Geology of the Grassy Lookout 7.5' quadrangle, Socorro County, New Mexico

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by

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Geologic Setting

The Grassy Lookout quadrangle encompasses a large part of the north-central San Mateo Mountains, a north-trending basin and range uplift on the west side of the Rio Grande Rift, near Socorro, New Mexico (Figure 1). The quadrangle is dominated, topographically, by the range's northern ridge crest between Mt. Withington (north end) and Grassy Lookout (south end). It is located entirely within Cibola National Forest, and most of the Mt. Withington Wilderness Area is contained within the northeast part of the quadrangle.

The Grassy Lookout Quadrangle is underlain by mid to late Oligocene silicic ash-flow tuffs of the northeast Mogollon-Datil volcanic field. Very little is known about the pre-Oligocene history of the area. The Mt. Withington Cauldron (Deal, 1973; and Deal and Rhodes, 1976) underlies most of the quadrangle, and is the source of the second youngest major regional ash-flow tuff unit (South Canyon Tuff (27.3 Ma, McIntosh, 1989a)) in the Socorro area.

The geologic history of the area can be divided into three parts: 1) late Oligocene formation of the Mt. Withington Cauldron; 2) a late Oligocene episode of thin-skinned style extension within the cauldron; 3) a Miocene through present phase of thick-skinned basin and range style extension that is responsible, to a large degree, for the area's present geomorphology.

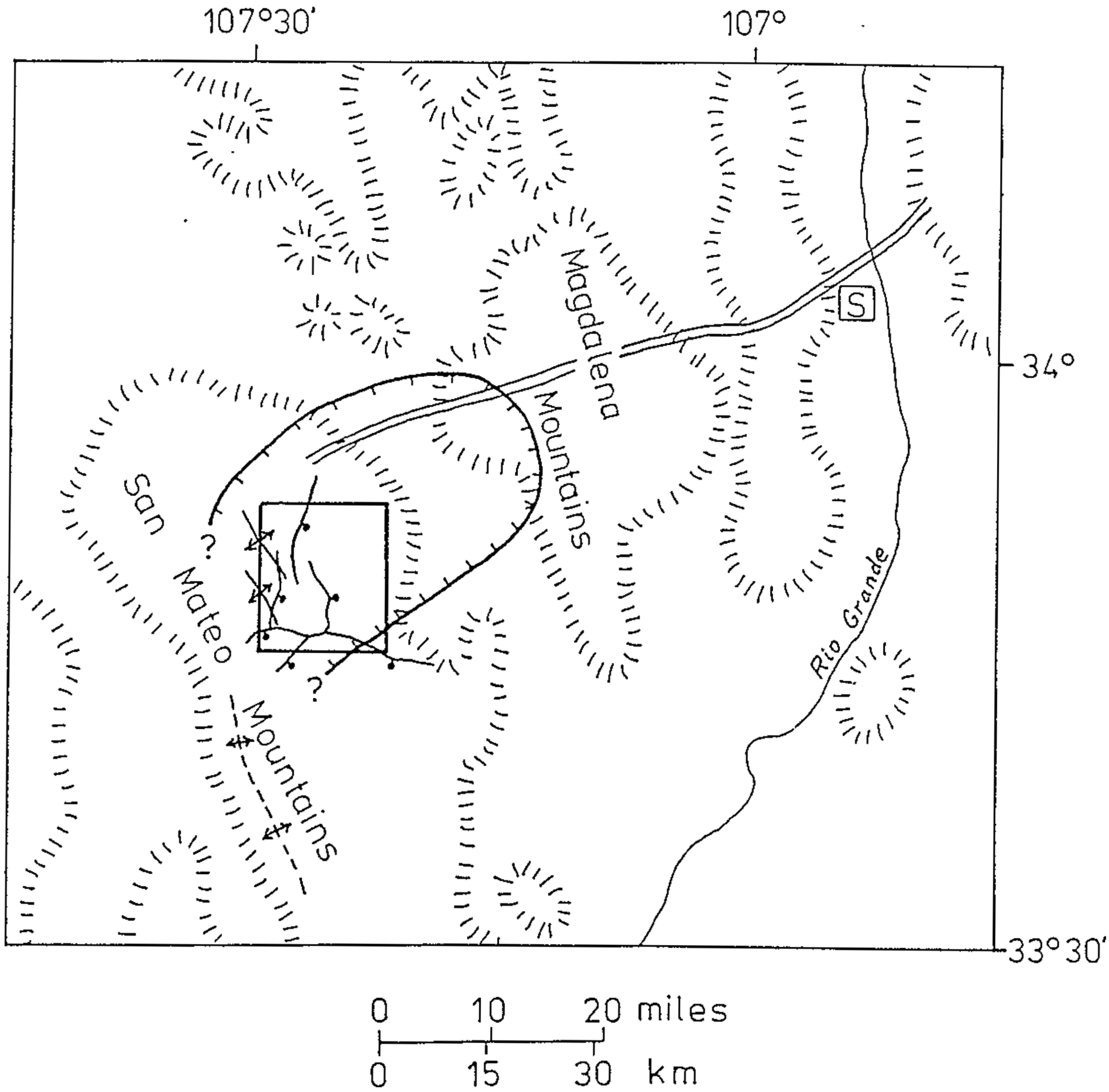

Figure 1. Location of the Grassy Lookout quadrangle (outlined by thick line) in the northern San Mateo Mountains. The Mt. Withington Cauldron margin is indicated by the thick barbed line. The solid double line is the Socorro Accommodation Zone. Important structural features of the northern San Mateo Mountains are also shown. The east-side-down and south-side-down normal faults combine with a pair of southwest-stepping en echelon anticlines to define a north-trending antiformal tilt-domain boundary along the west edge of the map area. A possible southward continuation of this boundary is shown (from unpublished mapping by Cox and Hermann).

Acknowledgments

Geologic mapping of the Grassy Lookout quadrangle was initiated in 1983 as part of a Master's Thesis at New Mexico Institute of Mining and Technology (Ferguson, 1986). The project was supervised by G. Robert Osburn, and the thesis was reviewed by Philip Kyle and David Johnson. Approximately 40% of the Grassy Lookout quadrangle was completed during the 1983 field season. The remaining 60% was mapped during May and June of 1989 and 1990. All of this mapping was funded by the New Mexico Bureau of Mines and Mineral Resources.

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Stratigraphy

Pre-cauldron units

The oldest rocks exposed in the Grassy Lookout quadrangle are only slightly older than the Mt. Withington Cauldron. These are outflow sheets of three major rhyolite ash-flow tuffs that were erupted from nearby cauldrons. From oldest to youngest these are: La Jencia Tuff (28.8 Ma); Vicks Peak Tuff (28.5 Ma); and Lemitar Tuff (27.9 Ma). The $^{40}Ar/^{39}Ar$ ages quoted here are from Bill McIntosh's geochronologic and paleomagnetic studies of the Mogollon-Datil volcanic field (1989a; 1989b). There is also a widespread sequence of rhyolite lavas that occur between the Vicks Peak and Lemitar Tuffs throughout the northern San Mateo Mountains.

La Jencia Tuff

The La Jencia tuff (Tj, Plate 1) is a crystal-poor (1-7% phenocrysts) sanidine bearing flow-banded rhyolite ash-flow tuff. It is at least 250 meters thick where it is exposed in the southeast corner of the quadrangle, and the flow-banding consistently trends E-W. The source of the La Jencia Tuff is the composite Sawmill Canyon - Magdalena Cauldron (Osburn and Chapin, 1983) in the northern Magdalena Mountains.

Vicks Peak Tuff

The Vicks Peak Tuff (Tvp, Plate 1) is a crystal-poor (0-3%) rhyolite ash-flow tuff with phenocrysts of sanidine and rare clinopyroxene. It is either very thin (<120 m) or absent where it's stratigraphic interval is exposed in the southeast corner of the Grassy Lookout quadrangle. To the south and east (Blue Mountain and San Juan Peak 7.5' quadrangles), it thickens dramatically (to at least 300 meters) across a south-facing scarp that trends nearly east-west along East Red Canyon

(Ferguson (1986). The Vicks Peak thickens across at least one more similar feature farther south (Mike Hermann, personal communication). South-side-down motion on these structures was probably related to formation of the Nogal Canyon Cauldron in the southern San Mateo Mountains, the source of the Vicks Peak Tuff.

Rhyolite lavas

Rhyolite lavas are present throughout the Grassy Lookout quadrangle below the Lemitar Tuff, but never with any lower age constraint. These lavas (Trl, Plate 1) are correlated chronologically with a dome and flow that occurs between Vicks Peak and Lemitar Tuffs just south of the quadrangle (Drift Fence dome; Ferguson, 1986). Rhyolite lavas of this age are widespread and voluminous throughout the central and northern San Mateo Mountains, and a similar sequence, occupying the same stratigraphic position, is found in the northern Black Range. The area of this rhyolite lava field is conservatively estimated at about 1,500 mi^2 (4,000 km^2), and probably represents a volume of between 100 and 400 km^3. This represents a very short-lived (600,000 year, McIntosh, 1989a) phase of rhyolitic volcanism of caldera-like magmatic volume and dimensions without any significant pyroclastic products.

Lemitar Tuff

The Lemitar Tuff is a crystal-rich (10-35% phenocrysts) reddish quartz-feldspar-biotite bearing rhyolite ash-flow tuff. Its source caldera has not yet been located, but is thought to be in the south-central Magdalena Mountains. The Lemitar is relatively thick (120 meters) in the southeast corner of the Grassy Lookout quadrangle, but it thins to a feather edge westward and northward until pinches out altogether in the Grassy Lookout and Big Rosa Canyon areas. At its distal fringe, the Lemitar is a fairly crystal-poor (5-10% phenocrysts) pinkish tuff, but even where it is less than 2 meters thick it is still densely welded.

South Canyon Tuff

The Mt. Withington Cauldron is the source of the (27.3 Ma, McIntosh, 1989a) South Canyon Tuff, a moderately crystal-rich quartz-feldspar bearing sometimes flow-banded rhyolite ash-flow tuff.

Nine mappable units were recognized in the Grassy Lookout quadrangle of the South Canyon Tuff: two basal units; two localized lithic breccia units; and five vertical zonations of the main caldera-fill, four of which are volumetrically significant.

Basal units

Throughout the Mt. Withington Cauldron, the base of the South Canyon Tuff is a crystal-poor (0-5% phenocrysts) dark reddish-brown or black vitrophyre. It ranges in thickness from 2-60 meters and tends to be thickest and darker toward the thickest part of the caldera-fill. The basal vitrophyre is mapped as Tscv on Plate 1.

Along the southeastern cauldron margin, where caldera-fill is thin, the welded base of the South Canyon Tuff is only slightly glassy, and it rests on a 0 to 30 meter thick sequence of thin to medium-bedded unwelded tuff (plinians and lithic ash-flow tuffs) and minor volcaniclastic sandstone. These strata, confined to the North Canyon area along the east edge of the map area, are mapped collectively as Tscu on Plate 1.

