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The Geology of the West-Central Magdalena Mountains

Socorro County, New Mexico

by

Samuel A. Bowring

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ABSTRACT

The Oligocene to Miocene geologic history of the west-central Magdalena Mountains has been dominated by the eruption of voluminous ash-flow tuffs and by extensional faulting and uplift related to the development of the Rio Grande rift.

Portions of three overlapping cauldrons are preserved in this study area. The oldest rock unit exposed is the Hells Mesa Tuff (32 m.y. ago) which was erupted from the North Baldy cauldron; rhyolites and ash-flow tuffs of the unit of Hardy Ridge filled the cauldron following its collapse. Collapse of the Sawmill Canyon and Magdalena cauldrons followed with the eruption of the A-L Peak Tuff. At least 2000 feet of densely welded, cauldron-facies, A-L Peak Tuff is exposed within the Sawmill Canyon cauldron. The Sawmill Canyon and Magdalena cauldrons are joined in a narrow zone near the summit of South Baldy and form a large, dumbbell-shaped structure. The unit of Sixmile Canyon (andesitic lavas, rhyolite lavas, ash-flow tuffs, laharic breccias, volcaniclastic sedimentary rocks) partially filled the cauldrons. Andesitic lavas dominate within the unit of Sixmile Canyon in the northern part of the Sawmill Canyon cauldron, rhyolite lavas in the south.

Deposition of the overlying tuff of Lemitar Mountains was influenced by the Sawmill Canyon-Magdalena

cauldrons, the upper and lower members are present within the cauldrons while only the upper member is present outside. Andesitic to dacitic lavas and the tuff of South Canyon were deposited on the tuff of Lemitar Mountains. In early Miocene time, fanglomerates, laharic breccias and sandstones of the Popotosa Formation were deposited over most of the study area. In the western part of the study area, rhyolite lavas (lavas of Magdalena Peak) overlie and are interbedded with the Popotosa Formation.

The structural development of the west-central Magdalena Mountains has been dominated by the interaction of cauldron structures with north-trending normal faults and a major structural break (the Socorro transverse shear zone). The shear zone trends through the northern part of the study area. In general, south of the shear zone, fault planes have been rotated to the west, strata dip towards the east, and step faulting is down-to-the-west; to the south the opposite is true.

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G. Robert Osburn drafted the map and figures. Sue Kent typed two drafts of the thesis and the final manuscript.

INTRODUCTION

General Geologic Setting

The Rio Grande rift transects the northeastern flank of the middle Tertiary Datil-Mogollon volcanic plateau. In the Socorro- Magdalena area, this intersection has broken the volcanic plateau into a series of north-trending, fault-block uplifts and basins. The Magdalena Mountains, La Jencia Basin, and the Socorro-Lemitar Mountains are examples of this complex basin-and-range structure (figure 1).

Further complicating the structure in the Socorro-Magdalena area is the intersection of the south-trending Rio Grande rift and the northeast-trending transverse shear zone of the Morenci lineament (Chapin and others, 1978). The transverse shear zone is acting as an incipient transform fault, connecting en echelon segments of the Rio Grande rift, and separating fields of tilted blocks undergoing rotation and step faulting in opposite directions (Chapin and others, 1978).

The Magdalena Mountains, a complex uplifted block approximately 20 miles long by 7 miles wide, trend north-south along the west side of the Rio Grande valley in central Socorro County, New Mexico. The northern Magdalena Mountains is a west-tilted fault block; the extreme southern Magdalenas an east-tilted fault block; both exhibit hogback topography. The structure in the central Magdalena Mountains

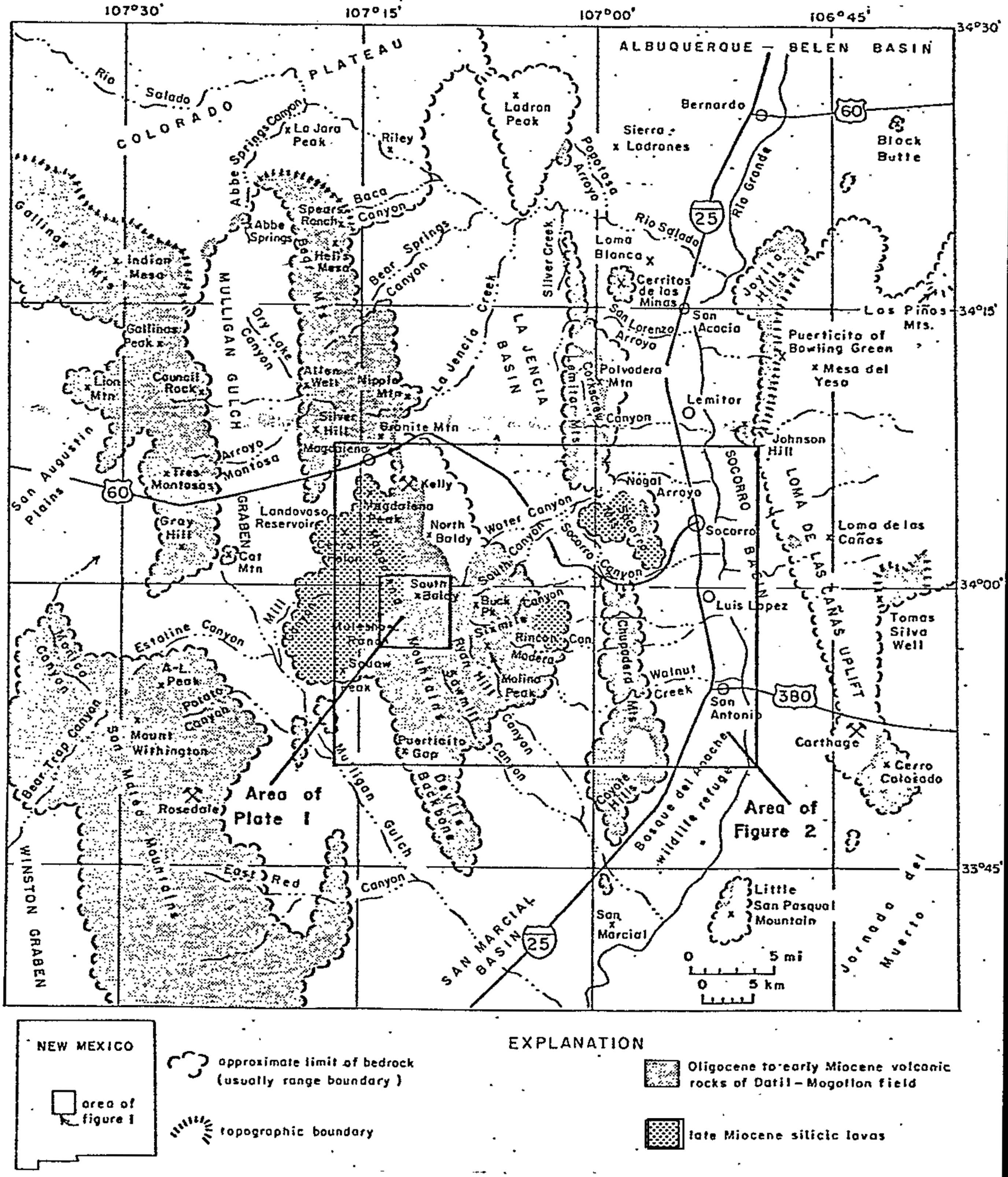


Figure 1. General location map showing the relationship of the study area to major mountain ranges and the distribution of Oligocene to Miocene rocks.

is greatly complicated by the presence of four overlapping cauldrons (Chapin and others, 1978) and their interaction with rift faulting and the transverse shear zone. Here, no consistent topographic expression of the geology is evident.

Area of Study

The study area is a region of about 17 square miles in the west-central Magdalena Mountains, the center of which is located approximately ten miles south of Magdalena. The relationship of the study area to geographic and physiographic features, surrounding study areas, and major routes of access are shown in figure 2. Most of the study area is within the Cibola National Forest and access is by U.S. Forest Service roads and trails.

Objectives

The primary objectives of this study are: 1) to extend the regional stratigraphic framework to the west-central Magdalena Mountains; 2) to explain the great thicknesses of ash-flow tuff known from reconnaissance in the Sawmill Canyon area; and 3) to evaluate the existence and nature of cauldron structures in the study area that have been suggested on the basis of reconnaissance.

