OPEN FILE REPORT 123

GEOLOGY OF THE SQUAW PEAK AREA, MAGDALENA MOUNTAINS, SOCORRO COUNTY, NEW MEXICO

by

Martin A. Donze

Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Science in Geology

New Mexico Institute of Mining and Technology

Socorro, New Mexico
May, 1980

TABLE OF CONTENTS

PLATES

FIGURES

ABSTRACT

The Squaw Peak area in the southwestern Magdalena Mountains has a complex volcanic history. Two overlapping cauldrons intersect in this area and a third cauldron may be present. The western margin of the North Baldy cauldron is probably buried beneath younger units in the central or western part of this area. The Magdalena cauldron margin is well exposed to the north (Allen, 1979; Bowring, 1979) and projects across the central part of this study area. The eastern margin of a cauldron related to eruption of the Tuff of Lemitar Mountains may be present in the western part of this study area or alternatively, the tuff of Lemitar Mountains may have filled the topographic depression of the older Magdalena cauldron. Rift-related fanglomerate sedimentation (Popotosa Formation) definitely occurred after eruption of the tuff of South Canyon and may have started prior its emplacement. Andesitic and rhyolitic lavas were emplaced contemporaneous with Popotosa sedimentation; the rhyolite of Magdalena Peak (13.6 m.y.) postdates the Popotosa deposition in this study area.

Extensional faulting began prior to, or during, the time interval 31.7 to 26.6 m.y. ago. In general, the faults trend north-northwest with normal, down-to-the-west

displacements and eastward rotation of fault blocks. A strong transverse structural trend occurs along the inferred Magdalena cauldron margin.

The Hells Mesa Tuff has been propylitically altered and the tuff of Lemitar Mountains, several domes and intrusions, and possibly the tuff of South Canyon have been potassically metasomatized. These alterations are consistent with the regional alteration in the Socorro-Magdalena area. Rhyolitic lavas interbedded with the Popotosa Formation were emplaced after the major geothermal alteration event. Minor manganese mineralization in joints and breccia zones is probably related to this geothermal event.

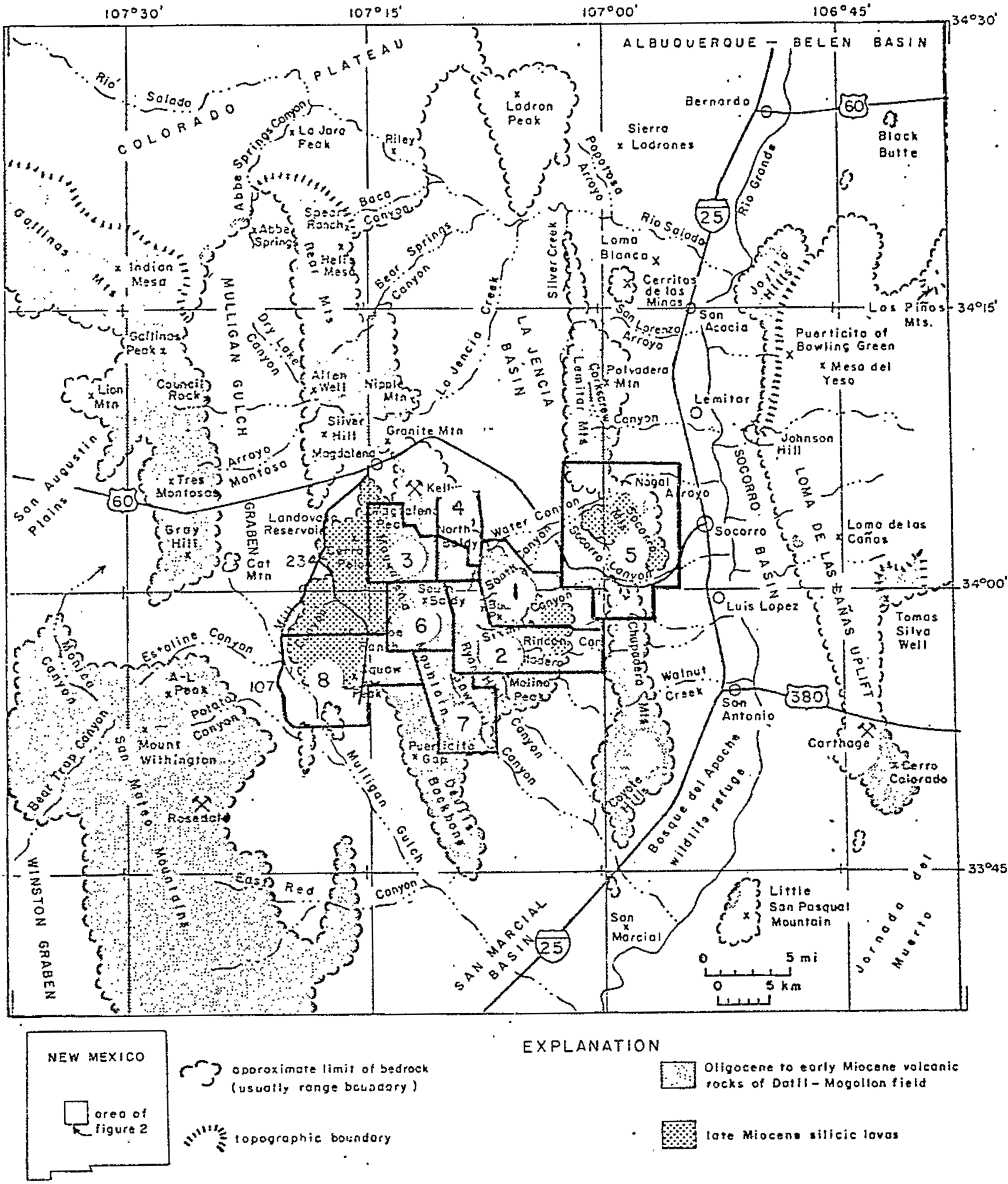
INTRODUCTION

Area of Study

This study area is in the southwestern Magdalena Mountains approximately 23 miles southwest of Socorro and about 14 miles south of Magdalena. The area encompasses approximately 35 square miles, including the southern half of the Squaw Peak quadrangle east of State Highway 107 and a two-mile-wide strip on the adjacent South Baldy quadrangle west of Hardy Ridge. Figure 1 shows the location of the study area in relation to other geographic and physiographic features, and routes of access.

Geologic Setting

The Rio Grande rift transects New Mexico forming a series of basins which extend into Colorado. In the Socorro-Magdalena area, the rift broadens forming a series of parallel basins and intrarift horsts (Chapin, C. E., 1971). The La Jencia Basin and Mulligan Gulch graben are examples of parallel basins separated by the Magdalena



1.) Osburn, 1978
2.) Petty, 1979
3.) Allen, 1979
4.) Sumner, 1980
5.) Chamberlin, 1980
6.) Bowring, 1980
7.) Roth, in progress
8.) This study

Figure 1. Location map showing this study area and relationship to some of the other studies done in the Magdalena and Socorro-Lemitar Mountains, routes of access, and other geographic and physiographic features.

Mountains which is an intrarift horst.

The volcanic rocks exposed in the Socorro-Magdalena area include latitic conglomerates, mudflows, sandstones, lavas, and ash-flow tuffs representing the volcaniclastic apron that formed around the Datil-Mogollon volcanic field before the ignimbrite climax (Chapin and others, 1978). Overlying this volcaniclastic apron are rhyolitic ash-flow tuffs with interbedded basaltic-andesite and rhyolitic lavas.

Two major crustal lineaments, the Morenci and Capitan lineaments, intersect in the Socorro area and have had a major influence on tectonics and magmatism in this area. The Morenci lineament forms a domain boundary that separates two fields of faulted and rotated blocks (Chapin and others, 1978). North of the lineament blocks are stepfaulted to the east and rotated to the west while south of the lineament the blocks are stepfaulted to the west and rotated to the east. This structural style greatly complicates interpreting the preexisting volcanic structures.

Objectives

The main objectives of this study area include: 1) to determine the Cenozoic stratigraphy of the area and to correlate stratigraphic units with those established in adjacent areas; 2) to establish the structural framework of the area; 3) to prove, or disprove, the existence of the North Baldy, Hop Canyon, and Magdalena cauldron margins which have been proposed to pass through the study area (Chapin and others, 1978); and 4) to evaluate the mineral potential of the area.

Previous Work

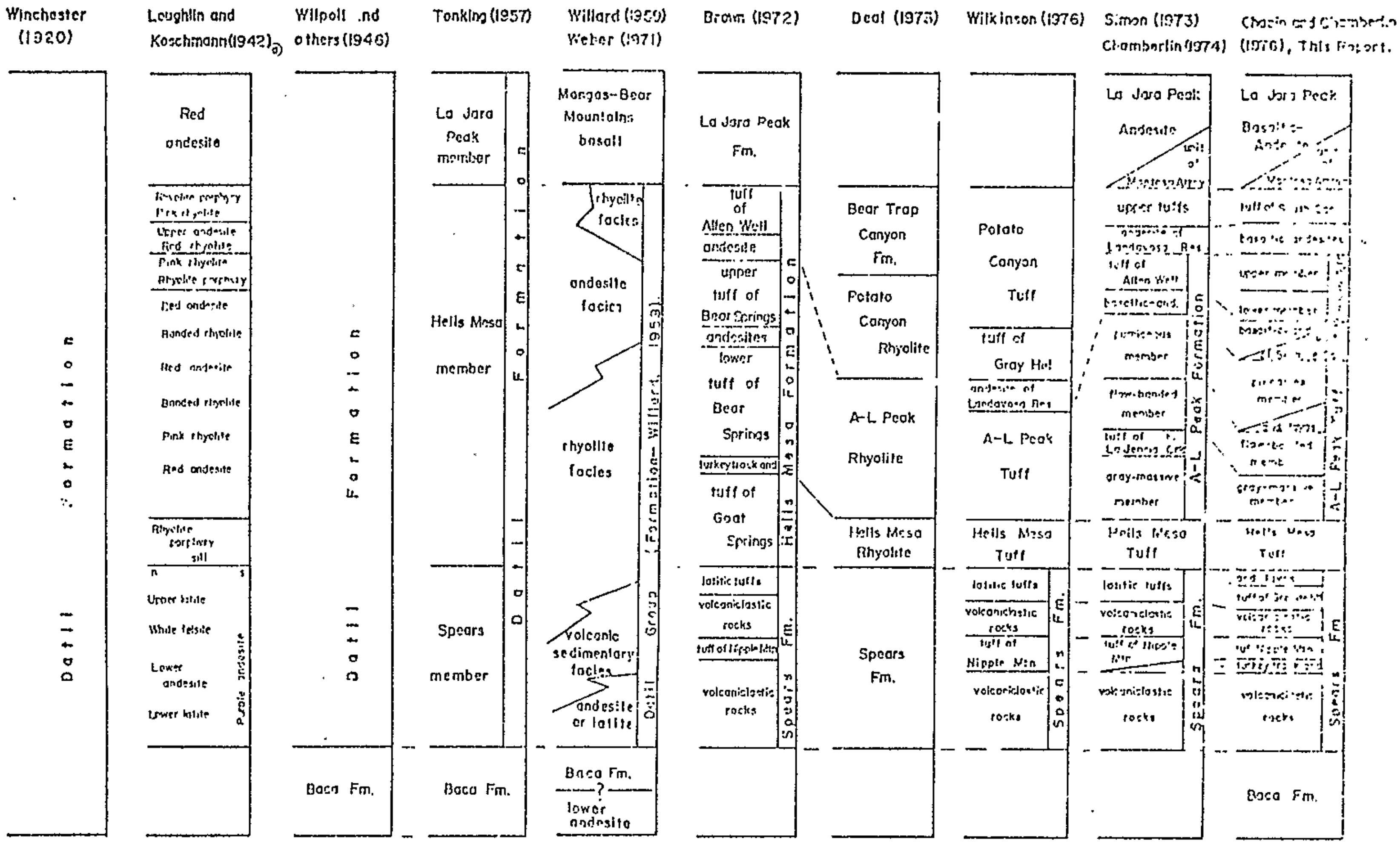
The stratigraphic nomenclature of the Datil-Mogollon volcanic field in the Socorro-Magdalena area has been developed over the past few years by a group of studies known as the Magdalena Project. Figure 1 summarizes some of the workers and areas mapped during the Magdalena Project.

Other recent investigations include Deal (1973), Krewedl (1974), and Spradlin (1976). Deal mapped nearly 300 square miles in the San Mateo Mountains on a reconnaissance basis and proposed a large resurgent cauldron with the eastern margin within this study area. Krewedl mapped an area in the central Magdalena Mountains on a reconnaissance basis. Spradlin (1976) mapped the volcanic rocks of the Joyita Hills at 1:24,000 and produced an excellent stratigraphic column. The chronologic development of the volcanic, stratigraphic nomenclature in the Socorro-Magdalena area is summarized in Figure 2.

Methods of Investigation

Geologic field mapping was done at a scale of 1:24,000 on the Squaw Peak and South Baldy 7 1/2-minute quadrangle maps. Color aerial photographs of the BLM-LCS series (1:31,680) were used to aid in mapping and structural interpretation.

Thin sections were analyzed to support field correlations and to define petrographic characteristics. All thin sections were stained for potassium with sodium cobaltinitrate using the standard procedures of Wilson and Sedeora (1979). Etching times were increased from 1-1.5 seconds to 30 seconds. Petrographic rock names are from Travis (1955). Rock colors reported are from the GSA rock color chart.



a) no straight-forward correlation of present units with Loughlin and Koschmanns volcanic stratigraphy is possible. This column is after Blakestad, 1977 where the reader will find more detailed information.

b) The tuff of La Jencia Creek is now known to be Lemitar Tuff in a paleovalley.

c) These basaltic andesite intervals may be tongues of lower La Jara Peak basaltic andesite.

Figure 2. Correlation diagram showing the relationship of units defined in previous stratigraphic studies to the stratigraphic section of this study.

Acknowledgments

I gratefully acknowledge the many individuals who helped me during this study. Larry Smith and Archie Wilson allowed access to their private property. Jane Dohze was a great help in the preparation of the manuscript. Bob Osburn supplied many ideas in the field and during informal discussions and critically read the manuscript. Dr. D.I. Norman and Dr. C.T. Smith served on my thesis committee and critically read the manuscript.

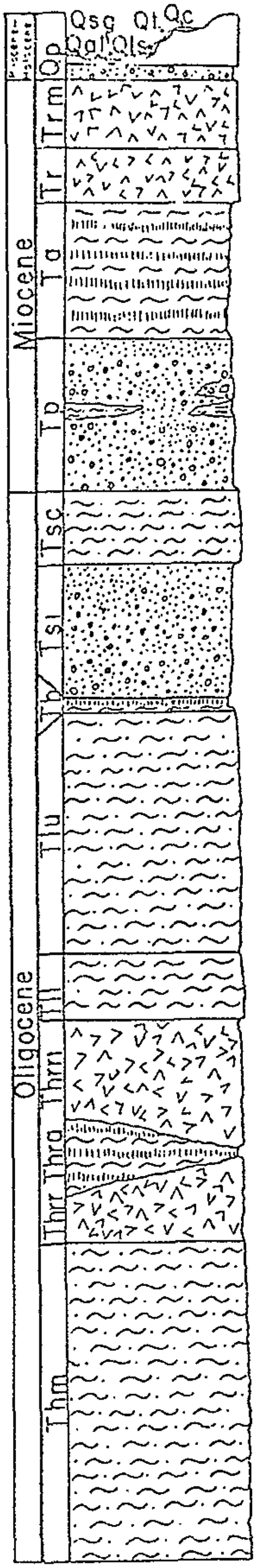
A special thanks to Dr. Charles E. Chapin for serving as my thesis advisor and for his generous advice in both field and office. The New Mexico Bureau of Mines and Mineral Resources provided financial support and use of a field vehicle.

STRATIGRAPHY AND PETROGRAPHY

General Tertiary Stratigraphy of the Socorro-Magdalena Area

The Tertiary stratigraphy of the Socorro-Magdalena area includes both sedimentary and volcanic rocks. Fluvial sands and mudstones of the Baca Formation, the basal Tertiary unit, are conformably overlain by the Spears Formation. The Spears consists of conglomerates, mudflows, and sandstones with interbedded lavas and ash-flow tuffs. The Spears is overlain by ash-flow tuffs and interbedded basaltic-andesite lavas (Oligocene to early Miocene). Regional extension began during the later stages of volcanism forming basins along the Rio Grande rift in which sediments of the Santa Fe Group accumulated. Silicic lavas were interbedded with the bolson sediments in early and late Miocene time.

The rocks exposed in this study area consist of rhyolitic to andesitic intrusions, and rhyolitic ash-flow tuffs with interbedded basaltic-andesite lavas, rhyolitic lavas, and sedimentary rocks. The map units are summarized graphically on Figure 3.



Alluvium. PIEDMONT SLOPES, STREAM TERRACES, STREAM GRAVELS, TALUS, COLLUVIUM, and LANDSLIDE DEPOSITS: poorly indur. cgls.; S.W. and S.E. sloping piedmont slopes; sand to cobble stream terrace deposits; gravels deposited in stream beds; active talus slopes and stabilized colluvium; and landslide deposits.

Rhyolite of Magdalena Peak: RHYOLITIC LAVAS: dense, mod. to xl.-poor rhyolitic lavas; lt. gryish. brn. w/ dk. vitrophyre at the base (ave. of 2 dates 11.6 m.y.)

Lava Flows: RHYOLITIC LAVAS: dense to vesicular, xl.-poor, flow-banded rhyolitic lavas; gryish. rd. to very lt. grey. w/ a dk. vitrophyric base, unit overlies a thin ash-flow tuff associated with the rhyolitic lavas; lavas are interbedded w/ Popotosa Formation.

Lava Flows: ANDESITIC LAVAS: dense to vesicular, xl.-poor, andesitic lavas: phenocrysts of plag., cpx., biot., and high-pressure qtz.; lavas are interbedded with the Popotosa Formation.

Popotosa Formation: SANDSTONES, CONGLOMERATES, LAHARIC BRECCIAS, and ASH-FLOW TUFFS: rift-related bolson deposits; mod. to poorly indur. mod.-rd. to lt.-brn. ss. and cgls.; well-indur. mod.-rd. mudflow deposits; xl.-poor, local ash-flow tuffs, pyroclastic-surge deposits (?) and reworked tuffaceous ss.

Tuff of South Canyon: ASH-FLOW TUFFS: rhyolitic, multiple-flow, simple to compound cooling unit, 2-feld. (?), mod. to densely welded ash-flow tuffs. The base of the unit is xl.-poor, poorly welded and compacted and is overlain by a xl.-poor, mod. to densely welded ash-flow tuff. The top of the unit is mod. to xl.-poor, moderately welded and compacted. The rock is lt. gry. to med. gry. w/ phenocrysts of qtz., sanid., plag. (?), and biot.; sanid. are chatoyant and qtz. are euhedral. (ave. of 2 dates 26.0 m.y.).

Lower Sedimentary Unit: SANDSTONES and CONGLOMERATES: either cauldron-fill of a tuff of Lemitar Mountains cauldron. or early-rift bolson deposits; mod. to poorly ind., mod.-rd. to lt.-brn. ss. and cgls. The top of the unit has an increase in tuffaceous material forming a gradational contact with the tuff of South Canyon.

Lava Flows: BASALTIC-ANDESITE LAVAS: dense to vesicular, xl.-poor lavas; med. gry. w/ phenocrysts of plag., cpx., and ol. (?).

Tuff of Lemitar Mountains: ASH-FLOW TUFFS: rhyolitic, multiple-flow, densely welded, 2-feld., ash-flow tuffs; xl.-poor, lineated, lower member; med. gry. to dk. rdish. brn. upper member w/ lineated pumice, mesobreccias, and megabreccias in some stratigraphic intervals; qtz.-poor, xl.-rich zone near the top. (ave. of 5 dates 27.6 m.y.).

Unit of Hardy Ridge: RHYOLITIC LAVAS and BASALTIC-ANDESITE LAVAS: cauldron-fill of the North Baldy cauldron; Thrr and Thrm: rhyolitic lavas; xl. poor to xl. free, 1 feld; lt. gry. to pale pink; Thra: dense to vesicular basaltic-andesite lavas; dk. gry. w/ green blotches.

Hells Mesa Tuff: ASH-FLOW TUFFS: rhyolitic, multiple-flow, densely welded, xl-rich, qtz.-rich, 2 feld., ash-flow tuffs; pale rd. purple to lt. gry. The base of the unit has a qtz.-poor, xl.-rich base (?). (ave. of 3 dates 31.7 m.y.).

Figure 3. Stratigraphic section of this thesis area. Graphic section and rock descriptions modified after Chapin and others (1978).

