Geology of Mesita Volcano, Colorado — Eruptive History and Implications for Basin Sedimentation During the Quaternary

By Ren Thompson, Michael Machette, Ralph Shroba, and Cal Ruleman

CHAPTER H

Introduction

The Taos Plateau volcanic field of the central and southern San Luis Valley of Colorado and New Mexico is the largest and longest-lived of the Miocene to Quaternary volcanic fields of the Rio Grande rift. Volcanism of the Taos Plateau volcanic field is predominantly basaltic and is associated with large monogenetic volcanic centers. Rocks ranging in composition from low-silica basalt to high-silica rhyolite are locally present and record a complex, 5 m.y.-long, eruptive history from many eruptive centers; the largest volume of eruptive material was deposited in actively subsiding grabens during the early Pliocene (Lipman and Mehnert, 1979; Appelt, 1998). Mesita Hill, located about 3 km west of the community of Mesita, Colo., on the Costilla Plain (see stop B8, chapter B, this volume), is underlain by volcanic deposits of Mesita volcano—the youngest (1.03 Ma; Appelt, 1998) and only Quaternary volcano of the Taos Plateau volcanic field. Mesita volcano is the last vestige of continental rift volcanism in the San Luis Valley portion of the northern Rio Grande rift. The well-preserved volcanic morphology, exposures created by recent quarrying, and geologic observations and subsurface interpretations (Epis, 1977; Kirkham, 2006) provide rare insight into (1) the eruptive history of Mesita volcano, (2) tectonic control on the eruptive-center location, and (3) stratigraphic constraints on post-1 Ma basin sedimentation of the ancient Culebra and Costilla Creek drainage systems.

Mesita Volcano

Unlike most rift volcanoes of the southern Taos Plateau, Mesita volcano is small (<5 km^2 in areal extent), short lived, and well exposed. Before quarrying, the volcano was a prominent geomorphic feature that protruded above the relatively flat, alluvial surface of the Costilla Plain. The volcano morphology is a classic basaltic shield (referenced to the shape of a warrior's shield) with a summit cone of about 15 m height and 750 m diameter, built on a nearly symmetric lava platform approximately 2.5 km in diameter. The erupted volume of magma is estimated at 0.2 km^3 on the basis of the prequarrying morphology of the volcano; little appears to have been removed by erosion. A geologic map of Mesita Hill is shown in figure H–1 and a topographic map and profile are illustrated in figure H–2.

The volcanic cone, the interior of which is beautifully preserved in the quarry walls, is a natural laboratory of eruptive processes and products. The cone is constructed of interbedded layers of variable-sized volcanic tephra and thin (<1 m) clastigenic (derived primarily from agglutinate) and nonclastigenic lava flows. The predominant fragmental ejecta are cinder or scoria, the glassy lava rock that vesiculated during explosive eruption. Locally, fragmental cinders became welded during rapid burial that retained heat—a result of rapid effusion rates. The cinder of Mesita volcano is typically medium to dark grey in fresh outcrops, but locally it was oxidized to brown and red hues during eruption. Variable dark grey to red transitions in color, observable in the quarry walls, commonly exhibit sharply delineated, crosscutting relations within the volcanic deposits and are likely related to local oxidation resulting from primary and ground-water-induced gas and steam evacuation from fumaroles. Blocks or fragmental solid rock fragments (>64 mm in diameter) ejected from the volcanic vent are intercalated with the cinders and were likely derived from solidified pieces of previously erupted lava flows or are disaggregated ballistic fragments of primary magma ejecta. Volcanic bombs (fig. H–3), ejected from vents in a partially molten state, commonly assume fusiform and spindle shapes during in-flight cooling. Bombs with such shapes are common at Mesita Hill. Less common are breadcrust bombs with fractured surface textures that develop as bomb interiors expand or deform and break or crack the cool, brittle exteriors. Clastigenic lava flows are formed by molten ejecta that agglutinate but remains hot, promoting flowage; the resulting coherent lava flows are typically thin and laterally discontinuous as observed in the quarry walls.

The reconstructed morphology (that is, the morphology before the quarry) of the Mesita cinder cone (as derived from 1935

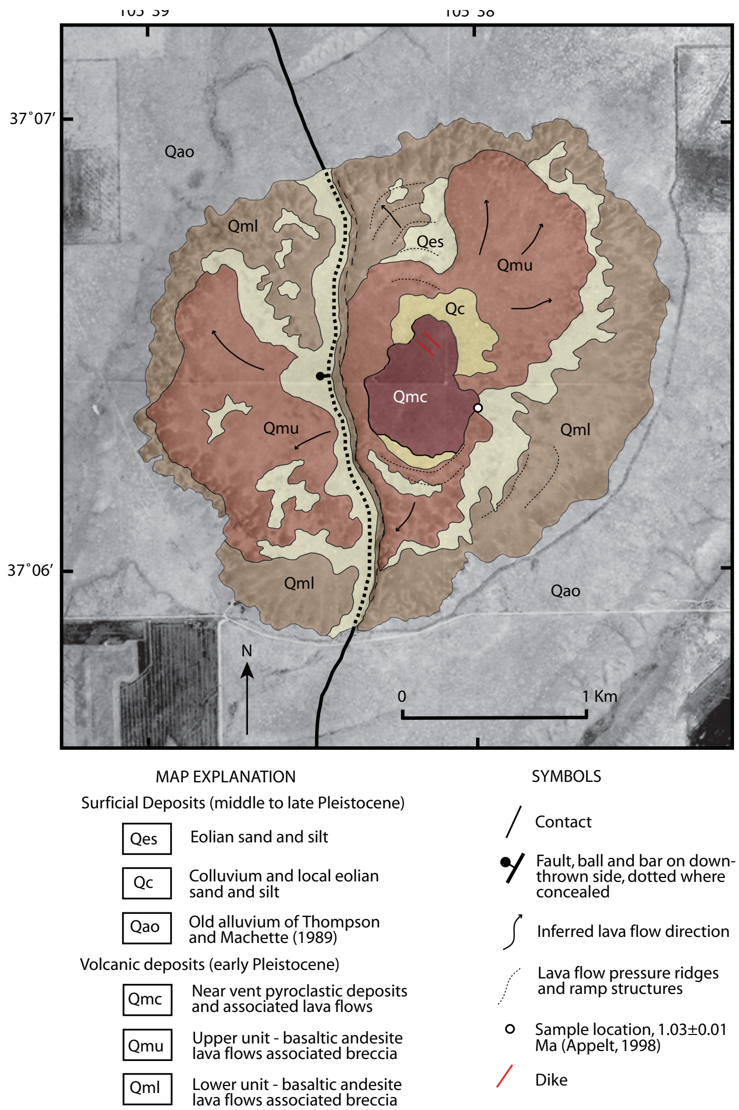


Figure H–1. Geologic map of Mesita volcano. Unpublished geology mapped by Thompson, 2007. Base image from 1936 aerial photography.

aerial photographs and 1967 U.S. Geological Survey topography compiled from 1965 aerial photographs) shows a very small, breeched summit crater immediately southwest of the cone summit and two small, northwest-trending dikes near the north end of the summit cone (figs. H–1 and H–2). All traces of the summit crater and the dikes have subsequently been removed by quarry operations at the Hank and Jake Mine (fig. H–4*A*–*D*; also see stop B8 of chapter B, this volume). The absence of feeder dikes exposed in the quarry walls suggests that the summit cone was the result of a short-lived eruption with little lateral migration of the vent area or feeder system. This suggestion is consistent with the generalized geologic cross section of Epis (1977), which shows a central conduit feeding the Mesita volcano (see stop B8, chapter B, this volume).

