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Introduction

Grassy Lookout 7½-min quadrangle in Socorro County, New Mexico, is in the north-central San Mateo Mountains, a north-trending uplift along the west edge of the Rio Grande rift near Socorro (Fig. 1). The San Mateo Mountains expose middle to late Oligocene silicic ash-flow tuffs of the northeast Mogollon–Datil volcanic field (Elston et al., 1973; Elston, 1989). The Mt. Withington caldera (Deal, 1973; Deal and Rhodes, 1976) occupies most of this area and is source of the South Canyon Tuff, the youngest of five major regional ash-flow tuffs in the Socorro area. Eruption of these tuffs between 32.0 Ma and 27.4 Ma (McIntosh, 1989a) was concurrent with initial stages of extension in the Rio Grande rift (Chapin, 1979).

The purpose of this report is to show how structural patterns and the timing of extension in the Mt. Withington caldera are controlled by the interaction of local, intense magmatism in a regional extensional stress regime. Depiction of these structural patterns requires detailed understanding of previously undescribed zonal variations in the intracaldera South Canyon Tuff.

Stratigraphy

The northern part of the Grassy Lookout quadrangle is underlain by as much as 1.8 km of intracaldera South Canyon Tuff. In the thickest part of the caldera fill, three distinct zones (herein called the lower, middle, and upper) are recognized primarily on the basis of phenocryst abundances and also because they are usually separated by lithic-rich intervals (Fig. 2). These zones are defined only within the thickest part of the caldera fill. They do not necessarily correspond to zonal variations of the South Canyon Tuff either near the southeastern caldera margin or in the outflow sheet where the tuff is significantly thinner.

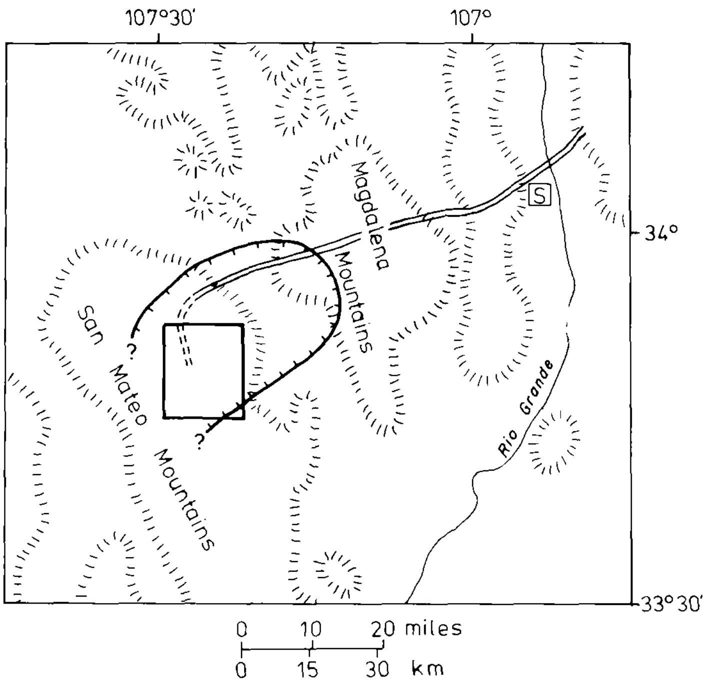


FIGURE 1—Location of the Grassy Lookout quadrangle (outlined by thick line) in the northern San Mateo Mountains. The Mt. Withington caldera margin is indicated by the thick barbed line. Tilt-domain boundaries are represented by double lines: the solid double line is the Socorro accommodation zone; the dashed double line is an antiformal boundary discussed in the text. S, Socorro.

Lower zone of the South Canyon Tuff

The lower zone of the South Canyon Tuff is about 600 m thick in the Mt. Withington–A-L Peak area. The basal 10 to 30 m is dark-brown to black vitrophyre that rests on either Lemitar Tuff (Osburn and Chapin, 1983) or a flow-banded rhyolitic lava and/ or dome complex. The main part of the lower zone is light-gray quartz and sanidine-bearing, crystal-poor (<10%), flow-banded ash-flow tuff. The lower zone correlates directly with Deal's (1973) A-L Peak Tuff. The A-L Peak Tuff was correlated originally with a texturally similar outflow sheet that was later shown to be an older unit now called La Jencia Tuff (Osburn and Chapin, 1983; McIntosh et al., 1986).