Hells Mesa Tuff

The Hells Mesa Tuff, a multiple-flow, densely welded, crystal-rich ash-flow tuff is the oldest unit exposed in this study area. The Hells Mesa is correlative with the lower part of Tonking's (1957) Hells Mesa Member of the Datil Formation and Brown's (1972) tuff of Goat Springs Member of the Hells Mesa Formation. Chapin (1974) and Deal and Rhodes (1976) restricted the Hells Mesa Tuff to include only the basal, densely welded, crystal-rich unit correlative with Brown's tuff of Goat Springs. The average for 3 K-Ar dates obtained for the Hells Mesa Tuff is 31.7 m.y. (Appendix A).

The source of the Hells Mesa Tuff is the North Baldy cauldron (Chapin and others, 1978) which encompasses part of this study area. All of the Hells Mesa exposed in this area is cauldron-facies; it reaches an apparent thickness of 3800 feet (1160 m) in the central Magdalena Mountains (Krewedl, 1974). The outflow-facies Hells Mesa Tuff has a thickness of 400 to 640 feet (120 to 95 m) (Brown, 1972).

The three locations where the Hells Mesa crops out in this study area include: 1) north-trending exposures along major range faults on the west side of Hardy Ridge; 2) a rectangular-shaped outcrop bound on two sides by major range faults near a small manganese mine (sec. 34, T.4S., R.4W.); and 3) a small isolated outcrop just north of Squaw Peak (sec 21, T.4S., R.4W.). This isolated outcrop has been interpreted as a float block which has been forced up by the rhyolitic intrusions in this area. An alternate hypothesis is that the Hells Mesa outcrop is a megabreccia block on the margin of the Magdalena cauldron. The maximum exposed thickness in this study area is 1850 feet (560 m); the base of the unit is not exposed. Cauldron-fill andesitic and rhyolitic lavas of the unit of Hardy Ridge overlie Hells Mesa throughout most the Hells Mesa exposures; however, along the crest of Hardy Ridge the Hells Mesa is unconformably overlain by the tuff of Lemitar Mountains, or tuff-breccias of the unit of Sawmill Canyon. These stratigraphic relationships on Hardy Ridge suggest that the area was deeply eroded prior to the deposition of the tuff of Lemitar Mountains and the breccias in the unit of Sawmill Canyon. The absence of A-L Peak Tuff in this exposed portion of the North Baldy cauldron further suggests that the area was topographically high during the emplacement of A-L Peak Tuff.

The Hells Mesa is typically bleached to pale red purple or light gray, weathers into small blocky rubble, and forms steep slopes. The Hells Mesa contains between 45-55 percent phenocrysts of quartz, sanidine, plagioclase, and biotite in a matrix of glass shards and devitrified glass. The average phenocryst size ranges from 1 to 2 mm, although quartz phenocrysts commonly reach 5 mm in diameter. In areas of deepest exposures of the Hells Mesa Tuff, a quartz-poor, crystal-rich tuff is present. This quartz-poor zone may be correlative with the quartz-poor zone observed in the Bear Mountains or may be megabreccia blocks exposed in the bottom of the North Baldy cauldron.

In thin section, the matrix of the Hells Mesa consists of devitrified glass and glass shards with most original shard structures obliterated during devitrification. Glass shards are deformed around phenocrysts indicating dense welding. Anhedral, rounded, and typically embayed quartz phenocrysts comprise about 10 percent of the rock. Sanidine is generally twice as abundant as quartz and is commonly altered to clays. Plagioclase, more abundant than quartz but less abundant than sanidine, makes up approximately 15 percent of the rock. The plagioclase has both albite and carlsbad twinning; however, alteration to clays has obscured some twinned crystals. The composition of the plagioclase is about An 32 (7 grains, Rittmann Zone Method) which agrees favorably with the compositions determined by Krewedl (1974) and Allen (1979).

Lath-shaped biotite phenocrysts, averaging 1 mm in length, comprise between 1 and 2 percent of the rock. The biotite is in varying stages of alteration to iron oxides. A trace of rounded magnetite grains, averaging 0.2 mm in diameter, are also present.

The reader is referred to Brown (1972), Chamberlin (1974), and Spradlin (1974) for petrographic characteristics of relatively fresh Hells Mesa.

Unit of Hardy Ridge

The unit of Hardy Ridge, named informally by Bowring (1980), is a thick sequence of rhyolitic and andesitic lavas. These lavas have been interpreted as cauldron fill of the North Baldy cauldron because of their great thickness and local extent. (Chapin and others, 1978).

The unit of Hardy Ridge conformably overlies the Hells Mesa Tuff in this and Bowring's study areas. These lavas are unconformably overlain by the tuff of Lemitar Mountains and tuff-breccias of the unit of Sawmill Canyon; nowhere is the A-L Peak Tuff exposed in this study area. The unit of Hardy Ridge is believed to dip 34 degrees to the east based on foliations and contact relationships with other units.

Thickness estimates from cross section using this dip give a maximum of 1680 feet (510 m). Crystal-poor rhyolitic lavas, andesitic lavas, and crystal-free rhyolitic lavas were mapped separately in this study area.

<u>Andesites.</u> The andesitic lavas in the unit of Hardy Ridge form a linear outcrop belt, marked by a topographic bench at approximately 8320 feet elevation on the west side of Hardy Ridge. These andesitic lavas overlie the Hells Mesa Tuff and are conformably overlain by rhyolitic lavas in Bowring's map area. In this study area, the andesitic lavas near the top of Hardy Ridge average about 440 feet (130 m) in thickness and are unconformably overlain by tuff-breccias of the unit of Sawmill Canyon. A small, triangular-shaped, andesitic outcrop is located near the western base of Hardy Ridge (northeast of manganese mine, sec 34, T.4S., R.4W.). These lavas are stratigraphically between two lithologically different rhyolitic lavas of the unit of Hardy Ridge. A definite correlation between these andesitic lavas and the andesitic lavas higher on Hardy Ridge is impossible because of the intense weathering of the small outcrop and dissimilar stratigraphic relationships.

In hand specimen, the andesitic lavas of the unit of Hardy Ridge are aphanitic and dense with some vesicles partially filled by secondary, drusy quartz. The rock is dark gray with green blotches, 0.5 mm in diameter, on the weathered surface. In thin section, these green blotches are micaceous chlorite after olivine and/or pyroxene. The groundmass is made up predominantly of plagioclase microlites, 0.3 mm long, which are oriented preferentially with the long axis of the crystals roughly parallel. The composition of the phenocrysts averages An 26 (3 grains, Rittmann Zone Method). The remaining 25 to 30 percent of the groundmass consists of small, rounded magnetite grains and iron oxide weathering products after mafic minerals.

<u>Rhyolites.</u> Two varieties of rhyolitic lavas of the unit of Hardy Ridge have been mapped separately in this study area. The stratigraphically lower, crystal-poor rhyolitic lavas occur near the western base of Hardy Ridge (east of manganese mine, secs. 34, 35, T.4S., R.4W.). In this area, the crystal-poor lavas overlie the Hells Mesa Tuff and are overlain by a small, discontinuous, andesitic outcrop and by crystal-free rhyolitic lavas.

In hand specimen, the crystal-poor rhyolitic lavas are light bluish gray and contain variable amounts of spherulites about 1 cm in diameter. In thin section, these crystal-poor lavas contain approximately equal amounts of quartz and sanidine phenocrysts, totaling about 5 percent of the rock, and averaging 1 mm and 1.5 mm in diameter, respectively. Approximately 1 percent rounded magnetite grains, 0.07 mm in diameter, are also present.

Stratigraphically above the andesitic and crystal-poor rhyolitic lavas is a thick sequence of crystal-free rhyolitic lavas. These crystal-free lavas overlie discontinuous andesitic lavas and crystal-poor lavas near the western base of Hardy Ridge (secs. 34, 35 T.4S., R.4W.); no base is exposed elsewhere is this study area. The upper member of the tuff of Lemitar Mountains unconformably overlies the crystal-free rhyolitic lavas on the west side of Hardy Ridge.

In general, the crystal-free rhyolitic lavas are pale pink along weathered foliation planes and medium light gray when fresh. These lavas commonly contain spherical to semispherical bodies (Fig. 4) localized along foliation planes, which are thought to be a form of spherulite (Bowring, 1980). The bodies range from about 10 cm to 0.2 mm in diameter and average approximately 5 cm in diameter.

Figure 4. Spherical to semispherical bodies localized along foliation planes in the rhyolitic lavas of the unit of Hardy Ridge. Hammer is approximately 30 cm in length.

For more detailed descriptions of these spherical bodies the reader is referred to Bowring (1980).

In thin section, these rhyolitic lavas contain essentially no phenocrysts. The groundmass has been spherulitically devitrified to quartz and alkali feldspar. Approximately 5 percent magnetite grains (0.02 mm in diameter) comprise the remainder of the rock.

Tuff of Lemitar Mountains

The tuff of Lemitar Mountains is a multiple-flow, compositionally zoned, simple to compound cooling unit of densely welded tuff (Chapin and others, 1978). The tuff of Lemitar Mountains was first described by Brown (1972) who named it the tuff of Allen Well. Osburn (1978) has presented a detailed description of the tuff of Lemitar Mountains in the eastern Magdalena Mountains and has divided the unit into a lower, crystal-poor member and an upper, crystal-rich member. Chamberlin (1980) has measured a reference section in the Lemitar Mountains after which the unit was named. Five K-Ar dates from 3 locations in the Socorro-Magdalena area average 27.6 m.y. (Appendix A).

Topographic lows at the time of eruption of the tuff of Lemitar Mountains greatly influenced the thickness and distribution of the tuff. Outside of the complex of nested cauldrons in the San Mateo and Magdalena Mountains, the lower member of the tuff of Lemitar Mountains has limited areal extent and is typically thin if present. However, the Sawmill Canyon cauldron, a topographic depression at the time of eruption of the tuff of Lemitar Mountains, has about 500 feet (150 m) of the lower member exposed. Approximately 2000 feet (600 m) of the lower member of the tuff of Lemitar Mountains is present on A-L Peak (A-L Peak of Deal, 1973; Osburn, oral communication). The upper member of the tuff of Lemitar Mountains is widespread. The tuff is about 100 feet (30 m) thick in the Joyita Hills, varies from 0 to 600 feet (0 to 180 m) thick in the Lemitar Mountains (Chamberlin, 1980), about 750 feet (230 m) thick in the Sawmill Canyon cauldron (Roth, in progress), about 1200 feet (360 m) thick in Potato Canyon (Potato Canyon of Deal, 1973; Osburn, oral communication), and about 1900 feet (580 m) thick in the western part of this study area. Both members of the tuff of Lemitar Mountains are absent in most areas north of Magdalena. The upper and lower members of the tuff of Lemitar Mountains make up a simple cooling unit; no welding reversal is observed. The nonplanar contact relationship of the two Lemitar members east of State Highway 107 (secs. 25, 26, 35, T.4S., R.5W.) suggest that some topography existed during the deposition of the upper member.

<u>lower member.</u> The lower member of the tuff of Lemitar Mountains consists of a crystal-poor, densely welded ash-flow tuff. This member crops out in the western part of this study area, but was not deposited on Hardy Ridge which was topographically high during emplacement of the lower Lemitar. In the Mulligan Gulch area, the lower Lemitar forms linear outcrop belts with a maximum exposed thickness of 500 feet (150 m). This is a minimum thickness since the base of the lower Lemitar is not exposed. In the eastern part of this study area, minor amounts of lower Lemitar may be present, but the unit is not exposed and would not exceed 30 feet (9 m) in thickness.

Primary laminar flow structures are well developed in the lower member (Fig. 5) and give an average flow direction of east-west. These laminar flow structures developed during deposition in a laminar boundary layer while the glassy particles were well above the softening point (Chapin and Lowell, 1979). Flow folds are present in the lower Lemitar (Fig. 6) with amplitudes varying from 6

Figure 5. Highly elongated and flattened pumice in the densely welded lower member of the tuff of Lemitar Mountains. Pencil in photograph is approximately 15 cm long and is parallel to the direction of flow. The photograph was taken east of Mulligan Gulch (sec. 26, T.4S, R.5W.).

Figure 6. Primary (?) fold in the lower member of the tuff of Lemitar Mountains. Hammer is approximately 30 cm long and is parallel to the axial plane of the fold. The axial plane dips toward the camera indicating a flow direction away from the camera (Chapin and Lowell, 1979). The photograph was taken in an arroyo east of Mulligan Gulch (sec. 26, T.4S., R.5W.).

to 30 feet (1.8 to 9 m). The best exposures of the folds are found in a small gully east of Mulligan Gulch (northeast 1/4, sec. 26 T.4S., R.5W.); however, only one trend on a fold axis was obtained because of the limited exposures. The fold axis was roughly perpendicular to the tuffs lineation indicating a primary fold based on the criteria of Chapin and Lowell (1979) who attribute these folds to local instabilities in the laminar flow regime, drag caused by passing of the next flow, or surges in the velocity of the ash flows. The axial plane of the fold dips to the west indicating that the tuff was flowing west to east (Chapin and Lowell, 1979). An alternate explanation in this case is that these are secondary folds formed by slumping off the Magdalena cauldron margin which trends perpendicular to the flow direction. In this same area, a few blocks of sandstones and rhyolitic lavas, as much as 6 feet (1.8 m) in diameter, are present as mesobreccia blocks in the lower member of the tuff of Lemitar Mountains.

On fresh surfaces, the lower Lemitar varies from medium gray to dark reddish brown with light-gray pumice. The pumice is highly compressed, lineated, and typically deformed around phenocrysts and lithic fragments. Andesitic and rhyolitic lithics, averaging 1.5 cm in diameter, vary from a trace to about 5 percent of the rock.

In thin section, the lower member consists of about 5 percent quartz, sanidine, plagioclase, and biotite phenocrysts in a matrix of glass shards and devitrified glass. The rock contains about 3 percent sanidine phenocrysts, averaging 0.8 mm in diameter, which are slightly altered along cleavage planes. Quartz comprises about 2 percent of the rock and averages about 1 mm in diameter. Trace amounts of plagioclase phenocrysts, averaging 0.7 mm in length, are extensively altered to phyllosilicates. Pleochroic, lath-shaped biotite phenocrysts, averaging 1.3 mm in diameter, are altered to iron oxides along crystal edges and cleavage planes.

Glass shards and pumice are compacted and deformed around lithic fragments and phenocrysts. The pumice has been partially devitrified to a mosaic of quartz and alkali feldspars which average 0.05 mm in diameter.

upper member. The upper member of the tuff of Lemitar Mountains is a densely welded ash-flow tuff which varies from 16 to 40 percent phenocrysts in this study area. In the western part of the area, the upper Lemitar forms continuous, linear outcrops. The upper member conformably overlies the lower member and is conformably overlain by basaltic-andesite lavas which sporadically crop out along the upper surface of the tuff of Lemitar Mountains. The upper member and the basaltic-andesite lavas are unconformably overlain by the lower sedimentary unit and by the rhyolite of Magdalena Peak which was deposited on a much younger unconformity. In the eastern part of the area, the upper Lemitar conformably (?) overlies the crystal-free rhyolitic lavas of the unit of Hardy Ridge and unconformably overlies the Hells Mesa Tuff near the head of Puertecito Canyon. The upper Lemitar is overlain by sedimentary rocks where the top of the unit is exposed.

Three variations of upper Lemitar are exposed in this study area. In ascending stratigraphic order they are: 1) a lower unit consisting of approximately 16 to 25 percent phenocrysts, which in this study will be called the intermediate zone of the upper Lemitar; 2) a quartz-poor, crystal-rich zone; and 3) a thin, quartz-rich, crystal-rich zone.

The intermediate zone of the upper Lemitar consists of a densely welded, flow-banded, ash-flow tuff. This zone conformably overlies the lower Lemitar and is overlain by the quartz-poor zone of the upper Lemitar; welding reversals are not observed at these contacts. A maximum thickness of 1500 feet (460 m) of the intermediate zone has been determined from cross-section. Osburn (1978) defined a

5-to 50-foot transition into upper Lemitar in the eastern Magdalena Mountains which contains approximately the same phenocryst content as the intermediate zone of the upper Lemitar in this study area. Figure 7 summarizes the general Lemitar stratigraphy in the Lemitar Mountains, southeastern Magdalena Mountains, and this study area.

Primary laminar flow structures are well developed in the intermediate zone. An average flow azimuth of north 85 degrees east was obtained using lineated pumice and stretched gas cavities from several localities. Rotated lithic fragments consistently gave a flow direction of west to east. Folds are uncommon in the intermediate zone; however, the one fold observed in an arroyo east of Mulligan Gulch (sec. 1, T.5S., R.5W.) had a fold axis roughly perpendicular to the flow direction which is characteristic of primary folds.

Megabreccias and Mesobreccias. In the western part of the study area, the intermediate zone of the upper Lemitar has lense-shaped zones of mesobreccias and megabreccias which stratigraphically interfinger with normal, lithic-poor, upper Lemitar. Lipman (1976) suggests that mesobreccias form by small to medium-sized rock falls and rock slides from unstable caldera walls during caldera collapse and that

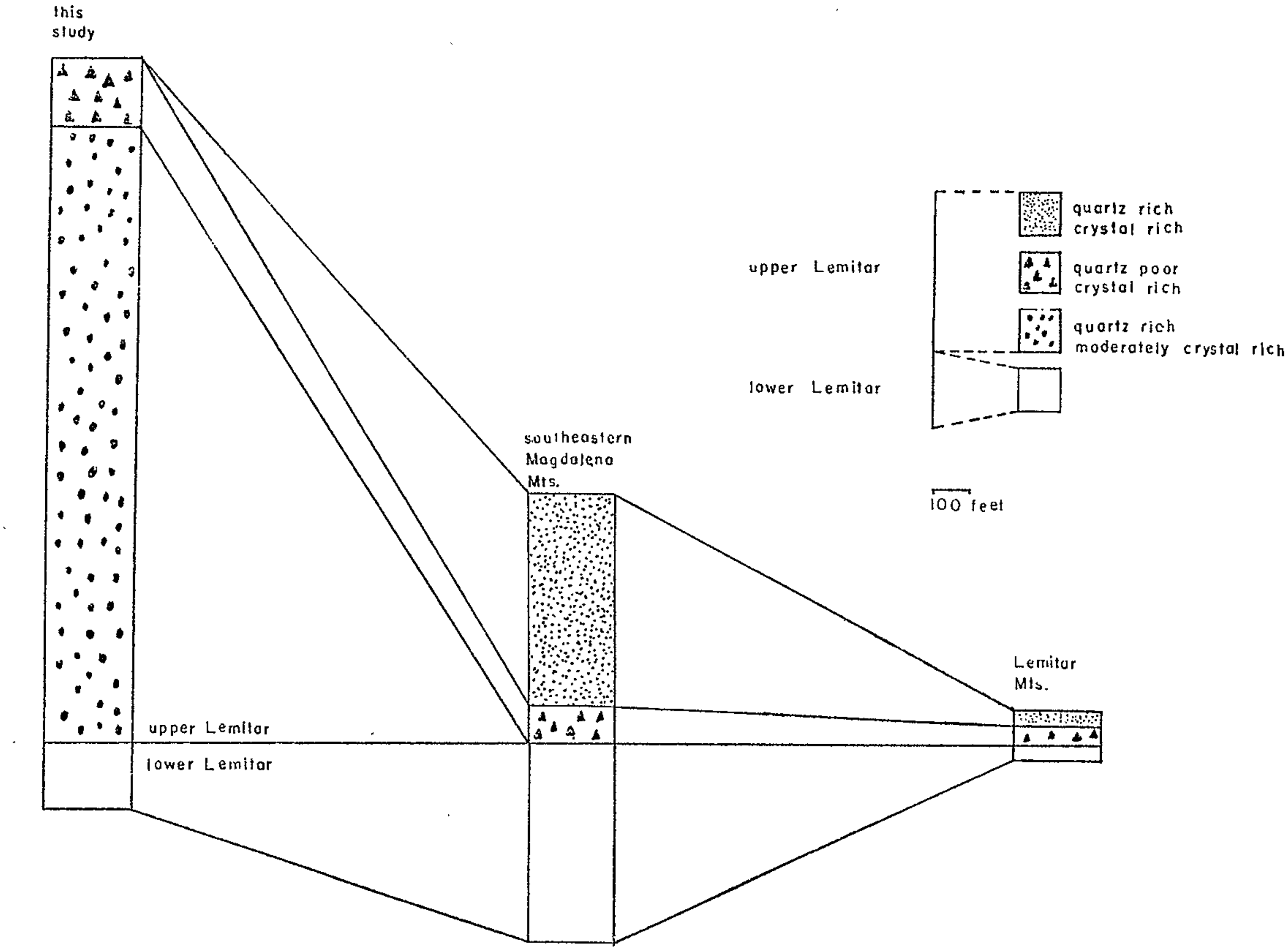


Figure 7. Fence diagram illustrating differences in the tuff of Lemitar Mountains stratigraphy in the Socorro-Lemitar Mountains, southeastern Magdalena Mountains, and this study area.

megabreccias originate from major slumping of the caldera wall.