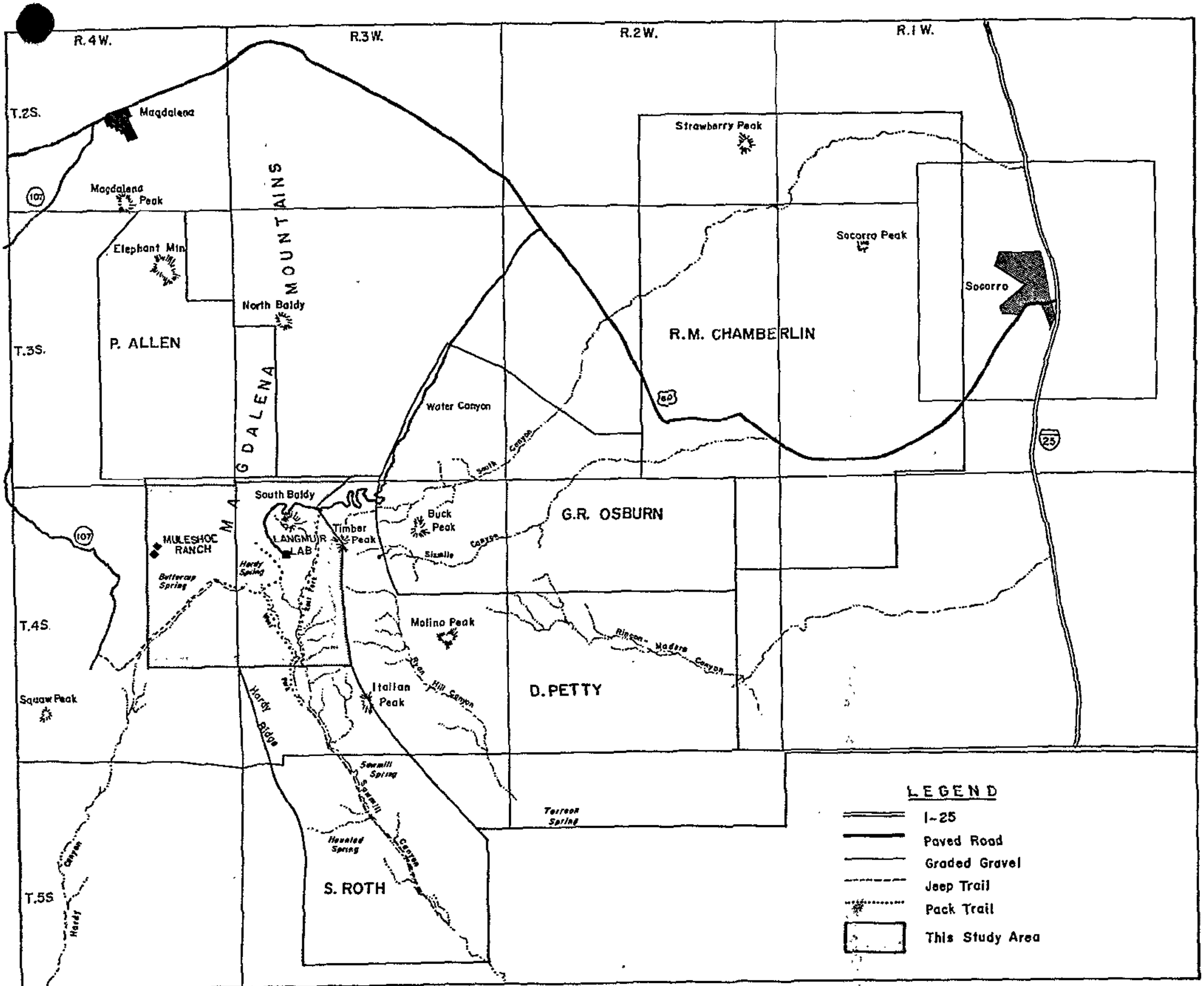


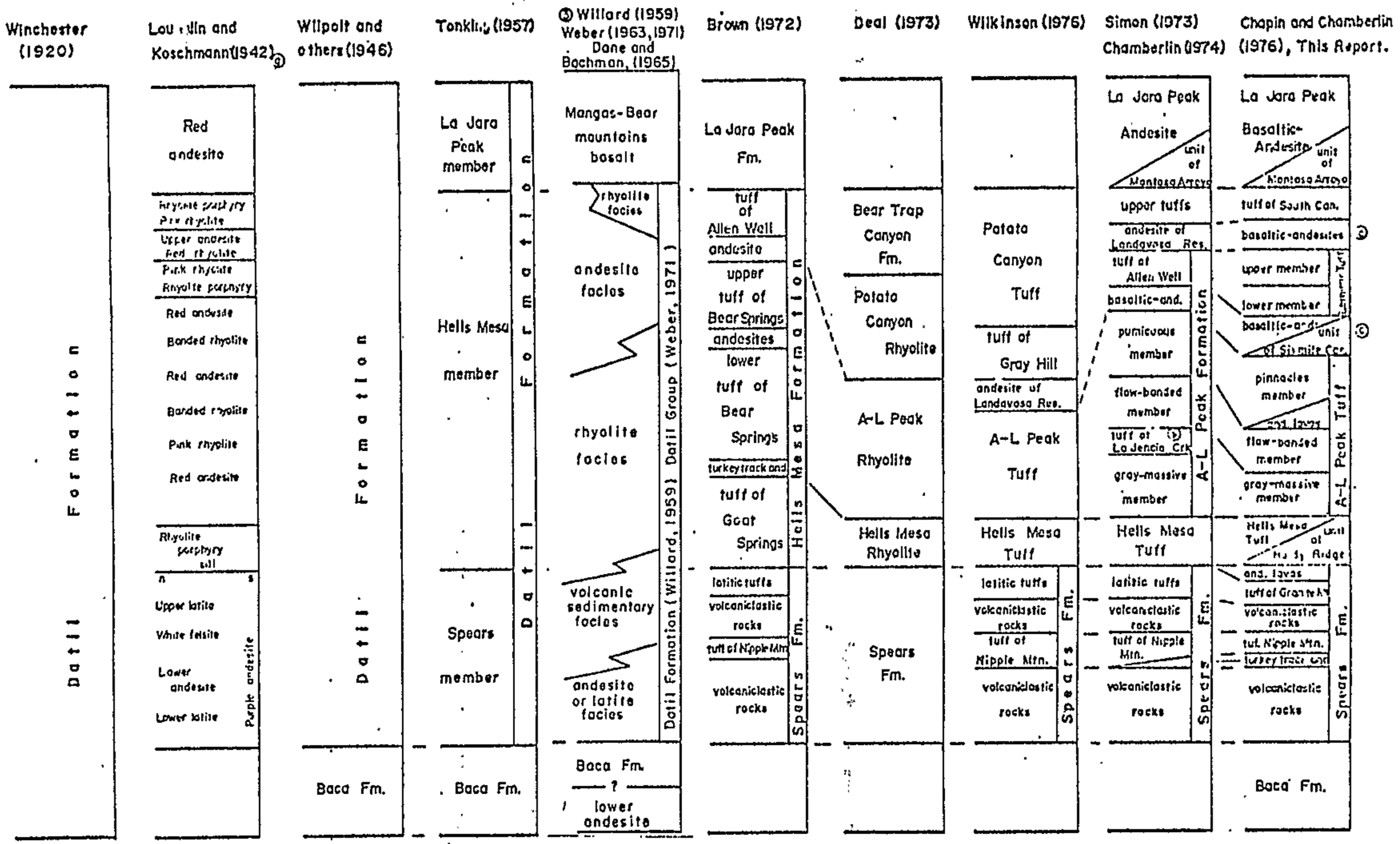
Figure 2. Relationship of the study area to stratigraphic and physiographic features, surrounding studies, and routes of access.

Previous Work

The Cenozoic volcanic stratigraphy and structure in the Socorro-Magdalena area has been developed over the past eight years through a series of detailed mapping projects (Brown, 1972; Chapin, unpublished maps; Simon, 1973; Chamberlin, 1974; Wilkinson, 1976; Osburn, 1978; and Chamberlin, 1978). These investigations as well as several ongoing studies, including this one, are known as the Magdalena Project and are supported by the New Mexico Bureau of Mines and Mineral Resources. The chronologic development of the stratigraphy in the Socorro-Magdalena area is shown in figure 3.

Other studies (Stacy, 1968; Deal, 1973; Bruning, 1973; and Krewedl, 1974) have added to the understanding of the area. Deal (1973) mapped approximately 300 square miles in the northern San Mateo Mountains on a reconnaissance basis. He proposed a large resurgent cauldron, centered about Mount Withington, and suggested that its eastern margin could be extended into the Magdalena Mountains. Krewedl (1974) mapped the northern portion of the present study area on a reconnaissance basis and Stacy (1968) mapped about one square mile in the Langmuir Laboratory-South Baldy area. Bruning (1973) described the outcrops of Popotosa Formation near South Baldy.

Mapping in the Socorro-Lemitar Mountains (Chamberlin, 1978) and eastern Magdalena Mountains (Osburn,



a) no straight-forward correlation of present units with Loughlin and Koschmanns volcanic stratigraphy is possible. This column is after Blakested, 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 3. Correlation diagram showing the relationship of units defined in previous stratigraphic studies to the stratigraphic section of this study. (after Osburn, 1978)

1978) has established a detailed stratigraphy that is being extended to the central and south-central Magdalena Mountains (this study, D. Petty, P. Allen, S. Roth, in progress). This mapping enabled Chapin and others (1978) to show the approximate location of proposed cauldrons in the Magdalena Mountains and to document a major transverse structure which projects through the northern portion of this study area (figure 4).

Methods of Investigation

Detailed geologic mapping was done at a scale of 1:24,000 on the South Baldy topographic quadrangle of the United States Geological Survey 7 1/2-minute series. United States Forest Service aerial photographs (4-10-71) at a scale of 1:12,000 were used to locate outcrops. Mapping was conducted during the summer and fall of 1977 and the spring and summer of 1978.