Middle zone of the South Canyon Tuff

The middle zone of the South Canyon Tuff is separated from the lower zone by a lithic-rich interval. It is light gray, commonly

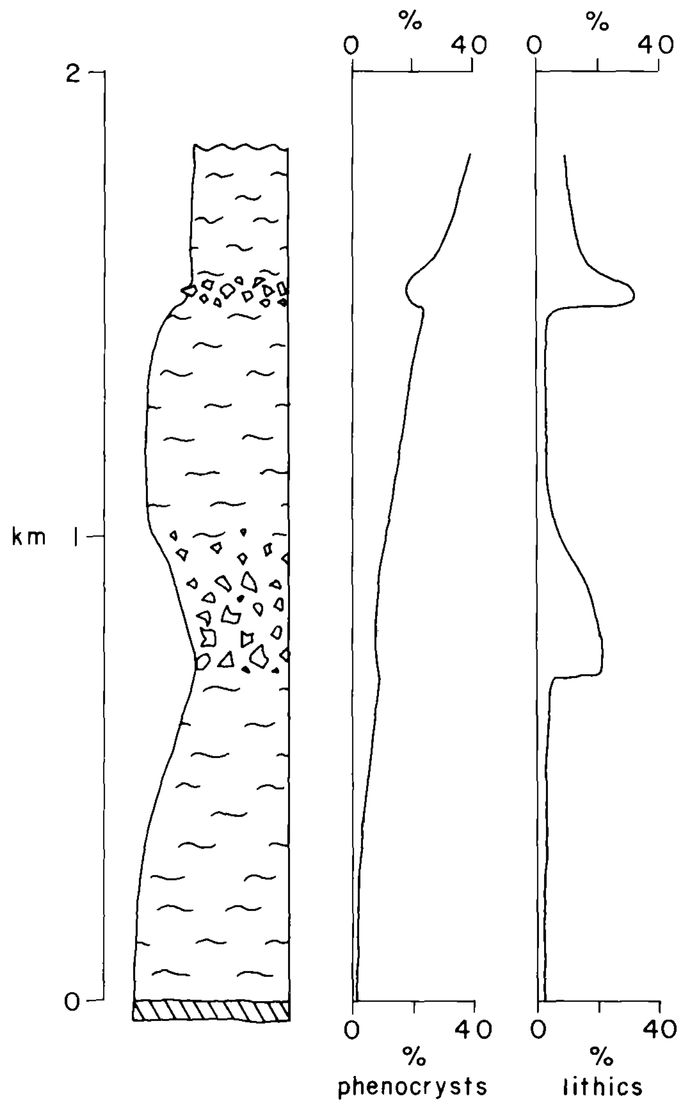


FIGURE 2—Generalized stratigraphic section of the thickest part of intracaldera South Canyon Tuff. The unit shown with closely spaced diagonal lines represents a basal vitrophyre. Two lithic-rich intervals divide the section into lower, middle, and upper zones.

flow banded, and vertically zoned upward from 10–15% to 20–25% phenocrysts. Phenocryst phases are dominated by subequal amounts of quartz and sanidine. Other phases include minor amounts of plagioclase and biotite and traces of opaque minerals and sphene. The middle zone is about 500 m thick in the northern part of the quadrangle and correlates with most of Deal's (1973) Potato Canyon Tuff within the Mt. Withington caldera. Strata mapped by Deal (1973) as Potato Canyon Tuff outside the caldera have been shown since to be several outflow sheets that include the South Canyon Tuff and older tuffs (Ferguson, 1986).

Upper zone of the South Canyon Tuff

The upper zone of the South Canyon Tuff gradationally overlies the middle zone in most areas, and to the northwest it is separated by a lithic-rich interval similar to the one at the base of the middle zone. The upper zone is characterized by high phenocryst abundances (25–35%), and dark reddish-brown color. In the northern part of the caldera it is up to 300 m thick; in the southern part of the caldera it is not present or is significantly thinner (less than 50 m). Phenocrysts in the upper zone are dominated by subequal proportions of quartz and sanidine, between 1% and 5% plagioclase, minor biotite, and traces of sphene and opaque minerals. The zone is unique in that it contains two types of pumice fragments: small (<5 cm) white fragments dominate; larger (>10 cm) dark gray-purple fragments that conspicuously lack quartz phenocrysts are rarer. In the northeast corner of the quadrangle, the upper zone grades upward into a medium-gray, moderately crystal rich (15–20%), feldspar-bearing tuff with little or no quartz phenocrysts.

Lithic-rich intervals in the South Canyon Tuff

In the thickest part of the caldera fill, two laterally continuous lithic-rich intervals between 50 and 300 m thick are recognized. They are characterized by reddish-brown color, general lack of eutaxitic foliation, and relatively low phenocryst abundances. The low phenocryst content probably reflects dilution by the lithic material and decreased compaction relative to adjacent zones. Lithics are less than 0.5 m and consist of volcanic clasts (silicic and andesitic lavas dominate) that compose 5% to 50% of the tuff.