The pyroclastic deposits and lava flows observed in quarry walls on the north end of the current pit are subparallel and dip gently north and northeast, away from the inferred primary vent area. Local unconformities, primarily reflecting depositional hiatuses, observed in the quarry walls appear to be the result of migration of depositional centers that may have resulted from local reorientation of the vent geometry or conduit system, or local changes in wind direction during eruption. Such variations in near-vent facies have been well described at the tholeiitic shield volcanoes of Albuquerque Volcanoes National Monument in the Albuquerque Basin of the Rio Grande rift (Smith and others, 1999). No interbedded soil horizons or alluvial deposits are observed in the quarry walls of the Mesita volcano, suggesting that deposition was rapid and nearly continuous throughout the eruptive history of the cone.

The lava platform on which the summit cone rests includes deposits from two eruptive episodes shown on figure H–1 as units Qml (lower) and Qmu (upper). Both map units are predominantly lava flows characterized by blocky to rubbly aa flow-surface textures (fig. H–4*E*, *F*), pressure ridges, and poorly defined flow edges delineating individual flow lobes. The lower unit (Qml) is broadly symmetric about the summit cone (unit Qmc), and the orientations of pressure ridges and flow lobe termini suggest that the lava erupted from a vent area now occupied by the summit cone and overlying lava flows of unit Qmu. Unit Qmu is more areally restricted and volumetrically subordinate to the underlying lava flows (unit Qml), but flow lobes also reflect flow directions radially away from the central summit cone (fig. H–1). In general, lava flows rarely erupt from the summits of cinder cones but are instead typically distributed marginally to the cone, erupting from breeches low on the flanks of cinder or spatter cones. Thus, deposits of map units Qmu and Qmc may be related to the same eruption. Large volumes of nonvesiculated magma erupted as lava flows, such as those of units Qml and Qmu, lack the buoyancy to rise any distance vertically within the cone; such magma capitalizes instead on the inherent instability of the enveloping fragmental deposits and erupts through the cone flanks. The distal reaches of lava flows then reflect local variations in topography; that is, lava always flows downslope. The lack of a preferred flow direction in the lower lava flows of unit Qml suggests that the flows erupted onto a very subdued or nearly flat topographic surface. Subsequent eruptions of lava flows in unit Qmu simply followed the paleotopographic surface created by the undulating and anastomosing lobes of the underlying, slightly older flows of unit Qml. No alluvial or other surficial deposits are observed between the lower and upper map units. It is possible the eruptions of Mesita volcano occurred for a period of perhaps days, weeks, or months.

The lava flows and summit cone deposits of Mesita volcano are petrographically and chemically basaltic andesite and, together with their morphology and inferred eruptive character, are similar to those of other small-volume eruptions of the Taos Plateau volcanic field. The rocks are weakly porphyritic to microporphyritic with pilotaxitic texture. Phenocrysts include

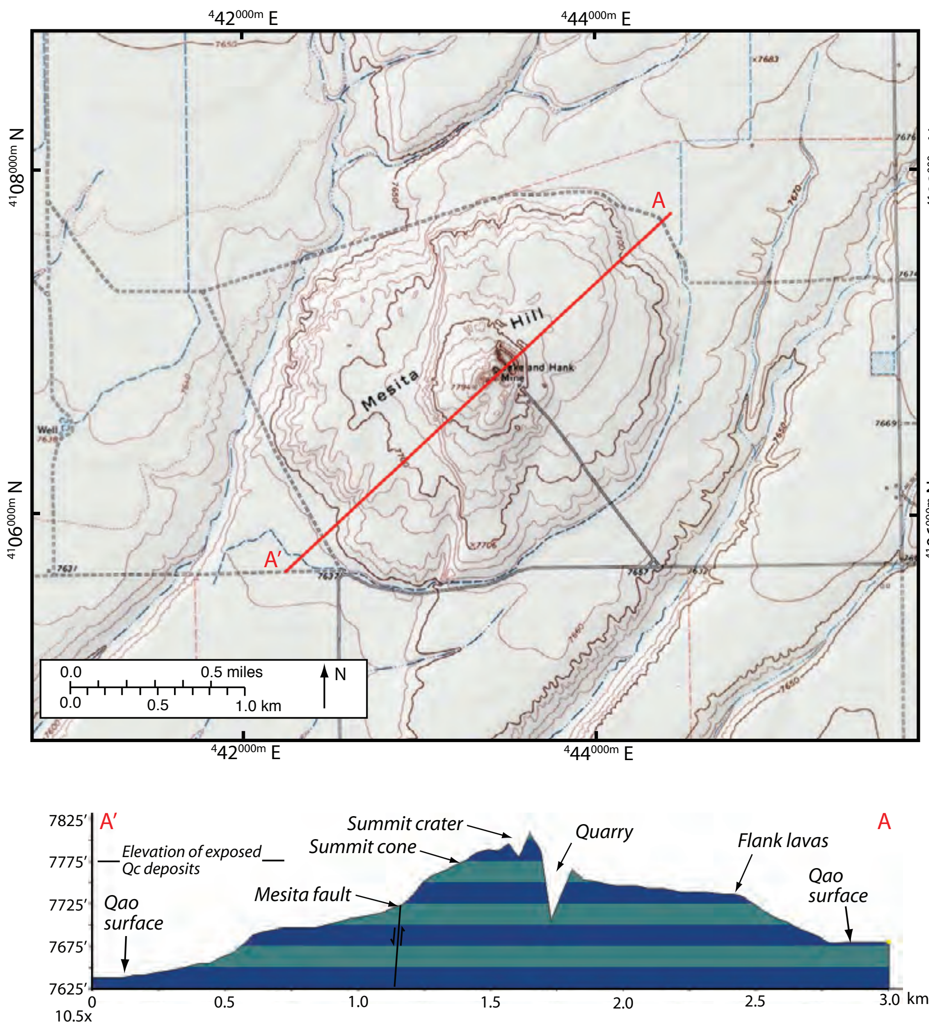


Figure H–2. Topographic map and profile (A′-A) of Mesita volcano, based on Sky Valley Ranch quadrangle 1:24,000-scale U.S. Geological Survey map of Mesita Hill area. Vertical exaggeration, 10.5x.