The mesobreccias in the intermediate zone of the tuff of Lemitar Mountains contain blocks of Hells Mesa Tuff, andesitic lavas, rhyolitic lavas, sandstones, and quartz-poor tuffs which vary from several inches to nearly 30 feet in diameter (Fig. 8). The individual breccia blocks are surrounded by spherulitically devitrified intermediate zone of the tuff of Lemitar Mountains (Fig. 9). The once vitric nature of the matrix gives an important bit of evidence supporting the hypothesis of the formation of some vitrophyres by chilling.

The megabreccias in the intermediate zone of the upper Lemitar are well exposed in the arroyo east of the small rhyolitic intrusion in Mulligan Gulch (sec. 1, T.5S., R.5W.). These megabreccias consist of large blocks of Hells Mesa Tuff, quartz-poor ash-flow tuffs, and blocks comprised of previously consolidated mesobreccias. These previously consolidated blocks consist predominately of Hells Mesa, quartz-poor tuffs, and minor amounts of rhyolitic and andesitic lavas surrounded by a white, crystal-rich, matrix. These previously consolidated blocks of mesobreccia suggest that two periods of brecciation occurred in this area. The matrix surrounding the megabreccia blocks consist of the

Figure 8. Typical mesobreccia in the intermediate zone of the tuff of Lemitar Mountains. The hammer is about 30 cm long and is on the contact of the grayish-red-purple Hells Mesa block and the moderate-reddish-brown matrix consisting of the tuff of Lemitar Mountains. Photograph was taken east of Mulligan Gulch (sec. 25, T.4S, R.5W.).

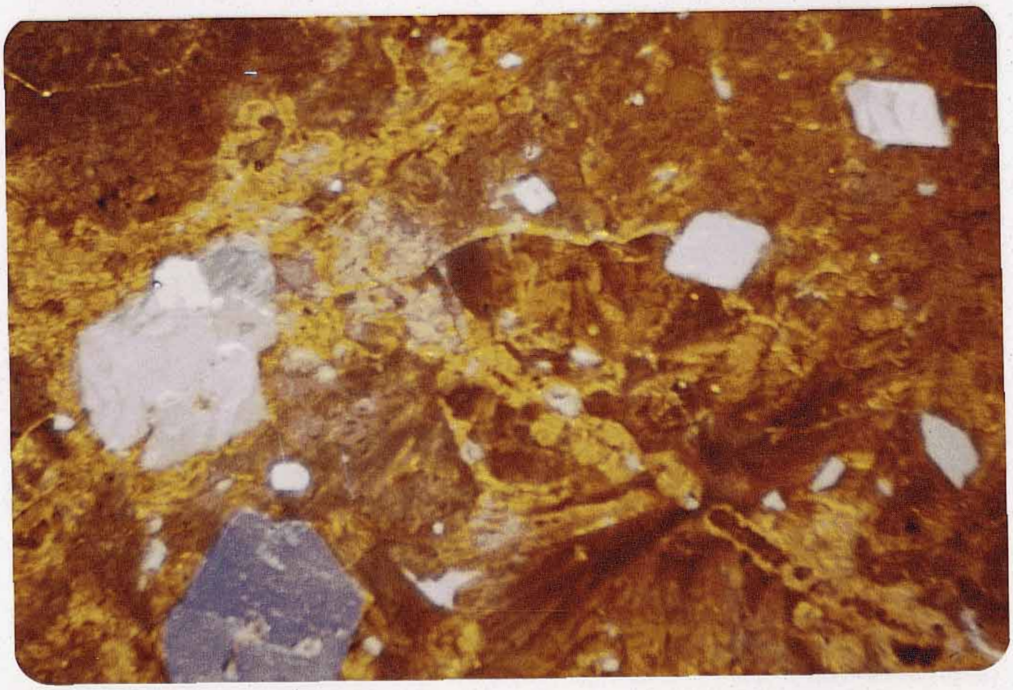


Figure 9. Photomicrograph of the matrix of the mesobreccias in the intermediate zone of the tuff of Lemitar Mountains. The spherulitically devitrified glass is an important bit of evidence supporting the hypothesis of the formation of some vitrophyres by chilling.

intermediate zone of the upper Lemitar and mesobreccia clasts of Hells Mesa, andesitic lavas, lower Lemitar, and quartz-poor tuffs (Fig. 10). Spherulites, gas cavities, and small-scale welding reversals normally occur at the contacts of the megabreccias with the Lemitar matrix (Fig. 11).

The crystal content of the intermediate zone of the upper Lemitar gradationally increases from about 16 to 18 percent phenocrysts at the base of the zone to about 25 percent phenocrysts near the top. The color varies from grayish red with light-gray pumice to light gray with yellowish-gray pumice. The pumice are large reaching a length of 1 foot in some areas and are commonly lineated. High concentrations of stretched gas cavities were observed in several localities.

Quartz phenocrysts make up 4 to 8 percent of the rock, average 0.8 mm in diameter, and are commonly embayed. Sanidine phenocrysts make up 8 to 12 percent of the rock and average 0.8 mm in diameter. The sanidine phenocrysts have a perthitic texture which may account for the white chalky appearance in hand specimen. The remaining sanidine phenocrysts appear clear and unaltered. The ratio of quartz to sanidine averages 0.61 for the intermediate zone of the upper Lemitar. This ratio is considerably higher than the

Figure 10. Mesobreccias and megabreccias in the intermediate zone of the tuff of Lemitar Mountains. The left side of the photograph (near hammer) consists of small-to intermediate-sized mesobreccia blocks in a matrix of the tuff of Lemitar Mountains. These blocks and breccia-free tuff of Lemitar Mountains surround a megabreccia block of Hells Mesa in the right half of the photograph. Photograph was taken in an arroyo east of the Mulligan Gulch rhyolitic dome (sec. 1, T.5S., R.5W.).

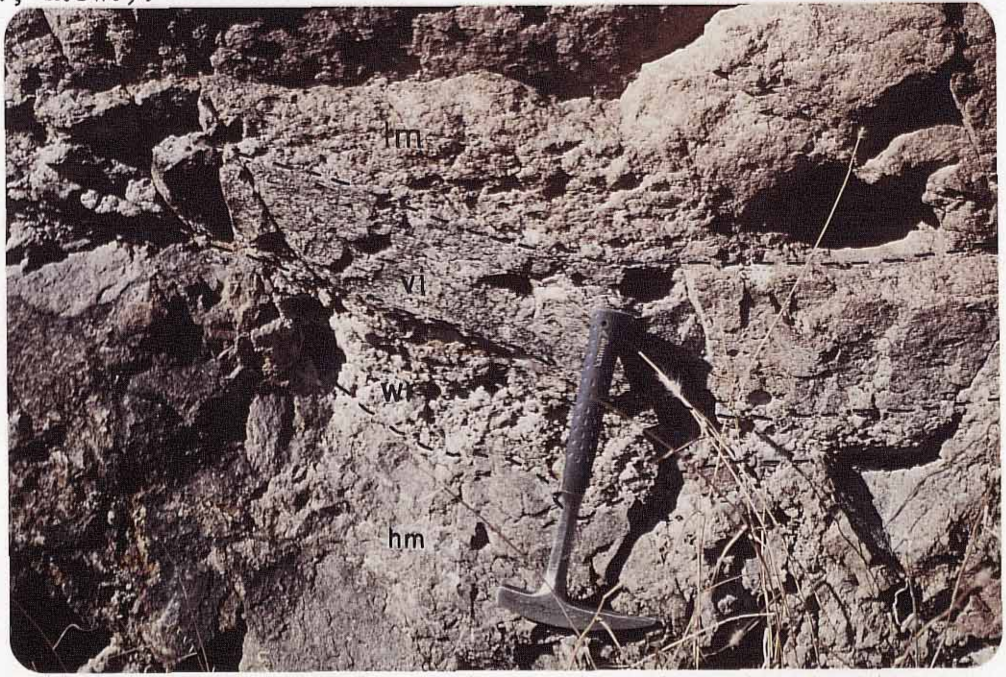
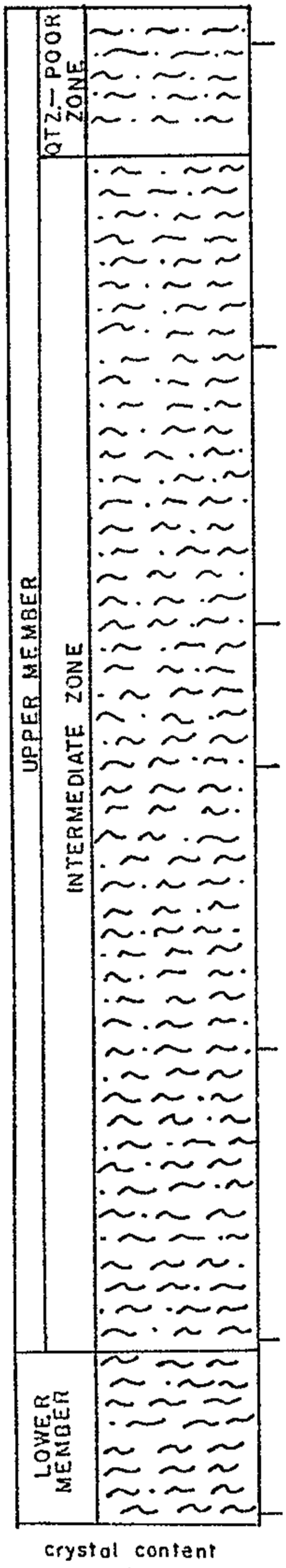


Figure 11. Contact zone of a Hells Mesa megabreccia block with the intermediate zone of the tuff of Lemitar Mountains. Contact exhibits a small welding reversal (wr) with an abundance of gas cavities, a vitric layer (vi), and typical-looking tuff of Lemitar Mountains (lm). Photograph was taken in an arroyo east of the Mulligan Gulch rhyolitic dome (sec. 1, T.5S., R.5W.).

upper Lemitar in the eastern Magdalena and Socorro-Lemitar Mountains (Osburn, 1978, and Chamberlin, 1980). About 1 percent of the rock consists of plagioclase phenocrysts which are extensively altered to phyllosilicates and replaced by potassium-feldspar. Biotite, 0.4 mm in diameter, partially replaced by iron oxides, and small, rounded magnetite grains each make up about 1 percent of the rock. See Figure 12 for a summary of modal data from the tuff of Lemitar Mountains.

Glass shards are deformed around phenocrysts and lithic fragments indicating that the rock was densely welded. The pumice and some of the glassy matrix has been devitrified to quartz and alkali feldspar crystals which average 0.15 mm in diameter.

The second variation in the upper member of the tuff of Lemitar Mountains consists of a quartz-poor, crystal-rich zone which overlies the intermediate zone of the upper member in this study area. The quartz-poor zone has a variable thickness because of an eroded upper surface; however, a minimum thickness of approximately 180 feet (55 mm) was obtained from a cross section in the western part of this study area (sec. 36, T.4S., R.5W.). The quartz-poor zone of the upper Lemitar weathers to moderately steep slopes which are covered with angular blocks of colluvium.



sample location	sample number	total phen.	Phenocrysts sanid.	Phenocrysts quartz	Phenocrysts plag.	Phenocrysts bio.	qtz/sanid.
1900ft 580m	MD-LU6	34.6	11.6	1.3	19.7	2.0	0.11
1565ft 477m	MD-LU5	22.6	11.7	4.0	6.5	0.4	0.34
1200ft 366m	MD-LU4	24.0	12.0	6.0	4.5	1.5	0.50
1010ft 300m	MD-LU3	16.3	10.3	4.6	0.7	0.7	0.45
630ft 192m	MD-LU2	17.4	9.4	7.7	0.1	0.2	0.82
175ft 54m	MD-LU1	17.9	8.2	7.9	1.2	0.6	0.96
10ft 3m	MD-LL1	4.7	2.6	1.8	0.2	0.1	0.69

Figure 12. Modal data and stratigraphic column of the tuff of Lemitar Mountains east of Mulligan Gulch (sec. 36, T.4S., R.5W.). All thin sections had 2000 points counted.

In contrast to the underlying intermediate zone, the quartz-poor zone of the upper Lemitar does not exhibit primary laminar flow structures. It also weathers more rounded and appears softer and more porous.

The quartz-poor zone of the upper Lemitar contains approximately 30 percent phenocrysts of plagioclase (?), sanidine, quartz, and biotite in a groundmass of devitrified glass and glass shards. Quartz phenocrysts make up about 1 percent of the rock, are commonly embayed, and average 0.75 mm in diameter. Sanidine and plagioclase (?) phenocrysts, averaging 0.75 mm in diameter, each comprise about 14 percent of the rock. The plagioclase phenocrysts (?) have been pervasively altered to montmorillonite that was commonly washed out during thin section preparation; some plagioclase phenocrysts have been partially replaced by potassium-feldspar. Sanidine phenocrysts typically have a perthitic texture which is identical to the sanidine phenocrysts in the intermediate zone of the upper Lemitar. Biotite phenocrysts make up about 2 percent of the rock and are altered to iron oxides.

The groundmass of the quartz-poor zone of the upper Lemitar consists of devitrified glass and glass shards. The degree of welding and compaction decreases gradationally through the intermediate zone and moderately welded and compacted quartz-poor zone of the upper Lemitar. Pumice fragments can be readily identified because of substantially larger devitrification crystals (1.2 mm in diameter) than those of the devitrified groundmass (0.05 mm in diameter).

The third variation of the upper Lemitar consists of a quartz-rich, crystal-rich zone which was observed in the eastern part of the study area (sec. 35, T.4S., R.4W.); however, the unit is quite thin and is not continuous over a large area. In hand specimen, the quartz rich zone of the upper Lemitar is medium light gray on fresh surfaces. The rock contains approximately 8 percent quartz phenocrysts, some exceeding 3 mm in diameter. Sanidine phenocrysts average 1.5 mm in diameter and make up about 17 percent of the rock. Approximately 7 percent of the rock is made up of plagioclase phenocrysts, about 1 mm in diameter, which are pervasively altered to phyllosilicates. Biotite phenocrysts, about 3 mm in diameter, make up approximately 2 percent of the rock. Although stratigraphic relationships are not clear cut in this area, the quartz-rich zone overlies the quartz-poor zone of the upper Lemitar in other areas.

Stratigraphic and structural information pertinent to an understanding of the caldera complex in the Socorro, Magdalena, and San Mateo Mountains has been obtained from the tuff of Lemitar Mountains in this study area. There is strong evidence that the eastern margin of the Mount Withington cauldron (source cauldron for the tuff of Lemitar Mountains) extends into, or east of the western part of this study area. A summary of this evidence includes: 1) mesobreccias and megabreccias in the tuff of Lemitar Mountains; 2) folding of the upper and lower members of the tuff of Lemitar Mountains which is characteristic of cauldron-facies tuffs; 3) a thickness of at least 2000 feet (600 m) of the tuff of Lemitar Mountains with no exposed base; 4) a 1500-foot (450 m)-thick intermediate zone which has not been documented elsewhere in the Socorro-Magdalena area; and 5) the presence of lower Lemitar in the western part of this study area and its absence on Hardy Ridge. However, there is significant evidence against the Mount Withington cauldron in the western part of this study area including: 1) the basaltic-andesite lavas conformably overlying the upper Lemitar were eroded, prior to the deposition of a sedimentary interval, indicating that the western part of this study area was probably not topographically low; 2) the sedimentary interval between the tuff of South Canyon and the tuff of Lemitar Mountains is only 400 feet (120 m) thick in some areas; 3) the tuff of South Canyon is not unusually thick in this area. In contrast to the above evidence, the well-exposed Sawmill Canyon cauldron has 1200 feet (360 m) of the tuff of Lemitar Mountains overlying nearly 2000 feet of cauldron-fill deposits above the cauldron-facies A-L Peak Tuff (Roth, in progress).

The Mount Withington cauldron margin may be present in this study area; however, much of the evidence from the tuff of Lemitar Mountains can be explained by an alternate hypothesis. The Magdalena cauldron margin is well exposed in the southwestern part of Bowring's (1980) study area and should trend across the central part of this study area; however, the cauldron margin must be inferred because rocks in this area are too young to expose the A-L Peak Tuff or its cauldron fill. The Magdalena cauldron could have been the topographic depression which was filled by the younger tuff of Lemitar Mountains. This would explain the great thickness, the presence of lower Lemitar, and the thick intermediate zone of the upper Lemitar which may be restricted to the Magdalena cauldron close to the Lemitar source cauldron in the San Mateo Mountains. This interpretation also explains the absence of thick cauldron fill units and the lack of thickening in the tuff of South Canyon. The folding in the tuff of Lemitar Mountains could have resulted from deposition of the tuff on the irregular surface of the Magdalena cauldron margin. The megabreccias and mesobreccias in the tuff of Lemitar Mountains are not easily explained by this interpretation. These types of breccias have been well documented in intra-caldera tuffs, but have not been documented in outflow sheets. However, the mesobreccias and megabreccias could have formed in the Magdalena cauldron if the cauldron margins were unstable from seismic activity during eruption of the tuff of Lemitar Mountains. Major slumping, rock falls, and rock slides on the Magdalena cauldron margin with simultaneous eruption of the tuff of Lemitar Mountains could have resulted in the development of breccias in the outflow-facies Lemitar tuff.

Future mapping to the west and development of a better understanding of the geology in the San Mateo Mountains should clarify the interpretation of the western part of this study area.

Lower Basaltic-Andesite Lavas

Conformably overlying the tuff of Lemitar Mountains are small discontinuous outcrops of basaltic-andesite lavas with eroded tops. These lavas crop out sporadically in the western part of this study area and a small, isolated outcrop of similar lithology and stratigraphic positioning is present on the west side of Hardy Ridge (sec. 25, T.4S., R.4W.). These lavas do not exceed 160 feet (49 m) in thickness. The basaltic-andesite lavas are unconformably overlain by sedimentary rocks in most areas and by the rhyolite of Magdalena Peak about one mile west of Alameda Spring (sec. 36, T.4S., R.5W.).

In hand specimen, the rock is medium gray on fresh surfaces and light olive gray on weathered surfaces. In thin section, the rock contains about 7 percent phenocrysts made up of approximately equal amounts of clinopyroxene and olivine (?) in a groundmass consisting of rounded magnetite grains, plagioclase microlites, and iron oxide alteration products after mafic minerals. Subhedral clinopyroxene phenocrysts, 0.8 mm in diameter, are compositionally zoned and partially altered to low-birefringent phyllosilicates. Olivine (?) phenocrysts are pervasively altered to low-birefringent phyllosilicates and iron oxides.

Lower Sedimentary Unit

The lower sedimentary unit consists of red, moderate to poorly indurated sandstones and conglomerates and varies from 400 feet (120 m) to 1000 feet (300 m) in thickness. This thickness variation may reflect variable deposition in strike valleys during the time of deposition. The lower sedimentary unit overlies eroded remnants of basaltic-andesite lavas and the tuff of Lemitar Mountains; the unit is conformably overlain by the tuff of South Canyon.

In the western part of this study area, the lower sedimentary unit crops out in topographically low areas between hogbacks of more resistant ash-flow tuffs. The unit is overlain by piedmont gravels in the central and eastern part of this study area with exposures commonly restricted to arroyos.

The lower sedimentary unit commonly consists of conglomerates interbedded with sandstones. The conglomeratic beds are made up predominantly of clasts of the tuff of Lemitar Mountains ranging from 1 to 20 cm in diameter. In addition to the cobbles, the conglomeratic beds consist of angular grains of quartz, feldspar, and biotite in a moderate-red, silt-sized matrix. Interbedded with the conglomerates are moderate-red to light-brown sandstones. These poorly indurated sandstones consist of grains of quartz, feldspar, and biotite. The lower sedimentary unit becomes more tuffaceous upsection and is interbedded with thin ash-flow tuffs and bedded air-fall deposits near the base of the tuff of South Canyon; these contacts are gradational in some places.

The lower sedimentary unit is significantly different near the western base of Hardy Ridge (south of manganese mine, sec. 34, T.5S., R.4W.). In this area, the lower sedimentary unit is very well indurated because of pervasive alteration and silicification. The silicification appears to be strongly controlled by the permeability of the original sedimentary rock and is probably related to the period of manganese mineralization. The clasts in this area consist of crystal-poor rhyolitic lavas, Hells Mesa Tuff, and minor amounts of the tuff of Lemitar Mountains.

The lower sedimentary unit was not mapped with the Popotosa Formation because the unit may be cauldron fill of a Lemitar-aged cauldron in the west and central portions of this study area. However, the variable thickness of the lower sedimentary unit and the angular unconformity between the tuff of Lemitar Mountains and the tuff of South Canyon suggests that the lower sedimentary unit may have been deposited in strike valleys during early stages of rifting.