Both lithic-rich intervals are interpreted as caldera-collapse mesobreccias similar to those described in several Tertiary calderas in southern Colorado (Lipman, 1976) and in the Chupadera Mountains near Socorro, New Mexico (Eggleston, 1982). Thickening of the intervals to the north implies derivation from avalanche-like failure of the northwestern caldera wall. Both intervals occur at the base of the middle and upper zones of intracaldera South Canyon Tuff. It seems reasonable to link the eruption of these two zones with avalanche events triggered possibly by episodic down-to-the-south fault displacements along the northern margin of the caldera.

Toward the southeast margin of the Mt. Withington caldera, the South Canyon Tuff decreases in thickness, and the definition of its three stratigraphic zones diminishes until the sequence appears as one continuous zone. Lithic-rich intervals near the southeast caldera margin occur as discontinuous lenses characterized by poorly welded to unwelded ash-flow-tuff matrix, lithic abundances to and greater than 50%, larger maximum fragment sizes (to 2 m), and in some cases clast-supported fabrics. The lens-shaped bodies occur vertically throughout the tuff but only within 1 to 2 km of the caldera margin. The clast-supported varieties, which are also the coarsest, are interpreted as co-ignimbrite lag-fall breccias and, following the original definition by Wright and Walker (1977), are thought to have been deposited from nearby collapsing eruption column(s). The source vent(s) were probably sealed during or slightly after caldera formation by rhyolitic intrusions along the southeast caldera margin.

Caldera formation

The Mt. Withington caldera appears to have collapsed as a northwest-tilted trap-door structure (Fig. 3). The northwest structural margin is a relatively simple, nearly vertical fault separating very thick intracaldera South Canyon Tuff to the southeast from outflow sheets of the South Canyon Tuff and older strata to the north (Osburn and Ferguson, 1986). The southeast structural margin is more complex. Just within the structural margin, the caldera floor block is cut by closely spaced southeast-dipping faults (Fig. 3). Fault motion is constrained by stratigraphic evidence (Ferguson, 1986) to be synvolcanic with the South Canyon Tuff. Large-scale tilting of the caldera floor block, coupled with magmatic stoping and pyroclastic ejection of material near the surface, are invoked to create the space needed for the small fault blocks to slide into the ring fracture zone.

Structural geology

In the northern part of Mt. Withington caldera, the strain pattern is dominated by north–northwest-trending, mostly parallel, west-side-down normal faults. Toward the north edge of the map area (Fig. 4), the faults swing north–northeast in concert with a master fault that runs along the east side of the northern San Mateo Mountains ridge crest. The high-angle east-side-down master fault separates steeply east-tilted blocks to the east from gently east- and west-tilted blocks to the west. Precaldera rocks are exposed only west of this fault, but intracaldera South Canyon Tuff stratigraphy is similar across the structure.

Two structural cross sections (Fig. 5) across the northern third of the Grassy Lookout quadrangle illustrate the geometry of the ☞