Cauldron-filling units

The northern part of the Grassy Lookout quadrangle is underlain by a 2 km thick sequence of intracauldron South Canyon Tuff. In the thickest part of the cauldron, three distinct zones within the South Canyon Tuff (herein called the lower, middle, and upper) were recognized. The zonations are defined primarily on the basis of phenocryst abundances, and also because they are usually separated by lithic-rich intervals (Figure 2).

The zones described below are defined only within the thickest part of the cauldron-fill, and do not necessarily

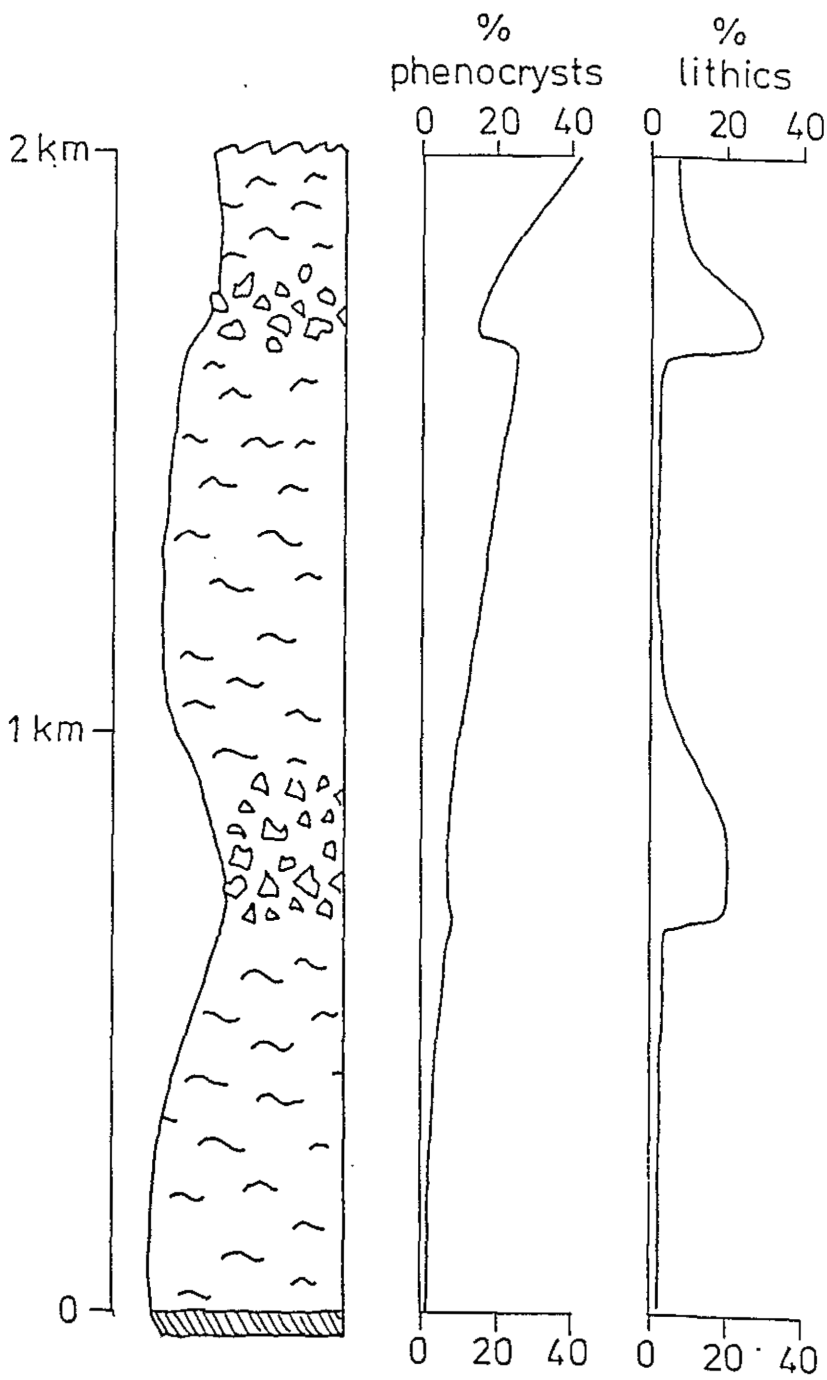

Figure 2. Generalized stratigraphic section of the thickest part of intracauldron South Canyon Tuff. The unit shown with closely spaced diagonal lines represents a basal vitrophyre. Two lithic-rich intervals are depicted which divide the section into three zones (lower, middle, and upper) discussed in the text.

correspond to zonal variations of the South Canyon Tuff near the southeastern cauldron margin or in the outflow sheet, where it is significantly thinner.

Lower zone of the South Canyon Tuff

Most of the lower zone of the South Canyon Tuff (Tsc1, Plate 1) is apparently confined to within the cauldron. It is at least 1 km thick in the northern part of the Grassy Lookout quadrangle. The lower zone is a light gray quartz and sanidine bearing crystal-poor flow-banded rhyolite ash-flow tuff. The lower zone correlates directly with Deal's (1973) A-L Peak Tuff. The A-L Peak Tuff was originally correlated with a texturally similar widespread outflow sheet, but later proven to be an older unit, the La Jencia Tuff, on the basis of mineralogic (Osburn and Chapin, 1983), stratigraphic (Ferguson, 1986), and paleomagnetic/geochronologic (McIntosh and others, 1986) evidence.

Middle zone of the South Canyon Tuff

The middle zone of the South Canyon Tuff (Tsc3, Plate 1) is bounded above and below by lithic-rich intervals. The lower lithic-rich interval is mapped separately as Tsc2 on Plate 1. The middle zone is light gray, commonly 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 (Ferguson, 1986). The middle zone is at least 1 km thick in the northern part of the quadrangle, and correlates with most of Deal's (1973) Potato Canyon Tuff, within the Mt. Withington Cauldron. Strata mapped by Deal (1973) as Potato Canyon Tuff outside the cauldron have since been shown to be a variety of outflow sheets older than and including the South Canyon Tuff (Ferguson, 1986, p. 92).

Upper zone of the South Canyon Tuff

The upper zone of the South Canyon Tuff (Tsc4, Plate 1) appears to be confined to within the cauldron. It gradationally overlies the middle zone, but 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% and up to 35%), and a dark reddish-brown color. Where its top and bottom is exposed, it is at least 300-500 meters thick, but it is not always present, particularly in the southern part of the cauldron. From petrographic work by Ferguson (1986), the zone is dominated by subequal proportions of quartz and sanidine, between 1% and 5% plagioclase, minor biotite, and traces of sphene and opaque minerals. Plagioclase typically contains glass inclusions and is commonly rimmed by sanidine growths. The upper zone is unique in that it contains at least two types of pumice fragments: small (<5 cm) white fragments dominate, and rarer large (>10 cm) dark gray-purple fragments which appear to be more intermediate in composition. In the northeast corner of the quadrangle, exposures of the upper zone are capped by a medium gray moderately crystal-rich (15-20%) feldspar bearing tuff with little or no quartz phenocrysts (Osburn, personal communication). This unit, only exposed in the northeast corner, is mapped separately as Tsc5 on Plate 1.

Lithic-rich intervals in the South Canyon Tuff

Within the thickest part of the cauldron fill, two laterally continuous lithic-rich intervals between 50 and 300 meters thick are recognized. The lower is mapped separately (Tsc2, Plate 1), but the upper one is included as part of the basal upper zone of the South Canyon Tuff. The lithic intervals are characterized by a deep reddish-brown color, general lack of eutaxitic foliation, and usually low phenocryst abundances. The low phenocryst content probably reflects dilution by the lithic material and (although densely welded) decreased compaction relative to adjacent zones. Lithics consist of volcanic clasts up to 30 cm in diameter (silicic and andesitic lava lithologies dominate) which comprise 5% to 30% of the tuff. The intervals are generally thickest and have higher lithic concentrations towards the northwest corner of the quadrangle.

Towards the southeast margin of the Mt. Withington Cauldron, the South Canyon Tuff decreases in thickness, and the definition of its tripartite stratigraphic zonal variations diminishes until the sequence appears as one continuous zone.

The South Canyon Tuff in these areas was not differentiated (mapped as Tsc on Plate 1). Lithic-rich intervals near the southeast cauldron margin, occur as discontinuous lenses with poorly-welded to unwelded matrix, and are characterized by lithic abundances up to and greater than 50%, larger maximum fragment sizes (up to 2 meters), and in some cases clast-supported fabrics. The lens-shaped bodies (mapped as Tscb, Plate 1) occur vertically throughout the tuff, but only within 1 to 2 km of the cauldron margin. The clast-supported varieties (which are also the coarsest) were interpreted by Ferguson (1986) as co-ignimbrite lag-fall breccias, and following the original definition by Wright and Walker (1978), 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 cauldron margin.

Another type of lithic breccia (mapped as Tscbv, Plate 1) is found within undifferentiated South Canyon Tuff along the southwest edge of the map area. Coarse lithic breccias (with clasts up to 50 cm), some of which are nearly clast-supported (30-60% clasts), are contained within moderately crystal-rich tuff near the top of the South Canyon Tuff. The pod and lens shaped breccia masses are surrounded by moderately crystal-rich black to reddish-brown vitrophyre which is itself slightly lithic-rich (5-10%). The vitrophyre probably indicates that the host tuff was "frozen" rapidly adjacent to the cool lithic zones. The lithic pods in this area are similar (except for the associated vitrophyre) to lithic zones near the southeast cauldron margin. It is likely that the western cauldron margin is relatively close to the southwest corner of the Grassy Lookout quadrangle.

Lithic-rich intervals in the thick cauldron-fill of the South Canyon Tuff (Figure 2) are interpreted as lithic concentrations near the base of major eruptive sequences. The three successively more crystal-rich caldera-filling units of the South Canyon Tuff (Tsc1, Tsc3, Tsc4; Plate 1) are genetically linked to separate, but closely spaced, eruption events representing the evacuation of progressively deeper, and less evolved levels of a large sub-caldera magma chamber.

The pod-shaped lithic breccia masses (Tscb, Tscbv, Plate 1) are interpreted as either co-ignimbrite lag-fall breccias, or parts of proximal syn-caldera collapse land-slide breccias. The association of these breccias and undifferentiated South Canyon Tuff seems to represent a caldera-margin facies of the Mt. Withington Cauldron-fill sequence.

Post-cauldron units

There are three late Oligocene units that postdate formation of the Mt. Withington Cauldron: 1) the unit of East Red Canyon, 2) rhyolite lava domes and flows, and 3) the tuff of Turkey Springs.

The unit of East Red Canyon

The unit of East Red Canyon overlies the South Canyon Tuff throughout the quadrangle and displays a wide variety of lithologies, which were described in detail for the East Red Canyon area by Ferguson (1986).

In the south-central part of the map area, the unit of East Red Canyon is dominated by epiclastic strata. Coarse angular breccias and conglomerates grade westward into a sequence of eolian sandstones. The upper 20-50 meters is characterized by thin to medium-bedded unwelded tuff (mostly plinians, but with some lithic-rich ash-flow tuffs) interbedded with epiclastic rocks. Ferguson (1986) interpreted the sequence in East Red Canyon as an alluvial fan with proximal facies preserved along the southeast Mt. Withington Cauldron margin. To the northwest, alluvial fan deposits interfinger with an eolian sand sea. Paleocurrents in the eolian sandstones are consistently northeast-directed.