Eighty thin sections of rocks collected in the study area were used to describe and correlate rock units. A Zeiss binocular petrographic microscope was used for thin section study. All thin sections were stained for potassium with sodium cobaltinitrate using standard procedures (Deer, Howie, and Zussman, 1966, p. 311). Etching times were increased from 15-20 seconds to 60-90 seconds. Petrographic rock names are from Lipman's (1976, fig. 3, p. 5) classification for volcanic rocks and are used in an informal

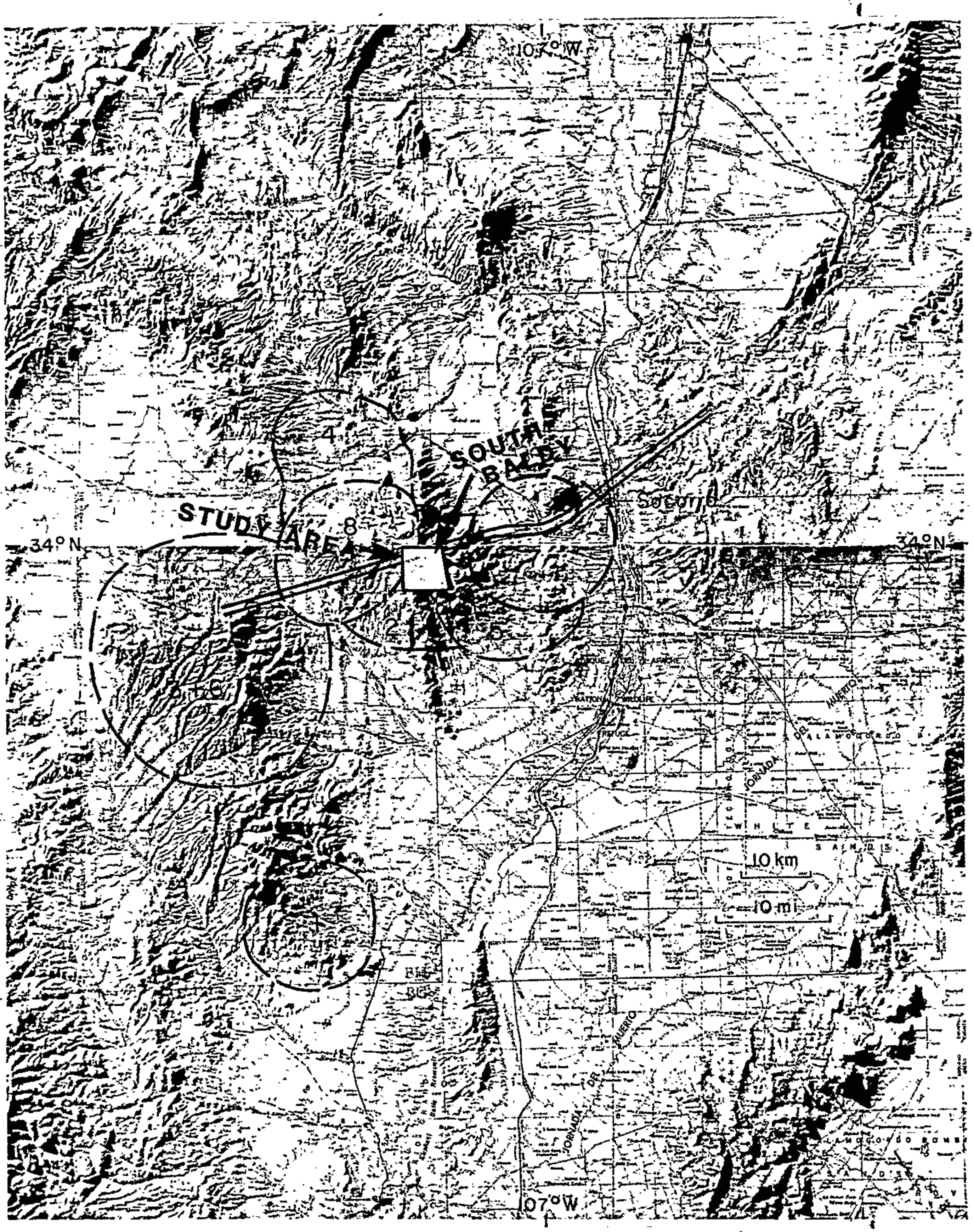


Figure 4. Location of major cauldron structures and the transverse shear zone in the Socorro-Magdalena area as proposed by Chapin and others, 1978. Approximate location of this study area shown by white block.

fashion as chemical analyses for most of the rocks in the study area are not available. Rock colors reported are from the GSA rock color chart.

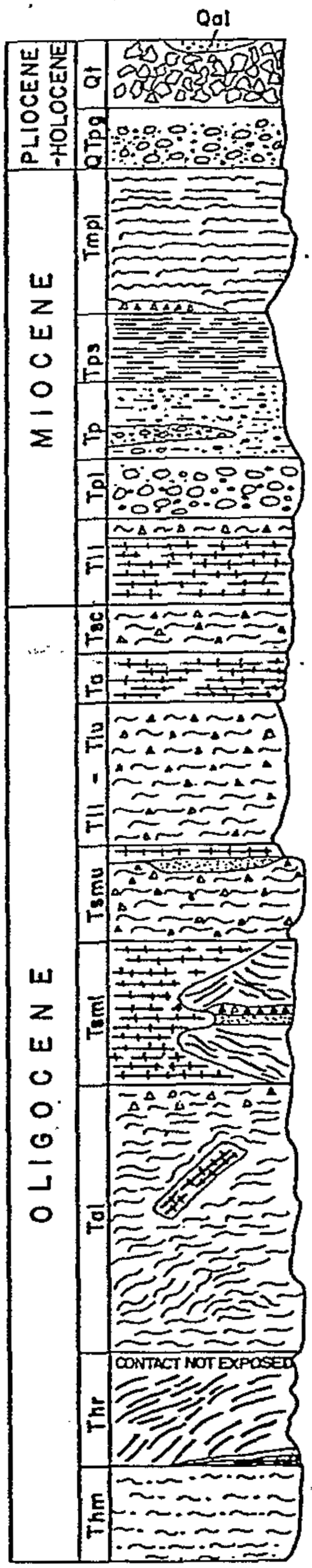
A sample for radiometric dating was collected from the lavas interbedded in the Popotosa Formation in the Muleshoe Ranch area.

STRATIGRAPHY AND PETROGRAPHY

General Tertiary Stratigraphy of Central Socorro County

The Tertiary sequence in central Socorro County consists of both volcanic and sedimentary units. The basal Tertiary unit is the Baca Formation (Eocene) which consists of arkosic sandstones and conglomerates. Overlying the Baca Formation is the Spears Formation, a series of latitic-andesitic conglomerates, laharic breccias, volcaniclastic sandstones, andesitic lavas, and three or more interbedded ash-flow tuffs. This largely sedimentary accumulation represents the alluvial apron that surrounded the Datil-Mogollon volcanic field prior to its Oligocene ignimbrite climax (Chapin and others, 1978). The pyroclastic eruptions are represented by a thick sequence of ash-flow tuffs overlain and interbedded with basaltic-andesite and rhyolite lavas (Oligocene-early Miocene). Regional extension contemporaneous with the late stages of this volcanism created basins in which the clastic sediments of the Santa Fe Group and basaltic and rhyolitic lavas have accumulated.

The rocks exposed in the study area consist of ash-flow tuffs and lavas of Oligocene to early Miocene age and a later sequence of fanglomerate and mudflow deposits overlain by rhyolitic lavas. The map units are shown graphically in figure 5.



Alluvium: (0-50 ft., 0-15 m) ALLUVIUM and COLLUVIUM: deposits of sand and gravel along stream channels and terraces. Colluvial deposits cover lower slopes, extensive talus is common at higher elevations.

Piedmont Gravels: (0-50 ft., 0-15 m.) UNCONSOLIDATED PIEDMONT GRAVELS: gravels predominantly of ash-flow tuff and andesite.

Lavas of Magdalena Peak: 14-13m.y. (500ft , 152 m) RHYOLITE FLOWS: brn to pink, dense, porphyritic, flow-banded rhyolite; vitrophyric zones common. Buff to gray brn. ash-flow tuffs occur locally.

Popotosa Formation (0-800 ft , 0-244 m) LAHARIC BRECCIAS, CONGLOMERATES, and SANDSTONES: dense, red, well-indurated, heterolithic laharic breccias at base (500 ft) overlain by and interbedded with conglomerates and sandstones. Uppermost portion finely laminated sandstones and siltstones.

Intermediate Lavas (0-400 ft , 0-122 m) ANDESITES, RHYODACITES: basaltic andesites overlain by rhyodacite lavas with large phenocrysts of alkali feldspar and quartz. Locally interbedded with lithic-rich ash-flow tuffs and laharic breccias.

Tuff of South Canyon 26.m.y. (0-100 ft , 0-30 m) ASH-FLOW TUFFS: multiple-flow, simple cooling unit of rhyolite ash-flow tuff; pink to gray, moderately to densely welded, crys.-rich, distinctive streaked pumice.

Lava Flows: (0-200 ft , 0-60 m) ANDESITE LAVAS: dark red to gray dense, basaltic andesites with distinctive oxidized ferromag. phenocrysts.

Tuff of Lemitar Moutains: 28 m.y. (600-1000 ft , 180-305 m) ASH-FLOW TUFFS: rhyolite, multiple-flow, densely welded, ash-flow tuff. Lt. gray to pale-red, crys.-poor, lower member (0-400 ft.) overlain by med. red, crys.-rich, qtz. and biotite rich, 2 felds. upper member

Upper Unit of Sixmile Canyon: 29 m.y. (500-750 ft ,152-230 m) ASH-FLOW TUFFS, SANDSTONES, ANDESITES: Lower and upper members of tuff of Caronita Canyon overlain by sandstone and andesite. Lower member is brick-red, crys.- poor, multiple-flow, and poorly to moderately welded. Upper member is gray to white, crystal-rich, with distinctive bipyramidal qyartz. Overlain by qtz.-rich, bedded, sandstone and dense, aphanitic, andesites.

