off the Sangre de Cristo Mountains filled the basin as it dropped down along the Taos fault (Cordell, 1978). The Rio Grande flows along the western boundary of the Taos graben. Its position is in part controlled by apparently long-lived normal faults associated with this boundary, and in part by alluvial fans prograding to the west from the mountain front. Exposures in the gorge reveal depositional systems only as old as late Pliocene.

The early history of this region is exposed along the uplifted southern margin of the Taos Plateau within the Embudo fault zone where the Picuris Mountains have been overriding the plateau since deposition of the early Pliocene Cieneguilla Member of the Santa Fe Group. The oldest Tertiary unit in the study area is the early Miocene(?) Bradley conglomerate member (informal name) of the Tesuque Formation (Fig. 3). This unit is exposed in a small area at the north base of the Picuris Mountains southeast of Pilar. The unit is composed of debris flows in which the dominant clast lithologies are granitic and quartzitic. This deposition appears to record the presence of an alluvial-fan surface fed by a source area 7-15 km south of the study area. The Bradley conglomerate represents the initial emergence of the southern Picuris Mountains (Leininger, 1982).

Approximately 18 to 13 m.y. B.P. the depositional regime changed and detritus shed off the uplifting Sangre de Cristo Mountains covered

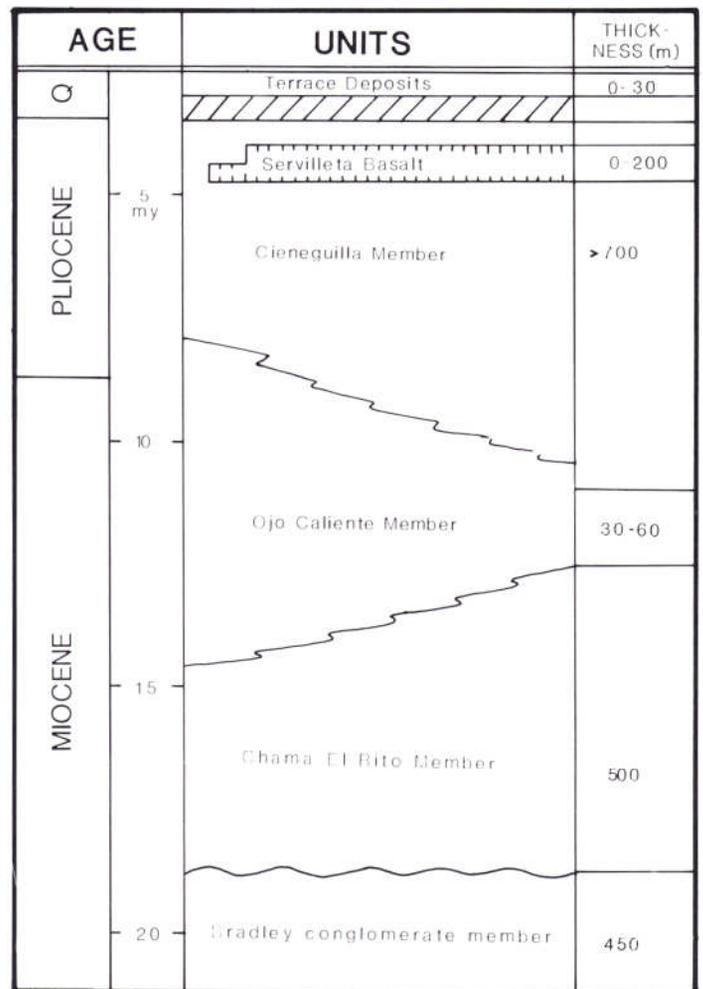


FIGURE 3. Cenozoic stratigraphy exposed in the study area. Except for the terrace deposits, all units are part of the Tesuque Formation, Santa Fe Group. Details of interfingering between the Cieneguilla Member, Servilleta Basalt (formerly Servilleta Formation), and other volcanic types are shown in Figures 5 and 7. Q—Quaternary.

the study area and extended southwestward well into the Espanola Basin. The southwesterly flowing braided streams of the Chama—El Rito alluvial fan buried the Bradley conglomerate. Streams scoured upper Bradley deposits, producing an unconformable surface of modest relief. The predominantly volcanoclastic Chama—El Rito unit has upward progressively more detritus of Precambrian quartzite derived from the emerging Picuris Hills south of the study area. Steinpress (1980) recognized a Dixon Member which overlies the Chama—El Rito near La Mesita (15 km SW of Pilar) that is characterized by predominantly Paleozoic detritus derived from the southeast, especially in the coarse fractions.

Deposition of the Ojo Caliente Member probably began around 15 m.y. ago. Prevailing westerly winds deflated the distal Chama—El Rito fan surface and other exposures along the western SLB margin, transporting the eolian sediment into the southern SLB. Early Ojo Caliente sands interfingered with Chama—El Rito fluvial sands and gravels (Fig. 3). Eolian sedimentation eventually dominated, perhaps reflecting a climatic change to a more arid environment. The upper Ojo Caliente Member interfingered with Cieneguilla Member sands and gravels that were shed north from the Picuris Hills rising nearby (Fig. 4).

Cieneguilla Member sedimentation was a result of uplift and erosion of the Picuris Range beginning at 8-10 m.y. Lower Cieneguilla deposits contain a high percentage of volcanic pebbles and thick sand lenses. This indicates that earlier Tesuque Formation deposits (Chama—El Rito Member and Ojo Caliente Member) were initially a major source for the lower Cieneguilla beds. Middle and upper Cieneguilla deposits were derived entirely from the Precambrian quartzite and schistose rocks of the Picuris Mountains and became progressively more coarse through the late Miocene and Pliocene, reflecting an increase in relief between the SLB and Picuris Mountains. In mid- to late Cieneguilla time a major uplift and tilting event juxtaposed coarse, proximal facies alluvial-fan sediments on top of early distal sandy-facies sediment, concurrently with Servilleta volcanism (Leininger, 1982).

LATE CENOZOIC VOLCANISM

Lipman and Mehnert (1979) classified and mapped the basin units of the TPVF and dated main phases of mafic and intermediate activity at between 4.5 and 2.5 m.y. (see also Ozima and others, 1967; Baldrige and others, 1980). Younger alkalic lavas, in part xenocrystic, postdate the eruption of the Servilleta Basalt. The Cerro Chiflo quartz latite is much older (10.2 m.y.) than the main phase of activity and is distinct from younger, intermediate-composition lavas. The No Agua rhyolite domes on the western edge of the Taos Plateau erupted during the main phase of activity, but do not seem to be petrologically related to the basalts, andesites, and dacites.

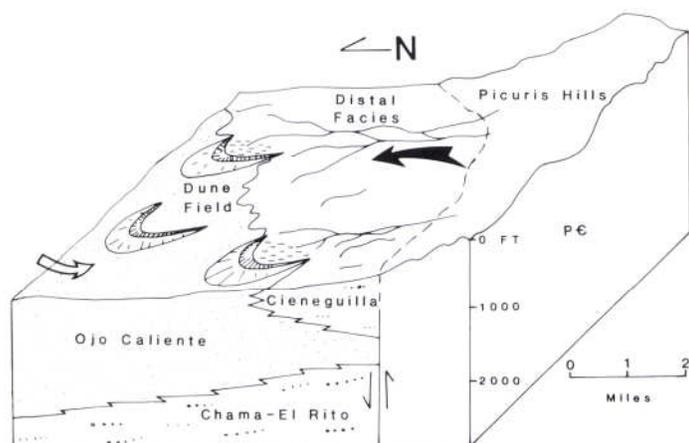


FIGURE 4. Block diagram of Pilar area during upper Ojo Caliente Member deposition. The dune sands interfinger with, and are reworked by, Cieneguilla Member braided streams from the rising Picuris Hills. Open arrow is prevailing wind direction; solid arrow is stream-sediment transport direction. From Leininger (1982).