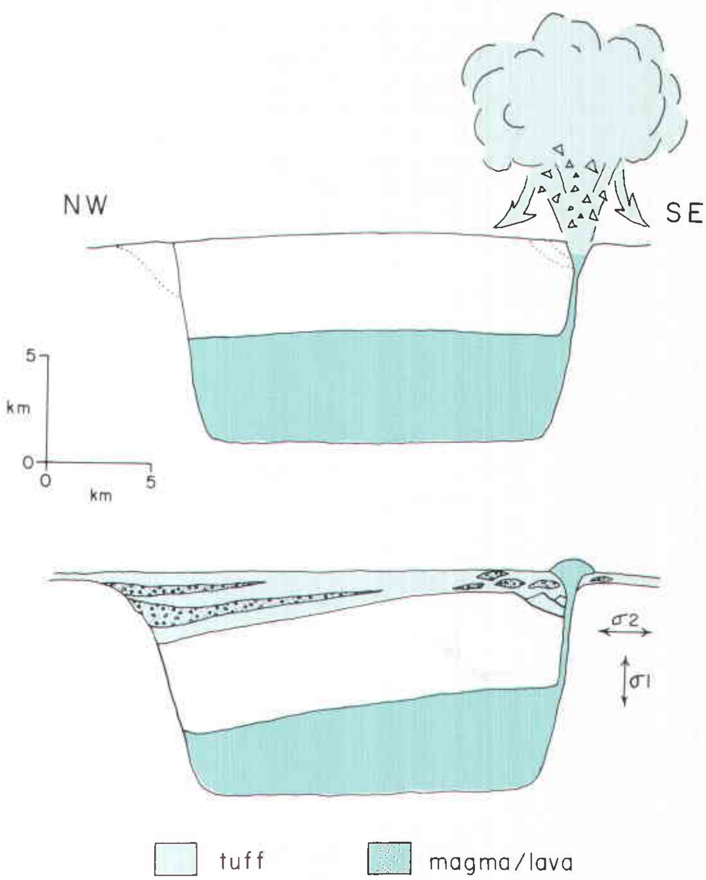


FIGURE 3—Structural model for formation of the Mt. Withington caldera. The plane of section is oriented so that it crosses the Grassy Lookout quadrangle from NW corner to SE corner and so that the mid-Tertiary least principal stress direction is perpendicular to the page. Also depicted are two types of lithic-rich zones. The two laterally continuous units are interpreted as caldera collapse breccias derived from the northern caldera wall. Pod-shaped zones to the south are thought to represent products of a nearby collapsing eruption column.

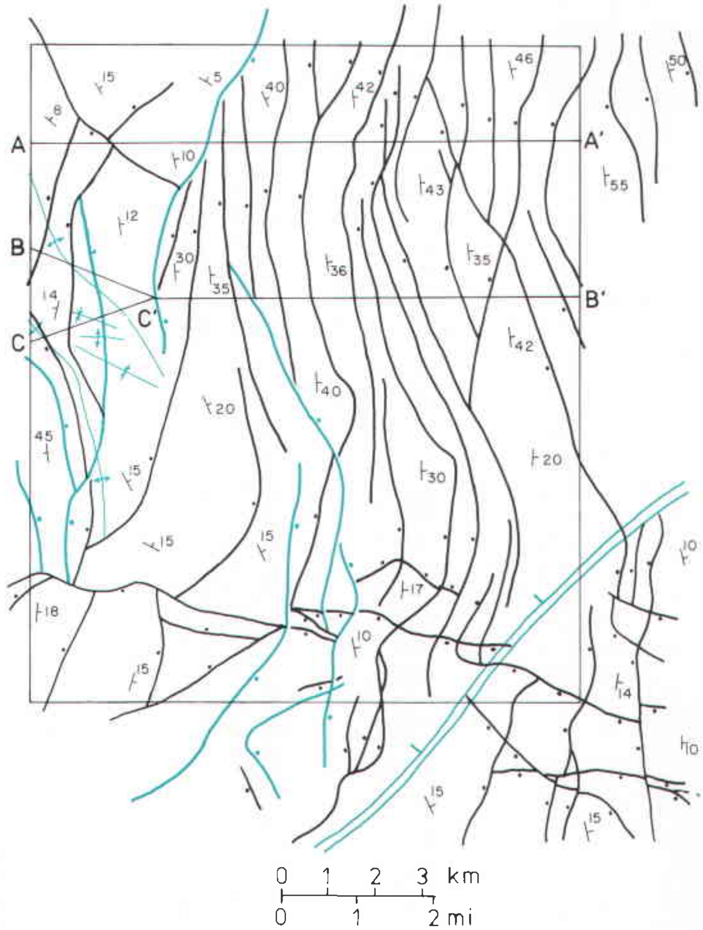
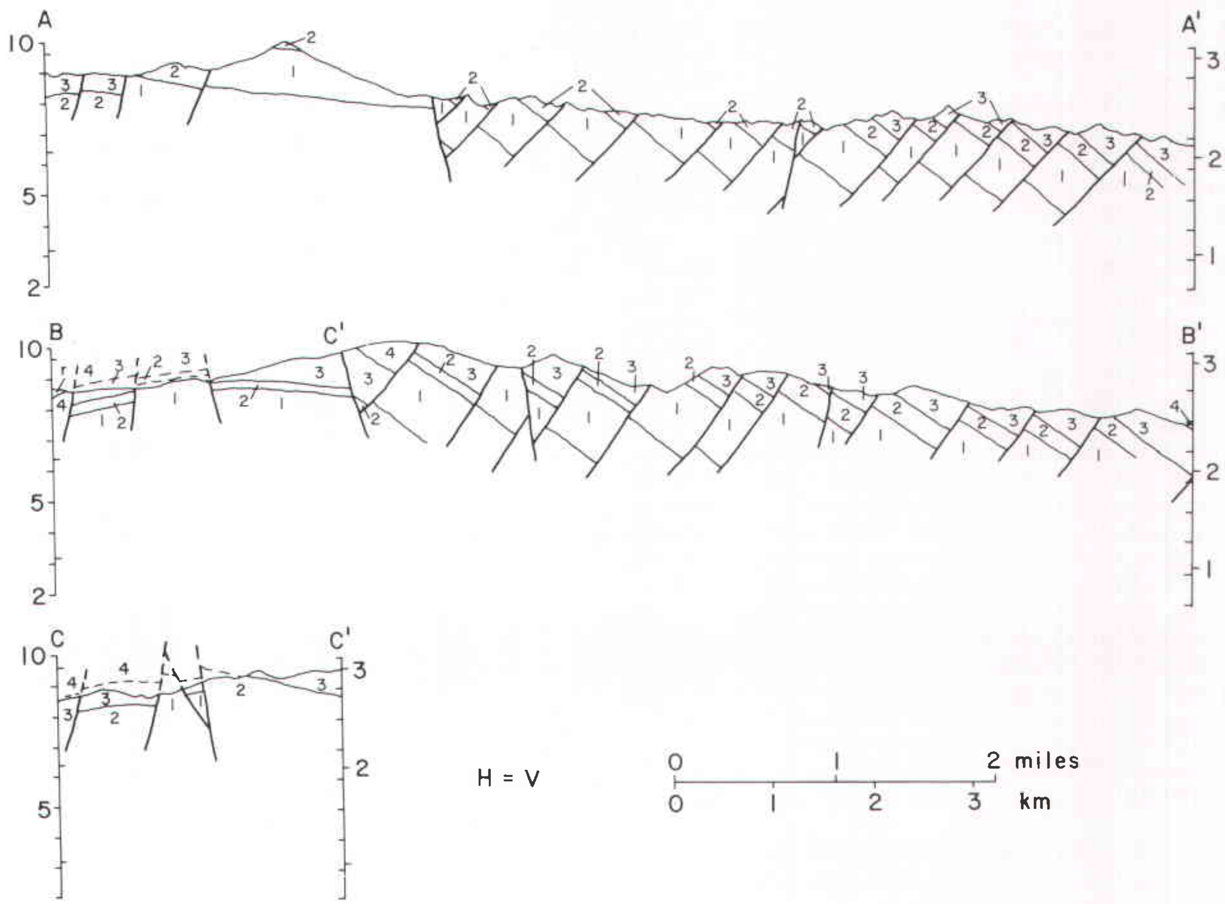