Tuff of South Canyon

The tuff of South Canyon is a multiple flow, simple to compound cooling unit of rhyolitic ash-flow tuff. The tuff of South Canyon was named informally by Osburn (1978) and is correlative with portions of Simon's (1973) "upper tuffs" and with Spradlin's (1974) "Potato Canyon Rhyolite". The average for two K-Ar dates obtained for the tuff of South Canyon is 26.0 m.y. (Appendix A). A 310-foot (93 m) section of the tuff of South Canyon was measured east of Chocle Well (sec. 35 T.4S., R.5W.) where the section is well-exposed. A maximum thickness of 550 feet (165 m) was obtained from a cross section east of Squaw Peak (sec. 35, T.4S., R.5W.). The tuff of South Canyon conformably overlies the lower sedimentary unit and is overlain by the Popotosa Formation and andesitic lavas. An angular unconformity occurs between the tuff of Lemitar Mountains and the tuff of South Canyon.

The tuff of South Canyon is exposed in many areas in the western and central portion of this study area; however, to the east on Hardy Ridge the tuff of South Canyon is not exposed because the nature of the faulting has repeated stratigraphically lower units. The tuff crops out as rounded hills covered with talus and forms steep cliffs along arroyos.

In this study area, the tuff of South Canyon can be divided into 3 units based on phenocryst content and welding characteristics. These units in increasing stratigraphic order are: 1) the basal unit which consists of poorly welded, crystal-poor, ash-flow tuffs; 2) a thin, moderate to densely welded, crystal-poor unit; and 3) the upper unit which consists of moderate to crystal-poor, moderately welded ash-flow tuffs.

The basal unit of the tuff of South Canyon consists of thin, crystal-poor ash-flow tuffs interbedded with minor amounts of bedded air-fall tuffs, or possibly pyroclastic-surge deposits. The tuff consists of about 5 to 11 percent aphanitic to crystal-rich lithic fragments which average about 1 cm in diameter. Angular pumice, 1.5 cm in diameter, make up about 20 percent of the rock and is preferentially weathered. The rock consists of approximately 2 percent quartz, sanidine, and plagioclase phenocrysts averaging 0.5 mm in diameter.

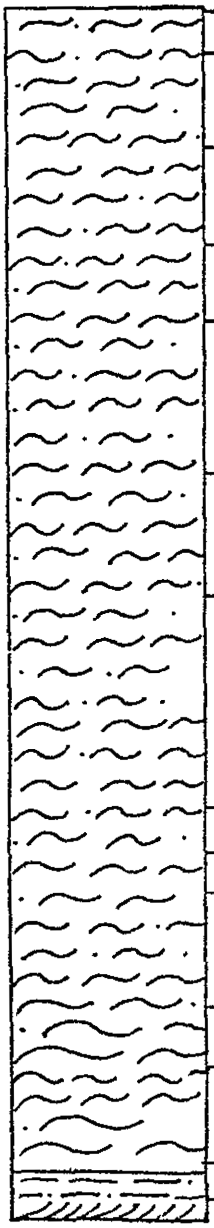
Overlying the basal, crystal-poor unit of the tuff of South Canyon is a moderately welded, crystal-poor unit. In hand specimen, the unit is light gray with medium-gray pumice that are flattened, average 1.5 cm in diameter, and have a cross-sectional thickness of about 0.25 cm. In thin section, the rock contains about 2 percent quartz and sanidine phenocrysts in approximately equal abundance. Rounded magnetite grains, averaging 0.15 mm in diameter, are present in trace amounts. The matrix consists of quartz and alkali feldspar crystals, 0.05 mm in diameter, which formed by devitrification. Glass shards are Y shaped and not extensively deformed around phenocrysts suggesting moderate welding and compaction.

Overlying the crystal-poor unit is a moderately welded, moderate to crystal-poor ash-flow tuff that contains a welding reversal in the basal portion of the unit. In hand specimen, the rock is light gray with very-light-gray pumice. On weathered surfaces, the pumice are preferentially weathered forming cavities which average about 1 cm in diameter. Chatoyant sanidine phenocrysts is a common characteristic of the tuff of South Canyon.

In thin section, the upper unit of the tuff of South Canyon consists of approximately 7 to 13 percent quartz, sanidine, plagioclase (?), and biotite phenocrysts in a matrix of devitrified glass and glass shards. Subhedral quartz phenocrysts, 0.7 mm in diameter, comprise about 3 to 7 percent of the rock and are commonly embayed. Approximately 4 to 7 percent of the rock consists of subhedral sanidine which averages 0.8 mm in diameter. Zircon euhedra and biotite, partially to completely altered to iron oxides, are present in trace amounts. Approximately 1 percent of the rock consists of void spaces which may have been altered plagioclase phenocrysts that were plucked during thin section preparation. Most of the glass in the matrix has been devitrified to quartz and alkali feldspar. The glass shards which have not been devitrified, are not extensively flattened or deformed around phenocrysts. Detailed petrographic data from a measured section east of Chocle Well (sec. 35, T.4S., R.5W.) is summarized on Figure 13.

Popotosa Formation

The Popotosa Formation, the basal formation of the Santa Fe Group, consists of laharic breccias, conglomerates, sandstones, and playa mudstones. The Popotosa Formation was named by Denny (1940) for exposures along Arroyo Popotosa



sample location	sample number	total phen.	Phenocrysts				lithic fragments
			sanid.	quartz	plag.	bio.	
320ft. 94.5m	CW-15	6.8	4.3	2.5		tr	
300ft. 91.4m	CW-14	9.0	4.7	4.3		tr	
275ft. 83.8m	CW-13	8.2	5.1	2.9		0.2	
250ft. 76.2m	CW-12	9.8	6.0	3.7		0.1	
230ft. 70.1m	CW-11	13.0	6.3	6.7		tr	
192ft. 58.5m	CW-10	12.3	6.6	5.7		tr	
160ft. 48.8m	CW-9	11.8	7.2	4.6		tr	
106ft. 32.3m	CW-8	9.5	4.7	4.6		0.2	1.0
95ft. 28.9m	CW-7	7.4	4.5	2.9			
85ft. 25.9m	CW-6	7.8	4.3	3.5	tr	tr	
55ft. 16.8m	CW-5	7.2	3.8	3.4			
40ft. 12.2m	CW-4	1.9	1.9				0.5
15ft. 4.6m	CW-3	2.0	0.8	0.7	0.5		5.2
5ft. 1.5m	CW-2	2.8	1.6	0.9	0.3		10.5

• crystal content

50 feet

∼ moderately welded

∼ poorly welded

▤ several, thin ash-flow tuffs

▨ pyroclastic-surge deposits

Figure 13. Modal data and stratigraphic column of the tuff of South Canyon near Chocle Wall (sec. 35, T.4S., R.5W.). All thin sections had 2000 points counted.

southeast of the Ladron Mountains. Bruning (1973) divided the Popotosa Formation into a fanglomerate facies and a playa facies. Chapin and others (1978) divided the Popotosa Formation in the Socorro area into upper and lower members. The lower member consists of mudflow deposits, fanglomerates and sandstones while the upper member is largely made up of mudstones, siltstones, and sandstones (Chapin and others, 1978).

The Popotosa Formation was deposited in a broad, early-rift basin during the interval from about 26 m.y. to 7 m.y. ago (Chapin and others, 1978). The source regions for the Popotosa Formation were the Colorado Plateau and the Ladron Mountains to the north and the Gallinas, San Mateo, and Magdalena Mountains to the west and south.

In this study area, the Popotosa Formation overlies the tuff of South Canyon (26.0 m.y.) and is overlain by the rhyolite of Magdalena Peak (13.6 m.y.). The lower sedimentary unit is lithologically similar to the Popotosa Formation and probably represents the earliest rift-related sedimentation in this study area; however, portions of this unit may be cauldron fill of a Lemitar-aged cauldron.

The Popotosa Formation crops out discontinuously throughout the west and central portions of this study area. The geometry of the local Popotosa basins appear to be wedge shape because of sedimentation in strike valleys. The dips of the sedimentary rocks decrease upsection indicating that faulting and rotation were occurring during sedimentation. A thickness of 1150 feet (350 m) was determined from a cross section in the northwest corner of this study area; however, the thickness decrease rapidly to the east where a thick section of rhyolitic and andesitic lavas is present.

Interbedded with, and overlying, the Popotosa Formation are rhyolitic and andesitic lavas which thicken where the sedimentary rocks thin and vice versa. For example, in the southern part of this study area the andesitic lavas are approximately 1000 feet (300 m) thick and the Popotosa Formation is very thin, or absent. To the north, the andesitic lavas are only about 30 feet (9 m) thick and are interbedded with a minimum of 1150 feet (350 m) of the Popotosa Formation (sec. 23, T.4S., R.5W.). In the north-central part of this study area, two rhyolitic lavas totaling approximately 500 feet (150 m) in thickness overlie and are interbedded with the Popotosa Formation which is here approximately 150 feet (45 m) thick. The interfingering of the rhyolitic and andesitic lavas in the Popotosa Formation is summarized on Figure 14.

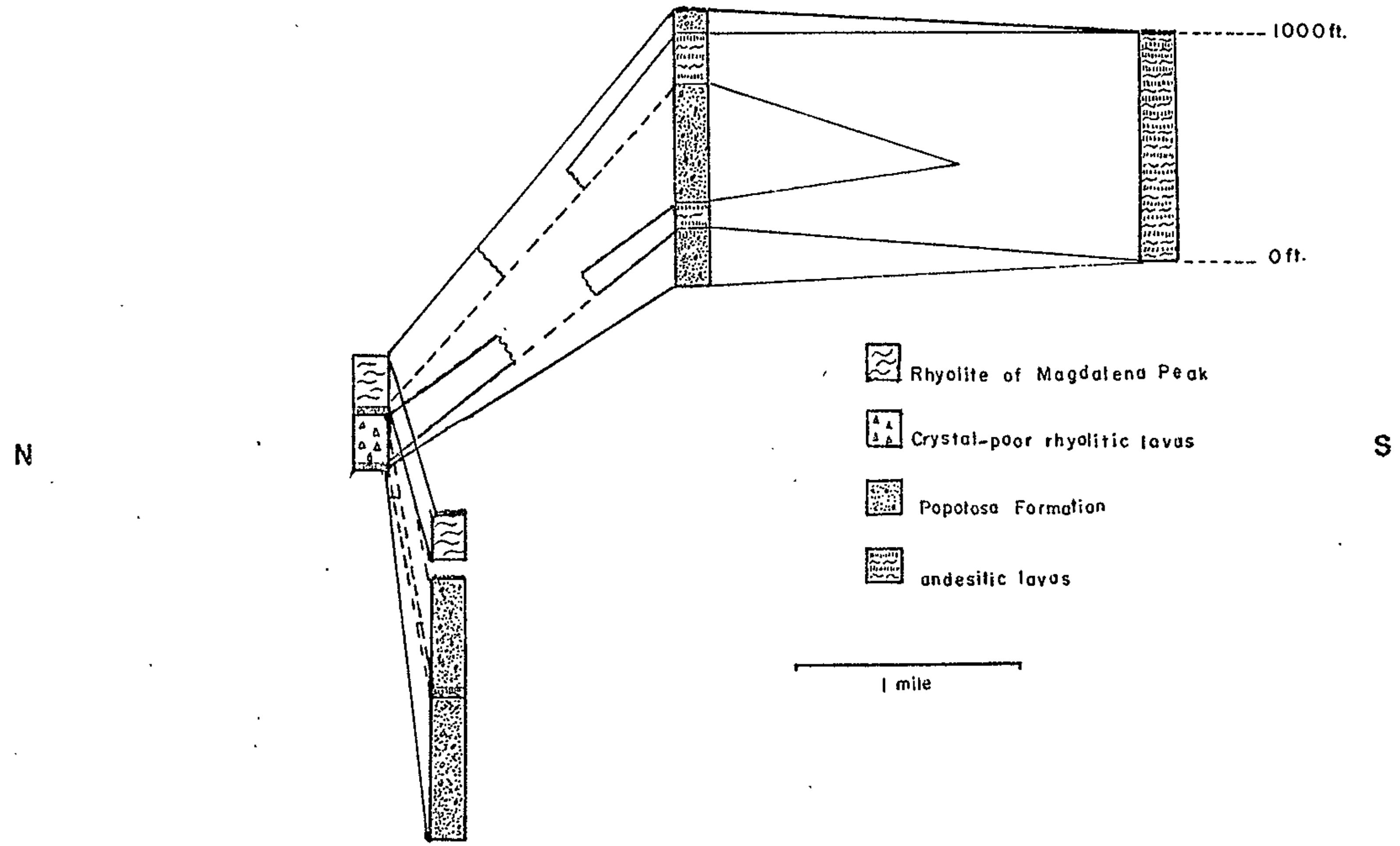


Figure 14. Fence diagram of the Popotosa Formation with interbedded rhyolitic and andesitic lavas and overlying rhyolitic lavas. Fence trends from the northwest to south-central part of this study area.

In this study area, the Popotosa Formation consists of sandstones, conglomerates, local ash-flow tuffs, air-fall tuffs and pyroclastic-surge deposits. The tuffaceous beds are most abundant where the Popotosa Formation overlies the tuff of South Canyon and beneath the rhyolitic lavas in the northern part of this study area. The tuffaceous beds exposed beneath the the rhyolitic lavas will be referred to as the unit of Garcia Ranch; however, this unit was not mapped separately except where exposures and thicknesses permitted.

Near the base of the Popotosa Formation, air-fall tuffs and/or pyroclastic-surge deposits are interbedded with sandstones. The tuffaceous units are commonly finely laminated, consist of fine-sand-sized tuffaceous grains, and are typically white. The sandstones contain grains of quartz, sanidine, biotite, and aphanitic lithic fragments in a tuffaceous matrix. The sandstones are light gray to white and poorly indurated. The tuffaceous material, believed to be associated with the eruption of the tuff of South Canyon, gradationally decreases with an increase in clastic material upsection.

The majority of the Popotosa Formation in this study area consists of sandstones and conglomerates. These clastic rocks typically crop out in arroyos and small gullies; however, in the northeastern part of the area the conglomeratic beds are well indurated and weather to rounded hills covered with clasts derived from the conglomerates. In general, the percentage of conglomeratic beds are more abundant in the northeastern portion of the area and the sandstones are more abundant in the central and western portions.

In hand specimen, the sandstones are light gray to grayish red and exhibit moderate to poor bedding and induration. The sandstones consist of grains of quartz, sanidine, biotite, and aphanitic lithic fragment in a fine-grained matrix. Interbedded with the sandstones are light gray to moderate-red conglomerates. The conglomerates are moderate to well indurated and contain clasts (1 to 5 cm in diameter) of the tuff of Lemitar Mountains, the tuff of South Canyon, Hells Mesa Tuff, andesitic lavas, and rhyolitic lavas.

Moderate-red siltstones are present in some localities; however, siltstones are not abundant. The siltstones are poorly bedded and vary from slightly to well indurated.

The small, rounded outcrop of Popotosa rocks northwest of Squaw Peak (sec. 28, T.4S., R.4W.) appears to be a laharic breccia. These breccias overlie sandstones, tuffaceous sandstones, and siltstones that are exposed in the road cut. The laharic breccias consist of matrix-supported clasts of Hells Mesa Tuff, tuff of Lemitar Mountains, tuff of South Canyon, and bedded sedimentary rocks exceeding 1.5 feet (0.46 m) in diameter; no internal stratification was observed. The matrix is moderate red and contains sand-sized grains of quartz, feldspar, and biotite.

tuffaceous unit of Garcia Ranch. Several, local, discontinuous ash-flow tuffs, pyroclastic-surge and/or air-fall deposits, and reworked tuffaceous rocks are interbedded with the Popotosa Formation in the northern part of the study area. Several, thin ash-flow tuffs are exposed in the gullies east of Mulligan Gulch (sec. 23 T.4S., R5W.); however, the tuffs are not continuous to the south. The ash-flow tuffs are typically white, crystal poor to moderately crystal rich, and rich in lithic fragments. Interbedded with the ash-flow tuffs are pyroclastic-surge deposits (?), air-fall tuffs (?), reworked tuffaceous rocks and sandstones. Because of the local extent, poor exposures, and thin, discontinuous nature, these ash-flow tuffs were mapped with the Popotosa Formation.

A thin, ash-flow tuff, associated with the eruption of the crystal-poor rhyolitic lavas, was mapped separately where thickness allowed. This ash-flow tuff crops out beneath the crystal-poor rhyolitic lavas southeast of Garcia Ranch (sec. 24, T.4s., R.5W.). It is quite thin and poorly exposed north of Squaw Peak, (sec.20, T.4S., R.4W), but is well exposed in a road cut north of this study area (sec. 9, T.4S., R.4W.). In hand specimen, this ash-flow tuff is moderate red with black pumice and is both phenocryst poor, and moderately welded. In thin section, the rock contains trace amounts of compositionally zoned plagioclase phenocrysts that range from 0.04 to 1 mm in length and average 0.1 mm in length. Biotite laths, 0.5 mm long, make up approximately 1 percent of the rock and are typically unaltered. The matrix consists of moderately flattened glass shards which drape over phenocrysts. Pumice fragments vary from spherulitically devitrified glass to fragments with very little devitrification.

The distribution and lithologies of the Popotosa Formation suggest that sedimentation was structurally controlled. Sandstones and alluvial fans were deposited in strike valleys during faulting. In the southern part of this study area, the Popotosa Formation thins and andesitic lavas interbedded with the sedimentary rocks thicken. In the northern part of the area, local ash-flow tuffs, pyroclastic-surge deposits, air-fall tuffs and rhyolitic lavas are interbedded with the Popotosa Formation. Clast lithologies and several transport directions suggest that source regions for the Popotosa Formation were structurally high areas between strike valleys.

Andesitic Lavas

In this study area, dense, phenocryst-poor andesitic lavas crop out in the stratigraphic interval above the tuff of South Canyon. The andesitic lavas form small, discontinuous outcrops in the north and central portion of this study area and thick, continuous outcrops to the south. The andesitic lavas conformably overlie, and are interbedded with, variable thicknesses of the Popotosa Formation; the lavas unconformably overlie the tuff of South Canyon where the sedimentary interval is absent. The andesitic lavas are conformably overlain by the Popotosa Formation or by the younger rhyolite of Magdalena Peak and Squaw Peak crater deposits. A maximum thickness of 1000 feet (300 m) was obtained for the andesitic lava from a cross section using the dip of the overlying Popotosa Formation; this thickness may be exaggerated by faults. In the northern portion of the study area, the andesitic lavas are only 30 feet (9 m) thick and seem to have thinned gradually from south to north.

The andesitic lavas of the area occur in the same stratigraphic interval and are lithologically similar to Osburn's (1978) intermediate lavas and Allen's (1979) and Bowring's (1980) andesites. Although the andesitic lavas have not been dated, the underlying tuff of South Canyon has been dated at 26.0 m.y. and the overlying rhyolite of Magdalena Peak has been dated at 13.6 m.y. If the andesitic lavas in this study area are correlative with Osburn's (1978) intermediate lavas, then the age of the lavas may be between 26.0 m.y. and the 20 m.y. age of the Water Canyon Mesa silicic lavas that overlie the intermediate lavas in the eastern Magdalena Mountains.

The andesitic lavas in this study area crop out as rounded hills covered with platy to angular colluvium; however, the lavas form steep cliffs along Mulligan Gulch (secs. 12, 13, 18, T.5S., R.5W.). In hand specimen, the andesitic lavas are medium dark gray to grayish black on fresh surfaces and greenish gray to dark greenish gray on weathered surfaces. The andesitic lavas are slightly porphyritic and range from dense to very vesicular. Weathered outcrops commonly have joints and vesicles coated with caliche.

The andesitic lavas contain 5 to 15 percent clinopyroxene, plagioclase, quartz, and biotite phenocrysts in a groundmass of plagioclase microlites, low-birefringent phyllosilicates and iron oxides after mafic minerals. Clinopyroxene phenocrysts, 0.2 mm in diameter, are partially to completely altered to low-birefringent phyllosilicates and iron oxides, and make up 3 to 8 percent of the rock. These clinopyroxene phenocrysts are occasionally polysynthetically twinned. Clinopyroxene rims, averaging 0.1 mm in thickness, commonly coat quartz phenocrysts.

Plagioclase phenocrysts, 0.6 mm long, make up about 3 percent of the rock. These plagioclase phenocrysts are embayed, compositionally zoned, and exhibit preferential alteration of the outer plagioclase zone which, in turn, commonly has a thin overgrowth of more sodic feldspar. The outer compositional zones average An 35 while the inner compositional zones average An 43 (9 grains, Rittmann Zone Method).