Lipman and Mehnert (1979) have called attention to the zoned distribution of vents on the Taos Plateau. Basalt shields on the western margin of the TPVF are partially surrounded on the east by olivine-andesite shields. Dacite cones, built in part on earlier andesite shields (San Antonio, Ute, Guadalupe), form an outer semicircular ring circumscribing all other vents. Most of the younger, alkalic lavas erupted from cinder cones localized near the greatest concentration of older shields. This organized pattern suggests a unified magmatic system during much of the Taos Plateau's volcanic history. The present study is an attempt to provide a temporal perspective that complements the spatial relationships revealed in Lipman's map.

Below we summarize the compositional, petrographic, and flow features that characterize the different units exposed within the Rio Grande and Red River gorges. One of the units is a new informal designation (San Cristobal lavas) used in subdividing the Servilleta Basalt (Figs. 6, 7). Consequently, we describe these rocks in more detail than the intermediate (andesite and dacite) or alkalic rocks which are discussed in Lipman and Mehnert (1979). Readers are asked to refer to that article plus Dungan and others (1981 a) for additional analyses and descriptive materials, and for a geologic map of the Taos Plateau.

Terminology

The volcanic-rock nomenclature used in this paper follows, with one exception, the terminology proposed by Lipman and Mehnert (1979). We have substituted dacite for rhyodacite and extended the compositional range (60-67.5% Sig) to which this name is applied on the basis of additional analyses. The distinctions between olivine andesite and dacite are discussed below. Lipman and Mehnert (1979) advocated substitution of the term Servilleta Basalt for Servilleta Formation and restriction of the former to the diktytaxitic olivine tholeiites which are the dominant unit of the TPVF. We concur with this usage and introduce the informal term San Cristobal lavas (SCL) to refer to a package of flows which is similar to, but distinct from, the Servilleta olivine tholeiites sensu stricto in terms of composition, petrography, and flow structure.

The major-element analyses of intermediate-composition lavas from the TPVF that were available to Lipman and Mehnert (1979) enabled them to distinguish two mineralogically distinct groups, an olivine-andesite rock type with 56-59% Sig, and more evolved "rhyodacites" which are characterized by pyroxene phenocrysts. The olivine-phyric rocks are dominantly in the range 56-58% Sig, but the entire range extends from 54 to 60% SiO₂. We retain the term olivine andesite for these rocks. The pyroxene-phyric rocks form a coherent group that ranges in SiO₂ from around 60 to 67.5%. The rocks with >65% Sig are comparatively rich in plagioclase and a few contain minor hornblende, but these samples appear to form a compositional continuum even though the majority still fall within the 62-64%-SiO₂ limits originally defined for "rhyodacite." We have chosen to apply the term dacite to the entire spectrum of pyroxene-phyric rocks ranging from 60 to 67.5% SiO₂ and have subdivided this range into low-SiO₂ (<64) and high-SiO₂ (>64) dacites. The entire suite, from andesite to dacite, falls into the high-K series of Gill (1981) and Pecerrillo and Taylor (1976). Both classifications use 65% SiO₂ as the boundary between andesite and dacite. Application of the name rhyodacite to rocks with less than 65% SiO₂ would be contradictory to the current usage of this term, particularly in light of the relatively high Mg/(Mg + Fe) of the TPVF low-SiO₂ dacites.

Silicic Alkalic Basalt

Lipman and Mehnert (1975) proposed the term silicic alkalic basalt (SAB) for Cenozoic mafic lavas of the Rocky Mountains which are distinct from both typical olivine tholeiites and nepheline-normative alkali-olivine basalts. SAB lavas of the TPVF are characterized by comparable to higher SiO₂ than typical tholeiites (50-53% SiO₂), higher alkalis (especially K₂O), and much higher concentrations of incompatible trace elements such as LREE, Rb, Nb, Zr, Th, and U. The trace-element signatures of SABs generally resemble those of alkali-olivine basalts. Their higher SiO₂ and higher alkalis result in normative compositions characterized by minor *by* or more rarely minor *ne*. Even

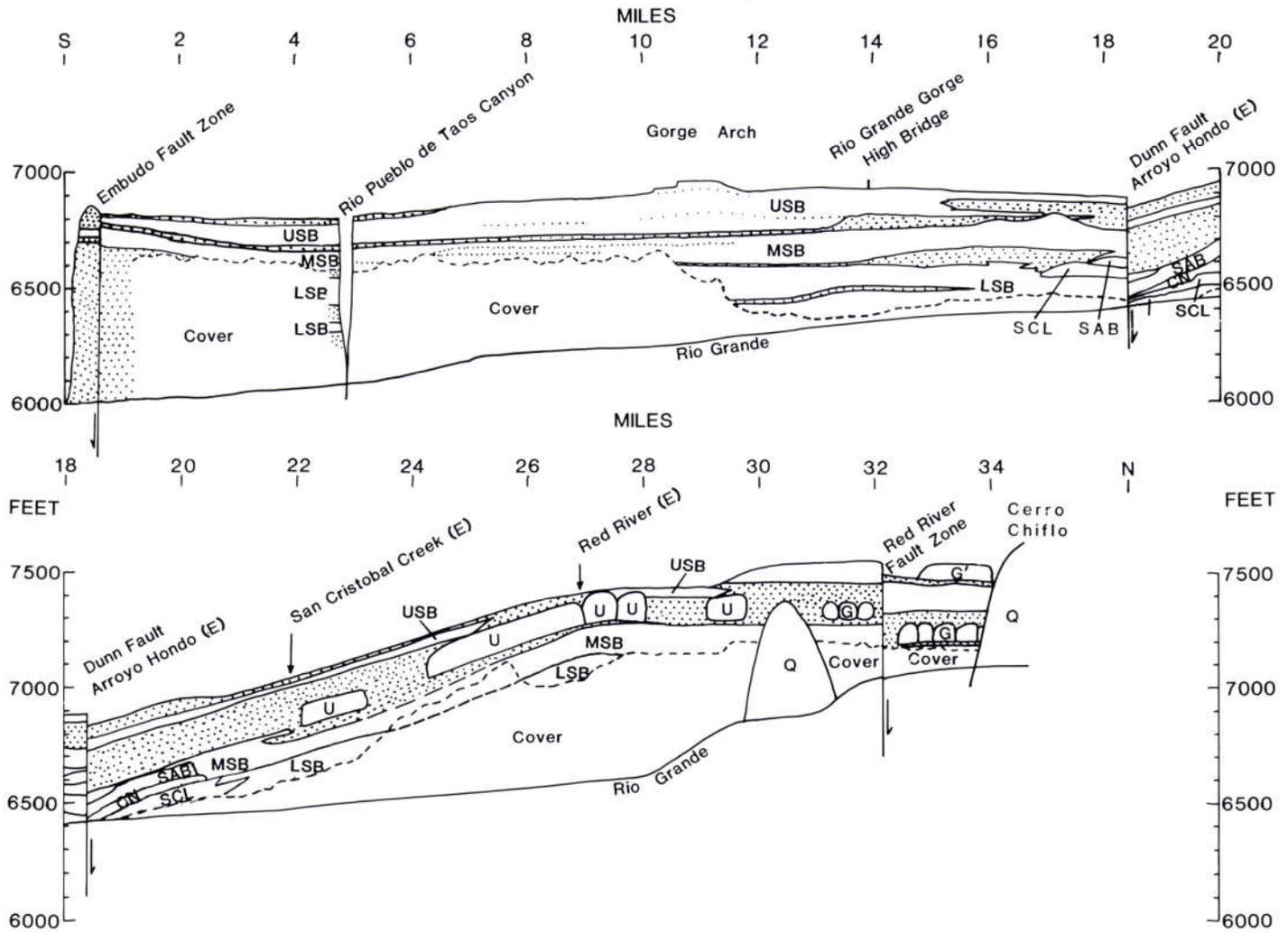


FIGURE 5. Generalized stratigraphy of Rio Grande gorge from Pilar (south end) to Cerro Chiflo (north end), showing sedimentary intervals (dot pattern) and volcanic intervals (labeled units). Symbols: Servilleta Basalt divided into lower (LSB), middle (MSB), and upper (USB) units; SAB—silicic alkalic basalt; CN—Cerro Negro dacite; SCL—San Cristobal basaltic lavas; U—dacite from unnamed cerrito east of Cerro Montoso (flows rim only west wall of canyon); G—older dacite from Guadalupe Mountain; G'—younger dacite from Guadalupe Mountain; Q—quartz latite from pyroclastic vent exposed in the Rio Grande gorge and flows from Cerro Chiflo; E—location of rivers entering the Rio Grande from the east. Modified from Leininger (1981) for strip from Pilar to High Bridge, and Peterson (1981) from High Bridge to Cerro Chiflo.