Lower Unit of Sixmile Canyon: (800-2000 ft) ANDESITE to BASALTIC ANDESITE LAVAS, RHYOLITE LAVAS, VOLCANOCLASTICS, ASH FLOW TUFFS: dark, aphanitic, andesites in northern portion of study area pinch out to the south against rhyolite flows and minor interbedded ash-flow tuff and sandstone.

A-L Peak Tuff-flow-banded member(?): 32-30 m.y. (2000-2500 ft , 600-760 m) ASH FLOW TUFF: Rhyolite, multiple-flow, crys.-poor, densely welded, tuff. Light gray to grayish-red purple; pumice often lineated; Megabreccia member consists of large blocks of older volcanic rocks which fell into the A-L Peak Tuff during cauldron collapse. Mod. crys.-rich member locally preserved near stratigraphic top. Erupted from the Sawmill Canyon cauldron.

Unit of Hardy Ridge: (500 ft , 152 m) RHYOLITE LAVAS, ASH-FLOW TUFFS, ANDESITE: Massive, aphanitic, white to pink flow-banded rhyolite lavas characterized by ovoid spherulite-like bodies (6 in. to 1 ft in diam.). Lavas intrude and overlie poorly welded, lithic-rich tuffs. Locally underlain by aphanitic, green, andesites.

Hells Mesa Tuff: 32 m.y. (900 ft , 275 m) ASH-FLOW TUFFS: rhyolite, multiple-flow, simple cooling unit of densely welded, crys.-rich, qtz.-rich, 2 felds., massive tuffs. Erupted from North Baldy cauldron.

Figure 5: Stratigraphic section of the thesis area. Graphic section and description modified after Chapin and others (1978). Thicknesses are exposed thicknesses and may not reflect true thicknesses of poorly exposed units.

Hells Mesa Tuff

The oldest Tertiary unit exposed in the study area is the Hells Mesa Tuff. The Hells Mesa is correlative with the lower, crystal-rich, quartz-rich, portion of Tonking's (1957) Hells Mesa member of the Datil Formation. Brown (1972) called this unit the tuff of Goat Springs Member of the Hells Mesa Formation. Three K-Ar dates have been obtained for the Hells Mesa Tuff: 1) 30.6 +/- 2.8 m.y. from the Bear Mountains (Weber and Basset, 1963); 2) 32.1 +/- 5 m.y. from the Gallinas Mountains; and 3) 32.4 +/- 1.5 m.y. from the Joyita Hills (Burke and others, 1963). The Hells Mesa Tuff was erupted from the North Baldy cauldron (Chapin and others, 1978), a remnant of which is preserved in the central Magdalena Mountains. Krewedl (1974) estimated the cauldron facies to be as much as 3850 feet thick. The outflow facies, however, is generally 400 to 600 feet thick.

All of the exposures in this study area are within the proposed North Baldy cauldron (Chapin and others, 1978). In the northeast portion of the study area, the Hells Mesa Tuff crops out in an east-trending band (secs. 31, 32, T.3S., R.3W.) with no exposed base. In this area, the lack of a consistent dip makes thickness estimates unreliable. This outcrop belt is the southern end of a remnant of cauldron facies Hells Mesa Tuff that is continuously exposed to the cauldron margin on North Baldy (Krewedl, 1974; Blakestad, 1978). In this area, the Hells Mesa Tuff is typically bleached to a light-gray to buff color, exhibits columnar jointing, weathers to blocky rubble, and forms steep slopes. In several places, thin, sandy layers, derived from the Hells Mesa Tuff, are interbedded in the tuff. These sand layers are limited in lateral extent and do not exceed three inches in thickness. The Hells Mesa Tuff is in contact to the south with the younger Unit of Sixmile Canyon along an east-trending structure that is interpreted to be the margin of the Sawmill Canyon cauldron.

On the east flank of Hardy Ridge, the Hells Mesa Tuff crops out in a roughly triangular pattern (sec. 19, T.4S., R.3W.) and is a minimum of 600 feet thick. Here, it is light gray to pale red purple, forms steep slopes, and weathers to blocky talus that forms extensive talus slopes. Near the southern end of this outcrop area, intense alteration and bleaching of the Hells Mesa Tuff has obscured all phenocrysts in hand specimen, except quartz grains and coppery biotite. This alteration may be related to a large body of rhyolite that intrudes the Hells Mesa Tuff about 1000 feet south of the southern boundary of the study area.

On the west side of Hardy Ridge, 50 to 100 feet of uppermost Hells Mesa Tuff is exposed along a major north-trending range fault; reconnaissance indicates that thicker sections of the Hells Mesa Tuff are exposed immediately to the south. These small exposures of Hells Mesa Tuff are very similar to those on the east.

Brown (1972), Chamberlin (1974), and Spradlin (1974) have described the petrographic characteristics of the Hells Mesa Tuff in areas where it has not been pervasively altered; the reader seeking detailed petrographic information is referred to their work. The Hells Mesa Tuff in the study area is consistently crystal-rich, and contains 45 to 55 percent phenocrysts of quartz, sanidine, plagioclase, and biotite. The average phenocryst size ranges from 2 to 3 mm, although quartz grains commonly reach 6 mm in diameter. The plagioclase phenocrysts are highly altered and in hand specimen appear either chalky or as skeletal remnants. Pumice is inconspicuous in most outcrops.

In thin section, the sanidine is partially altered to sericite and/or replaced by calcite. Plagioclase is usually completely altered and plucked from the slide during thin section preparation; remnants of sericite and clay minerals occasionally remain. Quartz occurs as large, rounded grains that are often embayed. Biotite occurs as lath-shaped crystals that are partially altered to hematite. Small magnetite grains (0.2 mm) are found throughout the rock, but comprise less than one percent.

Unit of Hardy Ridge

A thick sequence of rhyolite lavas, poorly welded ash-flow tuffs, and andesites with associated volcaniclastic sedimentary rocks overlie the Hells Mesa Tuff in the southwestern portion of the study area. This sequence is informally named the unit of Hardy Ridge for good exposures on the high ridge west of Sawmill Canyon. The unit crops out extensively along Hardy Ridge and to the west, but no outcrops are found to the north or east. The contact relationships between subunits within the unit of Hardy Ridge are usually obscured by talus and no marker horizons were found. These problems hinder the recognition of faults and decrease the accuracy of thickness estimates. Rhyolite lavas, ash-flow tuffs with minor associated lavas, and andesites with volcaniclastic sedimentary rocks were mapped separately. A minimum thickness of 800 feet was estimated from cross section (A-A').

<u>andesites and sedimentary rocks</u> The basal portion of the unit of Hardy Ridge is composed of andesite flows and associated volcaniclastic sedimentary rocks. They directly overlie the Hells Mesa and crop out in a north-trending band on the west side of Hardy Ridge and in two small areas on the east side (sec. 19, T.4S., R.3W.). Most of these andesites contain 5 to 20 percent oxidized pyroxene (?) phenocrysts; smaller amounts of nonporphyritic andesite are also present. Sandstones with minor conglomerate intervals occur locally on top of the andesite.

Dense, light-gray to medium-gray andesites with an aphanitic groundmass containing 5 to 20 percent oxidized pyroxene phenocrysts, 2 to 3 mm long, are the most abundant lavas. Where vesicular, amygdaloids of light-green clay minerals and calcite are common.

Dense, aphanitic, dark-gray to grayish-green andesites, with no visible phenocrysts, are found directly above the Hells Mesa on the west side of Hardy Ridge, in the extreme southern portion of the map area. They occur sporadically along the andesite outcrop belt. In hand specimen, some of the samples contain small, 0.5 mm, ovoid, green blotches. In thin section, most of these are seen to be chlorite and epidote after olivine (?); others may be vesicle fillings. The groundmass consists of plagioclase microlites, 0.2 mm long, partially obscured by a cloudy, brown alteration product. This material has moderate birefringence and is probably a clay mineral. Euhedral to rounded magnetite grains, 0.2 mm in diameter, make up 10 to 15 percent of the rock.

<u>ash-flow tuffs</u> Overlying the andesites and sediments on both sides of Hardy Ridge are a series of poorly welded tuffs with minor associated pyroclastic breccias and rhyolite lavas. A rectangular outcrop of tuffs, lavas, and breccia is found in the southeastern corner of section 19, T.4S., R.3W. The contacts at this exposure suggest that these rocks were deposited in a scallop, or channel, developed on the underlying Hells Mesa. A cross section (X-X') indicates a

minimum thickness of 400 feet. Similar relationships between this tuff interval and the Hells Mesa are seen extensively to the south (S. Roth, 1978, oral commun.). More extensive exposures of correlative tuffs are found on the crest and flanks of Hardy Ridge. At one locality (SW 1/4, sec. 19, T.4S., R.3W.), the tuffs are overlain by younger rhyolite lavas of the Hardy Ridge Group.