In the western part of the Grassy Lookout quadrangle, the unit of East Red Canyon is thinner (< 100 meters) and pyroclastic strata dominate the sequence. Medium and thick-bedded unwelded to poorly welded lithic-rich tuffs and thin to medium-bedded plinian sequences are interbedded with extremely coarse-grained epiclastic rocks composed of very angular clasts, some up to 3 meters in diameter. This pyroclastic/sedimentary sequence was deposited in a very proximal alluvial fan environment along the east side of a narrow north-northwest trending fault-bounded basin. Depending on the level of exposure, the basin-fill usually buries the west-side-down fault zone that bounds its west side, and overlaps the degraded eastern footwall. Original dips of up to 30-35° are preserved in talus-slope like strata above the degraded footwall. Dips decrease gradually away from the fault zone (Figure 3), but in some cases, steeply dipping sequences of epiclastic breccia and plinian beds are sharply truncated (20-30° angular differences) by younger sequences. In many cases it is difficult to interpret whether a contact is a fault or depositional (for example, see fault that crosses Hudson Canyon directly west of Grassy Lookout). To complicate matters, the degraded fault zone is cut by younger faults, exposing different levels along strike.

Rhyolite lavas

The unit of East Red Canyon is intruded by and in some areas overlies rhyolite lava domes, flows, and dome-like masses. The rhyolite domes are clustered along the southeast Mt. Withington Cauldron margin, and along the west-side-down fault zone in Hudson Canyon that is largely concealed by sediments and pyroclastic strata of the unit of East Red Canyon.

Tuff of Turkey Springs

Overlying both the unit of East Red Canyon and rhyolite lava flows and domes is the tuff of Turkey Springs (24.3 Ma,

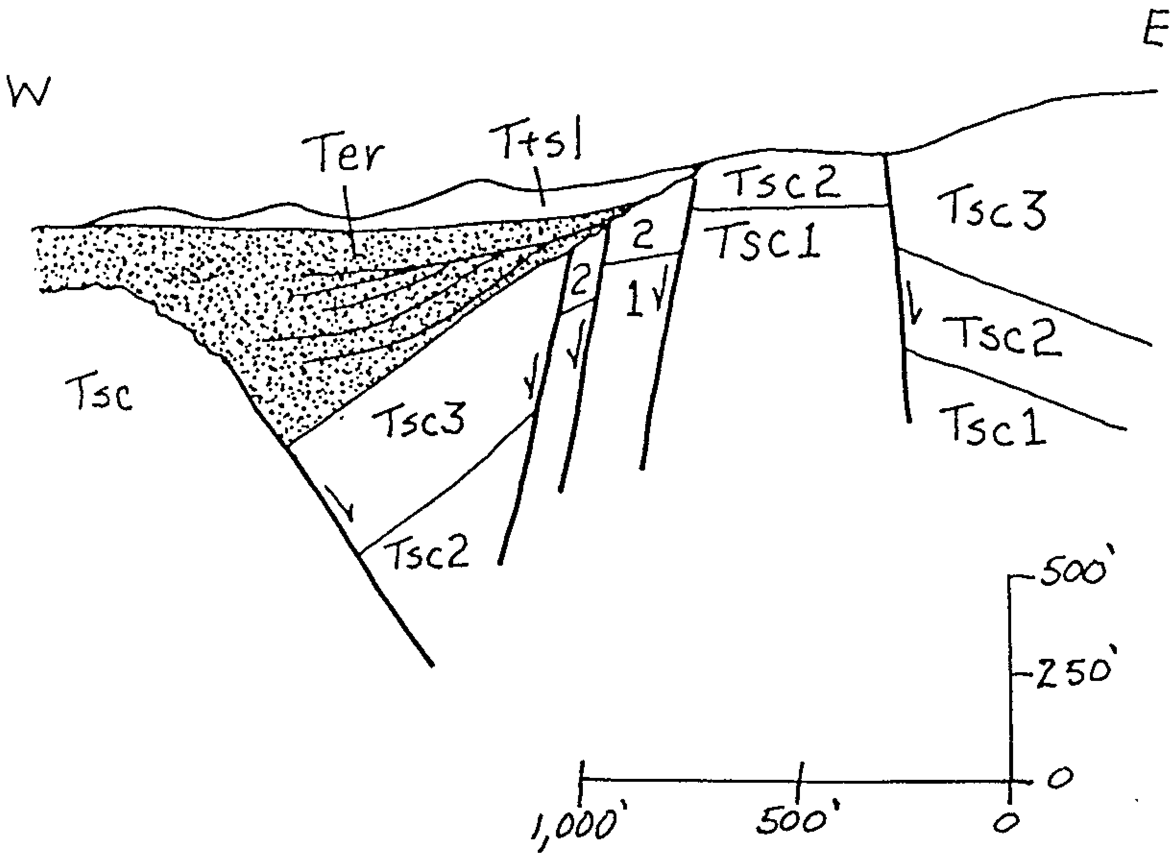

Figure 3. Schematic sketch across the faulted anticlinal structure partially buried by deposits of the unit of East Red Canyon (Ter) along the southwest edge of the Grassy Lookout quadrangle. View is to the north combining field sketches of exposures in Hudson Canyon, Spring Canyon, and Whitewater Canyon. Tsc: undifferentiated South Canyon Tuff, Tsc1: lower zone, Tsc2: lithic-rich interval: Tsc3: middle zone, Ttsl: tuff of Turkey Springs.

McIntosh, 1989a). It is a quartz-sanidine bearing pinkish-gray rhyolite ash-flow tuff that is petrographically and usually texturally similar to the South Canyon Tuff. Two members are recognized, a lower unwelded to poorly welded zone (Ttsl, Plate 1) between 0 and 40 meters thick, and an upper welded member (Tts, Plate 1) up to 100 meters thick, but with no exposed top. Both members are present near its type section at Turkey Springs (located along the north-central edge of the Blue Mountain 7.5' quadrangle just to the south of this map sheet). In the Hudson Canyon area, along the west edge of the map area, only the lower member is preserved where it overlies coarse-grained pyroclastic strata of the unit of East Red Canyon.

The source of the tuff of Turkey Springs is not yet been identified. A possible circular structure to the southwest, in the Welty Hill 7.5' quadrangle, may represent the source caldera (Mike Hermann, personal communication; Ferguson, unpublished mapping).

No Tertiary units younger than the tuff of Turkey Springs are exposed in the map area.

Other Tertiary units

Two locally mappable units occur below the South Canyon Tuff in two areas of the Grassy Lookout quadrangle. A rhyolite lava (Tr2, Plate 1) occurs in the North Canyon area along the east edge of the quadrangle. It is mapped as a separate unit (apart from the pre-Lemitar lavas) because of relationships established just to the east in the Tenmile Hill 7.5' quadrangle (Ferguson, 1988).

In the Indian Creek area, just off the south edge of the map sheet (Plate 1), a 30 meter thick red sandstone and conglomerate unit overlies a less than 2 meter thick sequence of Lemitar Tuff, and is overlain by the South Canyon Tuff. This sedimentary sequence differs from the unit of East Red Canyon in that it contains no pyroclastic strata. It is mapped as the unit of Indian Creek (Tic), but is shown only on cross-section G-G' (Plate 2).

Quaternary units

A sequence of partially consolidated alluvium forms terrace-like deposits along the upper reaches of major canyons in the Grassy Lookout quadrangle. These strata are correlated with the Palomas Formation (Qp, Plate 1; Lozinsky and Hawley, 1986) which represents the youngest sequence of rift-basin fill prior to the Rio Grande becoming a through-flowing river system about 400,000 years ago (Gile and others, 1981).

Quaternary alluvium filling present day canyon bottoms and major talus deposits were also mapped (Qa and Qt, Plate 1).

Structural Geology

Caldera Structure

The Mt. Withington Cauldron is a trap door-like structure tilted to the northwest about a hinge along its southeast margin. The southeast cauldron margin is a complex hinge-like structure with associated faults that are constrained to be synvolcanic with respect to the South Canyon Tuff. The northwest cauldron margin, located about 5 km to the northwest of the Grassy Lookout quadrangle, (Osburn and Ferguson, 1986) is a relatively simple near vertical fault bounding very thick intracauldron South Canyon Tuff on the southeast from outflow sheets of the South Canyon Tuff and older tuffs on the north. The cauldron floor can be modeled simply as a northwest-tilted trapdoor (Figure 4), with complex structure in the southeastern hinge area explained by rotation of relatively narrow fault blocks into the space created by whole scale tilting of the cauldron floor block. Structure of the southeast hinge-like margin is discussed in more detail in Ferguson (1986).

Strain patterns

Most of the Grassy Lookout quadrangle is situated to the east of the San Mateo Mountains ridge crest. Fault patterns, east of the crest (Plate 1) are dominated by a north to northwest-trending set of mostly parallel, often en echelon,