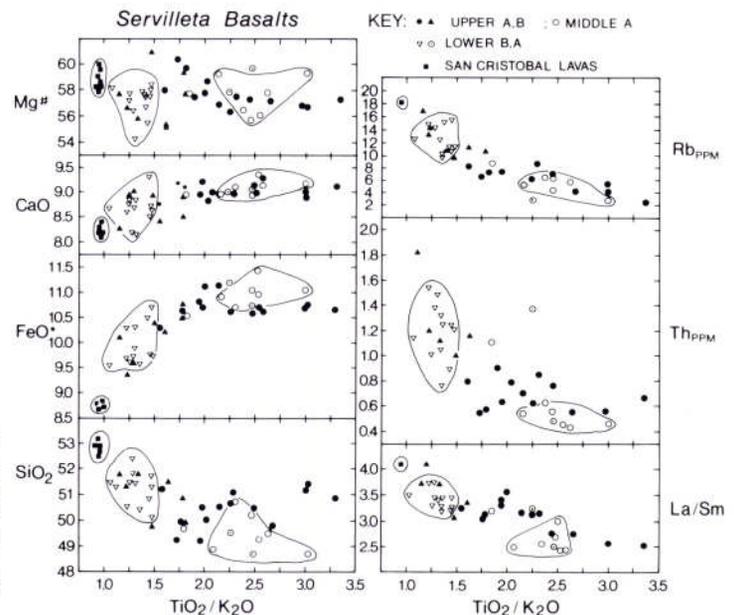


FIGURE 6. Servilleta Basalt and San Cristobal lava, chemical variations for select major and trace elements. ($Mg\# = 100 Mg/(Mg + Fe^{2+})$). Circled fields are SCL (■), LSB type B (▽) and MSB type A (○). Closed symbols are types A (○) and B (△) from the USB. Two samples of type A within LSB are denoted by 0. Note the large variations in incompatible elements such as Rb and Th in comparison to the relatively minor range of major elements, and the nearly constant Mg#. These relations eliminate simple fractional crystallization of a single parent as the primary source of major- and trace-element variations.

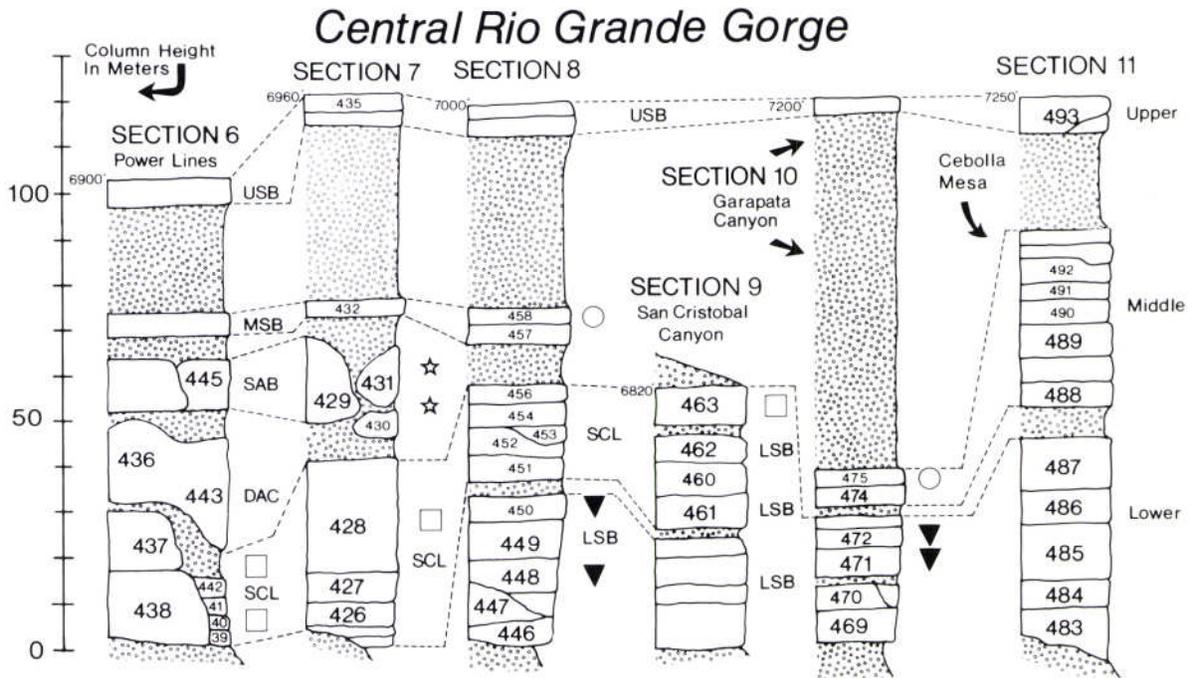
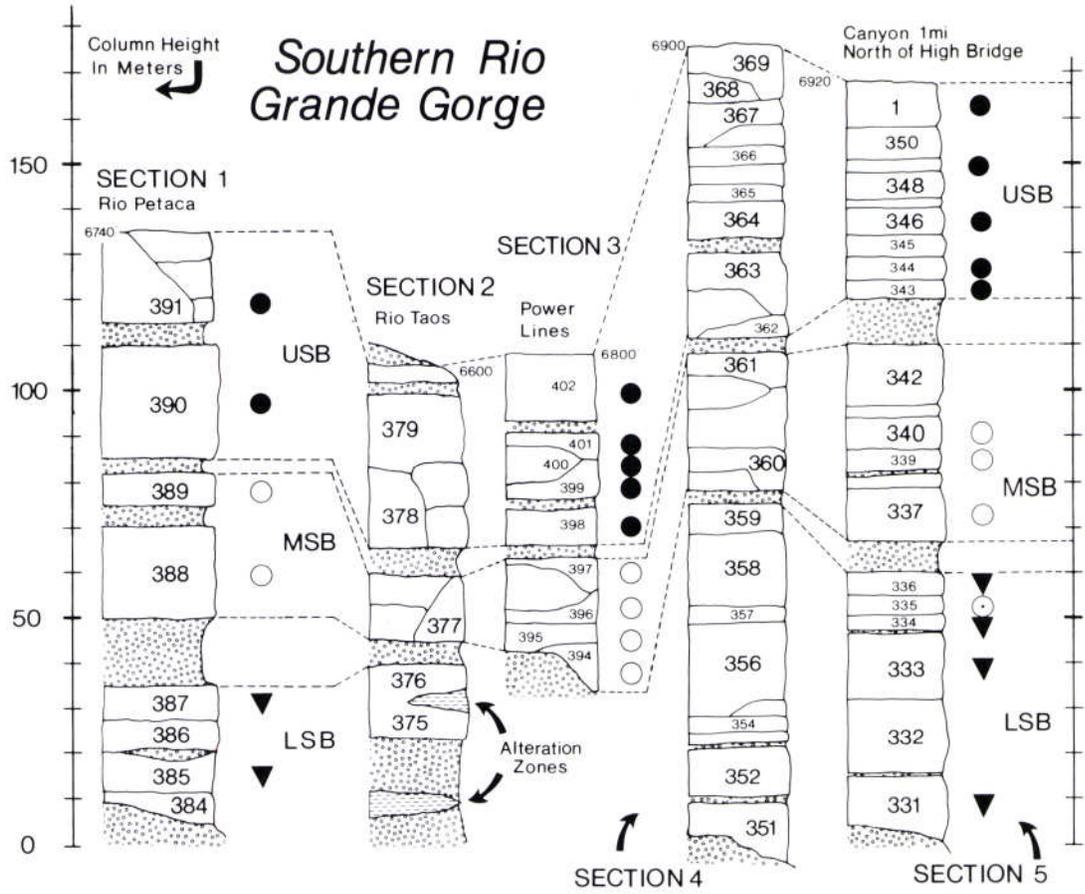