The ash-flow tuff unit weathers to blocky talus that forms extensive talus slopes. The tuffs vary in color from pinkish gray to very pale blue, are poorly to moderately welded, and are commonly pumice and lithic rich. One prominent tuff that crops out on the east flank of Hardy Ridge, and in the southeast corner of section 19, contains more than 50 percent light-colored, disc-shaped pumice. In most outcrops, lithic fragments are predominantly angular fragments of aphanitic andesite that average 1 to 2 cm in diameter. Occasionally, clasts of the underlying Hells Mesa Tuff, ranging in size from 3 cm to 30 cm can be found in the tuffs. In the extreme southwestern corner of section 19, a pyroclastic breccia (Fisher, 1960) crops out which contains more than 50 percent lithic fragments that exhibit a preferred alignment. The lithic fragments are flow banded rhyolite and andesite that average 2 to 3 cm in diameter, but may be as large as 15 cm. A small amount of crystal poor lava is associated with the tuffs in section 19 but appears to have a very limited extent.

The tuffs usually contain less than 10 to 15 percent phenocrysts which consist of approximately two times as much quartz as sanidine and a small amount of plagioclase. The feldspars are partially to completely altered to clays and the pumice is often replaced by calcite. Quartz grains average about 0.75 mm in diameter and are usually rounded and embayed. Trace amounts of magnetite, partially oxidized to hematite, are present.

rhyolite lavas A sequence of rhyolitic lavas that locally overlie the tuffs and andesite crops out extensively in section 23 and 24 (T.4S., R.4W.) and on Hardy Ridge. Mapping to the south (S. Roth, 1978, oral commun.) indicates that similar lavas both intrude and overlie the Hells Mesa Tuff and the lower subunits of the unit of Hardy Ridge. The contacts between the tuff and lava units on Hardy Ridge may also be partly intrusive. Steep dips and a crude radial pattern of dips in the outcrop located in section 24 may indicate an intrusive dome. The only constraint on the minimum age of these lavas is the fact that the tuff of Lemitar Mountains overlies the lavas on Hardy Ridge and to the west and has been dated at approximately 27 m.y. (R.C. Chamberlin, unpublished data).

In general, the lavas are light colored, crystal poor, flow banded, and show varying degrees of devitrification and hydrothermal alteration. A poorly understood but distinctive and widespread textural feature of these lavas is the occurrence of overlapping, spherical to semi-spherical bodies which are localized along foliation planes. In outcrop, they appear similar to rounded cobbles and range in size from 1 cm to 0.6 m; the average size is 10 to 20 cm (figure 6). In some areas, individual flow planes can be traced from the lava through the bodies with no obvious deflection. When separated from the enclosing rhyolite, they often appear as circular layers, less than one millimeter in thickness, stacked on top of one another with successively smaller radii. No lithologic or textural difference has been found between the bodies and the surrounding lavas. However, a thin rind (less than 1 mm thick) surrounds some bodies. Occasionally, these bodies show internal concentric or radial structures, but they are quite distinct in appearance from spherulites. The latter are also common in the lava but usually do not exceed 1 cm in diameter.

In thin section, the lavas are very crystal poor. Usually, the only phenocrysts are trace amounts of irregular magnetite grains 3 to 4 mm in diameter. In one sample, a rounded grain (1 mm) of leucoxene was noted. The groundmass of the lavas is spherulitically devitrified to radiating aggregates of alkali feldspar and silica minerals. In some samples, 3 to 4 mm cavities are filled with inward growing quartz crystals. Flow planes are defined by zones 1 to 2 mm thick filled with quartz crystals.

Figure 6. Spherulite-like bodies associated with the rhyolite lavas of the unit of Hardy Ridge.

The unit of Hardy Ridge is a heterolithic accumulation of andesites, sediments, ash-flow tuffs, and rhyolite lavas which probably filled the topographic depression caused by collapse of the North Baldy cauldron (Chapin and others, 1978). Voluminous intrusive rhyolites, lithic-rich tuffs, and pyroclastic breccias are suggestive of local vent areas, possibly along ring fractures. Further mapping to the south and west will test this hypothesis.

A-L Peak Tuff

The A-L Peak Tuff, a composite ash-flow tuff sheet (Chapin and Deal, 1976), crops out extensively in the east-central portion of the study area. Deal (1973) and Deal and Rhodes (1974) originally named the tuffs the A-L Peak Rhyolite for exposures in the northern San Mateo Mountains; the name has since been modified to A-L Peak Tuff (Chapin and others, 1978). The A-L Peak Tuff is correlative with the "banded rhyolite" of Loughlin and Koschmann (1942), the middle 65 feet of Tonking's (1957) Hells Mesa Member, and the tuff of Bear Springs (Brown, 1972). E.I. Smith and others (1974) dated the A-L Peak Tuff at 31.8 +/- 1.7 m.y. by the fission track method.

There are three generally recognized members of the A-L Peak Tuff--the basal gray-massive, the flow-banded, and the upper pinnacles members. All three members are moderately to densely welded, crystal-poor, ash-flow tuffs with 4 to 10 percent phenocrysts. Sanidine, 3 to 8 percent, and small rounded quartz, 1 to 2 percent, are the most common phenocrysts; minor amounts of plagioclase and biotite are also found (Chapin and others, 1978). The lower light-gray, pumice-poor, gray-massive member grades upward into the gray or reddish-brown flow-banded member which has abundant, lineated pumice. In the Lemitar and Bear Mountains a tongue of basaltic-andesite lavas separates the upper pinnacles member from the flow-banded member (Chapin and others, 1978). The pinnacles member typically has abundant non-lineated pumice and is named for its characteristic outcrop pattern.

The thickness of the A-L Peak Tuff in the Socorro-Magdalena area generally varies from 0 to 700 feet (Chapin and others, 1978). In this study area, an estimate from a cross section (B-B') indicates a minimum thickness of 2000 to 2500 feet. This thickness may be inaccurate due to: 1) non-uniform orientation of foliation in the A-L Peak, largely due to secondary folding; 2) lack of an exposed base; and 3) difficulty in recognizing faults within a thick unit that shows no well-defined vertical zonation and has no marker horizons.

The source areas for the A-L Peak Tuff are poorly understood at this time. Deal (1973) interpreted a total thickness of about 2000 feet for all three members on A-L Peak to reflect a source cauldron for at least some of the A-L Peak in the San Mateo Mountains. However, all three members are recognized within this section (Chapin and Deal, 1976), and there is a great deal of vertical variability in degree of welding, development of lineation, and pumice content. A very similar section of about 1700 feet was seen in reconnaissance of Devils Backbone, south of the Magdalena Mountains, where there is clearly no cauldron present. Current thoughts are (Chapin, 1978, oral commun.) that none of the three members were erupted from the Mount Withington cauldron and that the gray-massive and flow-banded members were erupted from the Magdalena cauldron (fig. 4).

The extensive exposures of the A-L Peak Tuff in the study area are believed to represent a cauldron facies of the Sawmill Canyon cauldron. It cannot be definitely correlated with any of the known members of the A-L Peak recognized in the outflow facies. The characteristics of the A-L Peak in the study area that are suggestive of a cauldron facies tuff are: 1) anomalous thickness; 2) uniform nature in terms of crystal content, pumice, and degree of welding; and 3) presence of megabreccia blocks in the vicinity of the proposed cauldron margin.

In the study area, the A-L Peak Tuff is well exposed along the East and West Forks of Sawmill Canyon. Good exposures continue to the south where the A-L Peak appears to pinch out against rhyolitic lavas which may be equivalent to the unit of Hardy Ridge (S. Roth, 1978, oral commun.). To the north and east, the A-L Peak is overlain by a thick section of the unit of Sixmile Canyon which is thought to be cauldron fill of the Sawmill Canyon cauldron (Chapin and others, 1978). Extensive exposures of both A-L Peak and the unit of Sixmile Canyon are found to the east in the Ryan Hill canyon area (D. Petty, 1978, oral commun.). To the west, the A-L Peak is in apparent fault contact with the Hells Mesa Tuff and the unit of Hardy Ridge. This apparent fault may be the cauldron margin of the Sawmill Canyon cauldron and will be discussed later.

The A-L Peak in the study area is densely welded with no obvious cooling breaks. It is characterized by prominent pumice lenses, low phenocryst content and a paucity of lithic fragments. Much of the A-L Peak possesses a strong foliation defined by highly flattened and often lineated pumice fragments. Locally the uppermost 0 to 300 feet of the A-L Peak shows a great deal of vertical variability in phenocryst content, degree of welding, and lithic content; this upper interval will be discussed separately. In the study area, the upper A-L Peak Tuff was not mapped separately from the lower A-L Peak. Mapping to the south and east (D. Petty, S. Roth, 1978, oral commun.) indicates that tuffs similar in appearance to the A-L Peak may be separated from the lower A-L Peak by thin, rhyolite lava flows.

<u>lower A-L Peak Tuff</u> The lower A-L Peak is well exposed throughout the south-central portion of the study area,

especially along the West Fork of Sawmill Canyon where it forms steep slopes and cliffs. Outcrops are usually cut by one or more closely spaced joint sets, often normal to the foliation; joint surfaces and fractures are ubiquitously stained with reddish-brown iron oxide and black manganese oxides. Outcrops typically weather to small platy slabs. The lower A-L Peak is usually light gray to grayish red in color. In most specimens, the pumice is grayish red-purple and contrasts with a light-gray matrix; however, in some places both matrix and pumice are shades of red-purple and the pumice is not immediately obvious.