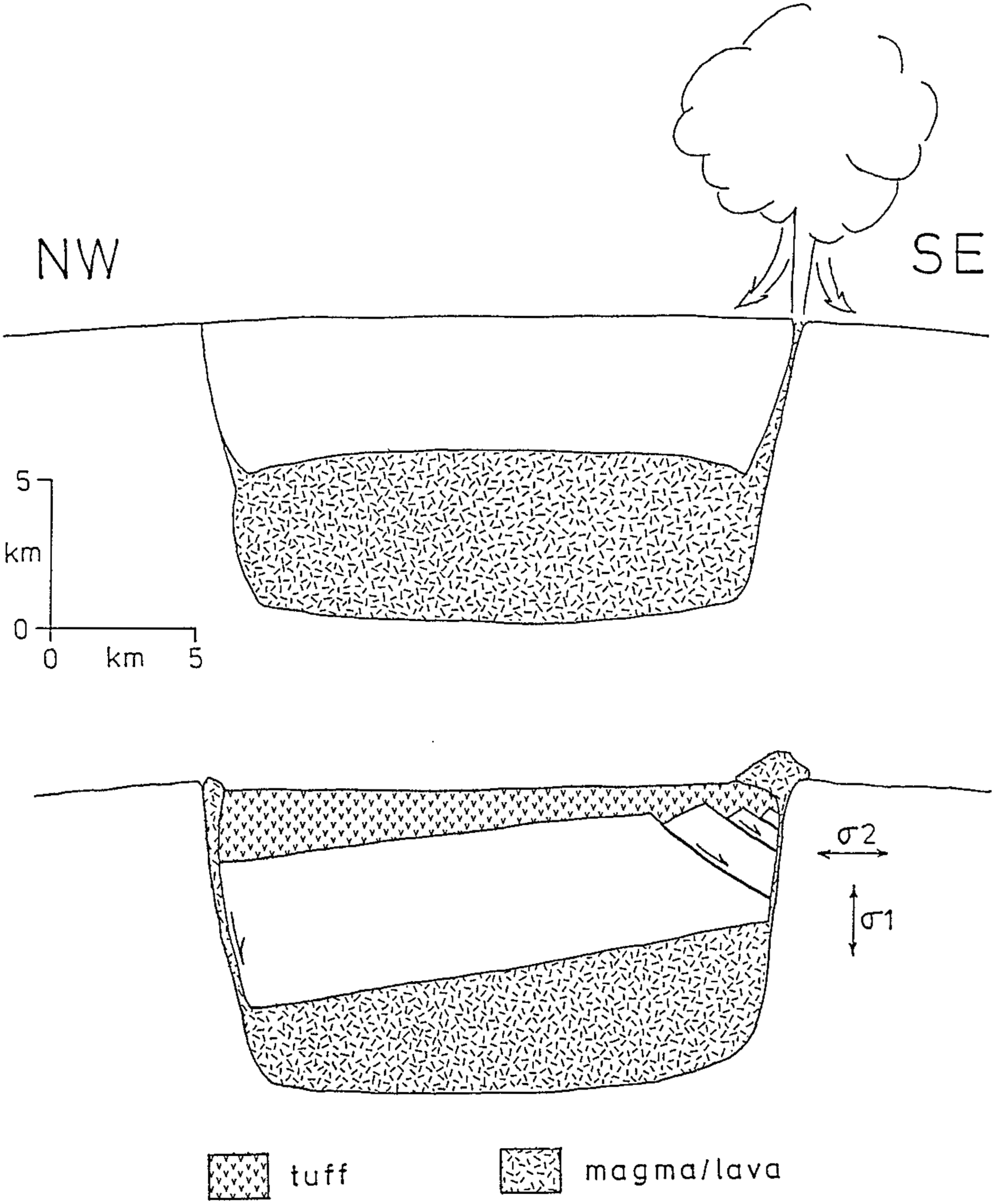

Figure 4. Structural model for formation of the Mt. Withington Cauldron. The plane of section is oriented so that it crosses the Grassy Lookout quadrangle from NW corner to SE corner, and so that the Mid-Tertiary least principle stress direction is perpendicular to the page. See text for discussion.

moderately-dipping west-side-down normal faults. Towards the north edge of the map sheet, the faults swing to the northeast in concert with a master fault that runs along the east side of the northern San Mateo Mountains ridge crest. The master fault is a high-angle east-side-down structure that bounds steeply east-tilted blocks to the east from gently east and west-tilted blocks to the west. Basement to the Mt. Withington Cauldron fill is exposed only to the west of this fault, but stratigraphic zonal variations in intracauldron South Canyon Tuff are essentially similar across the structure.

Structural cross-sections (Plate 2) across the northern third of the quadrangle illustrate the geometry of an abrupt change in tilt across the master fault discussed above. A major problem with this fault stems from the abrupt change in dip which, 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 towards a listric master fault. The fault blocks in this area, however, rotate away from the master fault, which is probably not listric. Note that these structural relationships are similar to those observed along the southeast cauldron margin (Figure 4).

The east-side-down master fault, in the northern Grassy Lookout quadrangle, dies out eventually in the west-central part of the quadrangle, near the head of Hudson Canyon (Plate 1). Its displacement is distributed into two other faults that branch out of nearby west-side-down faults. One starts in the upper part of Bear Canyon on the west side of the divide, and runs southward towards a large bend in Hudson Canyon. The other runs down the east side of the ridge crest parallel to the upper part of North Canyon into "The Park" area and than southwest across East Red Canyon towards Allen Spring and the head of West Red Canyon. Faults east of this major fault, in the southern part of the quadrangle, swing to the southwest into parallelism with the Mt. Withington Cauldron margin (Plate 1).

Along the ridge crest of the San Mateo Mountains, in the northern part of the Grassy Lookout quadrangle, intracauldron South Canyon Tuff is gently folded into an anticline trending 345° with its axis about 2 km west of the ridge crest. The fold is cut by a set of mostly north-trending very high angle faults which change from east-side-down to west-side-down across the ridge crest (Plate 1). This broad anticline dies out in the west-central part of the quadrangle. Another complex and tighter anticlinal structure continues southward from this area, but it offset en echelon style into the southwest corner of the map sheet (Figure 1).

Along the very southwestern edge of the quadrangle, a strip of steeply west-dipping South Canyon Tuff is exposed below gently-dipping strata of the unit of East Red Canyon and tuff of Turkey Springs. This strip, which constitutes the western limb of the anticline discussed above, is bounded by the north-northwest trending west-side-down fault zone, partially buried by coarse-grained talus slope deposits of the unit of East Red Canyon. In Hudson Canyon, this west-side-down fault is cut and offset by the western branch of the east-side-down master fault discussed earlier. Both structures are truncated by a major east-west trending south-side-down fault that runs the entire width of the quadrangle (Plate 1). Its displacement of about 2,000 feet (600 meters) accounts for all of the topographic difference between the northern ridge crest at Grassy Lookout (10,000 feet, or 3,050 meters) and the San Mateo saddle at the south edge of the map area (8,000 feet or 2,440 meters).

Structure along the southwest edge of the quadrangle is probably similar to structure in the northeast corner, except that the fault blocks are steeply west-tilted. Similarly, the west-side-down fault zone (overlapped by strata of the unit of East Red Canyon) is probably akin to the east-side-down master fault on the east side of the ridge crest. Very little is known about how far this strip of west-tilted South Canyon Tuff continues. It must die out to the north, because there is no evidence of it in the quadrangle which joins the Grassy Lookout quadrangle to the northwest (Osburn, 1990). To the west, detailed mapping does not exist, but Deal's (1973) reconnaissance map shows no evidence of extensive areas of steeply west-tilted strata.

Definition of tilt domains

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 bounds 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 cauldrons in the Socorro area (including the Mt. Withington Cauldron) overlap the SAZ. The SAZ probably represents a long-lived crustal flaw coincident or related to the Morenci lineament. Generation and propagation of the Oligocene magmas appears to be related to the zone. The SAZ is usually shown dying out in the northern San Mateo Mountains (Chapin, 1989, p.49) somewhere within the northern Mt. Withington Cauldron. In the northern Grassy Lookout quadrangle, the east-side-down master fault (discussed earlier) trends northeastward towards a possible connection with the SAZ (Figure 1).

Structural geology of the northern San Mateo Mountains ridge crest as described above, is similar to structural patterns of fault blocks within the SAZ farther east (Chapin, 1989). However, the northerly trend of the tilt domain transition in the San Mateo Mountains is actually more compatible with it being classified as an anticlinal 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). On Stewart's (1980) map of tilt domains in the basin and range of the southwestern United States, an orthogonal junction is shown between a transverse (the SAZ) and an antiformal boundary in the northern San Mateo Mountains. Detailed mapping shows that this junction is probably a curved transitional change from transverse to antiformal achieved partially through broad folding by a pair of northwest-trending en echelon (southwest-stepping) anticlines along the San Mateo ridge crest, and partially by abrupt tilt changes along the curving east-side-down master fault in the northern part of the quadrangle. Location of this transition in the northwest corner of the Mt. Withington Cauldron 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. Area underlain by silicic cauldrons in the Socorro area are characterized by moderate to severe extension. Terrain to the north and west of the Mt. Withington Cauldron, on the other hand is characterized by the absence of major Oligocene silicic centers, and is part of a weakly extended domain transitional between the basin and range province and the Colorado Plateau to the north.

The anticlinal tilt-domain boundary in the southern part of the Grassy Lookout quadrangle occurs across the complex west-side-down fault zone that is partially buried by coarse-grained deposits of the unit of East Red Canyon. This anticline is an en echelon continuation of a broader anticline in the northern part of the quadrangle. Very little is known about the southward continuation of this anticlinal feature. A north-trending broad anticline that folds latest Oligocene strata has been mapped along the southwest edge of the San Mateo Mountains by Mike Hermann and Gene Cox (unpublished mapping, see anticline on Figure 1). This may be the continuation of the structure recognized in the Grassy Lookout quadrangle.

Timing of extensional deformation

Shortly after formation of the Mt. Withington Cauldron, an episode of rapid thin-skinned style extension led to the development of two highly extended terrains in the Grassy Lookout quadrangle: 1) throughout most of the northeast corner, and 2) along a narrow strip in the southwest corner. The fault blocks are composed of moderately to steeply dipping (35° to 60°) intracauldron South Canyon Tuff. These fault blocks are east-tilted to the east of the San Mateo Mountains ridge crest, and west-tilted to the west.

In the southern Grassy Lookout quadrangle, and in the Tenmile Hill 7.5' quadrangle (Ferguson, 1988), a shallow east-dipping (5° to 15°) latest Oligocene sequence of volcaniclastic strata (unit of East Red Canyon) and the tuff of Turkey Springs, unconformably overlies both of the steeply dipping terrains of intracauldron South Canyon Tuff. Precise $^{40}Ar/^{39}Ar$ geochronology of the South Canyon Tuff (27.3 Ma) and the tuff of Turkey Springs (24.3 Ma) by Bill McIntosh (1989) constrains most of the tilting (30° to 45°) within a narrow interval of time at the end of the Oligocene. The relationship of tilt versus time in the Grassy Lookout and Tenmile Hill quadrangle (Figure 5a) shows a pronounced tilt rate decrease near the end of the Oligocene. In terms of total extension for this area, 75% of it was achieved during the final 3 million years of the Oligocene, and it is likely that most of it occurred within 1 million years after eruption of the South