Quartz phenocrysts, averaging 0.4 mm in diameter, are present in trace amounts and are rimmed by a thin layer of clinopyroxene (Fig.15). There is strong evidence suggesting that most of the quartz are phenocrysts rather than xenocrysts from upper crustal material. Only one possible polycrystalline quartz grain was observed and other

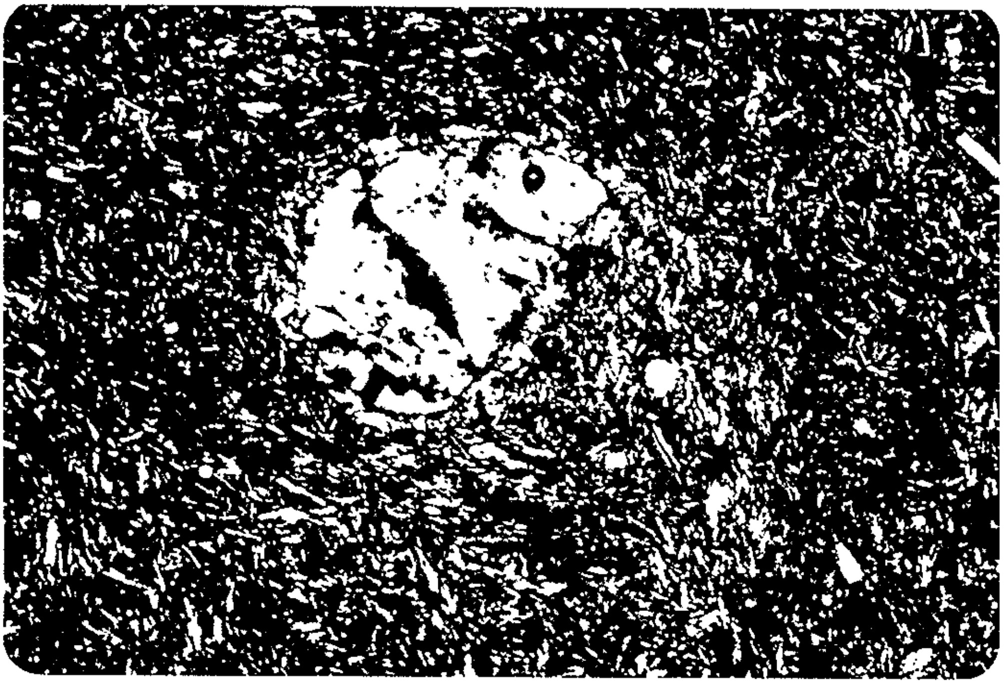


Figure 15. Photomicrograph of a high-pressure quartz phenocryst (large center phenocryst) rimmed with a thin layer of clinopyroxene. (crossed nichols)

polycrystalline rock fragments are absent. Concentrations of Sr in the basaltic-andesite lavas in the Socorro-Magdalena area average 820 ppm Sr (Chapin unpublished data). This high concentration of Sr suggests that crustal contamination of a more basaltic composition by upper crustal material was insignificant since contamination should lower Sr concentrations. Plagioclase phenocrysts are compositionally zoned (An 35 to An 43), indicating that the chemical and physical parameters of the melt changed through time. It is hypothesized that the quartz phenocrysts are high-pressure quartz and that the melt moved up rapidly through the crust during incipient rifting. The clinopyroxene coatings on the quartz phenocrysts slowed down, or prevented, the expected reaction of quartz with the melt at low pressures from going to completion. The single polycrystalline quartz grain suggests that some xenocrysts may be present.

Crystal-poor Rhyolitic Lavas

In the northern part of this study area, phenocryst-poor, flow-banded rhyolitic lavas are interbedded with the Popotosa Formation and locally overlie thin ash-flow tuffs. These lavas form steep, cliffy slopes covered with angular blocks of colluvium. A dark vitrophyre, locally autobrecciated, occurs at the base of the flow. The crystal-poor rhyolitic lavas crop out extensively north of this study area. A thick section of the lavas is well exposed in road cuts west of McDaniel tank (sec. 9, T.4S., R.4W.). The maximum exposed thickness in this study area is about 420 feet (130 m). These crystal-poor rhyolitic lavas have well-defined primary flow foliations that are intricately folded in many areas. In hand specimen, the lavas are finely foliated and contain moderately abundant, flattened vesicles 0.3 to 3 mm in diameter. On fresh surfaces, the rock is grayish red with very-light-gray layers along foliation planes.

In thin section, the crystal-poor rhyolitic lavas contain only trace amounts of plagioclase, sanidine, and biotite phenocrysts. Both plagioclase (An 20, 1 grain, Rittmann Zone Method) and sanidine phenocrysts average about 0.15 mm in diameter. Biotite euhedra, averaging 0.5 mm in length, are preferentially oriented along foliation planes and are partially altered to iron oxides. Small, rounded magnetite grains comprise 3 to 8 percent of the rock. The groundmass consists of finely laminated, hematite-rich layers alternating with quartz-rich layers. The quartz was probably precipitated during cooling or from later fluids. Minor amounts of feldspar microlites are present in some horizons. The texture and color of the crystal-poor lavas suggest a more silicic composition than does the phenocryst assemblage.

Rhyolite of Magdalena Peak

The rhyolite of Magdalena Peak, a porphyritic lava, is the youngest flow in this study area. These rhyolitic lavas were first described by Loughlin and Koschmann (1942) who called them "pink rhyolites" and noted their occurrence on Magdalena Peak and Elephant Mountain. Weber (1957) has done a detailed petrographic and chemical study of part of the rhyolite of Magdalena Peak at the Stendel perlite deposit south of Magdalena Peak (sec. 10, T.3S., R.4W.). Deal (1973) identified a porphyritic "quartz latite" in the northern part of this study area. Osburn (1978) and Chamberlin (1980) have described lavas of similar lithologies interbedded with the Popotosa Formation; however, these lavas are not continuous with the rhyolite of Magdalena Peak. Allen (1979) and Bowring (1980) have documented the rhyolite of Magdalena Peak over much of the distance between this study area and the Magdalena Peak vent (Fig. 1).

A K-Ar age of 13.6 m.y. (average of 2 dates) has been obtained for the rhyolite of Magdalena Peak (Appendix A). The source of the rhyolitic lavas is believed to be the vent which is well exposed on Magdalena Peak (Allen, 1979); no evidence for vents was found in this or Bowring's study areas. These rhyolitic lavas form continuous outcrops along the west flank of the Magdalena Mountains from Alameda Spring, in the central part of this study area (sec. 34, T.2S., R.4W.), to Magdalena Peak just south of the town of Magdalena (sec. 34, T.2S., R.4W.). In this study area, the rhyolite of Magdalena Peak forms a broad, continuous outcrop belt which appears to have been deposited in a paleovalley.

The rhyolite of Magdalena Peak conformably overlies the Popotosa Formation which becomes more tuffaceous near the contact of the lavas.

The rhyolitic lavas also overlie various other units on pronounced angular unconformities. These units including the tuff of Lemitar Mountains, the lower sedimentary unit, the andesitic lavas, and the crystal-poor rhyolitic lavas. The rhyolite of Magdalena Peak has a maximum thickness of 500 feet (150 m) in this study area; however, there is a considerable variation of thickness because of deposition on paleotopography and subsequent erosion.

The rhyolite of Magdalena Peak forms steep cliffy hills covered with angular blocks of colluvium. The base of the rhyolitic lavas typically has a dark vitrophyre as much as 80 feet (25 m) in thickness. The rhyolite of Magdalena Peak exhibits primary flow structures (ie. foliations, elongate gas cavities, lineations, etc.) which are intricately folded in many area; in addition, secondary folding may have occurred in areas of steep topography at the time of the lavas emplacement.

On fresh surfaces, the rhyolite of Magdalena Peak is light brownish gray with white feldspars and black to moderate-brown biotite and hornblende phenocrysts. Mineralogically, the rhyolite of Magdalena Peak is an andesite (Travis, 1955) containing 13 to 18 percent plagioclase, sanidine, biotite, and hornblende phenocrysts; however, chemically the lavas are rhyolites (Weber 1957). Euhedral to subhedral plagioclase phenocrysts, averaging 0.7 mm diameter, exhibit normal compositional zoning (An 23 to An 31, 11 grains, Rittmann Zone Method). Sanidine phenocrysts, 1.5 mm in diameter, are present in some thin sections in amounts as great as one percent; sanidine is absent in other thin sections. Lath-shaped hornblende phenocrysts, about 0.6 mm long, are present in trace amounts; some crystals are partially altered to low-birefringent phyllosilicates and iron oxides. Biotite phenocrysts, about 0.5 mm in length, are commonly altered to iron oxides and make up about 3 percent of the rock. The lavas contain approximately 3 percent small, rounded magnetite grains. The groundmass typically consists of devitrified glass with minor spherulitic textures.

The rhyolite of Magdalena Peak is part of the bimodal rhyolitic to rhyodacitic and basaltic volcanism that occurred in the Socorro-Magdalena area during the interval of 20 to 7 m.y. ago (Chapin and others, 1978; Osburn, 1978). The rhyolite of Magdalena Peak, the Pound Ranch lavas in the eastern Magdalena Mountains, and the rhyolitic flows in the Socorro Peak area postdate the cauldrons in which they lie by 16 to 18 m.y.. The rhyolitic lavas in the Socorro-Magdalena area are in close proximity to the Socorro transverse shear zone suggesting that this structure, in conjunction with pre-existing cauldron-related structures, may have controlled the emplacement of the lavas (Chapin and others, 1978).

Tertiary Domes and Intrusions

Locations, petrographic characteristics, and informal names for eleven domes and intrusions in this study area are summarized in Appendix B. These eleven domes and intrusions will be discussed individually below. The age of these rocks are not constrained by overlying stratigraphic units and ages have not been obtained. A maximum age is given for each by the age of the youngest unit intruded.

Chocle Windmill Rhyolitic Intrusion

A small rhyolitic intrusion located west of Chocle Windmill (sec. 35, T.4S., R.5W.) has well-exposed, steep, intrusive contacts with the tuff of Lemitar Mountains. Several, discordant blocks of the tuff of Lemitar Mountains, exceeding 10 feet in diameter, are surrounded by the rhyolite. In hand specimen, the rock is dense, phenocryst-poor, and varies from a very light gray to medium light gray. In thin section, the rock contains only trace amounts of quartz, sanidine, and biotite phenocrysts in a groundmass of blocky quartz and alkali feldspar devitrification crystals.

Mulligan Gulch Rhyolitic Dome

A small, intrusive-extrusive complex, dissected by Mulligan Gulch (sec. 1, T.5S., R.5W.), consists of bedded, pyroclastic crater deposits intruded by a rhyolitic plug. The pyroclastic material was probably deposited by phreatic pyroclastic eruptions preceeding, or during, the intrusion of the rhyolitic plug. The pyroclastic deposits consists of angular fragments of pumice, as much as 12 cm in diameter, and lithic fragments of the surrounding country rock, 0.5 to 25 cm in diameter, surrounded by a tuffaceous matrix. The pumice are typically white and the matrix light gray to grayish orange pink. These pyroclastic deposits are bedded and dip inward toward the rhyolitic intrusion (Fig. 16).

The rhyolitic plug which intrudes the pyroclastic deposits consists of crystal-poor, commonly autobrecciated rhyolitic bodies with intricately contorted foliation planes. In the autobrecciated portions, the rock consists of very-light-gray fragments surrounded by a medium-light-gray matrix. In areas where autobrecciation did not occur, the foliation planes are defined by alternating very-light-gray to medium-light-gray layers. In thin section, the rhyolitic lavas contain only trace amounts of biotite phenocrysts, 0.05 mm in length, in a groundmass

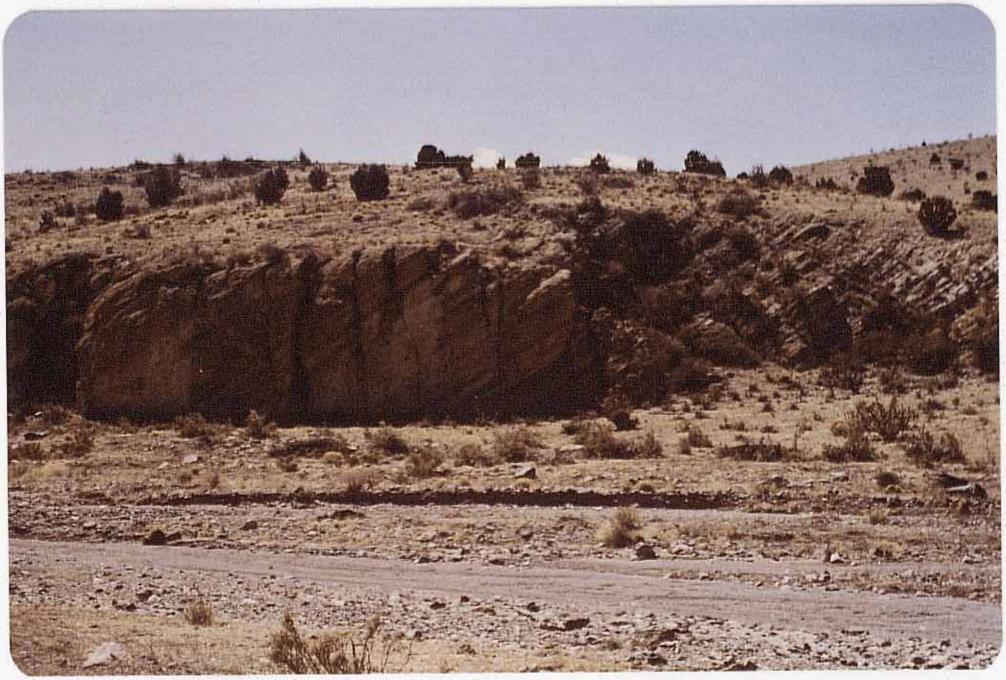


Figure 16. Bedded, pyroclastic deposits of the Mulligan Gulch dome. Beds dip toward the rhyolitic plug which is just to the left of the photograph.

of devitrified glass; minor amounts of alteration minerals including low-birefringent phyllosilicates and iron oxides are also present.

B. O. Ranch Rhyolitic Dome

The B. O. Ranch rhyolitic dome consists of bedded pyroclastic deposits intruded by a rhyolitic plug. This intrusive-extrusive complex is quite similar to the Mulligan Gulch rhyolitic dome; however, the dome is much larger and forms a tall, steep, rounded hill west of the B. O. Ranch (secs. 6, 7, T.5S., R.4W.). Bedded pyroclastic deposits crop out sporadically around the perimeter of the igneous complex and dip toward the rhyolitic plug. The pyroclastic deposits are white with light-gray to black glassy fragments (Fig. 17).

In thin section, the pyroclastic rocks contain trace amounts of quartz, sanidine, and plagioclase phenocrysts averaging 0.25 mm in diameter; trace amounts of biotite, 0.05 mm in length, are also present. Phenocrysts and glassy, unaltered pyroclastic fragments are surrounded by a partially devitrified matrix.

Figure 17. Glassy, slightly perlitic, fragments associated with the pyroclastic deposits of the B. O. Ranch rhyolitic dome.

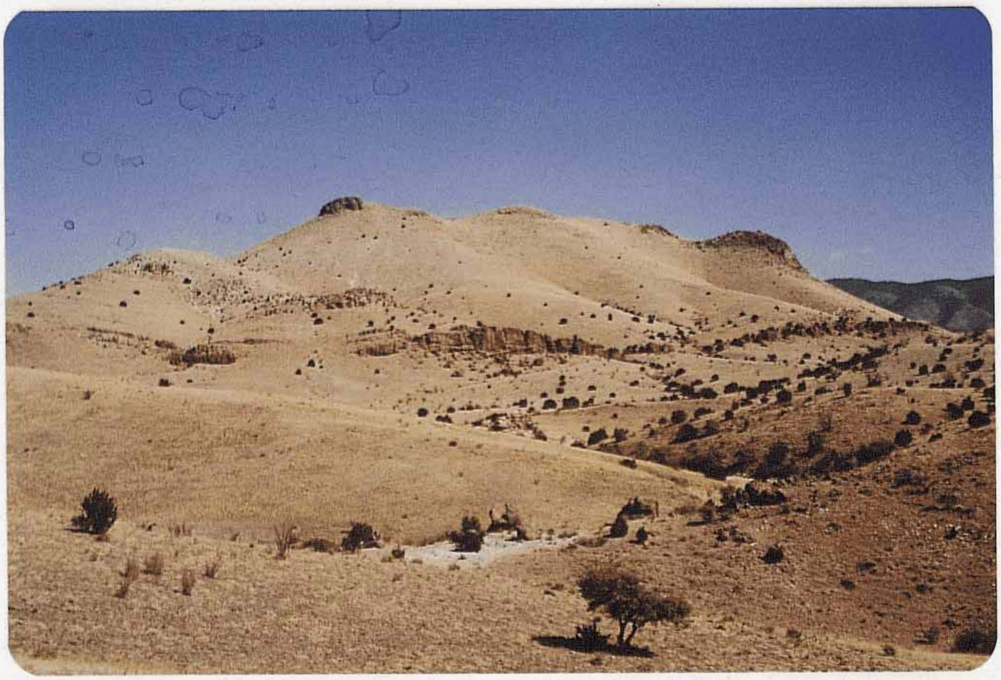


Figure 18. A dark, vitric, autobrecciated zone surrounds the B. O. Ranch rhyolitic dome and forms a prominent, dark-colored ledge.

A dark, vitric, autobrecciated zone, on the perimeter of the rhyolitic intrusion, is more resistant to weathering than the pyroclastic deposits and forms a dark-colored ledge around the dome (Fig. 17). The rhyolitic lavas that are not autobrecciated are very light gray to light gray. In thin section, the rock contains trace amounts of quartz and sanidine phenocrysts that average 0.75 and 0.5 mm in diameter, respectively. The groundmass consists of glass which has been devitrified to quartz and alkali feldspar; as much as 10 percent iron oxides are also present. Spherulites, about 1.4 mm in diameter, typically have a nucleus of quartz crystals. These nuclei are free of iron oxides which appear to have diffused to the outer portions of the spherulites during crystallization.

Squaw Peak Rhyolitic Dome

A large rhyolitic dome intrudes the andesitic lavas and the Popotosa Formation in the central part of this study area (secs. 29, 32, T.4S., R.5W.). The dome forms steep, cliffy, poorly dissected hills covered with large, angular blocks of colluvium. Associated with the dome are several, small rhyolitic lava flows that have dark vitrophyres at their bases (Fig. 19). Bedded, tuffaceous crater deposits that are lithologically similar to the Mulligan Gulch and B. O. Ranch pyroclastic deposits are present north of the dome (sec. 29 T.4S., R.4W.). Foliation planes are very steep and dip toward the center of the dome (Fig. 19). The rock is typically medium light gray and appears glassy in some areas.

In thin section, the Squaw Peak rhyolitic dome contains approximately 15 percent phenocrysts of quartz, sanidine, plagioclase, biotite, and hornblende in a devitrified to glassy matrix. Approximately 10 percent of the rock is made up of subequal amounts of quartz and sanidine phenocrysts which average 0.4 mm in diameter. Plagioclase phenocrysts, 0.5 mm in diameter, make up about 5 percent of the rock and have a composition of An 24 (6 grains, Rittmann Zone Method). Biotite phenocrysts which average 0.2 mm in length, are strongly pleochroic and commonly unaltered. Trace amounts of hornblende phenocrysts are extensively altered to iron oxides. The groundmass consists of glass or partially to completely, devitrified spherulitic glass.

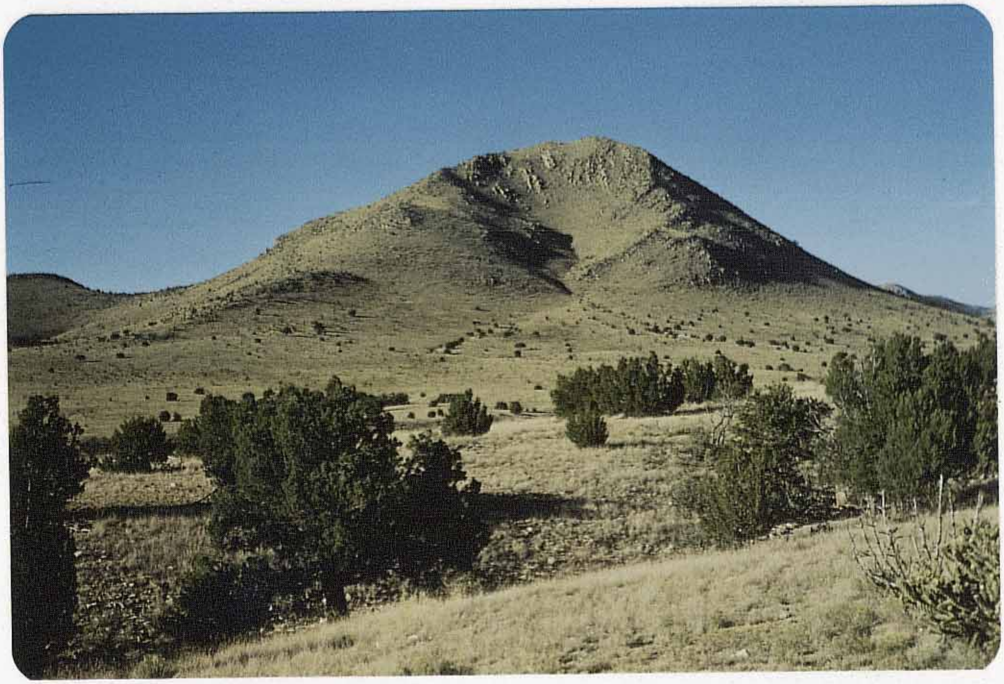


Figure 19. Nearly vertical flow foliations of the Squaw Peak rhyolitic dome are well exposed in the dissected portion of the dome. The dark area in the left center portion of the photograph is a small rhyolitic flow associated with intrusion of the dome.