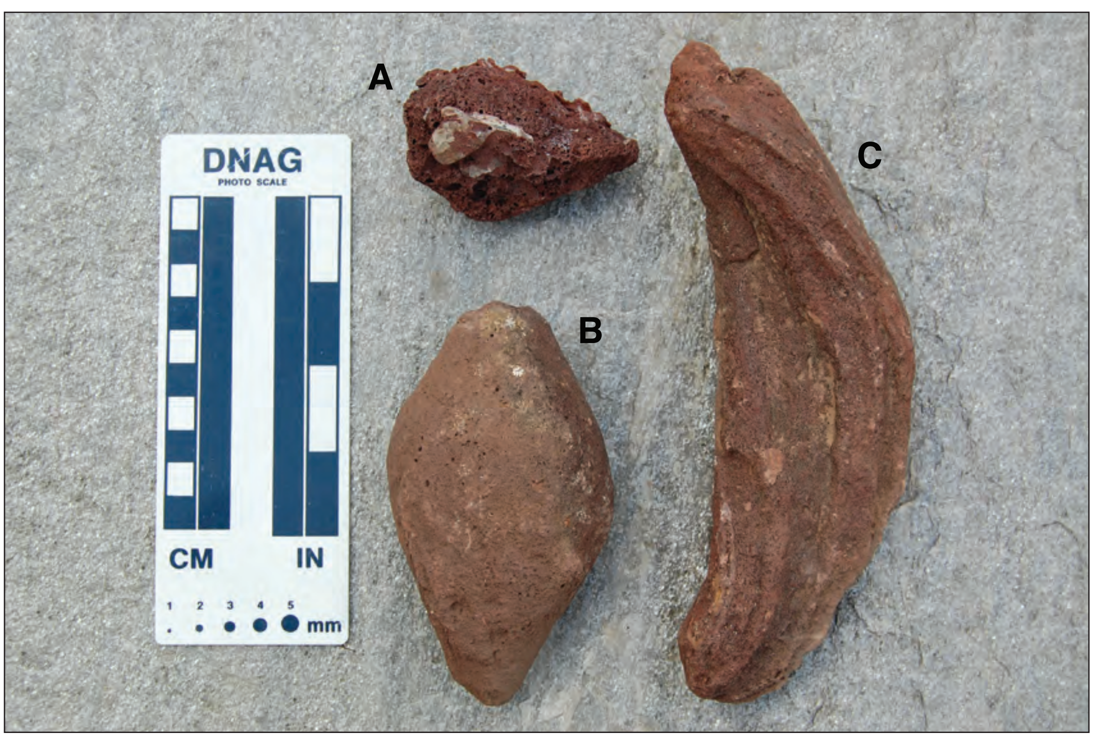


Figure H–3. Volcanic cinder or scoria (A), fusiform bomb (B), and spindle bomb with twisted ends (C) are representative of eruptive material from Mesita volcano. Some rare elongate bombs may be as much as 0.5 m in length. Note large plagioclase xenocryst in A; smaller (2–3 mm) plagioclase and quartz xenocrysts are more typical.

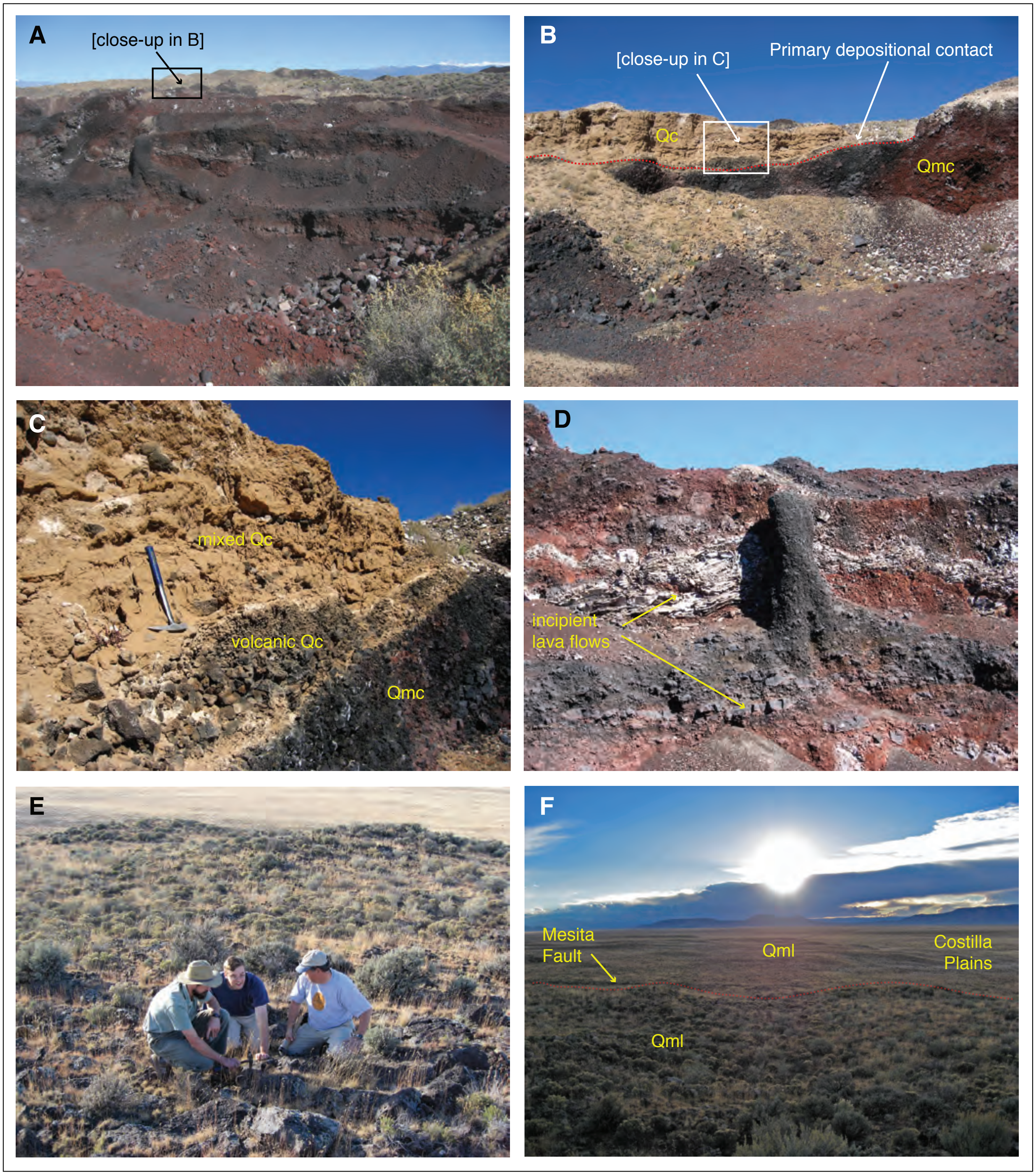


Figure H–4. *A*, View north across quarry pit at Cinder Hill (2007 photograph). *B*, Mixed colluvium and eolian sedimentary deposits (unit Qc) overlying primary volcanic-scoria deposits (unit Qmc). *C*, View of stratigraphic relations between three units: primary volcanic deposits (unit Qmc), volcanic-clast-dominated colluvium (volcanic unit Qc), and matrix-supported mixed aeolian and colluvial deposits (mixed unit Qc). *D*, Gently dipping volcanic scoria, incipient lava flows, and variably oxidized and sintered scoria exposed in east wall of quarry. *E*, Blocky aa flow surface on north flank of Mesita Hill (unit Qml; fig. H–1). Geologists from left to right: Cal Ruleman, David Marchetti, Michael Machette. *F*, View west toward San Luis Hills across nearly horizontal flow surface of unit Qml (Fig. H–2), Mesita fault trace, and Costilla Plain from north end of Mesita Hill.