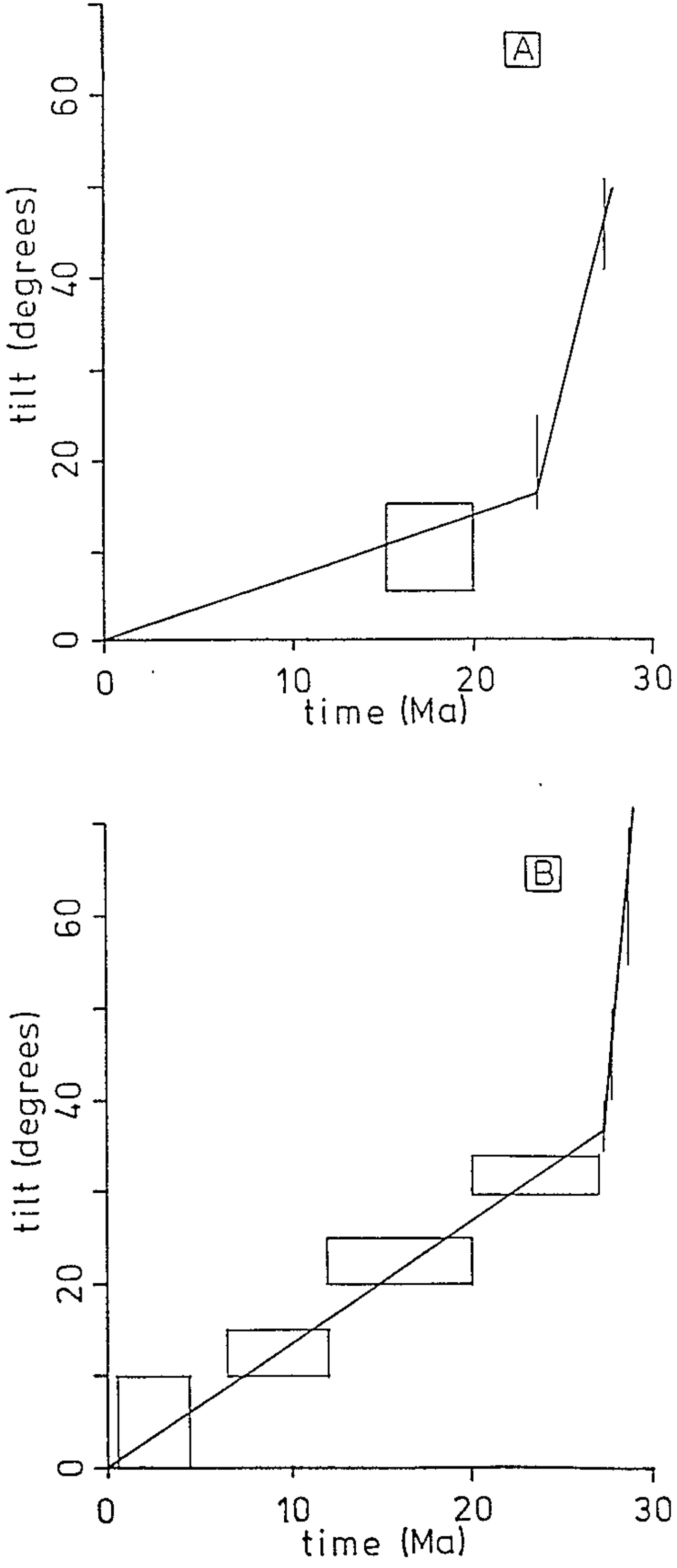

Figure 5. Tilt-versus-time curves for Mid-Tertiary strata in two areas of the Rio Grande Rift near Socorro. The range of variation in tilt and age for each sequence is shown. Precisely dated ash-flow tuff units are depicted by vertical lines and sedimentary sequences by boxes. A) Curve for strata in the Milligan graben area between the San Mateo Mountains and Magdalena Mountains. Data from Ferguson (1988). B) Curve for strata in the Lemitar Mountains just northeast of Socorro. Data from Chamberlin (1983).

Canyon Tuff. A tilt versus time graph (Figure 5b) for another zone of high extension near Socorro where about 60% of the total extension occurred between 28.5 Ma and 27.3 Ma (Chamberlin, 1983) is included for comparison.

Neogene tectonic activity has been documented in the basin immediately east of the San Mateo Mountains (Milligan graben). West-side-down recent faults that cut the 400,000 year old Cuchillo surface (Gile and others, 1981) are described by Machette (1987) in the southern part of the graben, and by Ferguson (1988) just to the east (in the adjacent Tenmile Hill 7.5' quadrangle). Displacement of the Cuchillo surface in the Tenmile Hill quadrangle is about 3 meters. This offset of a 400,000 year old surface is qualitatively compatible, by comparison of fault throw with magnitude of tilt for a reasonable (2-5 km) spacing of fault blocks, with the youthful part of the extensional history curve for this area (Figure 5a).

Importance of a sub-caldera pluton

Because basin and range extension was initiated during the waning stages of silicic volcanism in the Socorro area (Chapin, 1979), it is not surprising that strain patterns were greatly influenced by young volcanic structures and shallow ductile intrusions. Osburn and Ferguson (1986) concluded that orthogonal fault patterns, northwest and southeast of the Mt. Withington Cauldron, reflected the influence of pre-Tertiary basement structures. Parallel faults, oriented normal to the probable late Oligocene least-principle stress direction, within the cauldron, and east of the San Mateo Mountains northern ridge crest, are thought to reflect the presence of a shallow pluton, which diminished the control of basement structure on strain patterns.

The intracauldron area displaying parallel fault patterns is characterized by large (60-100%) magnitudes of extension, most of which occurred in a less than 3 million year interval at the end of the Oligocene. A shallow sub-caldera pluton could help explain this rapid pulse of high extension which is conspicuously confined within the Mt. Withington Cauldron. Just after its emplacement, it is likely that the hot pluton was extended in a ductile fashion parallel to the least-principle stress direction. Concurrently, extension at the surface was achieved through brittle faulting of the thick intracauldron sequence. This scenario is depicted in a structural model (Figure 6) where domino-style faulting occurs above a detachment which represents the brittle-ductile transition elevated to shallow depths (~ 5km) just after emplacement of the sub-caldera pluton. A steep breakaway fault is depicted near the west edge of the cauldron complex, and corresponds to the tilt-domain bounding master fault that occurs along the east side of the San Mateo Mountains ridge crest. The space problem across this structure is 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 into the gap.

The final stage of the model (Figure 6) depicts a

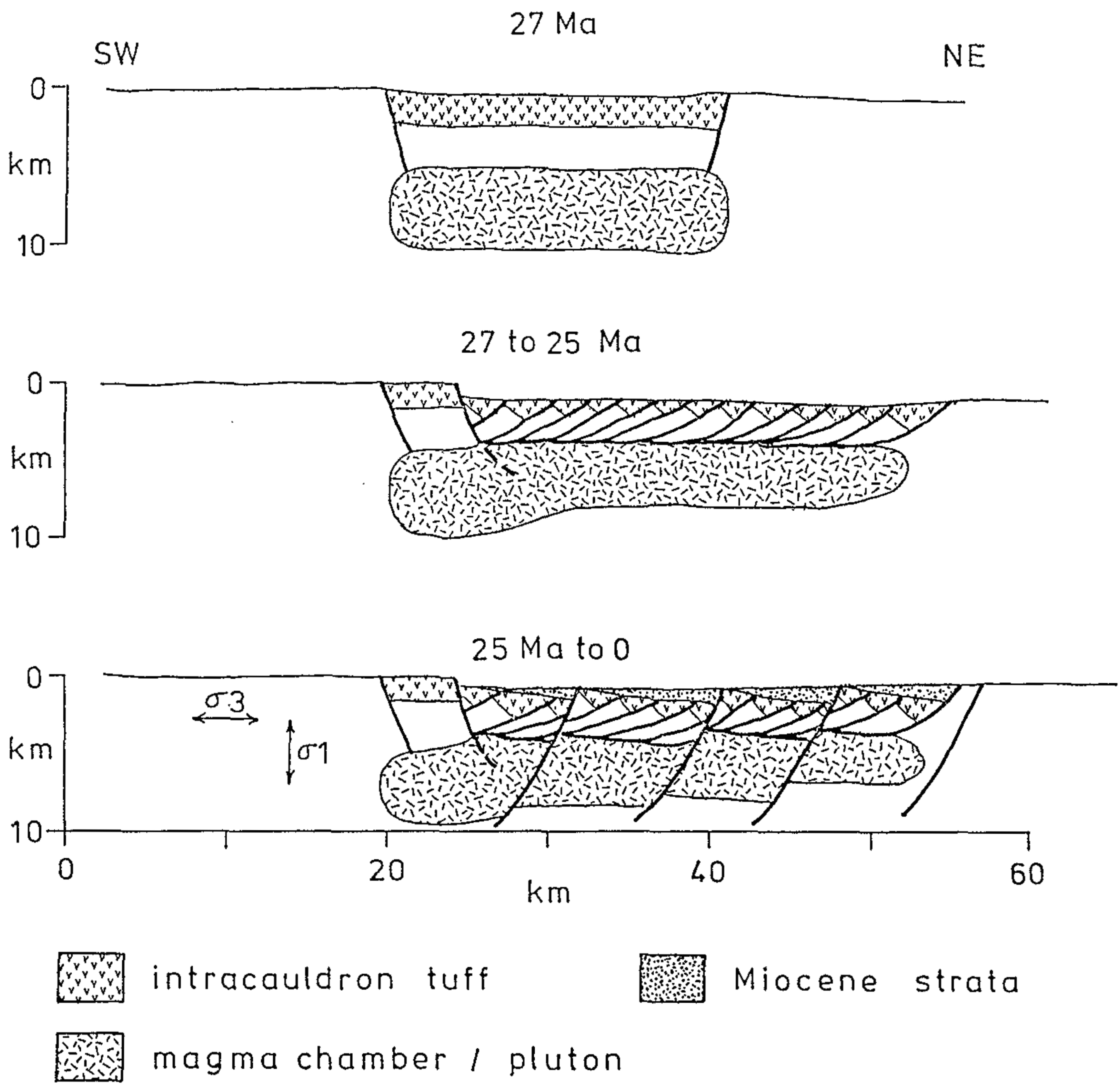

Figure 6. Structural model for extensional evolution of the Mt. Withington Cauldron, late Oligocene through present. The cross-sectional plane is oriented parallel to the long dimension of the cauldron (Figure 1a) and with the Mid-Tertiary least principle stress direction parallel to the page. The first stage (27 Ma) depicts the crustal section just after formation of the cauldron. The second stage (27 to 25 Ma) depicts a rapid pulse of extension expressed at the surface by listric faulting above a shallow detachment, and ductile stretching of the sub-caldera magma chamber. The final stage (25 Ma to present) depicts a brittle pluton, a gently east-dipping Oligocene-Miocene angular unconformity, and deep-seated normal faulting.

protracted phase of deep-seated faulting characterized by weak magnitudes of extension. This stage reflects post magmatic cooling, depression of the brittle-ductile transition, and strengthening of the crust. Similar changes in structural style and behavior of the continental crust in other areas of the Rio Grande Rift during this time interval are described by Morgan and others (1986).

Economic Geology

The Grassy Lookout quadrangle is host to the Rosedale epithermal gold district (Neubert, 1983), and much of the north-central part of the quadrangle is underlain by large areas of altered and mineralized intracauldron South Canyon Tuff. The most intense alteration is concentrated along the north-northwest trending faults between North Canyon and Big Rosa Canyon, and along the Lemitar Tuff - South Canyon Tuff contact near the head of North Canyon. Areas affected by argillic alteration (of varying degrees) are shown on Figure 7. Timing of the mineralization and alteration in the Rosedale district was probably shortly after emplacement of the South Canyon Tuff. Argillic alteration typically overprints and cross-cuts fault zones attributed to the late Oligocene thin-skinned phase of extension, but younger basin and range style high-angle faults sometimes juxtapose altered and unaltered rock. The driving force for the epithermal system was most likely the sub-caldera pluton.