Much of the lower A-L Peak Tuff possesses a strong foliation defined by highly flattened and often lineated pumice fragments. The pumice content varies from less than 2 percent to greater than 20 percent and averages 10 to 15 percent. Typically the pumice are 2 to 6 cm long and 0.5 mm thick. Where the pumice are particularly large, individual pumice fragments are 1 to 2 meters long and 1 to 2 cm thick. The length to thickness ratio of the pumice is often greater than 100. Differential compaction is often seen around phenocrysts and lithic fragments. In planes parallel to the foliation, the pumice are typically cigar-shaped and filled with grainy vapor-phase crystals. In contrast, in the upper A-L Peak and in non-lineated portions of the lower A-L Peak, the pumice tend to be disc-shaped.

In thin section, the lower A-L Peak has an average of 3 percent phenocrysts; locally, the phenocryst content may be one percent or less. Sanidine is from four to five times as abundant as quartz and occurs as euhedral to subhedral crystals approximately 0.5 to 2.0 mm long. Quartz phenocrysts are rounded and are usually less than 1.0 mm in diameter. Euhedral to rounded magnetite grains that range in size from less than 0.05 mm to 0.5 mm occur in the groundmass and as phenocrysts. One to two percent small andesitic lithic fragments, usually less than 1 cm in diameter, are common in the lower A-L Peak. These lithic fragments, however, are not easily seen in hand specimen. Trace amounts of plagioclase are found in some samples. The original vitroclastic texture of the A-L Peak has been destroyed by recrystallization of the matrix to a fine-grained intergrowth of alkali feldspar and silica minerals; in thin section the tuff resembles a flow banded lava.

Elongate pumice fragments and ellipsoidal cavities filled with quartz define the foliation. The ellipsoidal cavities average approximately 0.05 mm x 1.0 mm and are made up of coarsely crystalline vapor-phase quartz. In some specimens, these quartz lenses make up as much as 15 percent of the rock. Pumice fragments are characterized by vapor phase minerals and hematite staining. The rims of the pumice fragments are composed of interlocking, inward growing, quartz and bladed alkali feldspar crystals. Their centers often contain aggregates of euhedral (0.4 mm) alkali feldspar crystals surrounded by larger anhedral quartz crystals; the alkali feldspar crystals are often altered to clay minerals and stained with hematite.

Primary laminar flow structures are developed in the lower A-L Peak Tuff in the study area. The development of primary flow structures varies laterally and vertically within the unit and are best observed in the south-central portion of the study area. Primary laminar flow structures have been recognized in many ash-flow tuffs (Schminke and Swanson, 1967; Walker and Swanson, 1968; Lowell and Chapin, 1972; Deal, 1973; Chapin and Lowell, 1979). Chapin and Lowell (1979) discuss, in detail, the mechanisms involved during deposition of ash-flow tuffs and suggest that temperature of emplacement will determine whether or not an ash-flow tuff will exhibit primary flow structures:

> If the temperature of the glassy particles is well above the softening point, the particles will agglutinate, collapse, and weld in the laminar boundary layer to form a viscous fluid with the rheological properties of a rhyolite lava. The resultant tuff will have a primary foliation and lineation and may contain lenticules representing pockets of gases trapped during welding.
>
> If the temperature is below the softening point, the glassy particles will fail to adhere and deposition will occur as loose ash in a laminar flow regime. In that case, collapse and welding may occur after deposition, as increasing load pressure depresses the minimum welding temperature to, or below, the temperature of the glassy particles. The time factor is also important in that particles at, or slightly above, the softening point may be too rigid to adhere in the laminar boundary layer but may slowly collapse and weld after deposition. The resulting tuff is not

> lineated and foliation is by secondary compaction. The tuff lacks conspicuous gas cavities because most of the entrained gases escaped during welding (exceptions may exist in thick, rapidly deposited tuffs).

Features of the A-L Peak Tuff in this study area which are consistent with or suggestive of primary laminar flow are: 1) foliation defined by highly flattened, lineated pumice fragments and elongate cavities; 2) folding of the lineated foliation; 3) foliation dips too steep to have been formed by secondary compaction.

Chapin and Lowell (1979) point out that the eutaxitic fabric of an ash-flow tuff may be a composite of foliation planes, gas cavities and pumice. Vapor phase crystallization has destroyed the original textures of pumice in the lower A-L Peak. Therefore, it is difficult to tell whether the long red purple bands that define the eutaxitic fabric of the lower A-L Peak represent large pumice fragments. Pumice fragments may localize escaping volatiles during welding and give rise to accumulations of vapor-phase minerals that exceed the dimensions of flattened pumice fragments. Regardless of their origin, the reddish streaks are pervasively lineated in the study area. The lineation was found to consistently strike east-west, in approximately the same direction as that reported by Deal (1973), Petty (1978, oral commun.) and Roth (1978, oral commun.). Such widespread development of lineation cannot be a local phenomena and must be a primary feature of the tuff. The small quartz-filled lenses seen in thin section probably represent gas cavities that were formed by escaping volatiles during welding of the tuff. Preservation of such a delicate feature argues for primary welding and against much post-emplacement compaction.

The foliation in the lower A-L Peak is often folded but the lineation is not deflected from parallelism with the overall lineation direction. The folds have amplitudes that range from a few millimeters to several meters. Styles of folding include broad, open synclines and anticlines, tight, isoclinal to recumbent folds, and sharp v-shaped antiforms. The latter are very similar to folds described by Brown (1972) and Chamberlin (1974) in the flow-banded member of the A-L Peak. Excellent exposures of these folds can be seen on the north side of Black Bear Canyon at about the 8100 foot elevation. In many places, the strike and dip of the A-L Peak varies considerably between outcrops less than 3 meters apart. This variation is suggestive of large folds with amplitudes of 3 to 15 meters.

Deal (1973) reported large folds with amplitudes as large as 30 meters in the A-L Peak Tuff in the San Mateo Mountains and Petty (1978, oral commun.) reports similar folds in the A-L Peak in the Ryan Hill Canyon area. Ash-flow tuffs may develop primary folds during deposition and secondary folds during post-depositional slumping. Chapin and Lowell (1979) noted that the axis of secondary folds are

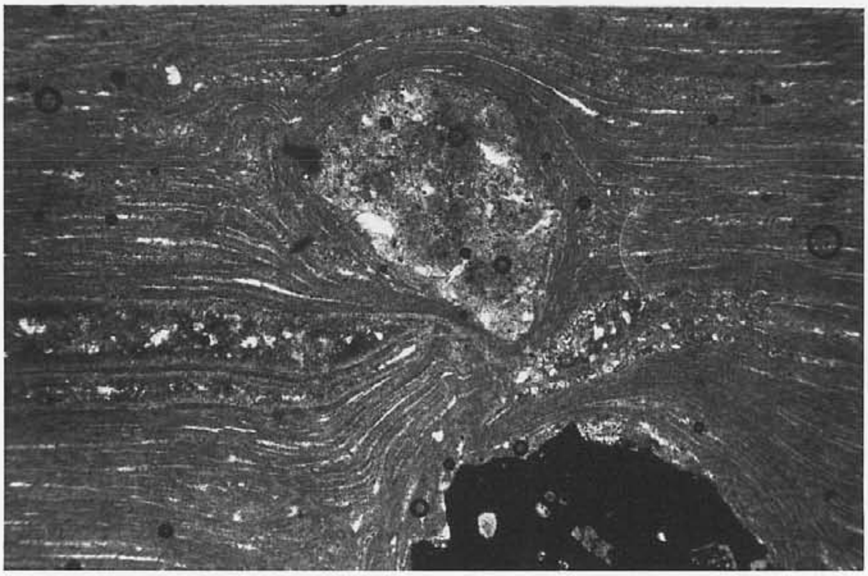


Figure 7. Photomicrograph of A-L Peak Tuff. Intricate folding of foliation around phenocryst is attributed to laminar flowage. Phenocryst is 1.5 mm in longest dimension.

parallel to the lineation. Using this criteria, the large folds described in the A-L Peak are secondary.

Evidence of rotated phenocrysts and lithic fragments can be seen in both hand specimen and thin section. Disturbed zones at the ends of individual phenocrysts or lithic fragments, where individual laminae form asymmetric folds and crenulations, are a major effect of this rotation. In some specimens, individual laminae can be traced around lithic fragments and phenocrysts; this also is attributed to rotation during laminar flow (figure 7). These folds and crenulations have axes that are normal to the lineation and are believed to be primary folds formed during deposition of the tuff. The folding of primary lineation and the preservation of small cavities along flow planes suggests that the tuff had welded prior to folding.

Dips consistently greater than 50 degrees are common over large areas in the A-L Peak. The regional dip is approximately 45 to 50 degrees to the east; thus the steeper dips are probably due to folding or were originally steep due to primary welding on pre-existing slopes.

The evidence presented above suggests that the lower A-L Peak was deposited and welded in laminar boundary layers along the bottoms of ash flows. The fact that development of the primary features varies laterally and vertically probably indicates that the temperatures of the erupted ash-flows varied. This variation complicates correlation of the A-L Peak in the study area with the corresponding outflow unit which may not exhibit primary welding. Further study of the primary and secondary welding features in the A-L Peak Tuff will be of value both in correlating cauldron- and outflow-facies tuffs and in more fully understanding deposition of ash-flow tuffs.

<u>megabreccia</u> On the west side of Timber Ridge (near the southern boundary of the study area) and on the ridge between the East and West Forks of Sawmill Canyon, large outcrops of volcanic rocks believed to be correlative with the unit of Hardy Ridge are completely surrounded by the lower A-L Peak Tuff. Large blocks of these rocks on the ridge between the forks of Sawmill Canyon are composed of poorly to moderately welded ash-flow tuffs, lavas, and volcaniclastic sediments. Large blocks on Timber Ridge are composed of sandstone overlain by poorly welded tuffs. The attitudes of the tuffs, lavas, and sediments within individual blocks is variable and usually not conformable with the surrounding A-L Peak. The blocks are commonly silicified, fractured, and hydrothermally altered.