FIGURE 7. Measured stratigraphic columns for mixed volcanic/sedimentary sections from the southern and central segments of the Rio Grande gorge, Taos Plateau. Locations of sections shown in Figure 2. Sampled flows are numbered, symbols to the right of some sections indicate chemical data were used to establish the magma type. Symbols are the same as in Figure 6 except for LSB type B, where filled triangles are used instead of open triangles. Elevations of the rim of the gorge at each section are given in feet adjacent to each column.

more SiO₂-rich lavas, which may be related to SABs, are the so-called xenocrystic basaltic andesites (XBA) which have SiO₂ as high as 57% and abundant xenocrysts of quartz and sodic plagioclase. XBA flows of the TPVF are closely associated in space and in time with SAB lavas and have similar trace-element concentrations. Most of the SAB and XBA flows of the TPVF are late-stage, post-Servilleta eruptives associated with monogenetic strombolian cones. The majority of vents are located along the western margin of the TPVF in the vicinity of San Antonio Mountain—No Agua—La Segita Peaks (see map in Lipman and Mehnert, 1979). In contrast to the thin and extensive pahoehoe lavas of the Servilleta, the SAB and XBA flows are thicker as lavas with substantial basal breccias.

The only recognized SAB lavas within the Rio Grande gorge are a group of closely related flows that occupy a narrow stratigraphic horizon between the lower and middle Servilleta. This group typically overlies the San Cristobal lavas (see below) and has a very similar, but more limited geographic extent. Thin sedimentary interbeds separate the SAB lavas from both the underlying and overlying volcanic units. The SAB "package" is more than one-flow thick at only one locality where we have observed several flow termini (section 7, Fig. 7), and consists of a single thick (10-15 m) flow through most its extent. The most extensive of these flows is exposed at road level at Dunn Bridge.

The SAB unit exposed within the gorge is chemically and petrographically distinct from all other SAB lavas. It has relatively high SiO₂ (52.5 wt%) K₂O and the LREE are lower (e.g., RG-15 in Table 1, #9; or TP-7 in Dungan and others, 1981a). Various flow units within the package have different ratios of 100 Mg/(Mg + Fe) ranging from 56 to 52, indicating variable degrees of olivine fractionation. All the flows contain olivine phenocrysts, but the less differentiated variants contain more abundant, coarse-grained olivine phenocrysts of a more magnesian composition (Fo₆₀, vs. Fo₅₀) than the more evolved flow. Despite evidence for variable olivine fractionation, the flows are closely similar in all other compositional parameters. The groundmass texture

is intergranular. Plagioclase phenocrysts in the SAB lavas exhibit a complex zoning pattern and abundant small crustal xenoliths (gabbros, norites, anorthosites) are present.

Intermediate composition Lavas

Dacite lavas flowed westward from the two double cones—Cerro Negro and Guadalupe Mountain (Fig. 2) and are exposed in the Rio Grande gorge several kilometers north of Dunn Bridge and in the vicinity of Cerro Chiflo, respectively. The upper Red River gorge is incised through a mixed section, comprising Servilleta basalt, olivine andesite, and low-SiO₂ dacite that form a composite shield beneath the south end of Guadalupe Mountain. The intermediate lavas interfinger with Servilleta Basalts to the west, and are absent in the lower Red River gorge. A vent located west of the Red River gorge and east of Cerro Montoso (UCEM—unnamed cerrito east of Cerro Montoso) is the source of a single, large dacite flow which crops out at or near the top of the west wall of the gorge for a length of 12 km.

The Cerro Negro, Red River, and Guadalupe dacites exposed in the gorge are comparable in composition and phenocryst mineralogy to dacite lavas exposed on the Cerro Negro and Guadalupe cones, and to those that comprise other dacitic shields on the Taos Plateau. The dominant phenocrysts are orthopyroxene and augite, although plagioclase phenocrysts are present in some rocks in minor abundance, and plagioclase microphenocrysts are widespread. Some low-SiO₂ dacites also contain relict, resorbed olivines jacketed by euhedral orthopyroxene phenocrysts. The UCEM dacite is unique among the TPVF intermediate lavas in occurrence (single flow vs. shield) and composition— anomalously low concentrations of incompatible trace elements (except Rh) more akin to the Servilleta Basalts. The UCEM flow is a high-SiO₂ dacite which is aphyric and exceptionally glassy.

TPVF dacites typically exhibit pronounced internal foliations, commonly expressed as well-developed platy zones. The flow fronts of the TPVF dacites are typically splayed into radial, finger-like extensions. The Cerro Negro and Guadalupe dacite flows exposed in the gorge have flow directions at approximately right angles to the canyon. As a consequence, the exposures of the dacite flows in the gorge occur as a series of isolated-finger cross sections with prominent concentric platy foliations. These fingers are as much as 50-100 m in diameter in the Rio Grande gorge south of Cerro Chiflo, where Guadalupe Mountain flows are exposed beneath a cap of upper Servilleta (Fig. 5).

The olivine andesites that comprise the middle portion of the stratigraphic section in the Red River gorge (Fig. 9) are also atypical in several respects compared to andesites which comprise other shields on the TPVF. These lavas are characterized by exceptionally large skeletal-olivine phenocrysts (2-5 mm) of Fo₆₀ composition. However, the outstanding feature of these lavas is the relatively wide spectrum of compositions present in a single section. Most olivine-andesite shields are remarkably homogeneous in the compositions of lavas exposed, whereas the Red River andesites range from 54-57% SiO₂. Moreover, there is a regular increase in SiO₂ from the base of the section to the

TABLE 1. Select major- and trace-element analyses of basaltic rocks.

Sample	1	2	3	4	5	6	7	8	9
Section #	5	5	B	5	CC	LS	5	6	DB
Unit	LSB	MSB	USB	USB	USB	USB	LSB	LSB	-
Magma Type	A	A	A	A	B	B	B	SCL	SAB
SiO ₂	48.69	48.73	50.83	50.67	51.81	51.70	51.34	53.20	52.01
TiO ₂	1.25	1.27	1.21	1.21	1.21	1.21	1.11	1.13	1.55
Al ₂ O ₃	16.36	16.44	16.41	16.45	16.46	15.77	16.77	16.49	16.94
FeO _T	1.93	2.79	1.13	3.40	2.13	2.92	2.36	9.05	3.27
FeO	8.94	8.50	9.64	7.53	7.72	7.52	7.43	-	5.87
MnO	0.17	0.19	0.17	0.17	0.16	0.16	0.16	0.14	0.15
MgO	7.98	8.02	7.20	6.88	6.14	6.94	6.80	6.17	5.64
CaO	9.07	9.21	9.16	8.99	9.00	8.76	8.72	8.23	7.74
Na ₂ O	3.13	3.04	3.03	2.96	3.16	3.13	3.22	3.21	4.08
K ₂ O	0.51	0.42	0.36	0.54	0.91	1.04	1.04	1.29	1.71
P ₂ O ₅	0.17	0.18	0.16	0.19	0.26	0.21	0.18	0.23	0.35
H ₂ O	0.40	0.66	-	0.93	-	-	0.90	-	-
Total	98.60	99.44	99.30	99.90	98.96	98.86	100.05	99.89	99.33
FeO*	10.68	11.01	10.66	10.59	9.64	10.15	9.55	8.86	8.81
Mg#	59.7	59.1	57.2	56.3	55.8	57.5	58.5	57.8	55.9
TiO ₂ /K ₂ O	2.45	3.02	3.36	2.24	1.33	1.16	1.07	0.88	0.90
Ta	0.48	0.40	n.a.	0.52	n.a.	n.a.	0.51	0.70	n.a.
La	7.73	7.71	7.63	10.19	16.4	14.0	12.23	18.25	22.8
Ce	19.2	18.5	17.4	24.0	36.5	33.0	28.00	39.1	50.4
Sm	1.11	3.06	3.00	3.21	4.35	3.71	3.45	4.00	5.29
Eu	1.11	1.13	1.03	1.10	1.35	1.18	1.18	1.29	1.58
Tb	0.52	0.54	0.62	0.57	0.72	0.67	0.57	0.66	0.79
Yb	1.79	1.95	1.90	1.90	2.10	1.96	2.03	1.95	2.33
Lu	0.28	0.29	0.31	0.28	0.32	0.31	0.32	0.31	0.40
Hf	2.26	2.16	2.14	2.75	2.99	1.84	2.74	3.40	2.24
Th	0.48	0.46	0.66	0.63	1.12	2.95	1.15	1.60	4.41
Sc	23.4	24.0	24.0	23.0	24.0	22.5	23.2	22.4	23
Cr	327	195	185	164	148	199	172	183	32
Ni	151	146	136	140	104	175	113	95	-
Nb	7.4	6.8	5.4	7.3	10.1	8.8	8.5	13.5	20.3
Zr	89	84	78	91	120	105	112	122	172
Y	18.9	20.6	20.5	19.8	22	20.6	20.1	25.2	-
Sr	371	354	280	323	410	343	428	534	616
Rb	4.3	2.7	3.6	6.5	11.9	17.2	12.6	18.1	26.7
Ba	234	270	195	295	440	-	367	568	625
V	154	139	-	146	-	-	132	137	-
La/Sm	2.49	2.52	2.54	3.17	3.77	3.77	3.54	4.56	4.31
La/Yb	4.32	3.95	4.01	5.36	7.81	7.14	6.02	9.36	9.79
La/Nb	1.05	1.13	1.41	1.40	1.63	1.59	1.44	1.35	1.12
Zr/Rb	20.7	31	21.7	14.0	10.4	6.1	8.9	7.3	6.4
Nb/Rb	1.72	2.5	1.50	1.12	0.88	0.51	0.67	0.75	0.76
Zr/Nb	12.0	12.3	14.4	12.5	11.9	11.9	13.2	9.8	8.5