FIGURE 4—Structure of the Grassy Lookout quadrangle (from Ferguson, 1990) and selected surrounding areas (Ferguson, 1986; 1988). Structural cross sections are shown in Fig. 5. Normal faults are depicted with ball on downthrown side. The southeast caldera margin (double barbed line), important east-side-down faults, and a pair of anticlines are shown in blue.

abrupt change in tilt across the master fault. A major problem with this fault stems from the abrupt change in dip that, because the dips are away from each other, creates a large space overlap at depth. Dip changes of this magnitude, in Basin and Range settings, typically occur at breakaways where blocks rotate toward a listric master fault creating a synformal geometry. The fault blocks in this area, however, rotate away from the master fault creating an antiformal geometry. Note that these structural relationships are similar to those observed along the southeast caldera margin (Fig. 3). Note also that the sections do not balance in this area. Further work is needed to explain this unusual structure.

West of the master fault, intracaldera South Canyon Tuff is warped into a series of northwest- and west-trending gentle folds. The folds are cut by a set of north-trending, very high angle faults.

FIGURE 5—Structural cross sections from the northern Grassy Lookout quadrangle (section lines shown in Fig. 4). Zones within intracaldera South Canyon Tuff are depicted by numbers. **1**, lower zone; **2**, lower lithic-rich interval; **3**, middle zone (including in some areas the upper lithic-rich interval), and **4**, upper zone. Vertical scale is in kilometers (right side) and in thousands of feet (left side).



The definition of tilt domains in the Socorro area of the Rio Grande rift is controlled primarily by a transverse boundary (oriented about 070°) called the Socorro accommodation zone (SAZ). The SAZ separates large domains of west-tilted strata on the north from east-tilted strata to the south (Chapin, 1989). In addition, four of the five major Oligocene calderas in the Socorro area (including the Mt. Withington caldera) overlap the SAZ. The SAZ probably represents a long-lived crustal flaw coincident or related to the Morenci lineament (Chapin et al., 1978). Generation and propagation of the Oligocene magmas appear to be related to the zone. The SAZ is usually shown ending in the northern San Mateo Mountains (Chapin, 1989, p. 49) somewhere in the northern Mt. Withington caldera. It probably merges in this area with a northern continuation of the east-side-down master fault. This junction is probably a curved transition from transverse to antiformal, achieved partially through broad warping of intracaldera strata along the San Mateo ridge crest and partially by abrupt tilt changes along the curving east-side-down master fault.