plagioclase with lesser amounts of olivine in a microcrystalline groundmass of plagioclase, pyroxene, olivine, and iron-titanium oxides. Ubiquitous but rare xenocrysts of plagioclase and lesser quartz can be larger than 1 cm long (fig. H–3) and also are characteristic of other small-volume eruptive centers in the region. As a result, we use the informal term "xenocrystic basaltic andesite" to describe these and similar rocks of the Taos Plateau (Lipman and Mehnert, 1979). Similar deposits from cinder cones have been interpreted as late-stage flank eruptions associated with larger volcanic edifices on the Taos Plateau (Thompson and Lipman, 1994a,b).

Petrographically similar rocks from small cinder cones on the Taos Plateau (to the south) have compositions ranging from basalt to andesite (50.5–57.6 weight (wt) percent SiO_2; 6.4–2.9 wt percent MgO), and the majority are mafic andesite (52–54 wt percent SiO_2 and 4–5 wt percent MgO) (Lipman and Mehnert, 1979; Kinsel, 1985). Xenocryst compositions of the suite range widely; quartz and plagioclase are the predominant assemblage, but these rocks locally contain potassium feldspar, clinopyroxene, and xenolith clots of gabbro and pyroxenite (Kinsel, 1985). All xenoliths and xenocrysts were out of equilibrium with their host magmas as reflected in ubiquitous resorbtion textures, glass inclusions, and mineral overgrowths suggestive of incorporation of cold country rock that partially assimilated within basaltic magma chambers and conduit systems. Kinsel (1985) suggested that many of these inclusions are likely derived from middle and upper Proterozoic crust. In spite of the propensity of these rocks to have excess "old" argon resulting from disaggregation and assimilation of xenocrysts and xenoliths such as those observed at Mesita volcano, Appelt's (1998) $^{40}Ar/^{39}Ar$ age of 1.03±0.01 Ma from the groundmass of a Mesita basaltic andesite yielded a surprisingly reasonable age plateau. Unfortunately, the sample location that Appelt (1998) reported is suspect (see fig. H–1 for an approximate location); nevertheless, it probably reflects the age of the unit Qmu eruptive event and, within error, the age of the entire eruption.

Mesita Fault

Mesita Hill is cut by the down-to-west Mesita fault (figs. H–4*F* and H–5), offsetting lava flows of both units Qml and Qmu (fig. H–1). This fault is one of three down-to-west normal faults that appear to step basinward toward the central basin graben, which is defined by the down-to-east Lasauses fault and the Mesita fault of opposing sense (fig. H–5). Reported offsets of 13 m on the Mesita fault (Thompson and Machette, 1989) reflect the average displacement across both lower and upper lava flow surfaces. The fault offset reflects progressive growth since at least the early Pliocene (4 Ma) based on a 40-m minimum displacement of Pliocene Servilleta basalt flows in the subsurface (see stop B8, chapter B, this volume). The Mesita fault or a similar intrabasin fault projects to the north through the eastern Fairy Hills (Thompson and Machette, 1989), where it cuts upper Oligocene volcanic rocks of the Conejos Formation. Timing of onset of displacement along this structure is not clearly defined owing to diverse stratigraphic facies preserved in volcanic rocks of the Conejos Formation. Regardless of the timing of onset of motion across this fault, the associated

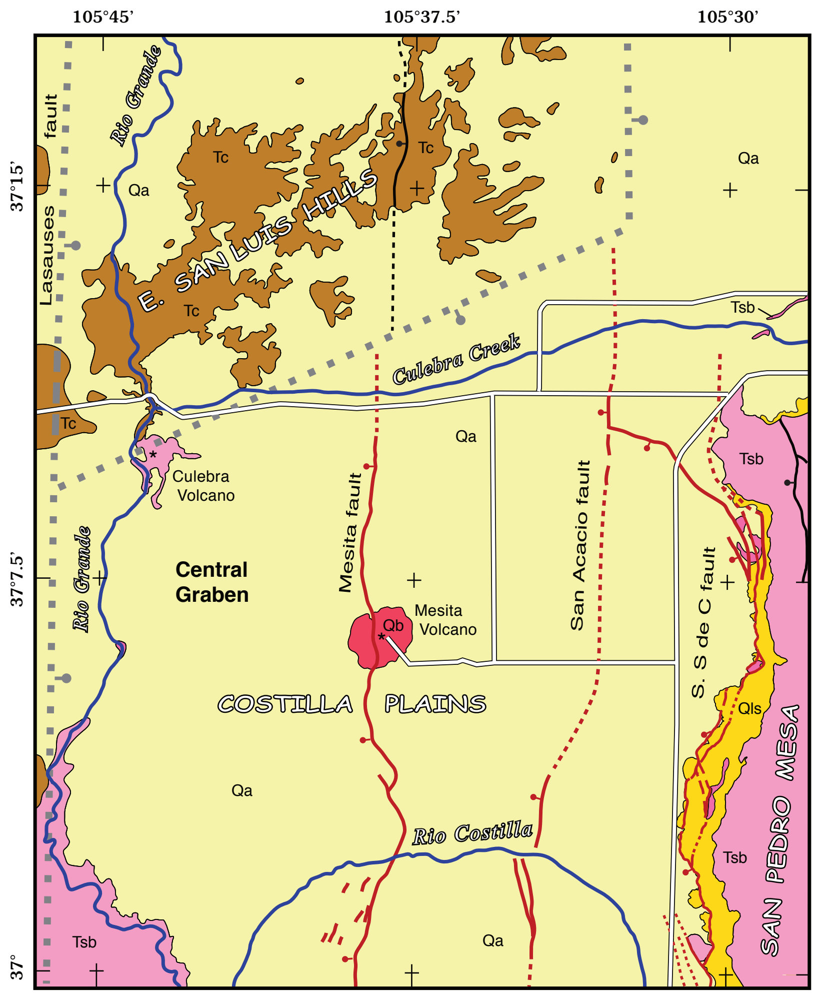


Figure H–5. Generalized geologic map of the Costilla Plain in Colorado showing Quaternary faults (red lines) and older faults (black lines). Major inferred, mostly Neogene, faults that block out the San Luis Hills are shown by thicker gray dashed or dotted lines. Bedrock units: Qb, Mesita basalt (1.0 Ma); Tsb, Pliocene Servilleta Basalt and age-equivalent basaltic rocks of Culebra volcano; Tc, Oligocene volcanic rocks. Quaternary units shown as Qa, with exception of landslide deposits (Qls) along San Pedro Mesa. S. S de C fault, southern Sangre de Cristo fault zone. Geology modified from Thompson and Machette (1989), Machette and others (2007), and Thompson and others (2007).