Section locations on Figure 2; CC = Gorge rim near Cerro Chiflo, LS = LaSegita Peaks, DB = Dunn Bridge

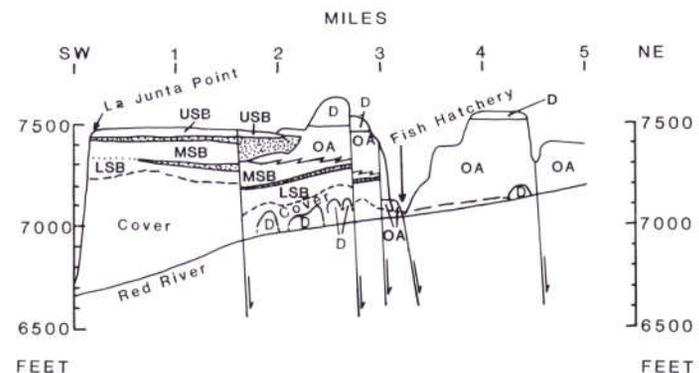


FIGURE 8. Generalized stratigraphy in Red River gorge for 5 mi upstream from its junction with the Rio Grande at La Junta point. Symbols as in Figure 6 except for: OA—olivine andesite; D—dacite. From McMillan (1984).

top which can be modeled as the result of pre-eruptive, two-component mixing between Servilleta Basalt and the low-SiO₂ dacite that caps the Red River section (McMillan and Dungan, 1982).

The Cerro Chiflo quartz latite and an apparently related pyroclastic cone exposed in the gorge to the south are the lone representatives of late Miocene volcanism in the TPVF. Cerro Chiflo is also compositionally and mineralogically distinct from later TPVF intermediate lavas in that it is more evolved (SiO₂ = 67.5, MgO<1.5 wt%), and contains abundant hornblende and biotite phenocrysts and crustal xenoliths.

San Cristobal Lavas

The San Cristobal lavas (SCL) are an extreme chemical variant of the Servilleta Basalts (Table 1, #8); they are characterized by high

SiO₂ (52.5-53.5), high K₂O (1.25 wt%), and high concentrations of incompatible trace elements (REE, Rb, Zr, Nb, Th, Hf, Sr, and Ba). The SCL comprise a package of flows that interfinger with the upper portion of the lower Servilleta between Manby Hot Springs and San Cristobal Creek. Near the middle of this range the entire section bounded by sedimentary interbeds consists of SCL. To the north and south of this area the proportion of typical lower Servilleta flows progressively increases until the SCL no longer are present. This geometry suggests that the SCL were erupted from a discrete vent contemporaneously with the younger package of lower Servilleta.

The SCL tend to form thick (15-25 m), massive flows, although several vertical sections are composed of multiple thin flows (<3 m). All SCL exhibit pahoehoe flow tops. However, the distinctive coarse ophitic—diktytaxitic groundmass texture and vesicular segregations typical of the Servilleta Basalt sensu stricto are absent. The SCL groundmass texture is intergranular. Plagioclase phenocrysts are rare, but the groundmass is very plagioclase-rich. Olivine phenocrysts are comparatively abundant (15%), coarse (2-4 mm), and most are skeletal to some degree. Chromite inclusions in olivine phenocrysts are more abundant than in typical Servilleta flows.

Servilleta Basalts

Introduction

The Servilleta Basalts (SB) are by far the dominant volumetric component of the TPVF. Our stratigraphic studies indicate that most of the SB were erupted in three major pulses that were short in duration compared to the intervening periods represented by sedimentary interbeds (Peterson, 1981). The stratigraphic units that correspond to these three eruptive periods are referred to as lower (LSB), middle (MSB), and upper (USB) Servilleta. The youngest subunits of the USB are two petrographically distinctive variants which are restricted in areal extent to the recognized vent areas on the western side of the TPVF and do not appear at the gorge rim. Geochemical studies indicate that the SB are rather uniform in most major elements (except $^{143}\text{Nd}/^{147}\text{Sm}$) and somewhat more variable in many trace elements (especially Rb, Nb, Sr, Ba, Zr, Th, and LREE). We have concluded that most of the variation observed among Servilleta and SCL samples is the product of mixing between a basaltic end member and andesite magma (Dungan and others, 1983c). Variable degrees of fractionation of the basaltic parent cannot produce the observed compositional spectrum. It also appears implausible that these variations are due to source-region heterogeneity or variable degrees of melting of the same source. In the sections below we briefly summarize some of the general characteristics of Servilleta lavas and then discuss the temporal variations as revealed in the gorge stratigraphy.

Petrography, Mineral Chemistry, and Segregation Features

Olivine phenocrysts (1-3 mm in the long dimension) are present in almost all SB in modest amounts (5-15%). A few flows within the upper Servilleta are aphyric, containing abundant olivine microphenocrysts (<<1 mm). Most of the olivine-phyric SB also contain small, iron-rich groundmass olivines in addition to the phenocrysts. The morphology of the phenocrysts varies from equant to moderately skeletal. We have observed a correspondence between olivine morphology (and size), groundmass texture, and stratigraphic unit. However, there is very little systematic variation in the compositions of olivine-phenocryst cores, as virtually all core compositions in phenocrysts >1 mm fall in the narrow range of Fo₈₅—Fo₈₀ (most are Fo₈₂₋₈₅). Olivine-phenocryst rims and groundmass grains are zoned to compositions as iron-rich as Fo₈₀, and the microphenocrysts in the aphyric SB flows are also iron-richer (Fo₈₅₋₉₀) than the large phenocrysts.