The north-trending tilt-domain boundary in the San Mateo Mountains is classified as an antiformal strike-parallel boundary. This boundary type is one of three possible Basin and Range regional tilt-domain boundaries (Stewart, 1980), the other two being synformal strike-parallel, and transverse (like the SAZ). Location of this transition in the northwest corner of the Mt. Withington caldera suggests a relationship between the distribution of late Oligocene silicic magmatism and the evolution of tilt domains during initial stages of extension in the Rio Grande rift. Silicic calderas in the Socorro area are contained in the same east-dipping tilt domain. The calderas are also characterized by moderate to severe extension. Terrain to the north and west of the Mt. Withington caldera lacks major silicic volcanic centers and is part of a weakly extended domain transitional between the Basin and Range province and the Colorado Plateau to the north.

Discussion

Timing of extension

The significance of structural tilt measurements in the Mt. Withington caldera, and the estimates of bulk extension they are used for in this section, depends on the assumption that eutaxitic foliation in the South Canyon Tuff was originally horizontal. In most cases, this is considered reasonable because the foliations are consistently parallel to stratigraphic layering of the South Canyon Tuff throughout the caldera. However, erratic paleopole positions of some intracaldera South Canyon Tuff sample sites (McIntosh, 1989b) cast doubt on this assumption.

A shallow east-dipping (5–15°) latest Oligocene volcaniclastic sequence (unit of East Red Canyon) and the tuff of Turkey Springs (Ferguson, 1986) unconformably overlie the South Canyon Tuff in the central Mt. Withington caldera. The angular discordance is typically between 20° and 35°. Precise $^{40}Ar/^{39}Ar$ geochronology (McIntosh, 1989a) of the South Canyon Tuff (27.4 Ma) and the tuff of Turkey Springs (24.3 Ma) constrains the tilting between these two units to a 3-million-year interval at the end of the Oligocene. This is illustrated by tilt versus time curves (Fig. 6A) using structural data from the south-central part of the caldera (Donze, 1980; Ferguson, 1988). Note that units Tll/Tlu, Ts1, and Tsc on Donze's (1980) map have been renamed Tsc (South Canyon Tuff), Ter (unit of East Red Canyon), and Tts (tuff of Turkey Springs), respectively. This is according to nomenclature of Osburn and Chapin (1983), and Ferguson (1986). The curves show a pronounced decrease in tilt rate near the end of the Oligocene (25 Ma). In terms of total extension for this area, 45 to 70% was achieved during the last 3 million years of the Oligocene. A tilt versus time curve (Fig. 6B) for another zone of high extension near Socorro, where about 60% of the total extension occurred between 28.5 Ma and 27.4 Ma (Chamberlin, 1983), is included for comparison.