Cibola Andesitic Intrusion

A small andesitic intrusion (?) located just north of Squaw Peak (secs. 21, 28, T.4S., R.4W.) forms a small, rounded hill covered with angular blocks of colluvium; the intrusion is surrounded by alluvium. The outcrop has been interpreted as intrusive based on steep foliation planes. In hand specimen, the andesitic intrusion is grayish orange pink with conspicuous black hornblende phenocrysts that are preferentially oriented.

In thin section, the andesitic intrusion contains approximately 14 percent plagioclase, hornblende, and biotite phenocrysts in a groundmass of plagioclase microlites and mafic alteration products. Plagioclase phenocrysts, 0.5 mm in length, exhibit normal compositional zoning and make up about 9 percent of the rock. The composition of crystals varies from An 55 to An 40 from the center to outer compositional zones (3 grains, Rittmann Zone Method). Hornblende phenocrysts make up about 3 percent of the rock, average 0.5 mm in length, and are altered to iron oxides along the crystal edges and cleavage planes. Approximately 2 percent of the rock is made up of biotite phenocrysts 0.25 mm in length. Small, rounded magnetite grains comprise 2 percent of the rock. The groundmass of the andesitic intrusion consists of plagioclase microlites, and low-birefringent phyllosilicates and iron oxides after mafic minerals.

National Rhyolitic Intrusions

Several crystal-poor rhyolitic bodies have intruded the Popotosa Formation approximately 1 mile north of Squaw Peak (secs. 20, 21, T.4S., R.4W.). Steep contacts with the Popotosa Formation, nearly vertical foliations, and vitrophyres located near the contacts with sedimentary rocks suggest that the bodies are intrusive. The elongate outcrop of the Hells Mesa (sec. 21, T.4S., R4W.) has been interpreted as a large block which has been forced up by these intrusions.

The National rhyolitic intrusions are medium gray to medium dark gray and exhibit closely spaced, contorted foliation planes in hand specimen. In thin section, these intrusive rhyolites contain embayed quartz and sanidine phenocrysts, 0.25 mm in diameter, that make up about 2 and 7 percent of the rock, respectively. Biotite phenocrysts, 0.1 mm in length, are present in trace amounts. The groundmass consists of quartz and alkali feldspar devitrification products and minor amounts of iron oxides. In areas where the intrusion has been autobrecciated, the matrix can be differentiated from the breccia fragments by slightly different devitrification texture and composition.

Deer Plot Tank Dacitic Intrusions

The Deer Plot Tank dacitic intrusions, named by Bowring (1980), consists of several, porphyritic dacitic bodies that crop out near Mill Place Spring and Deer Plot Tank (secs. 21,

22, 26, 27, 28, T.4S., R.4W.). These rocks intrude the tuff of Lemitar Mountains, the lower sedimentary unit (Bowring's Popotosa Formation) and the tuff of South Canyon. The Deer Plot Tank intrusions erode to steep, cliffy slopes covered with angular blocks of colluvium.

In hand specimen, the Deer Plot Tank intrusions are dense, white to very light gray, and extensively altered. In thin section, the rock contains about 10 percent phenocrysts of quartz, plagioclase, and biotite in a devitrified matrix. Approximately 5 percent of the rock is made up of embayed quartz phenocrysts that average 0.5 mm in diameter. Plagioclase phenocrysts (?), 0.5 mm in length, make up about 5 percent of the rock and are pervasively altered. Some of the plagioclase phenocrysts have been replaced by an optically continuous mineral which appears to be alkali feldspar. Quartz crystals commonly fill void spaces formed by alteration of plagioclase (?) phenocrysts. The groundmass of the lavas consists of a mosaic of quartz and alkali feldspar devitrification crystals and secondary quartz.

Hardy Ridge Andesitic Intrusion

A small latitic to andesitic plug intrudes the unit of Hardy Ridge in the northwestern corner of section 26 (T.4S., R.4W.) and has the texture commonly called "birds eye" porphyry in the mining literature. The andesitic intrusion is largely covered by colluvium of the unit of Hardy Ridge; however, the andesitic outcrops can be identified by a reddish soil containing andesitic fragments averaging 0.5 cm in diameter. In hand specimen, the rock is medium light gray on fresh surfaces. The rock contains large feldspar phenocrysts (?) that exhibit reaction rims and may have been incorporated during emplacement of the intrusion. Lithic fragments, of unknown identity, averaging 1 cm in diameter, are also present in the intrusion.

In thin section, the andesitic lavas contain approximately 3 percent plagioclase, 5 percent biotite, and trace amounts of quartz phenocrysts in a matrix of plagioclase microlites and iron oxides. Plagioclase phenocrysts, 0.5 mm in diameter, are commonly altered to calcite and have an average composition of An 29 (3 grains, Rittmann Zone Method). Biotite laths, 0.5 mm in length, are partially altered to iron oxides. Quartz phenocrysts average 2 mm in diameter and are typically embayed. The groundmass of the rock consists of plagioclase microlites and low-birefringent phyllosilicates and iron oxides after mafic minerals.

Hardy Ridge Rhyolitic Intrusion

A phenocryst-poor rhyolitic body intrudes the Hells Mesa Tuff, the unit of Hardy Ridge, and the tuff of Lemitar Mountains on the west side of Hardy Ridge (sec. 36, T.4S. R.4W.). The intrusion erodes to steep, cliffy slopes that are covered with small, platy colluvium. In hand specimen, the rock is very light gray on fresh surfaces and weathers to medium light gray. In thin section, the rock contains trace amounts of quartz phenocrysts, 0.3 mm in diameter. The groundmass consists of a mosaic of quartz and alkali feldspar devitrification products with minor amounts of high-birefringent phyllosilicates in fractures and between groundmass crystals. Close proximity and lithological similarities of the Hardy Ridge rhyolitic intrusion to the intrusions of the unit of Sawmill Canyon suggests that they may be correlative.

Puertecito Canyon Dacitic Dome

Porphyritic dacitic bodies intrude the unit of Hardy Ridge in this study area (sec. 32, T.4S., R.4W.) and the tuff of Lemitar Mountains south of this study area. The Puertecito Canyon dacitic dome forms steep, cliffy slopes covered with large, angular blocks of colluvium. Steep contacts of the dome with the unit of Hardy Ridge and nearly vertical foliation planes near the contacts suggest that the dome is intrusive.

In hand specimen, rocks of the Puertecito Canyon dacitic dome are moderate to grayish red on fresh surfaces and weather to pale red. Small, rectangular-shaped cavities are common on weathered surfaces and form by the preferential weathering of plagioclase (?) phenocrysts. In thin section, the rock contains approximately 30 percent phenocrysts of plagioclase (?), sanidine, and biotite in a groundmass of devitrified glass. Approximately 26 percent of the rock is made up of plagioclase (?) phenocrysts, 0.7 mm in diameter, that have been extensively altered to calcite and high birefringent phyllosilicates or replaced by an optically continuous mineral which appears to be alkali feldspar (?). Fresh sanidine phenocrysts, 0.7 mm in diameter, make up about 3 percent of the rock. Biotite phenocrysts have been completely altered to iron oxides and comprise approximately 3 percent of the rock. The groundmass consists of a mosaic of quartz and alkali feldspar devitrification products and minor amounts of iron oxides.

Unit of Sawmill Canyon

The unit of Sawmill Canyon consists of a large complex of rhyolitic domes and pyroclastic crater deposits that intrude units as young as the tuff of Lemitar Mountains. The domal complex forms a large, continuous outcrop along the crest of Hardy Ridge from about 1 mile north (sec. 19, T.4S., R.3W.)

to approximately 0.5 miles south of this study area (sec. 6, T.5S., R.3W.) and eastward to the bottom of Sawmill Canyon. Rhyolitic, crystal-poor pyroclastic deposits overlie the andesitic lavas of the unit of Hardy Ridge and the Hells Mesa Tuff in this study area and cut across the rhyolitic lavas of the unit of Hardy Ridge in Bowring's study area (1980). The pyroclastic deposits probably formed by phreatic eruptions prior to, or during, the emplacement of the rhyolitic intrusions of the unit of Sawmill Canyon.

In hand specimen, the pyroclastic deposits are very light gray to medium light gray. The rock consists of fragments of crystal-poor rhyolite, minor amounts of dark, aphanitic lithic fragments, and lithic fragments of the tuff of Lemitar Mountains surrounded by a tuffaceous matrix. In thin section, the rock primarily consists of rhyolitic fragments that can be distinguished from the groundmass by variations in the amount of devitrification and differences in the size of the quartz and alkali feldspar devitrification crystals. Minor amounts of mafic lithic fragments and fragments of the tuff of Lemitar Mountains are also present. Quartz and sanidine phenocrysts, 0.25 mm in diameter, are present in trace amounts. Intruding or overlying the pyroclastic deposits are phenocryst-free, dense rhyolitic lavas. The contact of the intrusive rhyolite with the pyroclastic deposits is marked by a topographic bench at an elevation of 8,680 feet. The rhyolite weathers to moderately steep slopes covered with a platy, pebbly colluvium.

In hand specimen, the rock is very light gray on fresh surfaces; it is dense and phenocryst-free in hand specimen and thin section. The rock consists of quartz and alkali feldspar devitrification crystals, trace amounts of high-birefringent phyllosilicates, and approximately 3 percent magnetite grains 0.02 mm in diameter.

Summary. In order to gain a better understanding of the genetic history of the domes and intrusions of this study area, ages for these igneous rock types must be obtained. Petrographically and geomorphically, many of the domes and intrusions appear significantly younger than cauldron-related intrusions. It is hypothesized that some of the domes and intrusions are related to magmatism along the Socorro transverse shear zone and that the magmas intruded through much older, cauldron-related structural flaws; however, without better age control, it is not possible to exclude the possibility of ring fracture volcanism of the type described by Smith and Bailey (1968).

Rhyolitic Dikes

Rhyolitic dikes are common throughout much of the Socorro-Magdalena area and this study area. Two elliptical areas of rhyolitic dikes are surrounded by piedmont gravels north of the of Deer Plot Tank dacitic intrusives (sec. 22, T.4S., R.4W.). In hand specimen, the dikes are phenocryst-free and very light gray to light gray. An outcrop of a lithic-rich variety of rhyolite dike is present in the same locality (Bowring, 1980) suggesting that a larger body may be present. These dikes are intruded along the hypothesized Magdalena cauldron margin.

Several, small rhyolitic dikes intrude along, or in close proximity to, a major north-trending fault on the west side of Hardy Ridge (sec.36, T.4S, R.4W.). In hand specimen, the rhyolitic dikes are phenocryst-free and very light gray to light gray. These dikes are quite similar to the rhyolitic lavas of the unit of Sawmill Canyon and may be correlative.

Tertiary-Quaternary Deposits

Piedmont Gravels

In the eastern and central portions of this study area, west- to southwest-sloping piedmont gravels, formed by coalescing alluvial fans derived from the western slope of the Magdalena Mountains, unconformably overlie Tertiary units. Similar east- to southeast-sloping piedmont gravels, derived from the eastern slope of the San Mateo Mountains, are present west of Mulligan Gulch. Two levels of piedmont gravels were mapped separately and are marked by prominent benches in many areas.

The piedmont gravels are partially dissected and thicknesses of 100 feet (30 m) have been observed; however, the gravels commonly constitute a thin layer unconformably overlying Tertiary units. The piedmont gravels consists of boulder-to sand-sized clasts of ash-flow tuffs and both rhyolitic and andesitic lavas; local variations in the components of the gravels reflect differences in the source areas.

Quaternary Deposits

Alluvium

Stream terraces along modern streams have been mapped as alluvium. The largest areas of alluvium in this study area occur along Mulligan Gulch and the stream east of the B. O. Ranch.

Stream Gravels

Sediments deposited in modern stream beds were mapped as stream gravels.

Talus/Colluvium

Active talus slopes and stabilized colluvium is widespread in this study area. In general, talus/colluvium was mapped where important geologic contacts or faults were obscured.

Landslide deposits

Large, landslide blocks have developed in areas where the rhyolite of Magdalena Peak has been dissected by stream valleys and where the underlying Popotosa Formation is tuffaceous and poorly indurated. The landslide blocks have moved downslope along low-angle slide planes and are characterized by either rubbly slopes with variable strikes and dips and/or by sharp offsets of the basal vitrophyre in the rhyolite of Magdalena Peak.

STRUCTURE

Four overlapping structural events have been documented in central New Mexico and are applicable to the Socorro-Magdalena area including: 1) late Cretaceous to middle Eocene (Laramide) uplifts which were eroded and the detritus deposited in adjacent downwarps (75 to 50 m.y. ago) (Chapin and Seager, 1975); 2) voluminous volcanic eruption and development of cauldrons during the Oligocene (37 to 26 m.y. ago) (Chapin and others, 1978); 3) regional extension and development of the Rio Grande rift (32 m.y. ago to present) (Chapin and others, 1978); and 4) regional uplift and block faulting of the Magdalena and San Mateo Mountains (about 7 m.y. to 4 m.y. ago) (Chapin and others, 1978).

Laramide Uplift and Erosion

Most of the area west of the Rio Grande, south of San Acacia, and westward to the San Mateo Mountains has been interpreted as a broad, Laramide uplift (Chapin, 1974, Chapin and others, 1978) which shed detritus into adjacent synclinal downwarps (Chapin and Seager, 1975). The Baca

Formation in the Socorro-Magdalena area received part of its detritus from this Laramide uplift (Cather, in progress). In the southern Rocky Mountains, relaxation of compressional stresses to an essentially neutral stress field occurred in Middle Eocene time (45-50 m.y.) and erosion rapidly planned the topography (Chapin and Seager, 1975). There are no accurate controls on the timing of the Laramide uplift of the ancestral Magdalena Mountains during Laramide time; however, uplift probably ceased at approximately the same time in this area as it did in the southern Rocky Mountains.

Cauldron-Related Structures

The period of volcanism in the Socorro-Magdalena area began about 37 m.y. ago and greatly influenced the regional structure. Several cauldrons have been documented in the Socorro-Magdalena area including: a lower Spears-aged cauldron approximately 27 miles northwest of Magdalena (Harrison, in progress); the North Baldy, Magdalena, and Sawmill Canyon cauldrons in the Socorro-Magdalena Mountains (Chapin and others, 1978); and the Mount Withington and tuff of South Canyon-aged cauldrons which are believed to be present in the northern San Mateo Mountains.

The eruption of the Hells Mesa Tuff and collapse of the North Baldy cauldron occurred about 32 m.y. ago. The topographic margin of the North Baldy cauldron is well exposed on Socorro Peak (called Socorro cauldron by Chamberlin, 1980), on North Baldy in the central Magdalena Mountains (Blakestad, 1978 and Allen, 1980), and in the southern Chupadera Mountains (Osburn, oral communication).

The Magdalena cauldron and the Sawmill Canyon cauldron are the source cauldrons for the A-L Peak Tuff (32 m.y.). The Magdalena cauldron appears to be the source cauldron for the gray-massive and flow-banded members of the A-L Peak Tuff, (Chapin, oral communication); however, more evidence is needed to make a definite correlation. The eastern margin of the Magdalena cauldron is well exposed on the western flank of the northern and central Magdalena Mountains (Allen, 1979, Bowring, 1980); Hells Mesa and Spears outcrops on the west side of Cat Mountain mark a western limit to the cauldron. The Sawmill Canyon cauldron appears to be the source cauldron for the pinnacles member of the A-L Peak Tuff. Segments of the Sawmill Canyon cauldron are well exposed in Osburn's (1978), Petty's (1978), Bowring's (1980), and Roth's (in progress) study areas and in the Torreon Springs area (Osburn, oral communication).

In this study area, original cauldron-related structures are not exposed; however, the structural margins of three cauldrons can be inferred to be present. Cauldron-facies Hells Mesa Tuff and the unit of Hardy Ridge (cauldron-fill of the North Baldy cauldron) have been documented in Bowring's (1980) study area, to the north, and the eastern part of this study area. These outcrops mark the western-most exposures of the cauldron-facies Hells Mesa Tuff indicating that the North Baldy cauldron margin is west of these outcrops.

Projecting the trend of the Magdalena cauldron margin from Allen's (1979) and Bowring's (1980) map areas, the southern part of this cauldron should be present in this study area. The strong transverse element in the rift-related faulting present in this study area is believed to mark the approximate location of the southern Magdalena cauldron margin. These transverse faults are believed to occur as a result of reactivation of older cauldron-related structural flaws which should be nearly perpendicular to the rift-related faults in this area. The presence of Hells Mesa and unit of Hardy Ridge outcrops on Hardy Ridge place a southern limit to the Magdalena cauldron.

In the western part of this study area, there is strong stratigraphic evidence suggesting that the eastern margin of the Mount Withington cauldron is present. The reader is referred to the description of the tuff of Lemitar Mountains for a summary of this evidence.

The Hop Canyon structure (Chapin and others, 1978) which should be present in the northern part of this study area appears to be a deeply subsided portion of the Magdalena cauldron. However, stratigraphic evidence to prove or disprove the Hop Canyon cauldron cannot be obtained because the level of exposure and structural relief do not expose old enough stratigraphic intervals. Plate 2 summarizes the rift-related structures, intrusions, and the approximate location of the cauldron margins in this study area and Figure 20 summarizes the current thought on the location of cauldrons in the Socorro-Lemitar and Magdalena Mountains and their respective out-flow facies tuffs. The nested cauldrons in the Socorro, Magdalena, and San Mateo Mountains lie on or near the Socorro transverse shear zone which is believed to have influenced magmatism during the past 32 m.y. (Chapin and others, 1978).

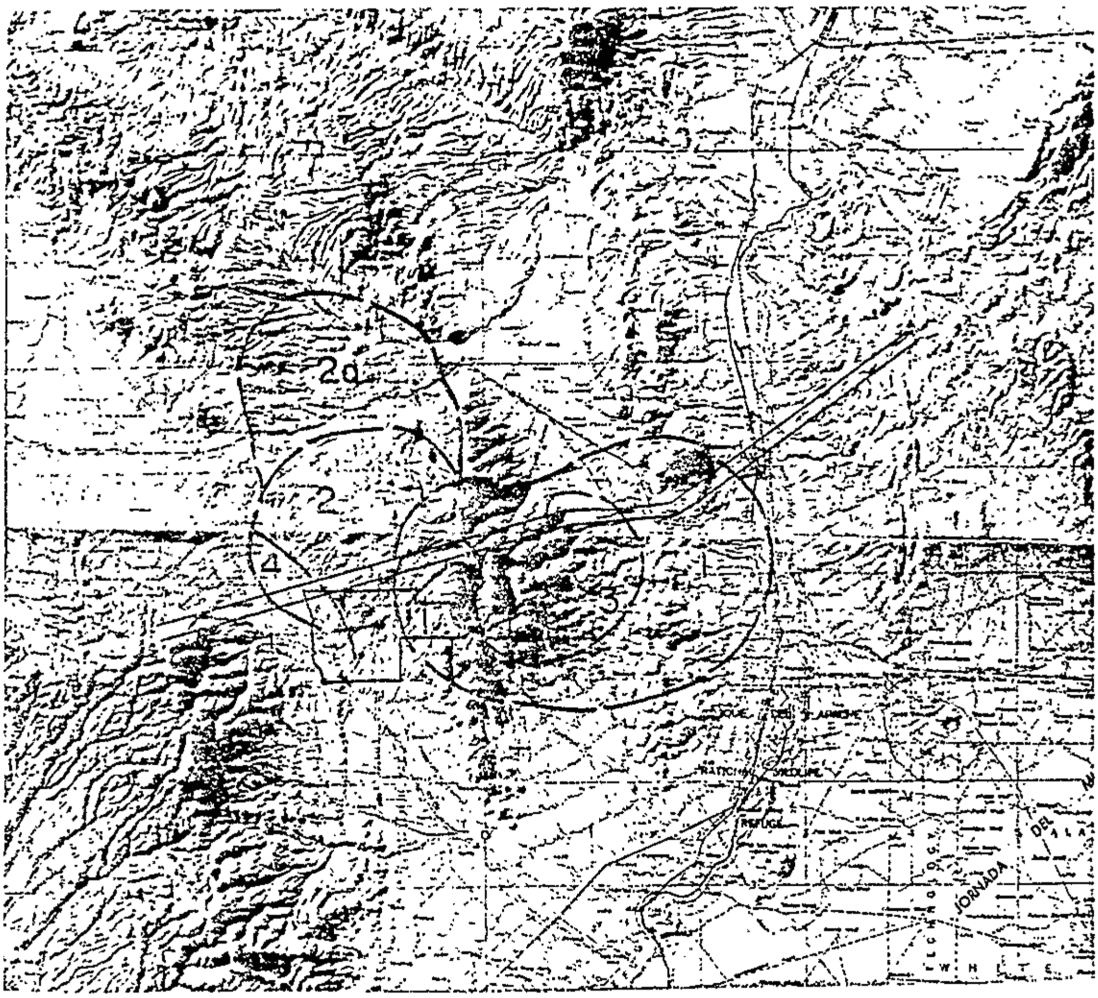


Figure 20. Overlapping and nested cauldrons and the Socorro transverse shear zone. From oldest to youngest, the cauldrons and associated ash-flow tuffs are: 1) North Baldy cauldron-Hells Mesa Tuff; 2) Magdalena cauldron-A-L Peak Tuff, gray massive and flow-banded members; 2a) less-subsided north end of Magdalena cauldron; 3) Sawmill Canyon cauldron-A-L Peak Tuff, pinnacles member (?); 4) Mt. Withington cauldron (?)-tuff of Lemitar Mountains (?). Modified from Chapin and others (1978).