Many olivine phenocrysts contain chromian-spinel inclusions, indicating that it was also an early crystallizing phase. Spinel inclusions within olivine-phenocryst cores are fairly uniform within a single sample and are similar among flows. Spinels partly or completely included in the groundmass are low-Cr, low-Al titanomagnetites. Ilmenite is also present in the groundmass, but is never present as inclusions except as

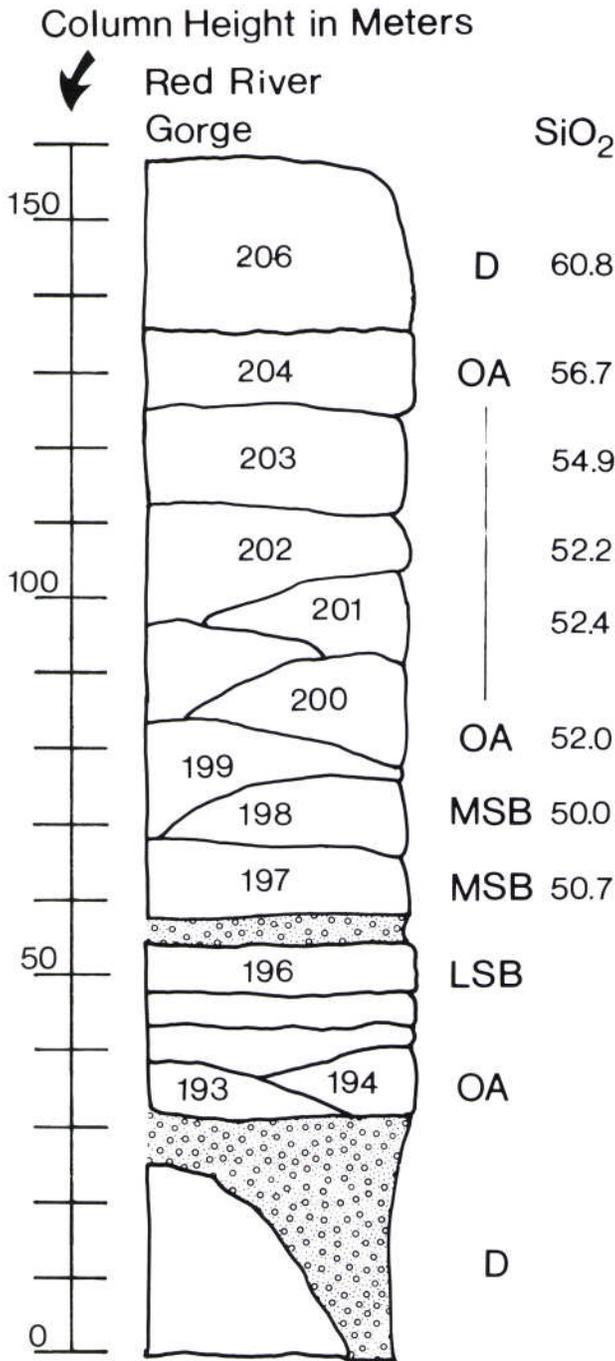


FIGURE 9. Measured stratigraphic column for a mixed volcanic/sedimentary section in the Red River gorge west of the Fish Hatchery fault. Rock types and SiO₂ contents are noted where chemical data are available.

partial enclosures in phenocryst rims. Plagioclase is virtually devoid of chromian-spinel inclusions.

Plagioclase is sparse as a phenocryst phase, but is ubiquitous as microphenocrysts and microlites in glassy-flow margins. The cores of the phenocrysts and microphenocrysts vary from An₇₀ to An₉₀. There is a close correspondence between plagioclase composition and bulk rock composition, particularly in terms of bulk rock K₂O and Or-content in the plagioclase. Low K₂O rocks (<0.80) typically have Or <1.0 and higher maximum An-contents than rocks with higher K₂O. Augite is the other important mineral in the groundmass, but it does not occur as phenocrysts.

The groundmass textures in the interiors of SB flows range from intergranular (uncommon) to coarse ophitic-diktytaxitic. Diktytaxitic groundmass texture is a distinguishing feature of the Servilleta Basalts and is present throughout the USB and MSB. Diktytaxitic textures are also present in some LSB flows, but some units (especially the SCL) have groundmass in which ophitic augite is poorly developed or absent and, therefore, have groundmass textures approaching intergranular. The lavas containing non-diktytaxitic textures have poorly developed vesicular segregations (see below), and coarse olivine phenocrysts that commonly are skeletal and include greater than typical quantities of chromian spinel.

One consequence of the diktytaxitic groundmass textures characteristic of the Servilleta olivine tholeiites is the development of vesicular segregations (cf. Kuno, 1960). These occur as vertical pipes (5-10 cm in diameter) and horizontal sheets (up to 30-40 cm thick in thick flows). The vertical pipes are largely confined to the lower one-third to one-half of the flows and commonly terminate upward in a horizontal sheet. The thickest and most extensive sheet-like segregation usually occurs at the top of the zone where the pipes terminate. The sheets decrease in thickness, length, and spacing upward, toward the vesicular pahoehoe-flow tops. The mineralogy of the segregations is the same as in the surrounding flow interiors, but segregations are mesostasis-rich, highly enriched in incompatible trace elements, and depleted in Ni, Cr, Sr, and Sc compared to the matrix. Together with the highly vesicular nature of these features, compositional contrasts between the matrices and segregations indicate that the segregations represent the effects of post-emplacement, in-situ differentiation which occurred in response to movement of residual liquid through the crystalline framework. The pipes represent diapirs rising through the porous framework in response to a density contrast between the crystals and the gas-rich residual liquid. The sheets fill horizontal fractures produced by contraction during cooling.

The vesicular segregations are best developed in flows with coarse ophitic-diktytaxitic texture and least developed in flows with ophitic-intergranular textures, but all true SB contain them. The geochemical trends defined by the trace-element enrichments and depletions in the segregations are superimposed on the primary, pre-eruption trends, resulting in some scatter in the data. Major elements are slightly affected as well by the development of the segregations.

Chemical Stratigraphy

Samples from volcanic sections exposed in the Rio Grande and Red River gorges and in the canyon of Rio Petaca have been analyzed by XRF and INAA. Chemical data exist for some or all of the flows present in sections 1 (Rio Petaca), 12 (Red River), 3, 5, 7, 8, 9, and 10 (Rio Grande gorge, see Fig. 7). Most of the samples have relatively complete data sets produced by merging major-element analyses by XRF (Washington University, Johnson Space Center, and University of Massachusetts) with trace elements (Zr, Rb, Nb, Y, Sr, Ba, Ni, Cr) by XRF (University of Massachusetts) and by INAA (REE, Th, Sc, Hf, and Cr—Washington University). Some trace elements were not analyzed in some samples, and for section 3 we have only INAA data.

We have subdivided the Servilleta Basalts exposed in the gorge and on the Taos Plateau surface into two chemical types termed A and B. These distinctions are based on a combination of major- and trace-element criteria. A number of criteria can be used to distinguish types A and B in the LSB and MSB. One excellent discriminant is TiO₂/K₂O (Fig. 6). Type-B flows have distinctively higher K₂O contents (plus higher Rb, Ba, Sr, Nb, Zr, LREE, Th, and Hf). Type B is also slightly

higher in SiO₂, but lower in TiO₂, FeO, and CaO. The sampled MSB lavas all have type-A compositions (e.g., Table 1, #2). The LSB stratigraphic unit is dominantly composed of type B and interfingering San Cristobal lavas (SCL) (Table 1, #7, #8). One notable exception is a single type-A lava present within the LSB in section 5 (Table 1, #1). Little or no overlap in composition for most elements occurs between types A and B lavas of the LSB and MSB. The smallest degree of overlap occurs for incompatible trace elements. The SCL are similar to type B, but are even more extreme in the above-mentioned enrichments and depletions in comparison to type A. The range of TiO₂/K₂O in the type-B Servilleta-SCL is 1.0-1.5, whereas the same ratio in the type-A lavas is 1.75-2.75.

The USB overlaps in composition with both the type-A and type-B Servilleta and extends the range of TiO₂/K₂O variation to 3.3 (Table 1, #3, 4, 5, 6). There is no clustering of compositions into groups in the USB; rather, a continuum is defined. USB lavas that fall within the 1.25-2.5 TiO₂/K₂O range are difficult to classify as either type A or B because of variations in elements that do not exhibit overlap between lower and middle type A and type B. Thus, the distinction between types A and B in the USB has less meaning than for the lower two units.

The USB has been analyzed more than the lower and middle units because of more widespread exposures. Thus, additional analyses might show more variability within the lower units. A suggestion of such variability is provided by a few of the relatively small number of samples analyzed from the northern segment of the gorge. Specifically, the apparent type-A sample from the MSB at Garapata Canyon, where the stratigraphic relations are straightforward, is transitional in composition between the well-defined groups, and a similar sample from apparent LSB at section 12 is also anomalous with respect to some elements. Nonetheless, in the southern TPVF, where we have better stratigraphic and chemical control, the correlations are excellent and the variability within stratigraphic units for many elements is small compared to the differences between adjacent units.