Neogene tectonic activity has been documented in the basin ☞

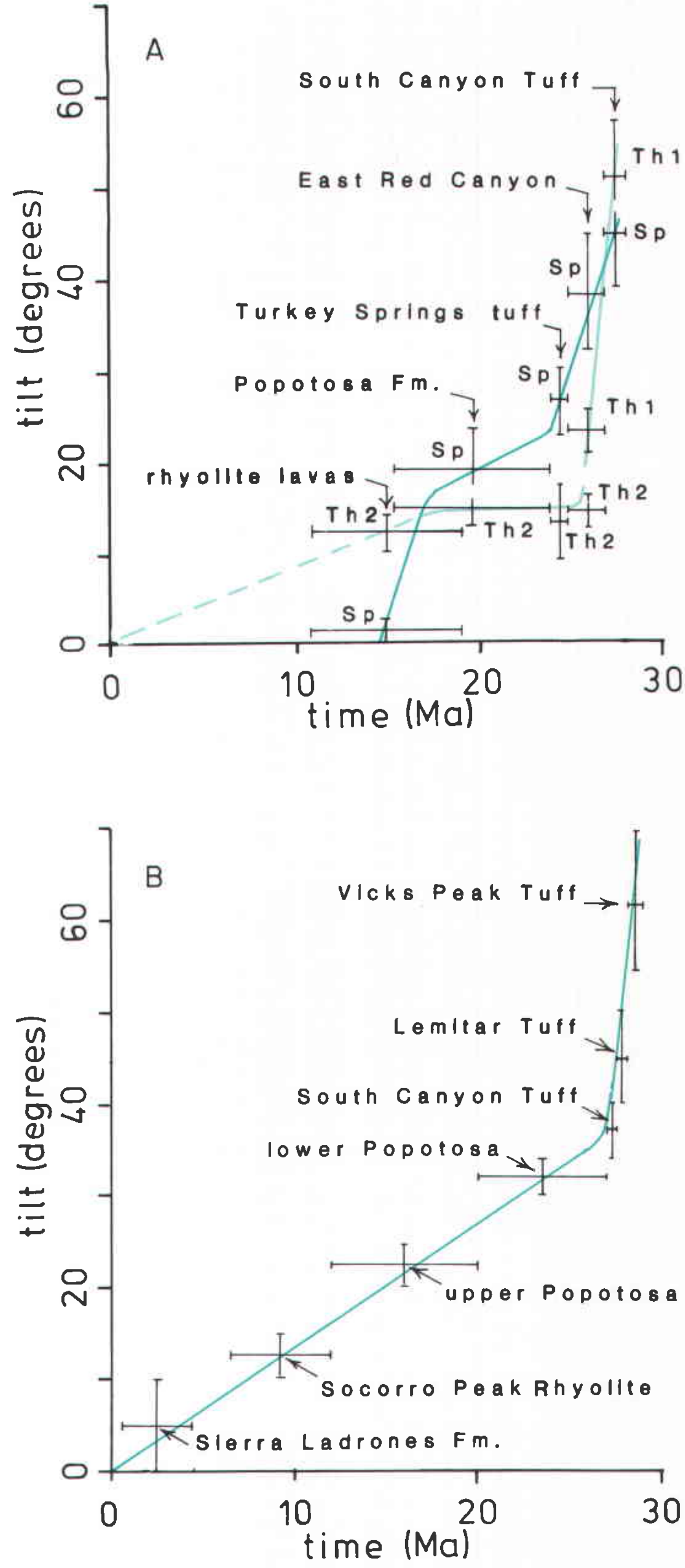


FIGURE 6—Tilt-versus-time curves for mid-Tertiary strata in two areas of the Rio Grande rift near Socorro. The range of variation in tilt and age for each sequence is shown with error bars; incomplete error bars indicate overlapping range. **A**, curves for two areas in Milligan graben. Curve in dark blue: data from south-central Squaw Peak (Sp) quadrangle (Donze, 1980). Curves in light blue: data from northwest (Th1) and north-central (Th2) Tenmile Hill quadrangle, respectively (Ferguson, 1988). **B**, curve for strata in the Lemitar Mountains just northeast of Socorro (Chamberlin, 1983).

immediately east of the San Mateo Mountains (Milligan graben). West-side-down faults that cut the 400,000-year-old Cuchillo surface (Gile et al., 1981) are described in the southern (Machette, 1987) and west-central (Ferguson, 1988) parts of the graben. Displacement of the Cuchillo surface across one of these faults just east of this study area is about 3 m. This style of faulting is thought representative of the slower rates of tilting depicted on the younger segment of the Tenmile Hill curves in Fig. 6A.

A series of flat-lying Miocene rhyolite lava flows and associated pyroclastic deposits intrude and overlie the youngest preserved Popotosa Formation sediments of the northeastern Milligan graben (northeast of the axial drainage). Southwest of the axial drainage, similar but as yet undated rhyolites are tilted east in apparent conformity with the underlying Popotosa Formation sediments.

The angular discordance between Popotosa Formation sediments and the flat-lying lavas in the northeastern Milligan graben implies a renewed pulse of extension during the middle Miocene. This is depicted on the Squaw Peak curve in Fig. 6A. In the southwestern Milligan graben, because the youngest rhyolite lavas are tilted and because Neogene tectonic activity has been documented, gradual tilting since the middle Miocene is depicted on the Tenmile Hill curve in Fig. 6A.

Importance of a subcaldera magma chamber

There is no direct evidence of a synvolcanic pluton below the Mt. Withington caldera. Deal (1973) interpreted it as a resurgent caldera implying, after the model of Smith and Bailey (1968), the presence of a synvolcanic pluton. Osburn and Ferguson (1986) used regional strain patterns as reflected in the local fault and fracture patterns to imply the presence of a pluton. They concluded that orthogonal fault patterns northwest and southeast of the caldera were controlled by pre-Tertiary basement structures. Faults within the caldera are oriented normal to the mid-Tertiary least principal stress direction of about 070° (Zoback et al., 1981; Aldrich et al., 1986). This led Osburn and Ferguson (1986) to suggest that a shallow magma chamber diminished the control of basement structure on the intracaldera strain pattern.