Quaternary movement and localization of volcanism along the fault is clearly evident.

Recent unpublished mapping by the authors shows a clear proximity of faults to large volcanic edifices (such as Ute Mountain in the northern Taos Plateau volcanic field; see stop C3, chapter C, this volume) although associative relations do not necessarily imply a causal relationship between faulting and eruptive activity. Rather, the proximity of volcanic loci to faults likely represents the ability of magmatic plumbing systems to capitalize on local perturbations of stress fields afforded by faulting and on migration pathways provided by faults. In the Cerros del Rio volcanic field of the Española Basin segment of the Rio Grande rift, the basinward migration of fault activity with constriction of the active zone of extension (Minor and others, 2006) was accompanied by a concomitant basinward migration of basaltic to intermediate-composition volcanic edifices (Thompson, Hudson, and others, 2006; Thompson, Sawyer, and others, 2006). Most eruptions of the Taos Plateau volcanic field occurred during the peak of basaltic volcanism during the Pliocene, and consequently much of the evidence for links to tectonism in the region was buried by younger lava flows and basin-margin sediments. The Quaternary volcanism at Mesita Hill preserves this relation as a result of the short-lived nature of this basaltic eruption during the waning stages of rift volcanism.

Implications for Basin Sedimentation

The volcano of Mesita Hill stands alone on the Costilla Plain, a gently westward-sloping surface of middle Pleistocene age underlain by pebbly to cobbly sand built on older, perhaps early Pleistocene, nearly horizontal silt and sand of the upper part of the Santa Fe Group (Thompson and Machette, 2007). Blanketing the leeward (east) side of lava flows that form the unit Qmu surface and the windward side of the Mesita fault are sedimentary deposits composed predominantly of young (Holocene and late Pleistocene?) eolian silt and sand that contains admixed angular cobble-sized basaltic blocks and scoria from the summit cone and flank lavas of Mesita volcano (unit Qes). Older analogs of middle Pleistocene (unit Qc) are exposed on the summit cone (fig. H–1) and contain well-developed calcic soil horizons within the deposits. These deposits are visible on the north and northeast side of the summit cone from aerial photographs taken during 1936 (fig. H–6) and are locally preserved in the walls of the abandoned quarry (fig. H–4*A,B,C*). The highest preserved outcrop seen on these photos is at an elevation of about 7,775 ft.

Epis (1977) and Kirkham (2006) cite evidence for Quaternary alluvial deposits containing rounded clasts of Precambrian granite in an arkosic sand matrix near the 7,775 ft elevation on the summit cone; much of these deposits have since been removed by mine excavation (see stop B8 discussion, this volume). Our geologic mapping and examination of archival aerial photography suggests that the remaining sedimentary deposits on the north rim of the excavated crater rim (stop B8.2, chapter B, this volume) represent the same stratigraphic unit as those observed and described by Epis and Kirkham. The deposits exposed at the quarry were excavated after 1953 and before 1985 (fig. H–6) and were likely to be accessible to previous researchers during their investigations. A significant and controversial conclusion of both Epis (1977) and Kirkham (2006) is that Mesita Hill was a buried volcanic construct, covered by prograding fan alluvium that is presumably related to the ancestral Culebra and Costilla drainage systems. Burial to at least 7,775 ft (top of mapped deposits) would require basin filling to about 100 ft above the current alluvial surface of the Costilla Plain (a surface underlain by unit Qao of Thompson and Machette, 1989). In this scenario, the current geomorphic form of Mesita Hill would represent an exhumed volcanic feature. This interpretation contradicts three lines of evidence based on recent mapping and examination of primary volcanic features and associated sedimentary deposits discussed below:

(1) Although pebble- to cobble-sized Precambrian clasts are reported by both Epis and Kirkham in their descriptions of alluvial deposits on the summit cone (unit Qmc of fig. H–1), no such clasts are currently observed in preserved deposits at the same stratigraphic level (fig. H–4*A,B,C*). These currently observed deposits are more appropriately interpreted as mostly colluvium with a large component of reworked eolian sediment that composes the sandy matrix.

(2) The interpretation of the volcanic geomorphic feature as "exhumed" requires erosion of the extensive surrounding alluvial deposits yet preservation of the scoriaceous summit cone as an undissected landform. There is no evidence to suggest that the original size of the cone, observable in the 1936 aerial photograph, is distinctly different from its expected original size and shape. Moreover, burial of the undulating, irregular flow surfaces of units Qml and Qmu by fan alluvium (fig. H–4*E,F*) should have left remnants of deposits rich in Precambrian clasts. Only a very limited number of pebble-size clasts are observable on the surfaces of the Qml or Qmu lava flows.

(3) The accumulation of an additional 100 ft of basin-fill alluvial sediment around Mesita Hill would have had dramatic impact on the distal basin morphology and subsequent erosion history. Figure H–7 illustrates the approximate extent of the unit Qao surface mapped by Thompson and Machette (1989) and two topographic profiles projected from the 7,775 ft elevation to points northwest and southwest from Mesita Hill. Based on the projection of the existing surface of unit Qao, the original surface would have extended west of the Rio Grande and intersected the footslope of the San Luis Hills at an approximate elevation of 7,640 ft. Also shown on figure H–7 is the projected elevation of the proposed pre–unit Qao alluvial surface of Epis (1977) and Kirkham (2006); it is based on a slope that parallels the existing unit Qao surface of Thompson and Machette (1989). Finally, we include a second projection to illustrate the effect of variable slope on the proposed pre–unit Qao surface.