Samples of quartz vein material and/or intensely altered

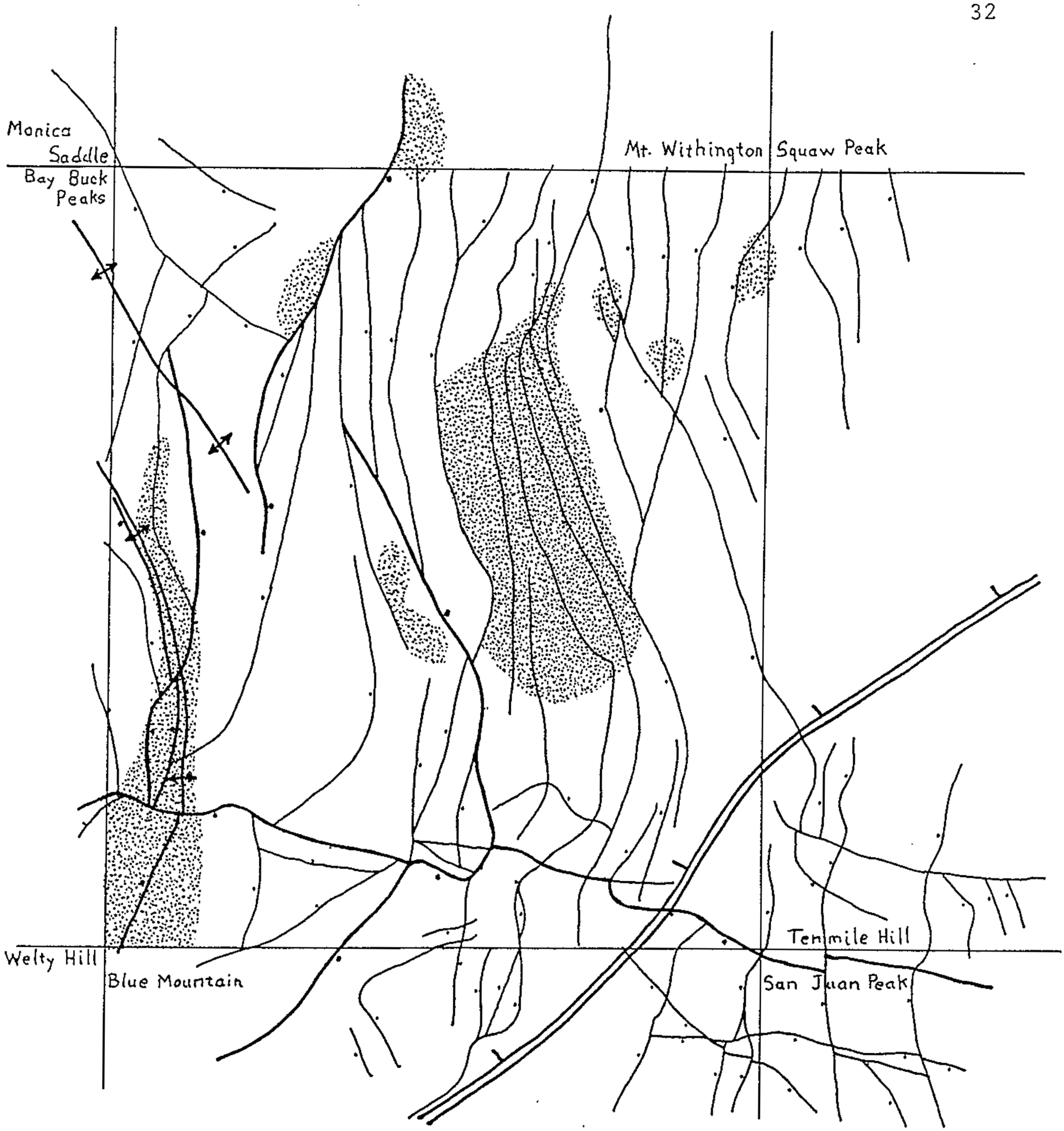

Figure 7. Structure of the Grassy Lookout quadrangle and adjoining areas (names of adjoining quadrangles are given). Faults depicted with extra thick lines are those discussed in text (fault patterns section). Also shown are a pair of en echelon anticlines on the west edge of the map area, and the southeast Mt. Withington Cauldron margin (Double barbed line). Stipled area represents regions of argillic alteration. The Rosedale epithermal gold district is located in the center of the largest alteration zone.

hematite coated South Canyon Tuff were collected from remote areas in the Grassy Lookout quadrangle for fire-assay. Most analyses (samples located on Plate 3) are unpromising (Table 1), but some areas certainly deserve more attention.

Another possible economic prospect worth investigating in the central San Mateo Mountains is from an industrial minerals perspective. The lower part of the tuff of Turkey Springs throughout the southern Grassy Lookout quadrangle is characterized by large fluffy pumice fragments that constitute up to 20% of the rock volume. In some areas these pumice are replaced by large amounts of pinkish and peach-colored zeolite minerals (unidentified). Because of the substantial thickness (200 feet or 60 meters) of this potentially mineralized interval, the central San Mateo Mountains should be considered as a possible resource area for zeolite minerals.

Conclusions

Detailed mapping within the Mt. Withington Cauldron has helped define three major stratigraphic zonal variations of intracauldron South Canyon Tuff. Each zone is thought to represent major eruptive phases that tapped progressively deeper and less evolved material from a sub-caldera magma chamber.

Mapping in the Grassy Lookout quadrangle has located a regional basin and range antiformal tilt-domain boundary defined by two structural features in the northern San Mateo Mountains. The first is a group of three en echelon

Table 1. Fire assay analyses of samples collected in the Grassy Lookout quadrangle. Analyses given in ounces per ton. Location of samples provided on Plate 3.

Sample	Gold	Silver
NM-89-1	0	0.44
NM-89-2	0	0.04
NM-89-9	0	0
NM-89-10	0	0.20
NM-89-10b	0	0
T-89-11	0	0
NM-89-13	0	0
NM-89-16a	0	0.12
NM-89-16b	0	0
NM-89-16c	0	0.04
NM-89-16d	0	0
NM-89-17	0	0
NM-89-18	0	0
NM-89-19a	0	0.12
NM-89-19b	0	0.04
NM-89-19c	0	0.90
NM-89-20	0.04	0.64
NM-89-23a	0	0.78
NM-89-23b	0	0.34
NM-89-23h	0	0.12
NM-89-24	0	0.08
NM-89-29	0	0
NM-89-33	0	0.04
NM-89-34	0	0.22
NM-89-35	0	0
NM-89-36	0	0
T-89-42a	0	0.26
T-89-43	0	0.10
T-89-XXX	0	0
NM90-2	0	0
NM90-14	0	0,02
NM90-22	0	0
NM90-45	0	0

east-side-down normal faults, two of which run along the east side of the northern San Mateo Mountains ridge crest. the third runs along the west side of the ridge crest. The two eastern faults, particularly in the north part of the map area, bound steeply east-tilted blocks on their east sides from gently tilted strata on the west. A second structure, defining the tilt-domain boundary, is a north-northwest trending broad anticline in the northwest part of the quadrangle. This broad anticline dies out in the west-central part of the quadrangle, but steps en echelon to the west into a tighter asymmetric anticline cut by a west-side-down fault zone. The antiformal tilt-domain boundary formed by these en echelon faults and folds probably merges within 5 to 10 km to the north with the Socorro Accommodation Zone, an important regional transverse tilt-domain boundary. Detailed mapping to the west and south is needed before I would comment seriously on the southward continuation of this tilt-domain boundary.

Detailed mapping (Ferguson, 1986; 1988; this report) along with paleomagnetic and geochronologic work by Bill McIntosh (1989) has constrained a rapid pulse of thin-skinned style extension within the Mt. Withington Cauldron just after its emplacement (the last 3 million years of the Oligocene). Domino-style listric faulting at the surface is inferred to be synchronous with ductile extension of an approximately 5 km deep sub-caldera magma chamber. A later phase of thick-skinned basin and range style extension (Miocene to present) was characterized by high-angle faulting and is thought to reflect a cooler and stronger crustal section.

The antiformal tilt domain boundary that runs north-south along the west-central part of the Grassy Lookout quadrangle joins with the S.A.Z. to the north and acts as a boundary between relatively thick continental crust, transitional to the Colorado Plateau, and thin crust of the Rio Grande Rift that was pierced and weakened by a suite of Oligocene plutons.

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Qal	Alluvium
Qt	Talus and colluvium covered talus
Qp	Palomas Formation. Semiconsolidated sandstone and sandy conglomerate.
Ttspb	Phreatic breccia pipe developed in welded tuff of Turkey Springs.
Tts	Tuff of Turkey Springs. Welded upper member.
Ttsl	Tuff of Turkey Springs. Unwelded basal member.
Tr3	Rhyolite lava flows and intrusions younger than South Canyon Tuff.
Tr3t	Ash-flow tuffs interleaved with lava flows in Horse Mt. Canyon area.
Ter	Unit of East Red Canyon. Volcaniclastic breccia, conglomerate, and sandstone and unwelded plinian ash beds and lithic-rich ash-flow tuffs. Epiclastic deposits dominate in East Red Canyon area. Pyroclastic deposits dominate in Box Draw, Hudson, and Spring Canyon.
Tsc	South Canyon Tuff undifferentiated. Rhyolite ash-flow tuff.
Tscbv	South Canyon Tuff. Lithic breccias associated with moderately crystal-rich (15%) brown to black vitrophyre. Found only in southwest corner.
Tscb	South Canyon Tuff. Clast-supported lithic breccia lenses. Restricted to southeast corner.
Tsc5	South Canyon Tuff. Moderately crystal-rich (10-20%) feldspar-bearing ash-flow tuff characterized by light gray color and lack of quartz phenocrysts. Restricted to northeast part of map area.
Tsc4	South Canyon Tuff. Crystal-rich (20-30%) quartz, feldspar bearing ash-flow tuff. Also characterized by reddish color and lithic fragment content up to 10%.
Tsc3	South Canyon Tuff. Moderately crystal-rich (10-20%) quartz, feldspar bearing light gray ash-flow tuff.
Tsc2	South Canyon Tuff. Crystal-poor (5-10%) lithic-rich (5-30%) quartz, feldspar bearing reddish ash-flow tuff.
Tscl	South Canyon Tuff. Crystal-poor (1-5%) quartz, feldspar bearing light gray ash-flow tuff.
Tscu	South Canyon Tuff. Basal Member, composed of unwelded bedded ash. Restricted to North Canyon area, eastern edge of map.
Tscv	South Canyon Tuff. Widespread basal member composed of crystal-poor quartz, feldspar bearing brown to black vitrophyre.
Tic	Unit of Indian Creek. Red volcaniclastic sandstone and conglomerate. Shown only on cross-section G-G'.

Tr2 Rhyolite lava older than South Canyon Tuff.

Tl Lemitar Tuff. Crystal-rich quartz, feldspar bearing reddish rhyolite ash-flow tuff. Characterized, when thicker than about 30 meters, by a quartz deficient internal zone.

Trl Rhyolite lava and intrusions older than the Lemitar Tuff.

Tvp Vicks Peak Tuff. Crystal-poor (0-3%) feldspar bearing light gray rhyolite ash-flow tuff.

Tj La Jencia Tuff. Crystal-poor (1-7%) light reddish gray feldspar bearing rhyolite ash-flow tuff.

All Tertiary units are late Oligocene in age.