Many of the measured sections contain thin sedimentary interbeds within the units defined as LSB, MSB, and USB on the basis of physical and chemical stratigraphic criteria. The LSB in particular contains a laterally extensive sedimentary interbed that has been recognized in all measured sections, in which the LSB is exposed between San Cristobal Creek (section 9) and Rio Petaca (section 1). Because the LSB is absent between sections 4 and 1, and occurs below river level at Dunn Bridge, we cannot be absolutely sure that this thin interbed is the same unit in all sections, but all indications are that it is. Peterson (1981) separated the LSB into two units, but our chemical data demonstrate that the flows on both sides of this sedimentary unit are nearly identical type-B lavas. Thus, the LSB was erupted during at least two episodes separated by a significant time break, and the bulk of the LSB lavas (except SCL) was derived from a homogeneous magma reservoir which was available for successive eruptions.

The single, petrographically distinct flow of type-A composition within the LSB at section 5 (Fig. 7, RG-335) is of uncertain importance stratigraphically. We lack sufficient control north and south of section 5 to ascertain how extensive and volumetrically important this subunit may be. Its importance to our petrologic model of Servilleta evolution is large, because it demonstrates that the type-A magma, and especially the low-K₂O (also low incompatible trace element) variant of type A, is present in all three units. A low-K₂O type-A basalt (RG-25 or TP-1 in Dungan and others, 1981a) has also been sampled from the USB (Table 1, #3).

The MSB is the most homogeneous of all the sampled units. It also is usually the thinnest in measured sections and apparently lacks sedimentary interbeds. On the basis of our data it appears that the MSB is a batch of basalt that erupted in a single event with a minimum of mixing with intermediate magmas.

The USB is compositionally the most variable and includes the distinctive petrographic variants confined to the vent areas. Several thin sedimentary interbeds, which are less extensive laterally than the unit seen within the LSB, are present in the southern gorge. The USB is

laterally, and in some cases vertically, heterogeneous. Although most of the samples from the southern plateau are intermediate in composition between the type-A and type-B lavas of the MSB and LSB, they are classified as type A. The type-B lavas of the USB are located primarily along the western margin of the plateau (extending southward to Black Mesa) and especially in close proximity to the vent areas. The three southern Servilleta vent areas are located east and northeast of Tres Piedras, New Mexico, and directly south of Cerro del Aire (see map in Lipman and Mehnert, 1979). These are covered by very coarse diktytaxitic lavas characterized by distinctive, large plagioclase laths (3-5 mm in length). The La Segita shield (Lipman and Mehnert, 1979) and the surrounding lavas derived from this vent area are distinctive because of the presence of xenocrysts. Some flows contain orthopyroxene, others contain quartz and sodic feldspar. The xenocrystic flows are dominantly type-B lavas. Crossey's (1979) detailed geochemical studies of one of the La Segita lavas exposed in the roadcut just west of northern No Agua peaks, and of the coarse diktytaxitic lavas exposed in roadcuts just east of Tres Piedras (Petaca Creek), demonstrate significant within-flow heterogeneity over and above what can be accounted for by in-situ differentiation that leads to development of the vesicular segregations. We regard these variations as primary heterogeneities resulting from incomplete homogenization during mixing. The variability that characterizes the entire USB is thought to reflect heterogeneities on a much larger scale in the batch of magma that was erupted during three to perhaps five separate events.

RED RIVER GORGE

An extensive NW-trending fault system is exposed in the Red River gorge and to the northwest along the Rio Grande gorge. The Red River volcanic section is comprised of a rare composite sequence in which dacite, andesite, and basalt are interbedded (Fig. 9). A portion of this sequence exhibits evidence for magma mixing between basalt and dacite to produce hybrid olivine andesites ranging from 54% to 57% SiO₂ (McMillan and Dungan, 1982).

The lowest unit exposed at Red River (west of New Mexico State Fish Hatchery on upthrown side of major fault) is a dacite which underlies basalt of the LSB. This is the only exposure of dacite older than the LSB. Elsewhere, stratigraphic relations suggest that andesite and dacite volcanism overlapped primarily with the USB and to a lesser extent with the MSB. However, this may be an apparent relationship because most of the andesite and dacite vents lie west of the gorge. Basalts of the LSB, plus interbedded andesites, overlie a sedimentary unit containing cobbles and pebbles of typical Precambrian lithologies, indicating a throughgoing, west-flowing drainage. The thin sedimentary interbed overlying the LSB lacks coarse material and Precambrian detritus in particular.

Basalts of the MSB, which apparently flowed eastward into the vicinity of the present Red River gorge, interfinger with a dominantly olivine-andesite section that thickens to the east and is increasingly dominated by andesite until at the Fish Hatchery only two basalt flows at the base of the package are present. The andesite flows apparently were erupted in rapid succession from a vent located just east of the Fish Hatchery. A thick dacite flow, erupted from another vent west of the Fish Hatchery that lies along the trend of several faults, caps the section. This dacite apparently predates the Guadalupe volcanoes which in part post-date and in part pre-date the USB. The andesites laterally equivalent to the MSB are the hybrids produced by mixing of basalt and the low-SiO₂ dacite that caps the section. No other dacite analyzed from the Taos Plateau serves as a suitable end member. These andesites are distinctive in containing large (2-5 mm) skeletal-olivine phenocrysts. The USB laps onto this andesite section only along the western margin.

These andesites apparently blocked the drainage of the ancestral Red River at the time they were erupted. Initially, gravels accumulated behind the volcanic pile and to the west of the Sangre de Cristo Mountains. Eventually, this basin was filled with fluvial and lacustrine sediments as indicated by remnant gravel caps on topographic highs adjacent to the Red River gorge. When the basin was topped off, the fan was diverted to the south relative to its previous position. Some of this

diversion may have been guided by movement (west side up) on the Fish Hatchery fault.

South of the Red River gorge, the MSB is capped by a gravel unit that thickens tremendously over a distance of several miles. This relationship is obscured on the west side of the gorge by the UCEM flow which partially occupies this stratigraphic interval, but it is well displayed on the east side between the Red River gorge and San Cristobal Canyon. This sediment package is the diverted fan.

Subsequent to USB time, the sediment-transport route to the south was blocked, either by other coalescing fans prograding westward from the Sangre de Cristo Mountains or by continued movement on the Fish Hatchery fault. The ancestral Red River was localized between the postulated southern topographic high and the dacite flow capping the gorge at section 12. At some point, downcutting into the USB and headward erosion re-established the Red River gorge in its present position.

LA MESITA AND BLACK MESA

La Mesita and Black Mesa are Servilleta Basalt-capped mesas which occur as outliers in close proximity to the southern end of the Taos Plateau. Black Mesa is an elongated, cigar-shaped mesa which extends southwestward from the southern tip of the Taos Plateau. It lies to the north of the Velarde graben and the present Rio Grande. La Mesita is a much smaller mesa which lies to the south of the Rio Grande at the north end of Black Mesa. The Embudo fault has produced displacements of as much as 50 m (down to the north) in basalts capping the south end of La Mesita. Structural relations at the north end of La Mesita are more complex, suggesting a local scissors motion in the Embudo fault. A set of NE-trending, en-echelon normal faults on Black Mesa is dominantly associated with displacements down to the southwest (Kelley, 1978). These structures demonstrate tectonic activity subsequent to upper Servilleta time and define the northeastern end of the Velarde graben, the actively subsiding portion of the Espaiola Basin.