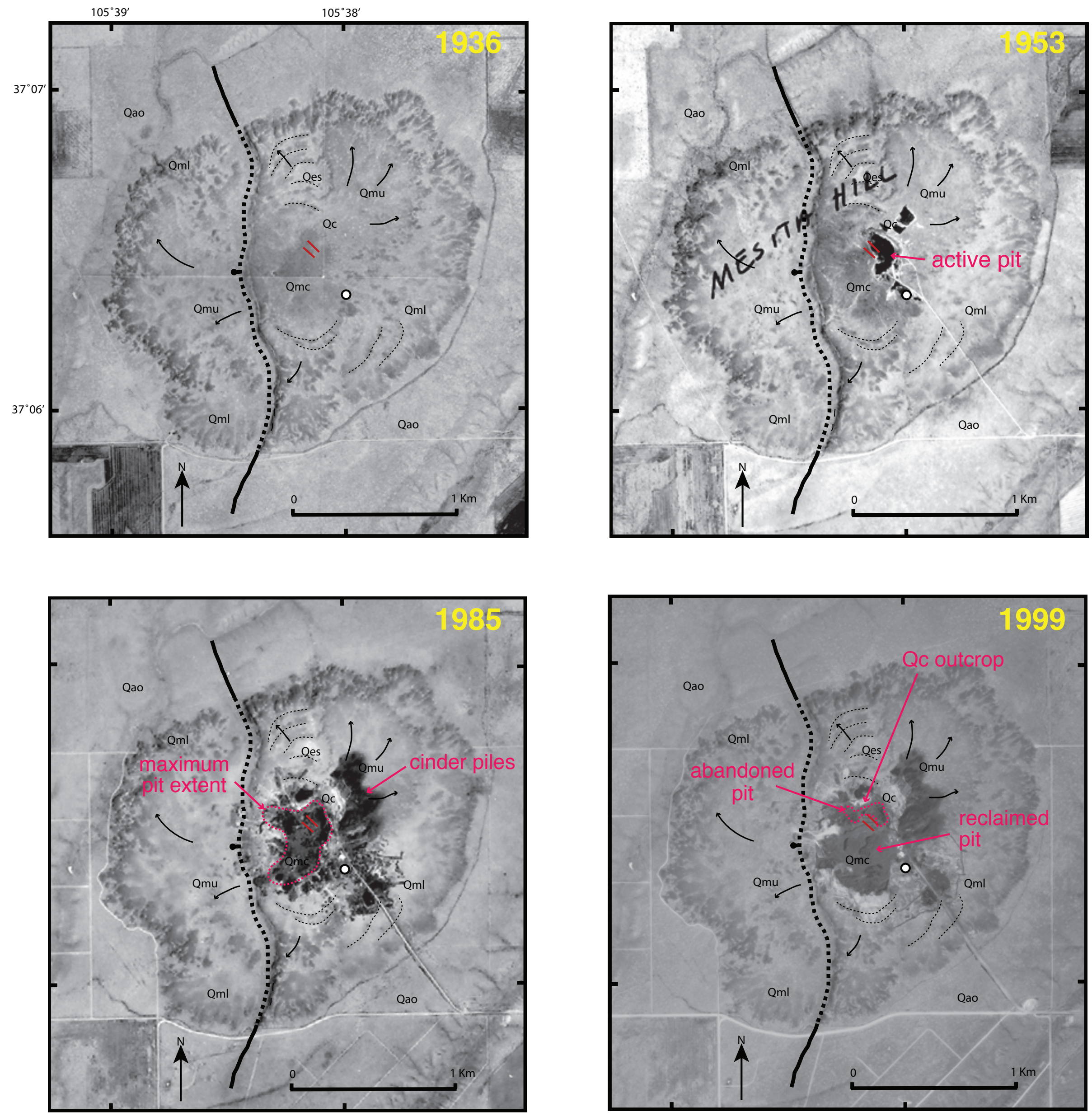
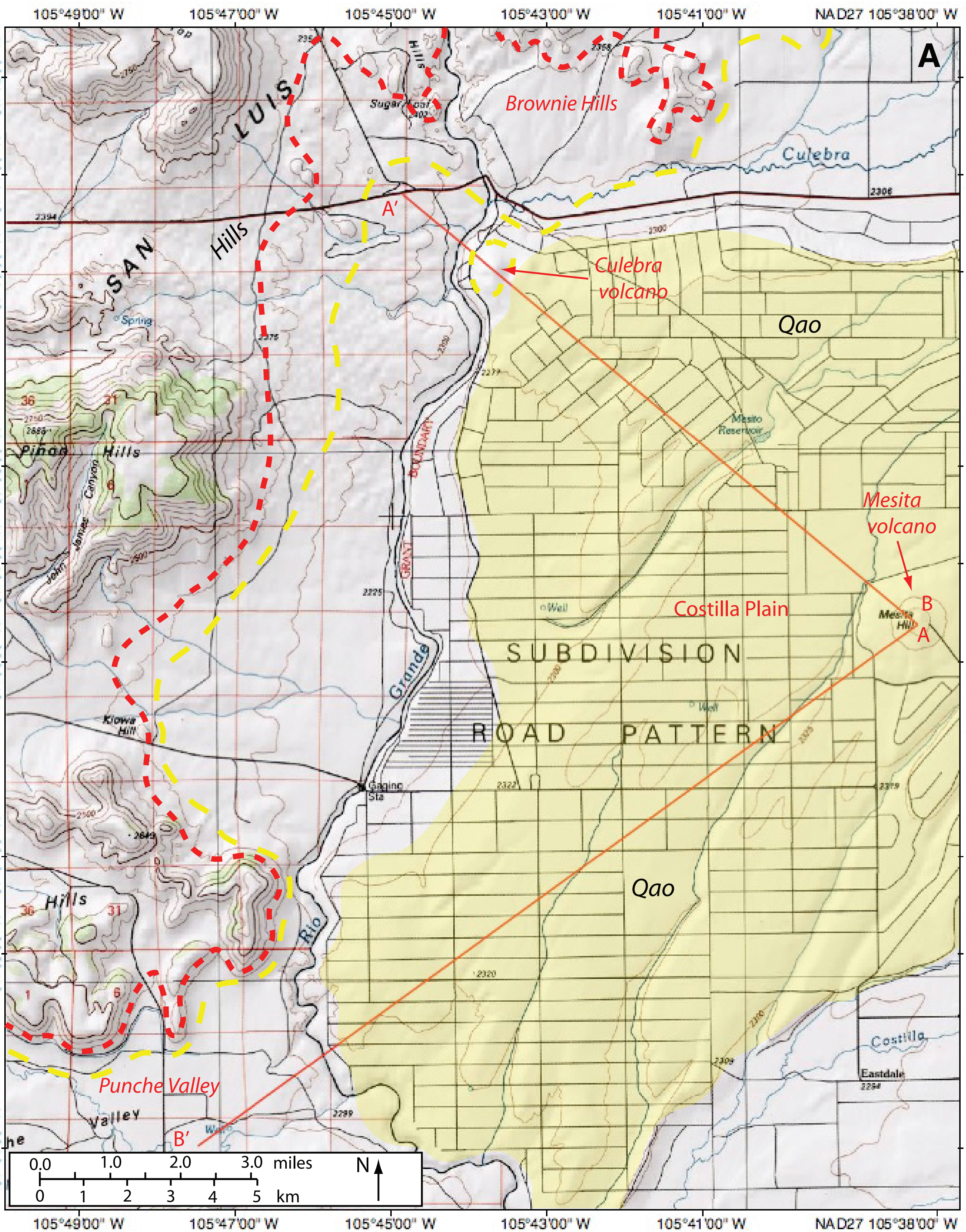


Figure H–6. Aerial photographs from 1936, 1953, 1985, and 1999 (U.S. Geological Survey digital orthophotograph) showing evolution of the cinder quarry at the Hank and Jake Mine on Mesita Hill, Colorado. Geologic map symbols defined on figure H–1.