Regional Extension and the Development of the Rio Grande Rift

The Rio Grande rift cleaves New Mexico in two and extends into southern Colorado (Chapin, 1971). The rift began about 32 m.y. ago with extension along major north trending zones of weakness (Chapin, 1976) and has continued to the present. In the Socorro-Magdalena area, the rift broadens into a series of parallel basins and intrarift horsts; the La Jencia basin, Magdalena Mountains, and Mulligan Gulch graben are examples of these basins and horsts. The most prominent style of rift-related faulting in the Socorro-Magdalena area consists of strongly rotated blocks repeated by low-angle normal faults. Similar block faulting has been described by Morton and Black (1975) in the Afar depression of East Africa and by Profett (1977) in the Yerington district in western Nevada. This style of faulting is probably associated with very high heat flow and rapid extension of relatively thin, brittle crust above a ductile substratum (Chamberlin, 1980).

The Morenci lineament, a major crustal lineament of probable Precambrian age, cuts across the central portion of the Socorro-Magdalena area (Chapin and others, 1978) (Fig. 20). The Socorro transverse shear zone occurs along the

Morenci lineament and is marked by a mile wide (1.5 km) zone of jostled fault blocks which separates two fields of fault blocks being rotated in opposite directions. North of the transverse shear zone, the fault blocks are rotated to the west and faulting is down to the east; south of the zone, the fault blocks are rotated to the east and faulting is down to the west. Transverse structures similar to the Socorro transverse shear zone have been documented in the Afar depression of East Africa (Barberi and Varet, 1977) and in the Basin and Range Province (Stewart, 1979).

The three overlapping cauldrons in the Socorro and Magdalena Mountains have had a significant influence on the structure of the Socorro-Magdalena area. Steep, nearly vertical ring fractures of the type described by Smith and Bailey (1968) have been documented in several places and are inferred in others; however, because of the overlapping character of the cauldrons and the overprint of rift-related faulting and sedimentation, many of the cauldron-related structures are not exposed.

Rift-related structures commonly reactivate older cauldron structures when these structural trends are parallel; however, when the structural trends are perpendicular, the rift-related faulting typically is disrupted and has a strong transverse element. In this study area, the rift-related faulting typically trends between north 20 degrees west and due north; some small east-west jogs are present. The fault blocks have been rotated 25 to 45 degrees to the east and displacement is down to the west. The faults dip between 30 to 50 degrees to the west, suggesting that they were high-angle, normal faults before rotation. Older stratigraphic units have been rotated more than overlying units. In the eastern part of the area, the Hells Mesa Tuff has been rotated approximately 10 degrees more than the 28.6 m.y.-old tuff of Lemitar Mountains. In the western part of this study area, the tuff of Lemitar Mountains has been rotated about 10 degrees more than the tuff of South Canyon, suggesting some faulting and rotation prior to the emplacement of the 26.0 m.y.-old tuff of South Canyon. This rotation can explain the variable thickness of the lower sedimentary unit and Popotosa Formation which appear to have been deposited in the strike valleys formed during faulting and rotation.

The 13.6 m.y.-old, flat-lying rhyolite of Magdalena Peak has not been appreciably affected by rift-related faulting and rotation. In this area, faulting and rotation appears to have started during the time span of 31.7 m.y. to 28.6 m.y. ago, based on the angular unconformity that exists between the Hells Mesa Tuff and the tuff of Lemitar

Mountains, and ended prior to the emplacement of the rhyolite of Magdalena Peak (approximately 13.6 m.y. ago).

In the northern part of the area, block faulting becomes complex and diverges from the simple trends observed to the south. This is thought to be caused by the tendency of the rift-related faults to reactivate or jog along structures related to the Magdalena cauldron.

In this study area, the normal, down-to-the-west faults appear to have a crude periodicity. Usually, several small faults (displacement 500 to 800 feet, 150 to 240 m) occur between major faults (displacement 3000 feet to 4000 feet, 900 to 1200 m). The large faults occur approximately 5 miles (8.0 km) apart and the small faults are approximately 0.75 miles (1.2 km) apart. This fault pattern results in the exposure of different parts of the stratigraphic section in different parts of this study area.

Regional Uplift and Block Faulting

The Popotosa basin was disrupted after 7 m.y. and before 4 m.y. by extensional forces which broke the basin into a series of parallel uplifts and grabens (Chapin and others, 1978). The San Mateo and Magdalena Mountains are examples of fault-block uplifts which are separated by a graben. The cause of the uplift is not known; however, it coincides in time with a major uplift event which occurred throughout the Rio Grande rift (Chapin and others, 1978).

In the eastern part of this study area (sec. 34, T.4S, R.4W.), a large normal fault with approximately 3000 feet (900 m) of stratigraphic displacement is believed to be continuous with the major range-bounding faults of Allen (1979) and Bowring (1980). This fault bifurcates at the approximate location of the underlying Magdalena cauldron margin which may have been reactivated at this time. In the northern Magdalena Mountains, Allen (1979) has determined displacement in excess of 2900 feet (880 m) for the range-bounding fault which agrees favorably with displacement of 3000 feet (900 m) in this study area.

ALTERATION AND MINERALIZATION

Alteration

Propylitic alteration (Meyer and Hemley, 1967) and potassium metasomatism which occur in the Socorro-Magdalena area are also present in this study area. Propylitic alteration is poorly developed and is characterized by intense bleaching of the rock and alteration of sanidine and plagioclase to high-birefringent phyllosilicates. The propylitic alteration is commonly present in cauldron-facies tuffs; however, it also occurs in some outflow-facies tuffs and other rock types. The propylitic alteration decreases in intensity away from plutons and ring fractures. Potassium metasomatism is the second type of alteration in which volcanic rocks are enriched in potassium and depleted in sodium.

In thin section, the propylitically altered rocks can be identified by the presence of high-birefringent phyllosilicates after sanidine and plagioclase. In the propylitically altered rocks, original phenocryst structures (cleavage, twinning, uniform extinction) are not destroyed. In contrast, the rocks affected by the potassium metasomatism (alkali-exchange) are characterized by plagioclase phenocrysts which are replaced by potassium-feldspar and clays. Although plagioclase phenocryst structures have been destroyed, sanidine and biotite phenocrysts are usually unaltered.

In this study area, all exposures of the Hells Mesa Tuff are cauldron facies. The unit has a weak, pervasive hydrothermal alteration. Clay minerals occur along cleavage planes in plagioclase and sanidine phenocrysts; original phenocryst structures are well preserved.

In the tuff of Lemitar Mountains, montmorillonite and potassium-feldspar replaces plagioclase and sanidine and biotite phenocrysts appear unaltered. This is petrographically similar to the alteration found throughout the potassium enriched zone in the Socorro-Magdalena area.

The tuff of South Canyon contains approximately 1 percent plagioclase phenocrysts in areas where the tuff is unaltered. In this study area, the tuff of South Canyon has no plagioclase phenocrysts; however, there are a few percent void spaces that probably represent clay pseudomorphs of plagioclase that were plucked during thin section preparation.

The basaltic-andesite lavas overlying the tuff of Lemitar Mountains and the andesitic lavas overlying the tuff of South Canyon have relatively fresh plagioclase phenocrysts indicating that the alteration fluids did not affect them. The crystal-poor rhyolitic lavas, the rhyolites of Magdalena Peak (13.6 m.y.), and some of the intrusions and domes within this study area have not been affected by alteration fluids; this suggests that alteration preceded emplacement of these rock types. The Deer Plot Tank dacitic intrusions and the Puertecito Canyon dacitic dome are pervasively altered indicating that these domes may be older than the other domes in this study area and that emplacement may have preceded the alteration event.

The plagioclase phenocrysts of the Deer Plot Tank dacitic intrusions were extensively altered to potassium-feldspar; biotite is fresh, and polycrystalline quartz replaces some subhedral areas believed to have been plagioclase phenocrysts. The plagioclase phenocrysts in the Puertecito Canyon dacitic dome are pervasively altered to potassium-feldspar, calcite, and high-birefringent phyllosilicates. The alteration assemblages for these domes are indicative of potassium metasomatism that may have occurred during regional alteration or shortly after emplacement by local hydrothermal fluids.

Piedmont gravels near Alameda Spring are bleached white (Fig. 21) suggesting that the spring waters were chemically different at some time. A chemical analysis of the spring water is presented in Appendix C.

The complex volcanic history of the Socorro-Magdalena area suggests that one or more geothermal systems could have existed. The alteration of the major ash-flow tuffs and the absence of alteration in younger rhyolitic lavas suggest that at least one geothermal system existed prior to the emplacement of the rhyolitic lavas. The small scale alteration of the piedmont gravels and the silicification of the Popotosa Formation near Alameda Spring suggests that some recent hydrothermal activity has occurred in the area.

Mineralization

Manganese mineralization occurs throughout this study area as thin coatings on joints and as open-space filling of breccia zones. The Black Goose, a group of 14 contiguous unpatented claims located in the foothills of the western flank of Hardy Ridge (secs. 27, 34 and 35, T.4S., R.4W.), was operated for a short period in the middle 1950's. The total production from the property is believed to have been only 36 long tons of ore averaging 18.2 percent manganese (Farnham, 1961).

The manganese mineralization occurs as psilomelane and pyrolusite surrounding brecciated fragments of Hells Mesa Tuff along a major northwest-trending fault. Mineralization occurs in a breccia zone, approximately 140 feet (42 m) wide and 800 feet (240 m) long, which is bounded on the north and south by a quartz and calcite vein approximately 30 feet (9 m) in thickness. The quartz and calcite vein is traceable north to Mill Place Spring and is discontinuous south of the Black Goose mine.

Several small prospects are located on a small, discontinuous quartz and calcite vein along the next fault east of Black Goose mine (secs. 26, 35, T.4S., R.5W.). A similar, small outcrop of a quartz and calcite vein occurs along the contact of the crystal-poor and crystal-free rhyolitic lavas of the unit of Hardy Ridge (sec. 35, T.4S., R.4W.); a small prospect is located on this vein. A fist-sized sample from this prospect and from a prospect approximately 2000 feet (610 m) northwest of the Black Goose mine were fire assayed for gold and silver. They contained 0.01 and 0.08 ounces per ton silver, respectively, and no gold.

Figure 21. Photograph showing the bleached piedmont gravels in the vicinity of Alameda Spring.

In the western part of this study area, quartz and calcite veins occur along the contact of the tuff of Lemitar Mountains and the overlying basaltic-andesite lavas southwest of B. O. Ranch rhyolitic dome (sec. 7, T.5S., R.4W.). A similar vein is well exposed in a gully east of Mulligan Gulch (sec. 26, T.4S., R.5W.) and occurs along a northwest-trending fault.

In this study area, the quartz and calcite veins do not exhibit sulfide mineralization and the two fire assays for silver and gold showed only trace amounts of silver. Manganese mineralization is probably not economic at the Black Goose mine since cuttings from several hundred, shallow drill holes in the area average only 4 percent manganese (Farnham, 1961).

The Hardy Ridge andesitic intrusion, a small "birds eye" porphyry, is located near the Magdalena cauldron margin. The porphyry intrudes rhyolitic lavas of the unit of Hardy Ridge but these rocks are not extensively altered at the contact. However, because of the lithologic characteristics of this intrusion and its close proximity to the Magdalena cauldron margin, the area may be worth a closer examination.

CONCLUSIONS

The following conclusions can be made from this study in the southwestern Magdalena Mountains. These conclusions are divided into stratigraphic, structural, and alteration and mineralization sections.

Stratigraphy

The rocks in this study area consist of ash-flow tuffs with interbedded sedimentary rocks, basaltic-andesite, andesitic, and rhyolitic lava flows. Several domes and intrusions of varying composition are also present. In general, the stratigraphic units exposed in this study area are correlative with the Tertiary stratigraphy developed by Chapin and others (1978) for the Socorro-Magdalena area. The variation for these rock types from the regional framework are listed below:

1) A quartz-poor, crystal-rich ash-flow tuff is present in areas of deepest exposures of the Hells Mesa Tuff and has been interpreted as either the quartz-poor zone of the Hells Mesa Tuff observed in other localities or megabreccia blocks exposed in the bottom of the North Baldy cauldron.

2) The A-L Peak Tuff is absent in the eastern part of the area which was probably a topographically high area on the margin of the Sawmill Canyon cauldron during the tuff's eruption.

3) An angular unconformity exists between the Hells Mesa Tuff and the tuff of Lemitar Mountains. This is believed to mark the beginning of rift-related faulting in this study area.

4) In the western part of the area, the tuff of Lemitar Mountains is approximately 2000 feet (610 m) thick and has a 1500-foot (460 m)-thick zone (intermediate zone) that has not been documented elsewhere in the Socorro-Magdalena area. The intermediate zone overlies the lower member and is overlain by the quartz-poor zone of the upper Lemitar. It contains lense-shaped zones of mesobreccias and megabreccias and has been interpreted as either cauldron fill near the eastern margin of the Mount Withington cauldron or post-collapse fill of the older Magdalena cauldron.

5) The lower member and the intermediate zone of the upper member of the tuff of Lemitar Mountains exhibit primary flow structures which includes lineated pumice, stretched gas cavities, and possibly primary folds. Primary flow structures are present in the tuff of Lemitar Mountains in the Mulligan Gulch area and in the northern San Mateo

Mountains where nearly 2000 feet (610 m) of the lower member is exposed (A-L Peak Tuff of Deal, 1973; Osburn, oral communication).

6) Basaltic-andesite lavas overlying the tuff of Lemitar Mountains in the western part of the area were eroded prior to the deposition of the lower sedimentary unit, suggesting that the area was not a closed basin before deposition of the sedimentary rocks.

7) Pyroclastic-surge deposits occur at the base and overlie the tuff of South Canyon forming gradational contacts between the underlying and overlying sedimentary rocks.

8) Andesitic lavas interbedded with the Popotosa Formation are similar to andesite flows in Allen's (1979) area. The andesitic lavas appear to have high-pressure quartz phenocrysts; however, the hypothesis that the quartz are xenocrysts cannot be disproved.

9) Quartz-poor rhyolitic lavas interbedded with the Popotosa Formation crop out in the northern part of the area and reconnaissance indicates extensive exposures to the north. The lavas contain trace amounts of biotite and plagioclase phenocrysts.

10) The rhyolite of Magdalena Peak forms continuous outcrops from the central part of the area to the inferred vent at Magdalena Peak. The deposition of these rhyolitic lavas was strongly influenced by paleotopography.

11) Several rhyolitic, dacitic, and andesitic domes and intrusions are present in this study area. Some of the intrusions appear to be quite young; however, no dates are available at this time. The intrusions are in close proximity to the Socorro transverse shear zone and probably intrude along cauldron-related structural flaws.

Structure

The major structural features in this study area are extensional faults associated with the Rio Grande rift.

1) North-northwest-trending, extensional, down-to-the-west, normal faults occur with rotation of the fault blocks to the east.

2) The simple pattern of north-trending faults is disrupted and has a strong transverse element in the area of the proposed Magdalena cauldron margin.

3) Several small faults tend to occur between major faults throughout the study area and this has resulted in the exposure of different parts of the stratigraphic section in different areas.

4) Original cauldron-related structures are not exposed in this study area; however, three cauldron margins are inferred to be present.

Alteration and Mineralization

1) Plagioclase phenocrysts have been altered in the major ash-flow tuff units in this study area. Propylitic alteration is observed in the cauldron-facies Hells Mesa Tuff and potassium metasomatism is observed in the tuff of Lemitar Mountains and may be present in the tuff of South Canyon. These types of alterations are consistent with the regional alterations in the Socorro-Magdalena area.

2) Plagioclase phenocrysts are not altered in either rhyolitic lavas interbedded with the Popotosa Formation or the majority of domes and intrusions, indicating that the geothermal system responsible for the alteration preceded the emplacement of these units.

3) Manganese mineralization occurs as coatings on joints and as open-space filling of breccia zones. The manganese mineralization is probably associated with the geothermal system that altered the rocks.

REFERENCES

Allen, P., 1979, Geology of the west flank of the Magdalena Mountains south of the Kelly mining district, Socorro County New Mexico [unpublished M.S. thesis]: New Mexico Institute of Mining and Technology, 153 p.

Bachman, G.O., and Mehnert,, H.H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America Bulletin, v. 89, p. 283-292.

Barberi, F., and Varet, J., 1977, Volcanism of Afar: small scale plate tectonics implications: Geological Society of American Bulletin, v. 88, p. 1251-1266.

Blakestad, R.B., 1978, Geology of the Kelly Mining district, Socorro County, New Mexico [unpublished M.S. thesis]: University of Colorado, 127p.

Bowring, S., 1980, The Geology of the west-central Magdalena Mountains, Socorro County, New Mexico [unpublished M.S.

thesis]: New Mexico Institute of Mining and Technology, 150p.

Brown, D.M., 1972, Geology of the southern Bear Mountains, Socorro County, New Mexico [unpublished M.S. thesis]: New Mexico Institute of Mining and Technology, 110 p.

Bruning, J.E., 1973, Origin of the Popotosa Formation north-central Socorro County, New Mexico [unpublished Ph.D. dissertation]: New Mexico Institute of Mining and Technology, 132 p.

Burke, W.H., Kenny, G.S., Otto, J.B., and Walker, R.D. 1963, Potassium-argon dates, Socorro and Sierra Counties, New Mexico, in Guidebook of the Socorro region: New Mexico Geological Society, 14th Field Conference, Guidebook, p. 224.

Cather, S., in progress, Petrology, diagenesis, and genetic stratigraphy of the Baca Formation, north of Gallinas Mountains west-central New Mexico [unpublished M.S. thesis]: University of Texas, Austin, 150p.

Chamberlin, R.M., 1974, Geology of the Council Rock district, Socorro County, New Mexico [unpublished M.S. thesis]: New Mexico Institute of Mining and Technology, 130 p.

Chamberlin, R.M., 1978, Structural development of the Lemitar Mountains, an intrarift tilted fault-block uplift, central New Mexico [abs.]: in 1978 International Symposium of the Rio Grande Rift: Los Alamos Scientific Laboratory, University of California, p. 22-24.

Chamberlin, R.M., 1980, Geologic framework of the Socorro Peak geothermal area, Socorro County, New Mexico [unpublished Ph.D. dissertation]: Colorado School of Mines, 500 p.

Chapin, C.E., 1971, The Rio Grande rift, Part 1: Modifications and additions, in Guidebook of the San Luis Basin, Colorado: New Mexico Geological Society, 22nd Field Conference, Guidebook, p. 191-201.

Chapin, C.E., 1974, Composite stratigraphic column of the Magdalena area: New Mexico Bureau of Mines and Mineral Resources Open-File Report 46.

Chapin, C.E., 1974, Three-fold tectonic subdivision of the Cenozoic in the Cordilleran foreland of Colorado, New Mexico, Arizona: Geological Society of America Abstracts with Programs, v. 6, p. 433.

Chapin, C.E., 1976, Evolution of the Rio Grande rift: Geological Society of America Abstracts with Programs, v. 8, p. 808.

Chapin, C.E., Chamberlin, R.M., Osburn, G.R., White, D.L., and Sanford, A.R., 1978, Exploration framework of the Socorro Geothermal Area, New Mexico: New Mexico Geological Society Special Publication 7, p. 115-129.