Black Mesa and La Mesita are at the same elevation as the USB lavas that mark the southern tip of the Taos Plateau, and almost certainly were once contiguous with it. Headward erosion by the Rio Grande during the Pleistocene, controlled by continued faulting and subsidence of the Velarde graben, resulted in the isolation of these outliers. The basalt section at the southern end of the Taos Plateau consists of two to three thin olivine-phyric USB flows typical of the lavas that form the western margin of the TPVF south of Tres Piedras (e.g., Comanche Rim). The flows combine to form a section less than 10 m in thickness. The volcanic sections on Black Mesa and La Mesita are up to 40 m thick and are in part petrographically distinct from the olivine-phyric lavas at the southern tip of the Taos Plateau. Gunn (1980) has measured the thickness of volcanic sections on La Mesita and at the northern end of Black Mesa. Slumping on the north side of La Mesita and structural complications associated with the Embudo fault limit the accuracy of the data locally. However, the thicknesses shown on the isopach map in Figure 10 are minimum estimates. Figure 10 illustrates that the

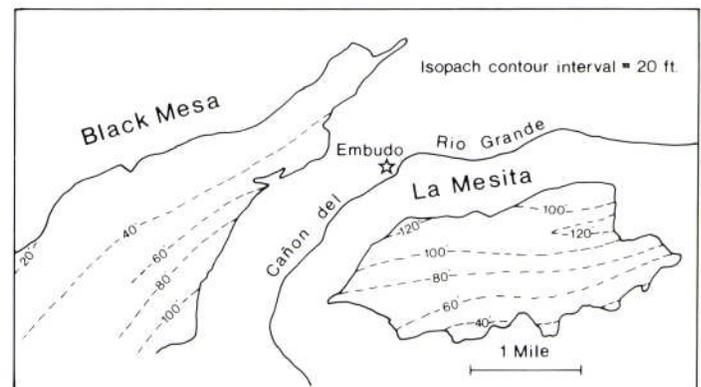


FIGURE 10. Basalt-thickness isopach map of La Mesita and Black Mesa from Gunn (1981). Minimum estimates of basalt thickness shown in feet.

thicknesses of the two volcanic outliers range from 7-15 m on their southern (La Mesita) and northern (Black Mesa) rims to approximately 30-35 m within the axis of the Velarde graben. The isopach contours approximately parallel the trends of normal faults associated with the Embudo—Velarde system. Even thicker volcanic sections were probably present to the north of La Mesita, but have been removed by the Rio Grande.

Basalts present on La Mesita and the southern rim of Black Mesa are distinctive aphyric lavas with fine-grained groundmass textures easily distinguished from the olivine-phyric, coarsely diktytaxitic lavas on the Taos Plateau and on the northern rim of Black Mesa. Olivine microphenocrysts in the aphyric lavas are more iron-rich ($Fe_{0.83}$) than the typical coarse olivine phenocrysts ($Fe_{0.83-0.90}$) observed elsewhere. In the areas of thickest section on La Mesita there are up to six aphyric flows which exhibit a progressive upward increase in thickness from less than 2 m to about 10 m.

The distinctive aphyric SB variety containing relatively Fe-rich olivine microphenocrysts that comprises La Mesita is present within the USB at sections 1, 2, 3, and 4. In addition to being absent at the southern tip of the Taos Plateau, aphyric lavas are not present in section 5. The presence of the aphyric lavas to the northeast of La Mesita, but not directly to the north (except on the southern rim of Black Mesa), suggests that the aphyric flows represent a single large eruption that initially moved to the southeast from vent areas near Tres Piedras and then turned southwestward along the depression between the SE-tilted plateau surface and the upthrown Picuris block. The anomalous thickness of USB at La Mesita and southern Black Mesa was produced by ponding in the actively subsiding depression associated with the Velarde graben. The monogenetic unit present on La Mesita indicates that the graben was not accessible to other SB units, probably because northward prograding fans served as a topographic barrier and southeast tilting of the plateau during SB time forced lavas eastward. Only when the fans were topped by earlier eruptive units were the aphyric lavas able to overcome the barrier and flow southwest. The coarse olivine-phyric lavas of the southern TPVF probably post-dated the aphyric unit and banked up against the lobe of aphyric flows filling the Embudo—Velarde depression.

SUMMARY AND CONCLUSIONS

Lateral variations in the thickness of SB units are controlled by the positions of alluvial fans, a shadowing effect produced by other volcanoes or the topographic high associated with the mid-graben horst of the San Luis Valley, distance from the vent, and local ponding in topographic lows. La Mesita is an example of ponding in an actively subsiding, fault-bounded basin. The thick section near the Rio Grande gorge bridge lies between major alluvial fans, south of the topographic obstruction of the horst, and in relatively close proximity to the vent areas. Thinning of the volcanic units to the north and south is caused by a combination of the factors listed above.

The LSB abruptly terminates against a thick gravel unit in the vicinity of the gorge arch, and the upper and middle units thin due to the topographic obstruction of this ancestral Rio Taos—Picuris alluvial fan. The MSB persists several miles farther south (e.g., section 3), but is largely absent southwest of Rio Petaca. The effect of prograding alluvial fans is well displayed in Rio Petaca which flows south at approximately a right angle to the fan axis. Two km north of the confluence of the Rio Petaca and the Rio Grande the section is thickened, from about 30 m at the rim to 125 m where the canyon narrows, by the addition and individual thickening of lower units. As it does in most areas of the southern plateau, the USB flowed over the fan with approximately constant thickness.

North of the Rio Grande gorge bridge, substantial thinning of the USB, MSB, and LSB resulted from the presence of the ancestral Arroyo Hondo fan and the shadowing effects of the horst, Cerro Montoso, and UCEM. LSB relations are complicated by the SCL shield, which probably vented comparatively near the gorge, and by the syn- to post-volcanic syncline which places all or much of the LSB below river level between Dunn Bridge and section 8. The SB is greatly thinned from section 9 to an area 1 km north of section 10, where all three

units abruptly thicken. This attenuation is due to the ancestral Red River fan and the shadow effect of the horst.

In most areas where high-angle faults cut the volcanic section, the thickness of volcanic units is closely similar on both sides of the faults. Notable exceptions occur where the USB is decreased from five flows to one across the Embudo fault, the MSB is truncated against the fault, and in the Red River gorge where the LSB and MSB are slightly thickened on the downthrown side. Large changes in thickness of interbedded sedimentary units are noted wherever these faults are exposed. A particularly good example occurs at the Dunn Bridge fault, where the sedimentary package between MSB and USB increases 17 m across the fault.

Chemical data combined with our physical stratigraphy indicate that the eruption of the Servilleta Basalts occurred in three major episodes which probably were very shortlived compared to the time intervals between eruptive periods. Although the USB is apparently heterogeneous in comparison to the MSB and LSB, each unit is characterized by a distinctive chemical signature. Flows within the major units are commonly separated by thin sedimentary interbeds (0.5-3 m). In most cases the basalt compositions on either side of these breaks are very similar. This suggests that major eruptive episodes may have lasted up to several hundred years and that magma reservoirs of nearly constant composition persisted over this time.

The chemical variation with time is clearly not consistent with a progressive temporal evolution for the SB. Petrologic arguments based on the positive correlations between SiO_2 , K_2O , and virtually all incompatible trace elements, combined with the presence of the low-K, low- SiO_2 variant of magma type A in all three units, suggest that source-region controls do not dominate chemical variability in the Servilleta. The nearly constant $Mg/(Mg + Fe)$ of the SB convincingly rules out fractional crystallization of a single parental basalt as the source of these variations. Mixing of the low-K basalt end member with andesitic magmas accounts very well for the range of compositions observed. The efficacy of mixing mafic and intermediate magmas in the TPVF is demonstrated at Red River where olivine andesites were produced by mixing of basalt and low- SiO_2 dacite magmas. Most TPVF andesites and dacites are the products of repeated episodes of mixing and fractionation combined with assimilation of a crustal anatectic melt.

Post-volcanic deformation of the TPVF is demonstrated by faulting along the Embudo fault zone and by other north or northwest-trending faults that occur in and around the Rio Grande gorge. The present location of the river is controlled by a combination of overall east-tilting of the plateau, westward prograding alluvial fans, and the local control exerted by the faults, which in turn are surficial manifestations of the deep Taos graben. Other drainages, especially those east of the Rio Grande gorge, have been greatly modified by contemporary warping of the plateau surface resulting from compressive deformation. Local compression within the axial graben of the rift is generated in this case by opposite rotations of rhomb-shaped crustal blocks, and is well displayed in the Embudo zone which is compressive at its northeastern end (NE of Pilar), but is clearly opening south of Embudo where the Velarde graben is undergoing active extension.

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