Southwest of the Costilla Plain, the basin-fill deposits would have spilled into present-day Punche Valley, covered the northern exposures of Servilleta Basalt to an elevation of approximately 7,640 ft, and lapped onto the lower slopes of the southern San Luis Hills (Thompson and Machette, 1989). Remnants of deposits related to the middle Pleistocene unit Qao surface of Thompson and Machette (1989) contain Precambrian clasts (derived from Sangre de Cristo Mountains). West of the Rio Grande they are not observed above an elevation of about 7,640 ft in Punche Valley, but they are preserved at lower elevations. Bedding attitudes of distal alluvial-fan deposits east of the Rio Grande are nearly horizontal suggesting that Punche Valley marks the distal reaches of unit Qao deposition in a depocenter that had aggraded to a nearly horizontal plane by the middle Pleistocene (about 500 ka; see stop B8, chapter B, this volume).

Northwest of Mesita Hill, the proposed basin-fill deposits of Epis (1977) and Kirkham (2006) would have projected above the summit of Culebra volcano, a Pliocene basaltic andesite shield that is bordered on the west by the Rio Grande. The upper flanks of Culebra volcano preserve no evidence for prior burial in the form of Precambrian-rich lag deposits, west


A
105°49'00" W
105°47'00" W
105°45'00" W
105°43'00" W
105°41'00" W
NAD27 105°38'00" W
37°12'00" N
37°11'00" N
37°10'00" N
37°08'00" N
37°07'00" N
37°06'00" N
37°04'00" N
37°03'00" N
37°01'00" N
Brownie Hills
Sugar Loaf
Culebra
SAN LUIS Hills
A'
Culebra volcano
Qao
Spring
Piñon Hills
John James Canyon
BOUNDARY
GRANT
Mesito Reservoir
Mesita volcano
B
A
Mesita Hill
Costilla Plain
Well
SUBDIVISION
ROAD PATTERN
Grande
Rio
Kiowa Hill
Gaging Sta
Hills
Qao
Costilla
Eastdale
Punche Valley
Valley
B'
0.0 1.0 2.0 3.0 miles
0 1 2 3 4 5 km
N

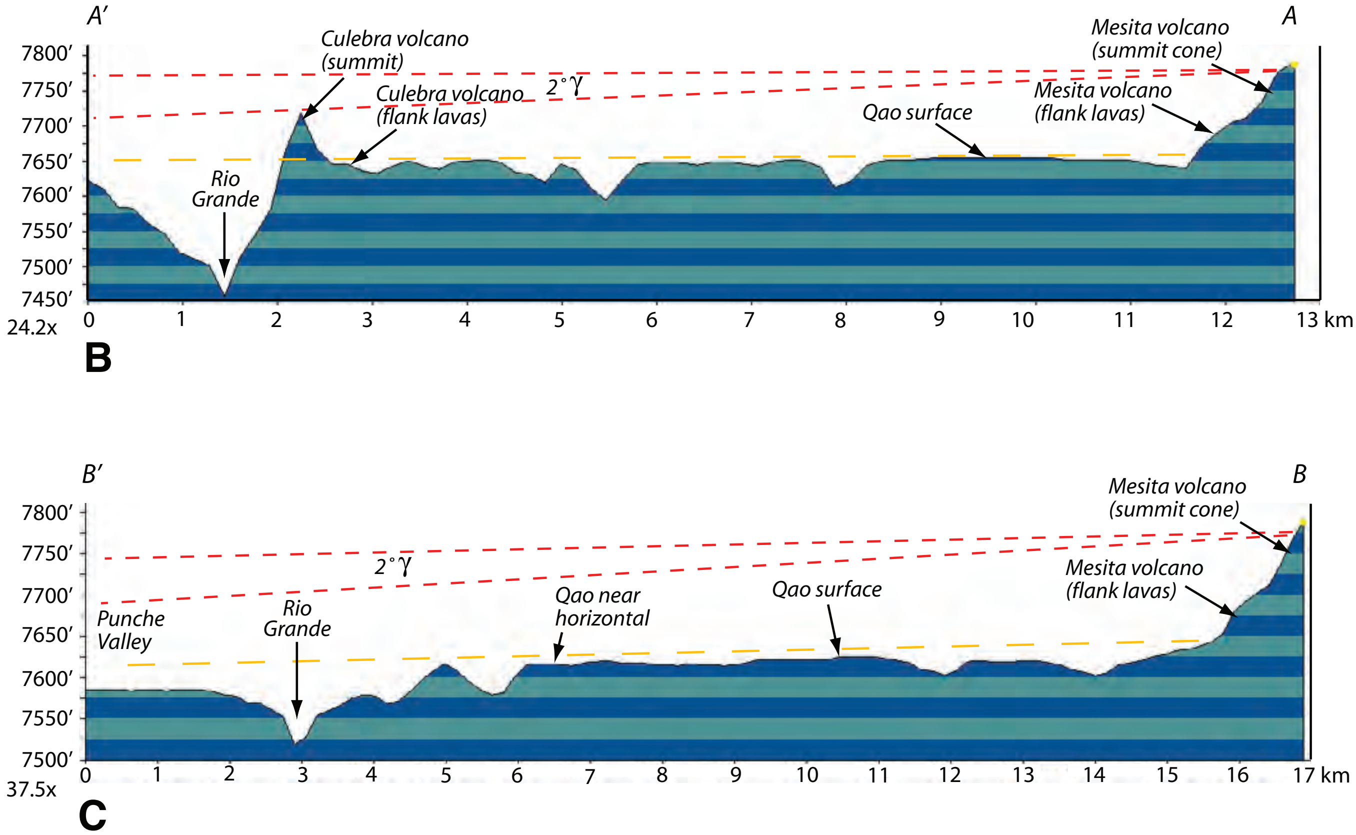


Figure H–7. *A*, Topographic map of the Costilla Plain showing aerial extent of mapped middle Pleistocene deposits (unit Qao in yellow) and profile lines for topographic profiles shown in B and C. Long dash (yellow) line represents projected original distal extent of unit Qao surface based on intersection of top of existing westward-sloping surface with existing topography. Short dash (red) line represents projection of middle Pleistocene volcano at an elevation of 7,775 ft. *B*, Topographic profile for line segment A'-A (vertical exaggeration, 24.2x). Long dash (yellow) line approximates slope of unit Qao surface of Epis (1977) and Kirkham (2006) based on an original slope identical to that observed for preserved unit Qao surface (<1°). Lower short dash (red) line illustrates the effect of variable slope on the projected unit Qao surface of Epis (1977) and Kirkham (2006). *C*, Topographic profile for line segment B'-B (vertical exaggeration, 37.5x). Symbols as in fig H–7B.

of the nearly horizontal lavas at the base of the volcano. These basal lava flows do preserve many subrounded Precambrian clasts believed to be derived from channel deposits of the ancestral Culebra drainage, which flowed across the eastern flanks of the volcano. This observation is consistent with map relations for the distal margins of the unit Qao surface of Thompson and Machette (1989) and the surface projections shown in figure H–7.