SYMBOLS

24 strike and dip of bedding, sedimentary and pyroclastic rocks

30 strike and dip of eutaxitic foliation, welded ash-flow tuffs

33 strike and dip of pilotaxitic foliation, flow-banded lavas and intrusions

trend of lineated pumice fragments in welded ash-flow tuffs, azimuth corrected for tilting

contact, dashed where approximately located

fault, ball on downthrown side, dashed where approximately located, dotted where concealed by younger deposits, dip shown where fault plane is exposed

apparent dip of eutaxitic foliation on cross-sections, shown only if not parallel to depositional contacts

arrow indicates direction of fault motion on cross-sections

Explanation NMBM&MR Open-file Report 366

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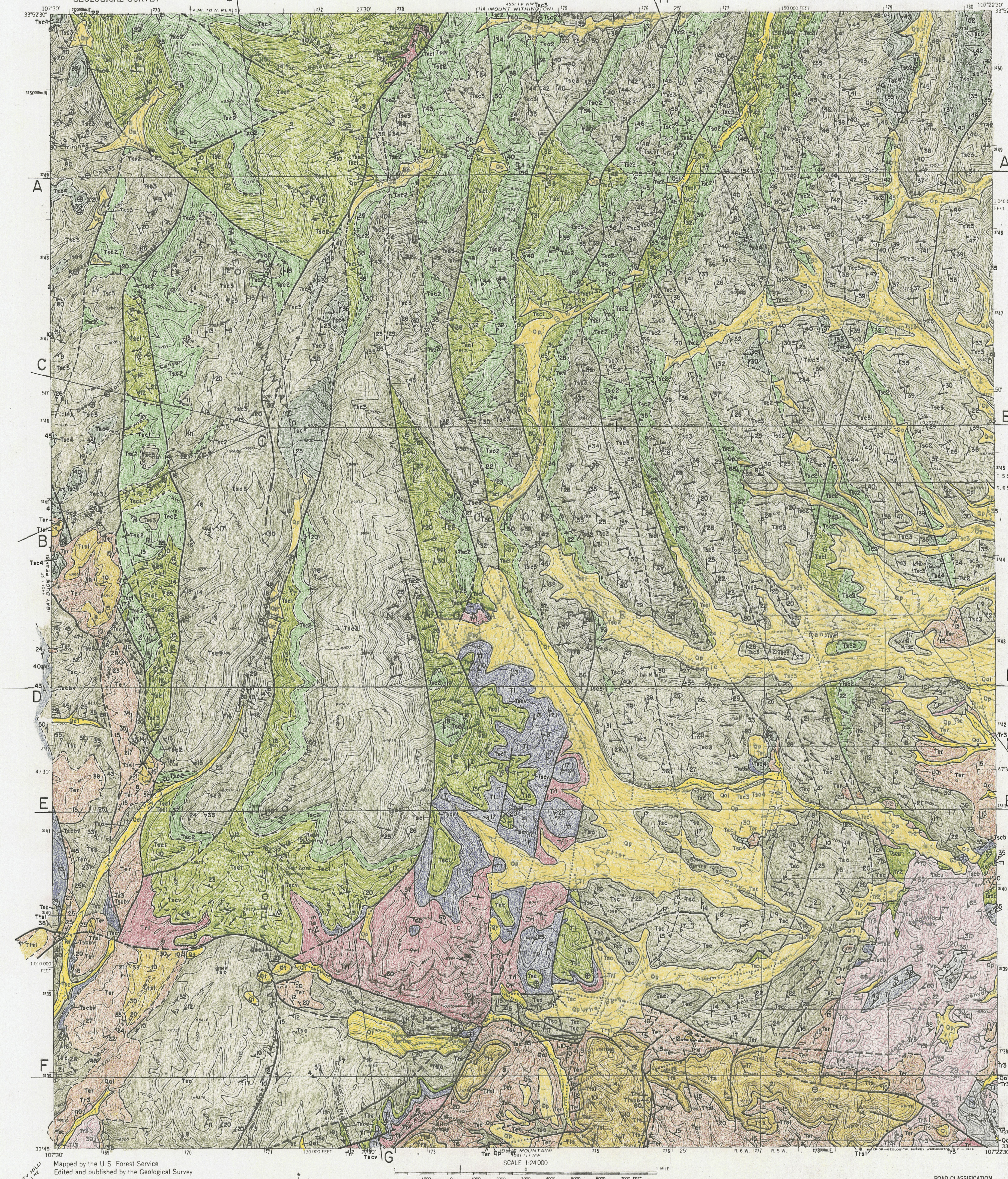
arrow indicates direction of fault motion on cross-sections

Geologic map, Grassy Lookout 7.5' quadrangle, Socorro County, New Mexico NMBM&MR Open-file Report 366 Plate 1

by Charles A. Ferguson June, 1990

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GRASSY LOOKOUT QUADRANGLE
NEW MEXICO–SOCORRO CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)



geologic mapping by C. A. Ferguson: 1983,1989,1990

assisted by Tim Janns, 1989

Gabriel Viehweger, 1990

Mapped by the U.S. Forest Service
Edited and published by the Geological Survey
Control by USGS, USC&GS, and U.S. Forest Service
Topography by photogrammetric methods from aerial photographs taken 1952 and 1956. Field checked by USGS 1964
Polyconic projection. 1927 North American datum
10,000 foot grid based on New Mexico coordinate system, central zone
1000-meter Universal Transverse Mercator grid ticks, zone 13, shown in blue
Certain land lines are omitted because of insufficient data

UTM GRID AND 1964 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24 000

CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL

ROAD CLASSIFICATION
Unimproved dirt

QUADRANGLE LOCATION

GRASSY LOOKOUT, N. MEX.

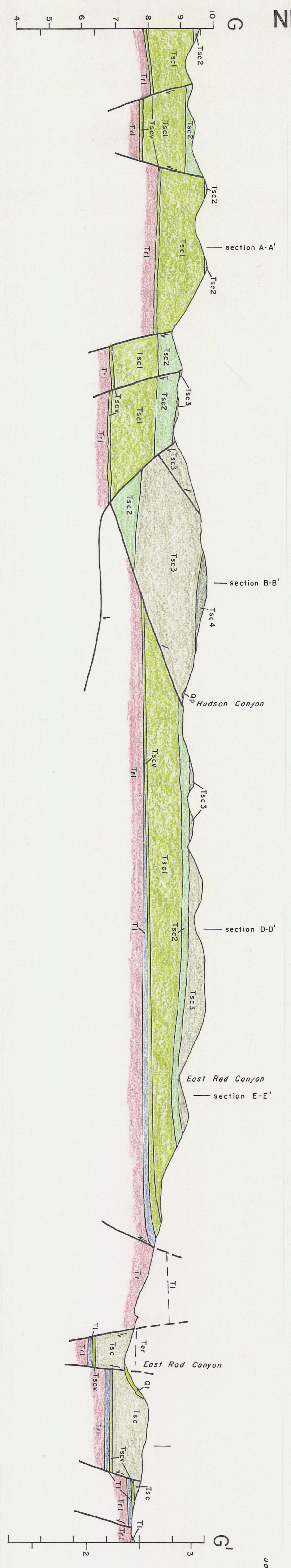
Geologic Cross-sections, Grassy Lookout 7.5' quadrangle

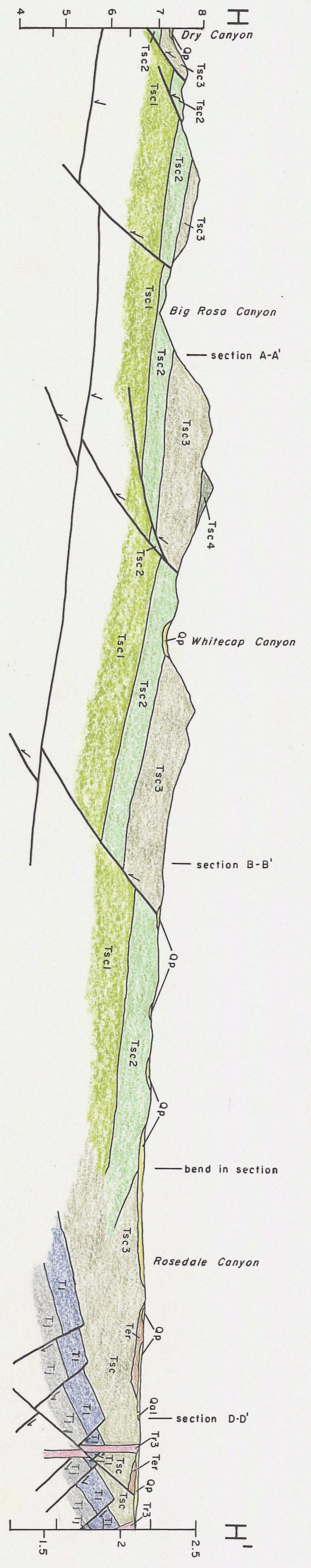
NMBM&MR Open-file Report 366 Plate 2

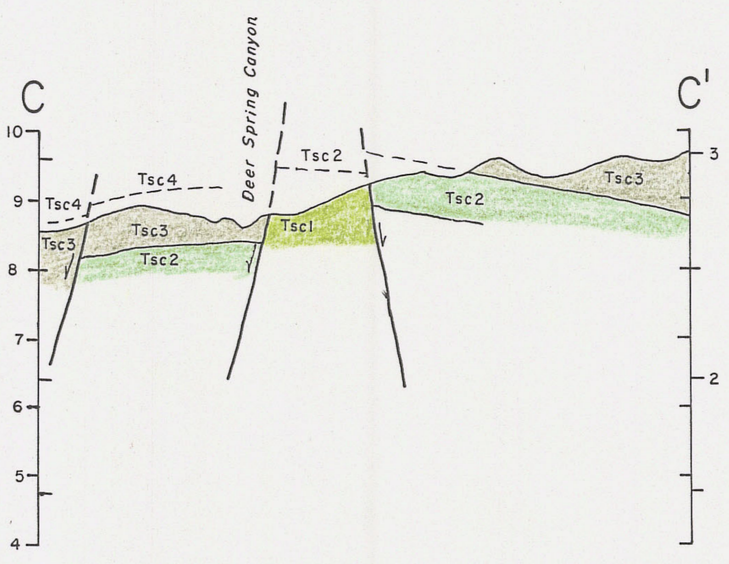
by Charles A. Ferguson, June, 1990

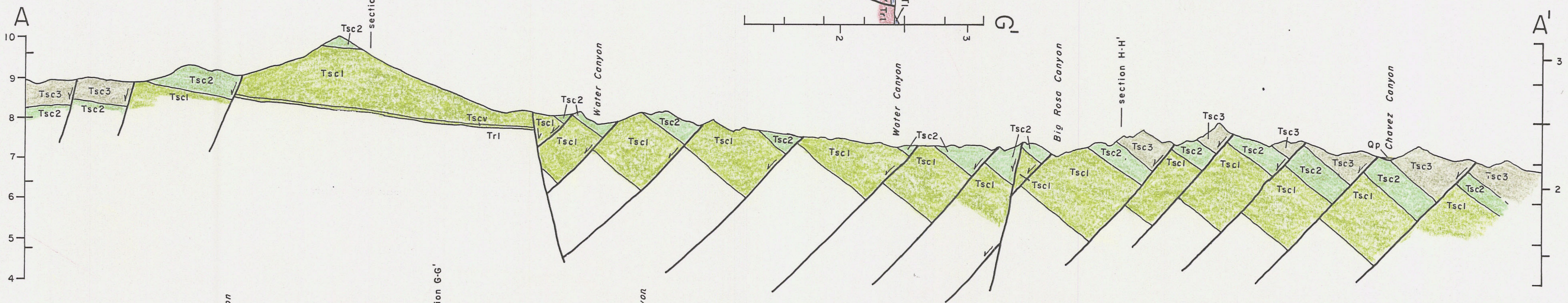
horizontal scale equal to vertical scale,