The most common tuff within the blocks is generally pale red to grayish pink and is poorly to moderately welded. Excellent exposures of this tuff can be found along the trail in the West Fork of Sawmill Canyon at about the 8100 foot elevation. In thin section, the tuffs contain 10 to 25 percent phenocrysts and 5 to 10 percent small, angular lithic fragments. Quartz is approximately twice as abundant as sanidine and plagioclase; it is rounded and has an average diameter of 0.4 mm. Sanidine phenocrysts are partially altered to clay minerals and seldom exceed 1.0 mm in length. Plagioclase is partially altered to potassium feldspar. Pumice are usually filled with clay minerals. The tuffs are very similar in appearance and mineralogy to tuffs in the unit of Hardy Ridge.

A distinctive porphyritic andesite or rhyodacite lava is common in the large blocks on Sawmill Ridge. In the large, embayed block on the west side of Sawmill Ridge, the tuff and lava are interbedded. The lava is typically grayish blue with white to pale-pink feldspar crystals that range from 4 mm x 1 mm to 11 mm x 6 mm. No similar lavas have been seen in the unit of Hardy Ridge in this study area or to the south (S. Roth, 1978, oral commun.).

In thin section, large plagioclase phenocrysts, sometimes exhibiting glomeroporphyritic texture, occur in an aphanitic groundmass composed largely of altered plagioclase microlites. The rims of the plagioclase phenocrysts are altered to a clay mineral having low birefringence; centers of plagioclase phenocrysts are partially altered to sericite. Lath-shaped phenocrysts of biotite about 0.5 mm long are in varying stages of alteration to magnetite and hematite. Euhedral to subhedral hornblende (?) phenocrysts that range in size from 0.3 mm to 4.0 mm are completely replaced by magnetite. A small amount of secondary quartz was seen in one thin section.

On the west side of Timber Ridge and southern side of Black Bear Canyon, one large block consists of poorly to moderately welded tuffs overlying a medium- to well-sorted sandstone. The sandstone is highly fractured and faulted; brecciated fault planes can be seen dipping in many directions. It is stained bright orange and cemented with secondary silica near the contact with the A-L Peak. The block on the north side of Black Bear Canyon consists largely of sandstone. At the base of the block, the sandstone is coarse-grained (1 to 2 mm grains) and exhibits planar bedding; grain size decreases towards the top of the outcrop. A minor amount of poorly welded tuffs and tuffaceous sedimentary are found near the top of the outcrop.

The contact relationships between megabreccia blocks and the enclosing A-L Peak are well exposed around the block on the south flank of Black Bear Canyon and along the base of the large embayed block along the West Fork of Sawmill Canyon (extreme SE 1/4, sec. 18, T.4S., R.3W.). At both localities, the A-L Peak surrounding the blocks is extremely phenocryst poor, in places less than one percent phenocrysts. The A-L Peak is often tightly folded and locally exhibits a megascopic lineation with ridge and groove striations having as much as 2 mm of relief. Roughly spherical masses, much like those described in the lava of the unit of Hardy Ridge, are found within five feet of the contact with the blocks (figures 8 and 9). In cross section, these spherical masses consist of a thin, light-colored rind surrounding densely welded A-L Peak. The foliation in the surrounding A-L Peak usually continues through the masses and they contain both lithic fragments and phenocrysts. Preliminary study suggests that the bodies may represent concentrations of silica and iron oxide. The best exposures of these spherulite-like bodies are found around the block on the south flank of Black Bear Canyon. W.A. Seager and others (1976) noted "spherulitic bodies 4 to 6 inches in diameter" near "intrusive contacts" of the Dona Ana Tuff near Las Cruces, New Mexico. The Dona Ana Tuff is very similar to the A-L Peak in degree of welding, phenocryst content, and development of laminar flow structures.

Another contact feature, associated with the embayed block in the West Fork of Sawmill Canyon, is what appears to be highly altered A-L Peak that has been intruded by thin veins of more A-L Peak. The resulting structure has a boxwork fabric (figure 10). There are also many anomalously steep dips in the A-L Peak in the vicinity of the block. It appears that large blocks of pre-existing rocks fell into the A-L Peak Tuff while it had the rheological properties of a rhyolite lava. The primary foliation and lineation was disturbed and dikelets of A-L Peak were injected.

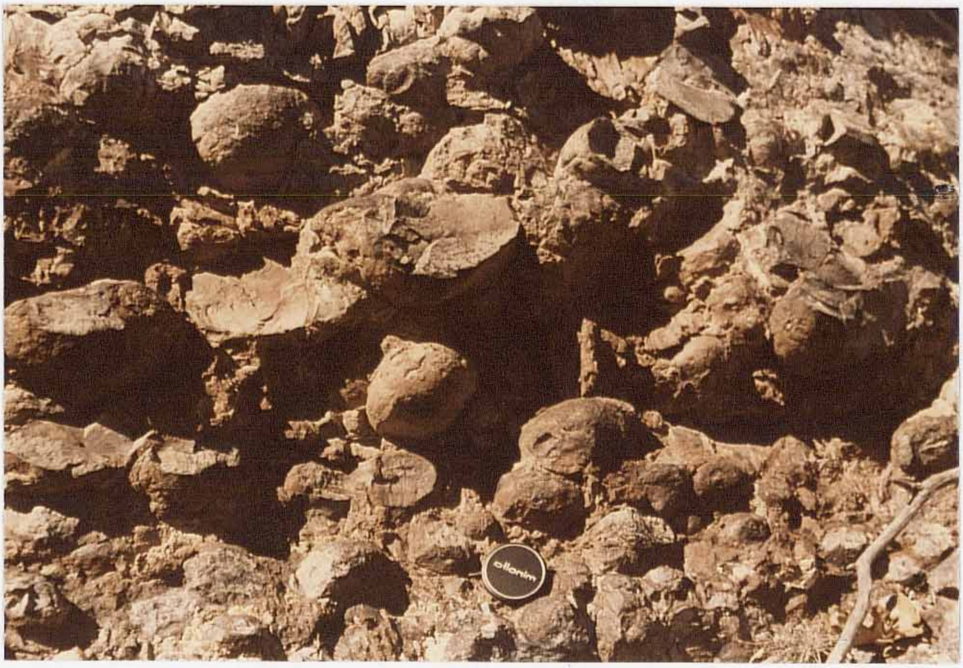


Figure 8. Spherulite-like bodies in the A-L Peak Tuff near contact with megabreccia block on the south flank of Black Bear Canyon.

Figure 9. Tightly folded A-L Peak Tuff and spherulite-like bodies from same outcrop as figure 8.

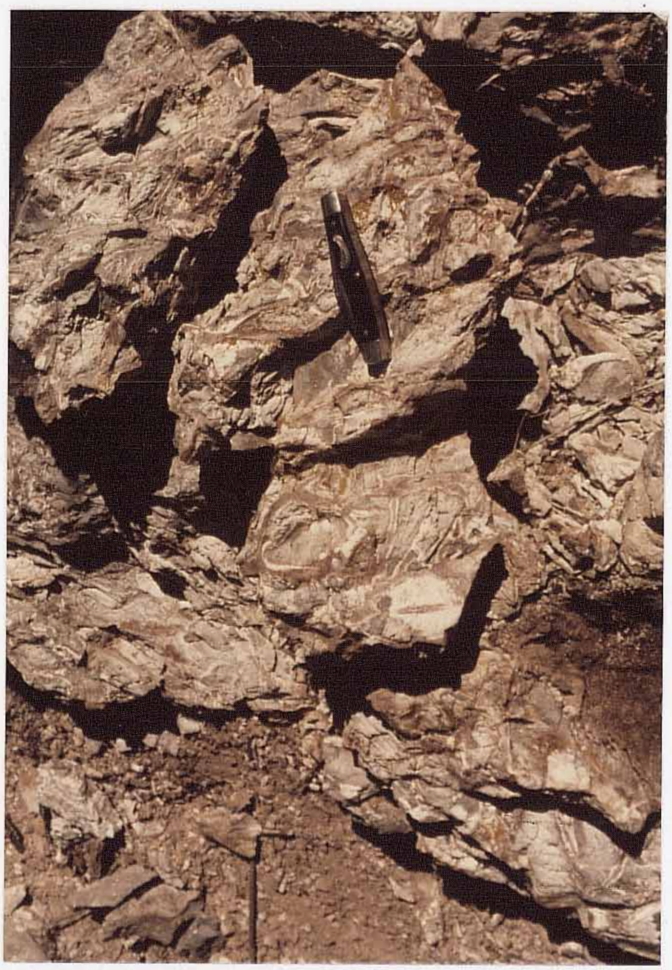


Figure 10. Boxwork fabric in A-L Peak Tuff near contact with megabreccia block, West Fork of Sawmill Canyon.