A significantly higher level of aggradation associated with the alluvial-fan system built by Rio Culebra would have deposited sediment against the southern margin of Oligocene volcanic rocks in the southeastern Brownie Hills. The southern Brownie Hills has considerable topographic irregularity, which should have preserved remnants of a topographically higher early(?) Pleistocene basin-filling event. In spite of our mapping throughout the area (Thompson and Machette, 1989; 2007), no such remnants have been observed. Additionally, progradation of an alluvial surface into an area now occupied by the canyon of the Rio Grande would imply relatively rapid, post-1.0 Ma deposition of coarse sediment into a basin during an interval of about 500 k.y. during the Pleistocene marked by slow, shallow sedimentation in Lake Alamosa, immediately to the north of the Fairy Hills (see chapter G, this volume). In fact, the northern distal margins of an areally more extensive Pleistocene surface may have extended into the area now underlain by sediments of the 440 ka Lake Alamosa. This interpretation would require that alluvium in the Costilla Plain deposited during the middle Pleistocene and the later part of the early Pleistocene (about 1.0–0.5 Ma) be stripped away prior to deposition of the overlying lake deposits. It's difficult to reconcile the tectonic or climatic drivers for these diverse sedimentation styles and erosion rates in proximity within the same depositional basin.

Conclusion

The Quaternary volcano at Mesita Hill reflects the last gasp of rift volcanism on the Taos Plateau volcanic field. Built on a subhorizontal dipslope of fine-grained sediment of the Santa Fe Group, the basaltic andesite lava flows of the lower flanks reflect the short-lived eruptive history of lava effusion from a central vent area now occupied by the excavated remnants of a low-relief cinder cone forming the volcano's summit. The 1.0 Ma volcano is cut by an active down-to-west graben-bounding fault of the present axial basin that may have served to localize the eruption. The base of the flank lavas were subsequently surrounded by prograding middle Pleistocene alluvial-fan deposits of the ancestral Culebra and Costilla drainage systems that were, in turn, dissected by the same creeks to the north and south of Mesita Hill, respectively, as they adjusted to a lowering base level dictated by the Rio Grande.

Acknowledgments

We appreciate the constructive and helpful comments of Margaret Berry (USGS) and Scott Minor (USGS), who reviewed a preliminary version of this manuscript. However, any errors that may remain are the responsibility of the authors.

References Cited

Appelt, R.M., 1998, $^{40}Ar/^{39}Ar$ geochronology and volcanic evolution of the Taos Plateau volcanic field, northern New Mexico and southern Colorado: Socorro, New Mexico Institute of Mining and Technology, M.S. thesis, 58 p.

Epis, R.C., 1977, Surface and subsurface geology of the Mesita volcano area, Costilla County, Colorado, *in* Zorich-Erker Engineering, Inc., Ground water availability of the San Marco property near Mesita in Costilla County, Colorado: Report submitted to San Marco Pipeline Company, Denver, Colorado, dated September, 30, 1980, Vol. III, Appendix A, 20 p., plus map and cross section.

Kinsel, Eric, 1985, Petrology of the silicic alkalic basalt and xenocrystic basaltic andesite of the Taos Plateau volcanic field, New Mexico: Dallas, Texas, Southern Methodist University, M.S. thesis, 50 p.

Kirkham, R.M., 2006, Surprises in the Culebra graben, a major sub-basin within the San Luis basin of the Rio Grande rift [abs.]: Geological Society of America Abstracts with Program, v. 38, no. 6, p. 14.

Lipman, P.W., and Mehnert, H.H., 1979, The Taos Plateau volcanic field, northern Rio Grande rift, New Mexico, *in* Reicker, R.C., ed., Rio Grande rift—Tectonics and magmatism: Washington D.C., American Geophysical Union, p. 289–311.

Minor, S.A., Hudson, M.R., Grauch, V.J.S., and Sawyer, D.A., 2006, Structure of the Santo Domingo Basin and La Bajada constriction area, New Mexico *in* Minor, S.A., ed., The Cerrillos uplift, the La Bajada constriction, and hydrogeologic framework of the Santo Domingo Basin, Rio Grande rift, New Mexico: U.S. Geological Survey Professional Paper 1720, p. 91–115.

Smith, G.A., Florence, P.S., Castrounis, A.D., Luongo, M., Moore, J.D., Throne, J., and Zelley, K., 1999, Basaltic near-vent facies of Volcan cone, Albuquerque volcanoes, New Mexico: New Mexico Geological Society 50th Field Conference, Guidebook, p. 211–219.

Thompson, R.A., Hudson, M.R., McIntosh, W.C., Miggins, D.P., Grauch, V.J.S., Minor, S.A., Sawyer, D., and Dethier, D.P., 2006, Temporal, stratigraphic and structural controls on the evolution of the Cerros del Rio volcanic field, northern Rio Grande rift, New Mexico [abs.]: Geological Society of America Abstracts with Programs, v. 38, no. 6, p. 37.

Thompson, R.A., and Lipman, P.W., 1994a, Geologic map of the Los Pinos quadrangle, Rio Arriba and Taos Counties, New Mexico and Conejos County, Colorado: U.S. Geological Survey Map GQ–1749, scale 1:24,000.

Thompson, R.A., and Lipman, P.W., 1994b, Geologic map of the San Antonio Mountain quadrangle, Rio Arriba County, New Mexico: U.S. Geological Survey Map GQ–1750, scale 1:24,000.

Thompson, R.A., and Machette, M.N., 1989, Geologic map of the San Luis Hills, Conejos and Costilla Counties, Colorado: USGS Miscellaneous Investigations Series Map I–1906, scale 1:50,000.

Thompson, R.A., and Machette, M.N., 2007, Preliminary geologic map of the Sanchez Reservoir and Garcia quadrangles, Costilla Counties, Colorado: U.S. Geological Survey Open-File Map 2007–1074, scale 1:24,000.

Thompson, R.A., Sawyer, D.A., Hudson, M.R., Grauch, V.J.S., and McIntosh, W.C., 2006, Cenozoic volcanism of the La Bajada constriction area, New Mexico *in* Minor, S.A., ed., The Cerrillos uplift, the La Bajada constriction, and hydrogeologic framework of the Santo Domingo Basin, Rio Grande rift, New Mexico: U.S. Geological Survey Professional Paper 1720–C, p. 43–60.

Zorich-Erker Engineering Inc., 1980, Ground water availability on the San Marco property near Mesita in Costilla County, Colorado: Denver, Colorado, Report prepared for San Marco Pipeline Company, 3 vols. with plates.