Chapin, C.E., Jahns, R.H., Chamberlin, R.M., and Osburn, G.R., 1978, First day road log from Socorro to Truth or Consequences via Magdalena and Winston, in Chapin, C.E., and Elston, W.E., eds., Field guide to selected cauldrons and mining districts of the Datil-Mogollon volcanic field, New Mexico: New Mexico Geological Geological Society Special Publication, no. 7, p.10.

Chapin, C.E., and Lowell, G.R., 1979, Primary and secondary flow structures in ash-flow tuffs of the Gribbles Run paleovalley, central Colorado, in Chapin, C.E., and Elston, W.R., eds., Ash-flow tuffs: Geological Society of America Special Paper 180, p. 137-154.

Chapin, C.E., and Seager, W.R., 1975, Evolution of the Rio Grande rift in the Socorro and Las Cruces areas: New Mexico Geological Society, 26th Field Conference, Guidebook, p. 297-321.

Deal, E.G., 1973, Geology of the northern part of the San Mateo Mountains, Socorro County, New Mexico; A study of a rhyolite ash-flow tuff cauldron and the role of laminar flow in ash-flow tuffs [unpublished Ph.D. dissertation]: University of New Mexico, 106 p.

Deal, E.G., and Rhodes, R.C., 1976, Volcano-tectonic structures in the San Mateo Mountains, Socorro County, New Mexico: New Mexico Geological Society Special Publication 5, p. 51-56.

Denny, C.S., 1940, Tertiary geology of the San Acacia area, New Mexico: Journal of Geology, v. 49, p. 225-260.

Farnham, L.L., 1961, Manganese deposits of New Mexico: U.S. Department of Interior Bureau of Mines Circular 8030, p. 162-163.

Harrison, R., in progress, Geology of northeast Datil Mountains, Socorro and Catron Counties, New Mexico [unpublished M.S. thesis]: New Mexico Institute of Mining and Technology, 150 p.

Krewedl, D.A., 1974, Geology of the central Magdalena Mountains, Socorro County, New Mexico [unpublished Ph.D. dissertation]: University of Arizona, 128 p.

Lipman, P.W., 1976, Caldera-collapse breccias in the western San Juan Mountains, Colorado: Geological Society of

America Bulletin, v. 87, p. 1397-1410.

Loughlin, G.F., and Koschmann, A.H., 1942, Geology and ore deposits of the Magdalena mining district, New Mexico: U.S. Geological Survey Professional Paper 200, 168 p.

Meyer, C., and Hemley, J.J., 1967, Wall rock alteration, in Geochemistry of hydrothermal ore deposits, H.L. Barnes, ed.: New York, Holt, Rinehard, and Winston, p. 166-235.

Morton, W.H., and Black, R., 1975, Crustal attenuation in Afar, in Pilgar, A., and other, eds., Afar depression of Ethiopia: Inter-Union Commission on Geodynamics Scientific Report no. 14, p. 55-65.

Osburn, G.R., 1978, Geology of the eastern Magdalena Mountains, Water Canyon to Pound Ranch, Socorro County, New Mexico [unpublished M.S. thesis]: New Mexico Institute of Mining and Technology, 136 p.

Petty, D.M., 1979, Geology of the southeastern Magdalena

Mountains, Socorro County, New Mexico [unpublished M.S. thesis]: New Mexico Institute of Mining and Technology, 157 p.

Profett, J.M., 1977, Cenozoic geology of the Yerington district, Nevada, and implications on the nature and origin of basin and range faulting: Geological Society of America Bulletin, v. 88, p. 247-266.

Roth, S., in progress, Geology of the Sawmill Canyon area, Magdalena Mountains, Socorro County, New Mexico [unpublished M.S. thesis]: New Mexico Institute of Mining and Technology, 150p.

Simon, D.B., 1973, Geology of the Silver Hill area, Socorro County, New Mexico [unpublished M.S. thesis]: New Mexico Institute of Mining and Technology, 101 p.

Smith, R.L., and Bailey, R.A., 1968, Resurgent cauldrons: Geological Society of America Memoir 116, p. 613-662.

Spradlin, E.J., 1976, Stratigraphy of Tertiary volcanic rocks, Joyita Hills area, Socorro County, New Mexico [unpublished M.S. thesis]: University of New Mexico, 73 p.

Stewart, J.H., 1979, Regional tilt patterns of late Cenozoic basin-and -range fault blocks in the Great Basin; Geological Society of America Abstracts with Programs, v. 11, no. 3, p. 130.

Sumner, W., 1980, Geology of the Water Canyon-Jordon Canyon area, Socorro County, New Mexico [unpubliched M.S. thesis]: New Mexico Institute of Mining and Technology, 150 p.

Tonking, W.H., 1957, Geology of Puertecito Quadrangle, Socorro County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 41, 67 p.

Travis, R.B., 1955, Classification of rocks: Colorado School of Mines Quarterly, v. 50, no. 1, 98 p.

Troger, W.E., 1959, Optische Bestimmung der gesteinsbildenden Minerale: Stuttgart, p. 111.

Weber, R.H., 1957, Geology and Petrography of the Stendel perlite deposits, Socorro County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 44, 24 p.

Weber, R.E., and Bassett, W.A., 1963, K-Ar ages of Tertiary volcanic and intrusive rocks in Socorro County, and Grant counties, New Mexico, in Guidebook of the Socorro region: New Mexico Geological Society, 14th Field Conference, Guidebook, p. 202-223.

Wilkinson, W.H., Jr., 1976, Geology of the Tres Montosas-Cat Mountains area, Socorro County, New Mexico [unpublished M.S. thesis]: New Mexico Institute of Mining and Technology, 158 p.

Wilson, M.D., and Sedeora, S.S., 1979, An improved thin section stain for potash feldspar: Journal of Sedimentary Petrology, v. 49., no. 2, p. 637-638.

APPENDIX A

Name	Location	Date	Method	Reference
Hells Mesa Tuff	Hells Mesa type section	30.6m.y.	K-Ar, biotite	Weber and Bassett, 1963
	Gallinas Mountains	32.1m.y.	K-Ar, biotite	Burke and others, 1963
	Joyita Hills	32.4m.y.	K-Ar, biotite	Burke and others, 1963
tuff of Lemitar Mountains	San Mateo Mountains	27.0 1.1m.y.	K-Ar, biotite	Chapin, unpublished dates
	Lemitar Mountains	26.3 1.0m.y.	K-Ar, biotite	Chapin, unpublished dates
	Joyita Hills	28.8 0.7m.y.	K-Ar, biotite	Chapin, personal communication
	Joyita Hills	27.6 1.1m.y.	K-Ar, biotite	Chapin, personal communication
	Joyita Hills	28.1 1.2m.y.	K-Ar, biotite	Chapin, personal communication
tuff of South Canyon	Joyita Hills	26.2 1.0m.y.	K-Ar, biotite	Chapin, unpublished dates
	Joyita Hills	25.8 1.0m.y.	K-Ar, sanidine	Bachman and Mehnert, 1978
rhyolite of Magdalena Peak	Magdalena Peak	13.1 0.5m.y.	K-Ar, biotite	Chapin, Jahns, and others, 1978
	Stendel perlite deposit	14.0 0.7m.y.	K-Ar, whole rock (?)	Weber and Bassett, 1963

Summary of radiometric dates for some of the units exposed in this study area.

Appendix B

Name	Location	Youngest Intruded Unit	Average Mineralogy	Matix Characteristics
1.) Charlie Windmill rhyolitic intrusion	sec. 35, T.4S., R.5W.	lower sedimentary unit	tr. quartz tr. sanidine tr. biotite	mosaic of quartz and alkali feldspar devitrification crystals
2.) Mulligan Gulch rhyolitic dome	secs. 1,12, T.5S., R.5W.	andesitic lavas	tr. biotite	mosaic of quartz and alkali feldspar devitrification crystals
3.) B. O. Ranch rhyolitic dome	secs. 6,7, T.5S., R.4W.	basaltic-andesite lavas	tr. quartz tr. sanidine tr. plagioclase tr. biotite	spherulitically devitrified glass, glassy autobrecciated margins, and glassy pyroclastic deposits
4.) Squaw Peak rhyolitic dome	secs. 29,32, T.4S., R.4W.	Popotosa Formation	5% quartz 5% sanidine 5% plagioclase 1% biotite	varies from all glass to completely, spherulitically devitrified glass
5.) Cibola andesitic intrusion	secs, 21,28 T.4S., R.4W	no contact relationships	9% plagioclase 2% biotite 3% hornblende	plagioclase microlites and iron oxides after mafic minerals
6.) National rhyolitic intrusions	secs. 20,21, T.4S., R.4W	Popotosa Formation	2% quartz 1% sanidine tr. biotite	mosaic of quartz and alkali feldspar devitrification crystals and glassy margins
7.) Deer Plot Tank dacitic intrusions	secs. 21,22,26,27,28 T.4S., R.4W	tuff of South Canyon	6% quartz 5% plagioclase 2% biotite	mosaic of quartz and alkali feldspar devitrification crystals and secondary quartz crystals
8.) Hardy Ridge andesitic intrusion	sec. 26, T.4S., R.4W.	unit of Hardy Ridge	tr. quartz 3% plagioclase 5% biotite	plagioclase microlites and iron oxides after mafic minerals
9.) Hardy Ridge rhyolitic intrusion	sec. 36, T.4S., R.4W.	tuff of Lemitar Mountains	tr. quartz	mosaic of quartz and alkali feldspar devitrification crystals
10.) Puertecito Canyon dacitic dome	sec. 36, T.4S., R.4W. sec. 31, T.4S., R.3W.	tuff of Lemitar Mountains	3% sanidine 26% plagioclase 1% biotite	mosaic of quartz and alkali feldspar devitrification crystals
11.) unit of Sawmill Canyon	sec. 25, T.4S., R.4W. secs. 30,31, T.4S., R.3W.	tuff of Lemitar Mountains	tr. quartz tr. sanidine	mosaic of quartz and alkali felspar devitrification crystals

Summary of the names, locations, youngest units intruded, average mineralogies, and matrix characteristics of the domes and intrusions in this study area.

PPENDIX C

New Mexico Bureau of M
Water Analysis

County Socorro Range 4 west Township 4 south Section 31 Collection Date 12/79
Collected by Special Handling Remarks
Sample Identification Lab Number Appearance

pH 5.5 Date
Analyst

Total Dissolved Solids
Residue at 180° + dish
dish
Solids
Date
Analyst
ppm 177

Conductivity
400 umhos
Date
Analyst

Carbonate
Sample size
ml acid
Date
Analyst
ppm $CO_3^=$ 0.0 epm 0.00

Bicarbonate
Sample size
Ml acid
Date
Analyst
ppm HCO_3 150 2.45

Chloride
Sample size
Ml $HgCl_2$
Date
Analyst
ppm Cl^- 7.7 0.22

Sulfate
Sample size
crucible + ppt
ppt
Date
Analyst
ppm $SO_4^=$ 30.0 0.62

Nitrate
Sample size
Abs.
Date
Analyst
ppm NO_3^-

Phosphate
Aliquot
Abs.
Date
Analyst
ppm $PO_4^=$

Fluoride
Aliquot
Mv
Date
Analyst
ppm F^-

Total epm anions 3.29

Silica
Aliquot
Abs.
Date
Analyst

Sodium
dilution
Abs.
Date
Analyst
ppm Na^+ 31.0 epm 1.35

Potassium
Dilution
Abs.
Date
Analyst
ppm K^+ 2.6 0.07

Magnesium
Dilution
Abs.
Date
Analyst
ppm Mg 4.6 0.38

Calcium
Dilution
Abs.
Date
Analyst
ppm Ca^{++} 26.0 1.30

Aluminum
Aliquot
Abs.
Date
Analyst
ppm Al^{+++}

Iron
Aliquot
Abs.
Date
Analyst
ppm Fe 0.1

Boron
Aliquot
Abs.
Date
Analyst
ppm B

Manganese
Aliquot
Abs.
Date
Analyst
ppm Mn 0.1

Total epm Cations 3.10
Cation-Anion Balance
% Error

Copper
Concentration
Analyst
Date
ppm Cu
epm

Cobalt
Concentration
Analyst
Date
ppm Co

Chromium
Concentration
Analyst
Date
ppm Cr

Cadmium
Concentration
Analyst
Date
ppm Cd

Lead
Concentration
Analyst
Date
ppm Cd

Molybdenum
Concentration
Analyst
Date
ppm Mo 0.05

Nickel
Concentration
Analyst
Date
ppm Ni

Zinc
Concentration
Analyst
Date
ppm Zn 0.02

Mercury
Concentration
Analyst
Date
ppm

Arsenic
Concentration
Analyst
Date
ppm

Nitrite NO_2 ppm
Vanadium ppm 0.01
Uranium ppm 0.02

Bromine ppm
Iodide ppm

Lithium ppm
Selenium ppm 0.005

Chemical analysis of Alameda Spring. Chemical analysis done by the New Mexico Bureau of Mines and Mineral Resources.

This dissertation is accepted on behalf of the faculty of the Institute by the following committee:

Adviser

David J. Norman

May 21 1986

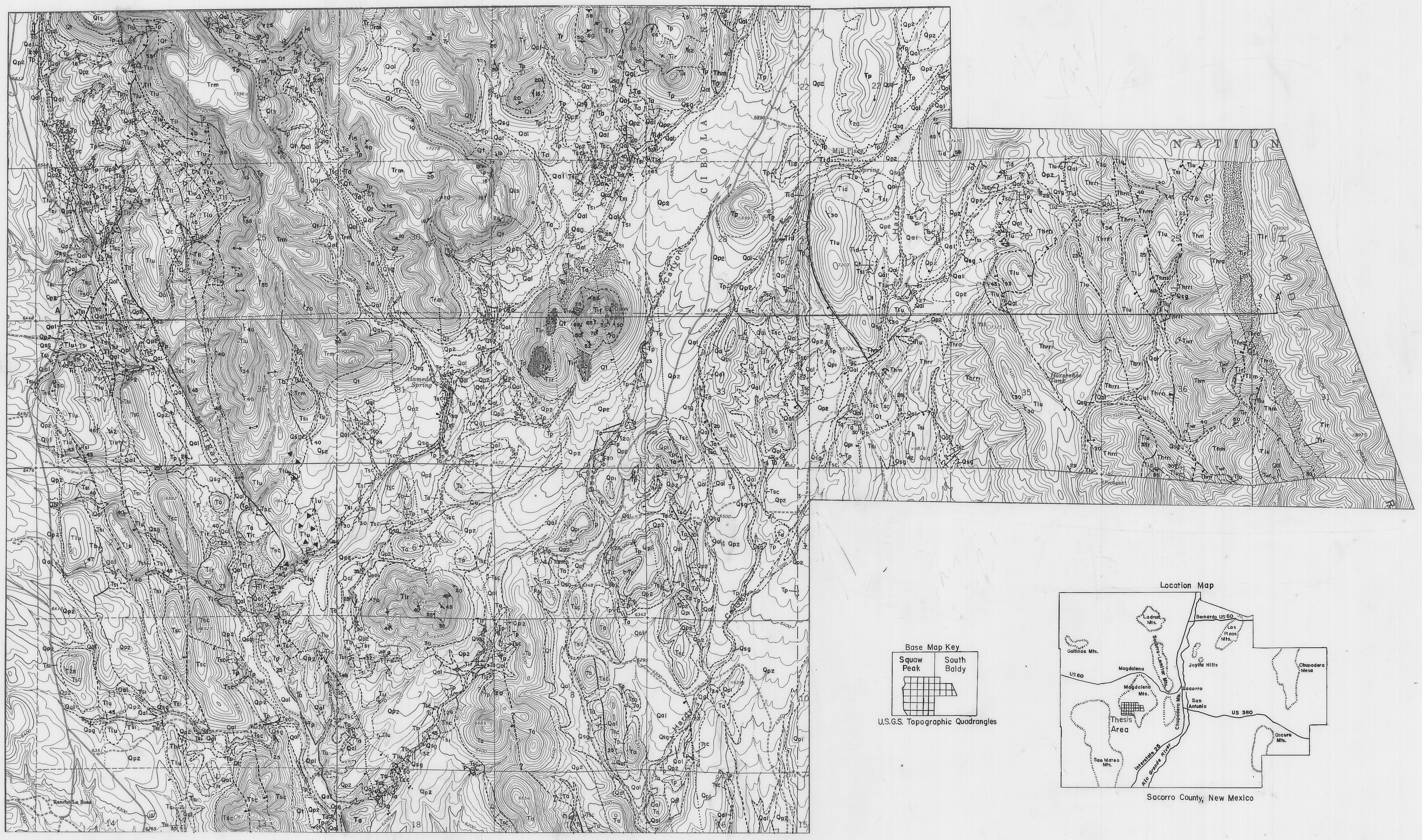
Date

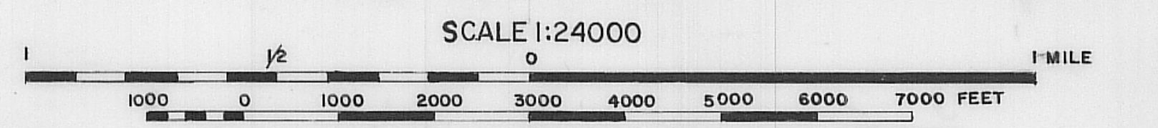
GEOLOGIC MAP AND SECTION OF THE SQUAW PEAK AREA, MAGDALENA MOUNTAINS SOCORRO COUNTY, NEW MEXICO

by

Martin A. Donze

1980



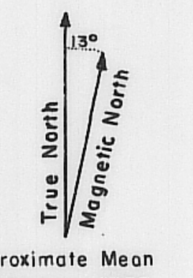


Contour Interval: Squaw Peak Quadrangle 20 Feet
South Baldy Quadrangle 40 Feet

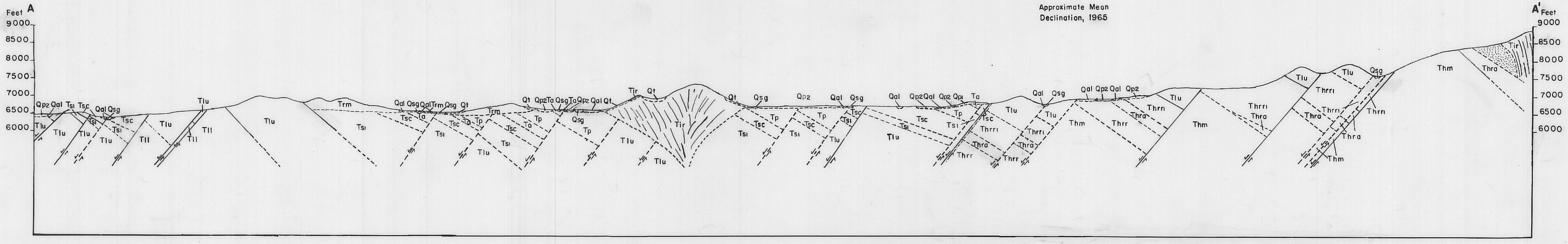
U.S.G.S. Topographic Quadrangles

Location Map

Socorro County, New Mexico



Approximate Mean Declination, 1965



EXPLANATION

Qsg	stream gravels	Quaternary
Qal	terrace gravels	
Qt	talus	
Qc	colluvium	
Qls	landslide deposits	
Qp1	piedmont gravels	
Qp2	piedmont gravels	Pliocene
Trm	*Rhyolite of Magdalena Peak* rhyolite lavas	Miocene
Tr Tr1 Tp Ta	crystal-poor rhyolite lavas (Tr) and associated ash-flow tuffs (Tr1), andesite lavas (Ta), *Popotosa Formation:* sandstones and conglomerates (Tp)	
Tsc	*Tuff of South Canyon:* rhyolite ash-flow tuff	Oligocene
Ts1	*Lower sedimentary unit:* sandstones and conglomerates	
Tb	basaltic–andesite lavas	
Tlu Tll	*Tuff of Lemitar Mountains:* crystal-rich member (Tlu) and crystal-poor member (Tll)	
Thrr1 Thra Thrr	*Unit of Hardy Ridge:* crystal-free rhyolite lavas (Thrr1), andesite lavas (Thra) and crystal-poor rhyolite lavas (Thrr)	
Thm	*Hells Mesa Tuff:* crystal-rich ash-flow tuff	

?

Tir rhyolite intrusions

Tid andesite to dacite intrusions

Twr white rhyolite dikes

SYMBOLS

Contact
dashed where approximately located

45

Normal Fault
dashed where approximately located, dotted where covered, queried where inferred, bar and ball on downthrown block, arrow and number indicate dip direction and inclination of fault plane

41

Strike and dip of bedding

78

Strike and dip of flow foliation in lavas

Trend of lineation

↗ *Transport direction*

Axial trend of fold

Quartz-carbonate veins

⚒ *Mine*

X *Prospect pit*

Lava flows associated with domes

Pyroclastic crater deposits associated with domes

▲ *Megabreccias*

△ *Mesobreccias*

Measured section

STRUCTURAL MAP

PLATE 2