In the vicinity of the Mt. Withington caldera, areas with significant amounts of pre-Miocene extension (30% to 50% of the total) are conspicuously confined within the caldera. A shallow subcaldera pluton could help explain this rapid pulse of extension. Just after emplacement it is likely that the hot pluton was extended in a ductile fashion. Concurrently, extension at the surface would have occurred by brittle faulting of the thick intracaldera sequence and an unknown thickness of precaldera strata. This is depicted in a structural model (Fig. 7). Domino-style faulting occurs above a detachment that represents the brittle-ductile transition (possibly the ceiling of the pluton) at shallow depths (~5 km). A steep breakaway fault near the west edge of the caldera complex corresponds to the tilt-domain-bounding master fault that occurs along the east side of the San Mateo Mountains ridge crest. The space overlap across this structure is relieved but not completely balanced by pulling the highly extended block away from the relatively stable block to the west. Steeply tilted, domino-style fault blocks can then rotate and slide into the gap.

The final stage of the model (Fig. 7) depicts a protracted phase of deep-seated faulting characterized by weak magnitudes of extension. This stage reflects postmagmatic cooling, depression of the brittle-ductile transition, and a stronger lithosphere. Similar and roughly contemporaneous changes in structural style and behaviour of the lithosphere in other areas of the Rio Grande rift are described by Morgan et al. (1986).

Conclusions

Three stratigraphic zones of the South Canyon Tuff are defined within the Mt. Withington caldera. The zones are separated by tabular to wedge-shaped lithic-rich intervals thought to be produced by caldera-collapse avalanches along the northern caldera margin. Lenticular clast-supported lithic breccias near the southeastern caldera margin are interpreted as co-ignimbrite lag-fall breccias, deposits of a nearby collapsing eruption column or columns.

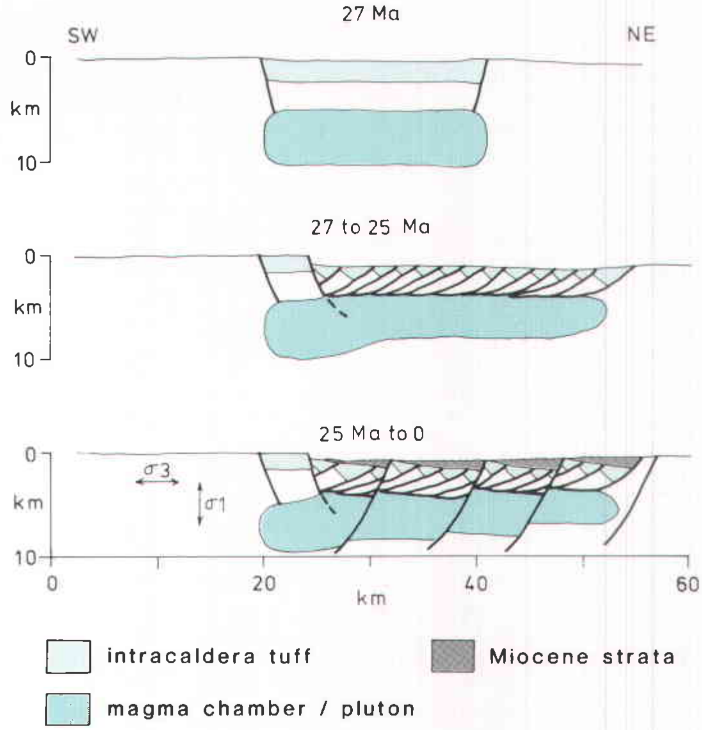


FIGURE 7—Structural model for extensional evolution of the Mt. Withington caldera, late Oligocene through present. The cross-sectional plane is oriented parallel to the long dimension of the caldera and with the mid-Tertiary least principal stress direction parallel to the page. The first stage (27 Ma) depicts the crustal section just after formation of the caldera. The second stage (27 to 25 Ma) depicts a rapid pulse of extension expressed at the surface by thin-skinned-style domino faulting above a shallow detachment and by ductile stretching of the subcaldera pluton. The final stage (25 Ma to present) depicts a brittle pluton, a gently east-dipping Oligocene–Miocene angular unconformity and deep-seated normal faulting.

A regional Basin and Range antiformal tilt-domain boundary is defined primarily by a steep east-side-down normal fault along the east side of the northern San Mateo Mountains ridge crest. The fault separates steeply east-tilted blocks on its east side from gently tilted strata on the west. The tilt-domain boundary is also defined by a north–northwest-trending broad anticline roughly coincident with the ridge crest itself. The antiformal tilt-domain boundary probably merges within 5 to 10 km to the north with the Socorro accommodation zone, an important regional transverse tilt-domain boundary.

A rapid pulse of thin-skinned style extension occurred within the Mt. Withington caldera just after its emplacement during the last 3 million years of the Oligocene. Domino-style faulting at the surface is inferred to be synchronous with ductile extension of a shallow subcaldera pluton. A younger phase of thick-skinned-style extension (Miocene to present) is characterized by high-angle Basin and Range faulting and is thought to reflect a cooler and stronger lithosphere.

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Grassy Lookout quadrangle

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