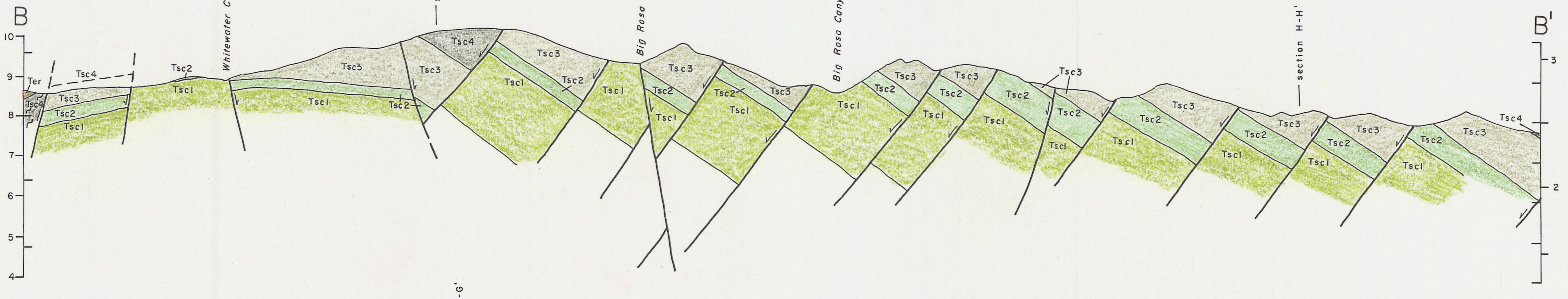
left: x 1,000 feet, right: x 1,000 meters

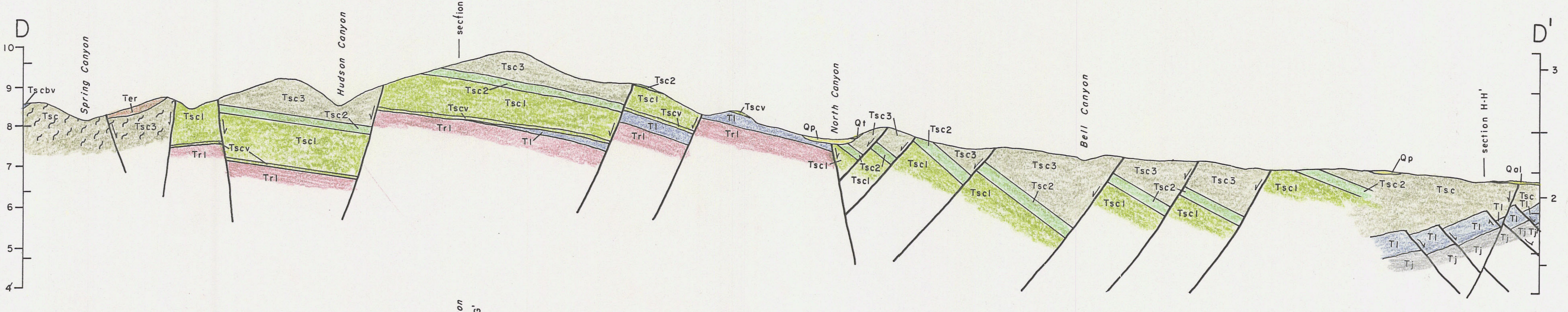


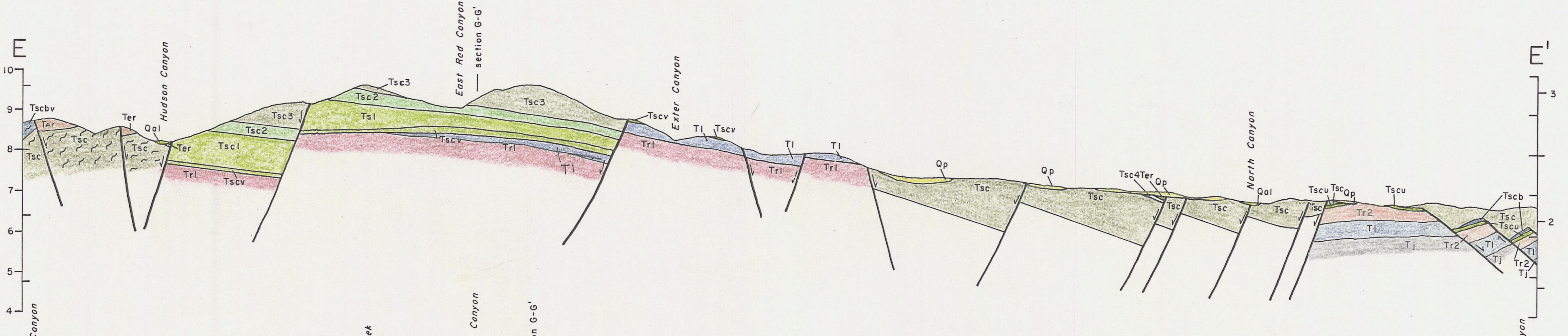


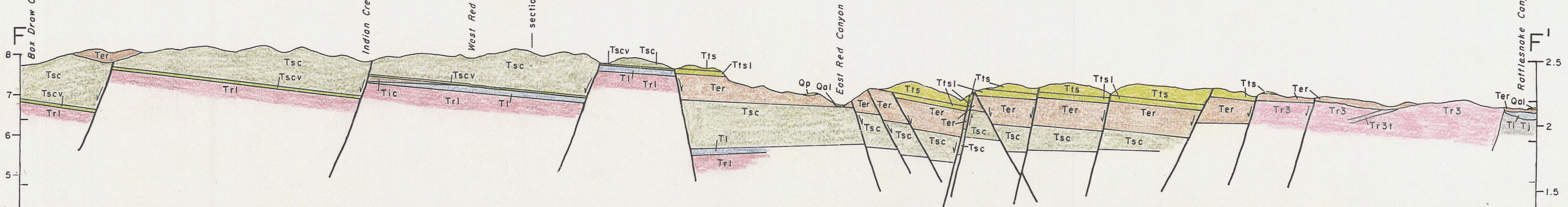












fire assay sample locations

Plate 3, NMBM&MR Open-file Report 366

UNITED STATES
DEPARTMENT OF THE INTERIOR
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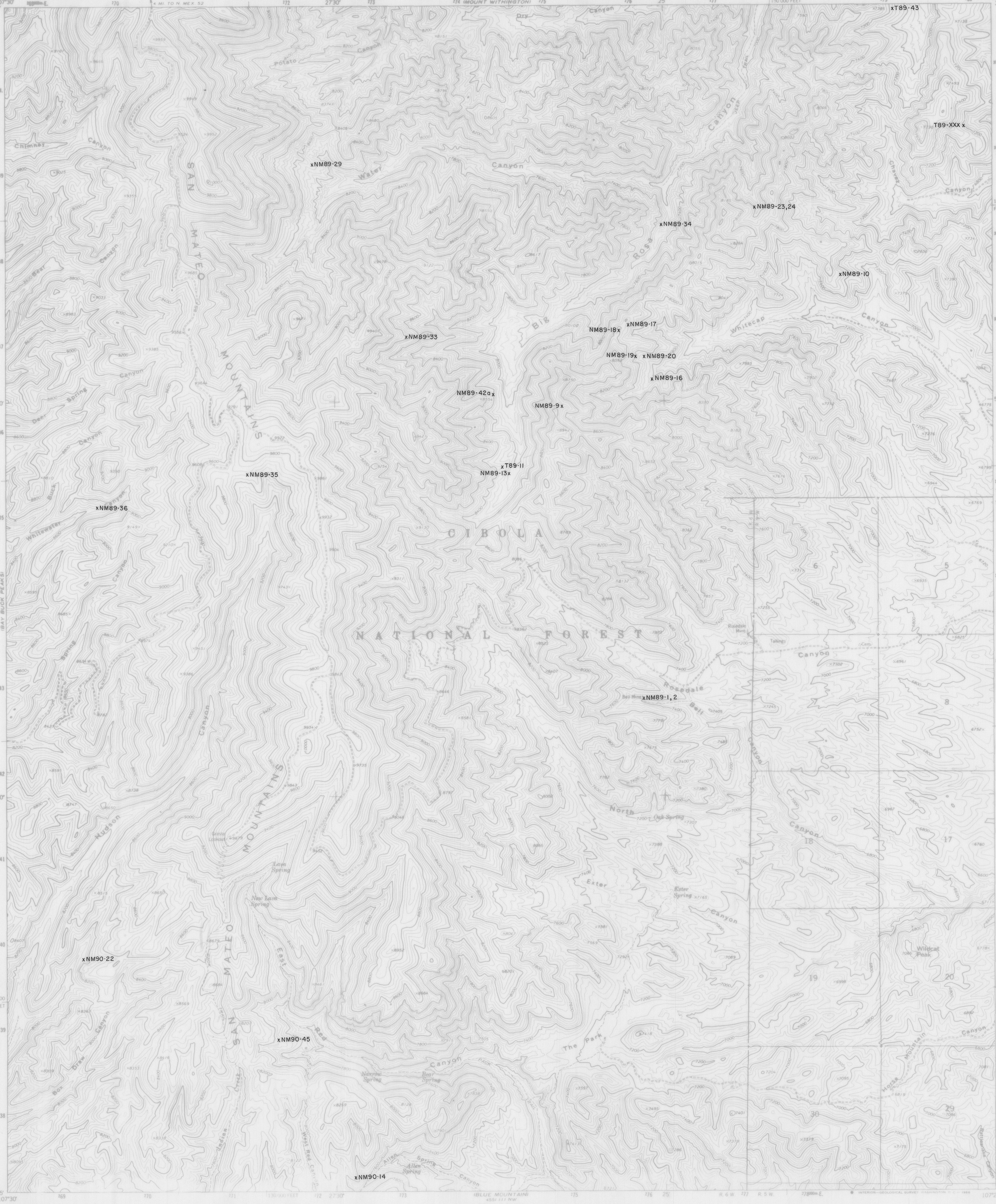
GRASSY LOOKOUT QUADRANGLE
NEW MEXICO–SOCORRO CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)



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Topography by photogrammetric methods from aerial photographs taken 1952 and 1956. Field checked by USGS 1964

Polyconic projection. 1927 North American datum
10,000-foot grid based on New Mexico coordinate system, central zone
1000-meter Universal Transverse Mercator grid ticks, zone 13, shown in blue

Certain land lines are omitted because of insufficient data

UTM GRID AND 1964 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

SCALE 1:24000

CONTOUR INTERVAL 40 FEET
DATUM IS MEAN SEA LEVEL

ROAD CLASSIFICATION
Unimproved dirt

QUADRANGLE LOCATION

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U. S. GEOLOGICAL SURVEY, DENVER, COLORADO 80225, OR WASHINGTON, D. C. 20242
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST

GRASSY LOOKOUT, N. MEX.
N3345—W10722.5/7.5

1964