The contact relationships of these blocks of tuffs, lavas, and sedimentary rocks with the A-L Peak, their lithologic similarity to the unit of Hardy Ridge and their proximity to the Sawmill Canyon cauldron margin (Chapin and others, 1978, and fig. 4) suggests that they are blocks of pre-caldera rocks that fell into the cauldron during eruption of the A-L Peak. Lipman (1976) has documented extensive landslide deposits of pre-caldera rocks, derived from oversteepened caldera walls, that fell into cauldrons in the San Juan volcanic field during eruption and collapse. The group of blocks in this study area are interpreted to be an example of Lipman's (1976) megabreccia.

upper A-L Peak Tuff Locally preserved at the stratigraphic top of the A-L Peak Tuff are ash-flow tuffs that show a great deal of variability in crystal content, pumice size, and lithic content. This variability contrasts strongly with the uniformly densely welded, crystal-poor, flow-banded, lower A-L Peak found throughout the study area. The best exposures of the upper A-L Peak are: beneath the unit of Sixmile Canyon immediately south of Langmuir Laboratory; in the East Fork of Sawmill Canyon at about the 8600 foot elevation; and on the north flank of Black Bear Canyon near the southeast border of the study area. In these areas, the tuffs are characterized by variable color, lack of flow banding, small size of pumice fragments and, locally, increased phenocryst content.

The upper A-L Peak shows a great deal of lateral variation. At the northern ends of Hardy Ridge and the ridge between the East and West Forks of Sawmill Canyon and in the East Fork of Sawmill Canyon are excellent exposures of moderately crystal-rich (15 to 30 percent phenocrysts), moderately to densely welded upper A-L Peak. The thickness of this A-L Peak is variable but it is at least 200 feet thick in the East Fork of Sawmill Canyon. Between Hardy Ridge and Sawmill Ridge, the crystal-rich tuff does not outcrop. Here, the upper A-L Peak is densely welded but not flow banded, contains 5 to 10 percent phenocrysts, and has very few lithic fragments.

The crystal-rich portion of the upper A-L Peak varies in color from grayish red purple to light greenish gray. Commonly, light-pink sanidine phenocrysts that average 1 to 2 mm in length are visible in hand specimen. Quartz is easily recognized in hand specimen and is usually about 1 mm in diameter. Lithic fragments, predominantly andesite, account for 5 to 10 percent of the rock. Pumice fragments are not lineated and, in planes parallel to the foliation, the pumice are roughly equidimensional; in planes perpendicular to the foliation, the pumice are lensoidal with delicately frayed ends.

In thin section, sanidine is the dominant phenocryst and occurs as broken euhedral crystals, many of which are highly embayed. Much of the sanidine is altered to clay minerals. Quartz makes up 1 to 2 percent of the rock and occurs as rounded, often embayed grains, 0.3 to 0.7 mm in diameter. The sanidine content varies greatly in this tuff while the quartz remains relatively constant. Pumice fragments are typically 2 cm in diameter and 3 to 5 mm thick. They are usually completely replaced by interlocking, anhedral quartz and occasionally alkali feldspar crystals; although in some samples, the pumice is filled with clay minerals. The matrix of the tuff has recrystallized to alkali feldspar and silica minerals and is pervasively stained with hematite. Glass shards are sometimes preserved and exhibit axiolitic texture. Minor amounts of highly altered plagioclase feldspar were found in some specimens.

On the west side of Timber Ridge, the upper A-L Peak occurs in scattered outcrops. On the north side of Black Bear Canyon at about the 8250-foot elevation are exposures of a crystal-poor, pumiceous, and very lithic-rich portion of the A-L Peak. Its thickness is a minimum of 200 feet. Individual pumice are small (2 cm x 1 cm x 0.5 cm) and exhibit a fine, tubular structure. Lithic fragments, 1 to 2 mm in diameter, make up 5 to 20 percent of the rock.

The discontinuous and variable nature of the upper A-L Peak is suggestive of it having been deposited in channels or topographic lows developed on the lower A-L Peak. Mineralogically, it is similar to the lower A-L Peak and may represent waning stages of A-L Peak volcanism. Further work to the east and south is needed to determine the extent of the upper A-L Peak and its relationship to the lower A-L Peak.

Blakestad (1978) interpreted a large brecciated zone along the western margin of the Magdalena Mountains, just south of the town of Magdalena, as the margin of a cauldron that erupted the flow-banded member of the A-L Peak. It is likely that the gray-massive member was also erupted from this cauldron (C.E. Chapin, 1978, oral commun.). The Magdalena cauldron is not well exposed due to basin-and-range faulting. However, a noteworthy feature of the exposed margin is that the pinnacles member is often conspicuously absent and the flow-banded member is overlain by post-collapse andesites. These relationships are not fully understood at this time.

If the flow-banded and gray-massive members were erupted from the Magdalena cauldron, it is likely that the pinnacles member was erupted from the Sawmill Canyon cauldron. The continuous stratigraphic succession of A-L Peak through the tuff of Lemitar Mountains, exposed along the west flank of Timber Ridge, supports this hypothesis. If the A-L Peak in this study area is the flow-banded member, the absence of the pinnacles member must be explained. Alternatively, the apparent absence of the pinnacles member in the Magdalena cauldron must also be explained.

An obvious problem with any interpretation is that the outflow facies of the pinnacles member is different in character from the A-L Peak in the study area. The outflow facies pinnacles member is usually not flow banded and is characterized by ovoid or lenticular pumice fragments. Differences between cauldron facies and outflow facies ash-flow tuffs in the San Juan volcanic field have been noted by Lipman (C.E. Chapin, 1978, oral commun.) and probably reflect different emplacement temperatures and/or different portions of the eruption.

Four viable hypothesis for the A-L Peak Tuff are: 1) the outflow facies pinnacles member represents an early series of eruptions that initiated cauldron collapse while the flow-banded tuff in the study area represents a later hotter eruptive sequence that puddled in the cauldron, contemporaneous with collapse; 2) the cauldron facies tuff is not related to the pinnacles member and is an intracaldera tuff not represented outside of its cauldron; 3) the outflow facies and cauldron facies are equivalent, but the cauldron facies is flow banded because emplacement temperatures near the vents were high enough to allow primary welding and development of laminar flow structures; and 4) the cauldron facies tuff in the study area is the flow-banded member of the A-L Peak Tuff. Further study of the A-L Peak Tuff is required to solve some of the problems raised in this report. Of particular interest is the significance of the upper A-L Peak Tuff.

Unit of Sixmile Canyon

Overlying the A-L Peak Tuff in Sawmill Canyon (secs. 5, 8, 17, T.4S., R.3W., unsurveyed) is a thick sequence of intermediate lavas, rhyolite lavas, ash-flow tuffs, volcaniclastic sedimentary rocks, and laharic breccias. This sequence was informally named the unit of Sixmile Canyon by Osburn (1978). He was not able to unequivocally determine its stratigraphic relationship with the A-L Peak Tuff; Krewedl (1974) believed it was stratigraphically below A-L Peak. In this study area and to the east (D. Petty, 1978, oral commun.) the unit of Sixmile Canyon lies directly above the A-L Peak Tuff and beneath the tuff of Lemitar Mountains. Chapin and others (1978) interpreted the unit of Sixmile Canyon to represent post-collapse fill of the Sawmill Canyon cauldron. The andesite of Landavaso Reservoir (Simon, 1973; Blakestad, 1978) occur at the same stratigraphic position as the unit of Sixmile Canyon and are probably equivalent.

In the Lemitar and Bear Mountains as much as 500 feet of basaltic andesite occurs between outflow facies A-L Peak and the tuff of Lemitar Mountains (Chapin and others, 1978). This succession contrasts with the thick cauldron fill of intermediate lavas, rhyolite lavas, ash-flow tuffs and volcaniclastic sediments that crop out in the study area. In this report, the unit of Sixmile Canyon is informally divided into upper and lower members. The lower member is characterized by lateral variability in rock type and thickness while the upper member is a relatively consistent sequence of two distinctive ash-flow tuffs and an interval of basaltic andesite.

lower member The lower unit of Sixmile Canyon crops out in a belt on the west flank of Timber Ridge; here, it overlies the A-L Peak Tuff and underlies the upper unit of Sixmile Canyon. At the northern end of this outcrop belt, in the northeast corner of the study area (secs. 5 and 6, T.4S., R.3W.), the lower unit of Sixmile Canyon is in depositional contact with the Hells Mesa Tuff along the east-trending Sawmill Canyon cauldron margin. Near the head of the East Fork of Sawmill Canyon the lower member covers a minimum topographic interval of 1200 feet and cross sections indicate that it may be as thick as 2000 feet. The lower unit of Sixmile Canyon also crops out on the west flank of South Baldy in the vicinity of Hardy Spring (secs. 12, 13, T.4S., R.4W.) Here it is bounded by faults on the west and south and is conformably overlain by the upper unit of Sixmile Canyon. Small exposures of the lower unit of Sixmile Canyon also occur immediately south and west of Langmuir Laboratory (secs. 7 and 18, T.4S., R.3W.) and on Hardy Ridge (south-central portion of sec. 18, T.4S., R.3W.).

In the northern part of the study area, the lower unit of Sixmile Canyon is composed largely of andesitic lavas; to the south, rhyolite lavas are dominant. This relationship can be clearly seen on the west flank of Timber Ridge where the rhyolite lavas pinch out to the north and are interbedded with the andesitic lavas; thick sequences of mafic lavas do not occur in the lower unit of Sixmile Canyon in the southern part of the study area. This pattern is also seen to the east (Osburn, 1978,; Petty, 1978, oral commun.) and to the south (Roth, 1978, oral commun.). In the central Magdalena Mountains, the majority of mafic lavas in the lower unit of Sixmile Canyon are restricted to an outcrop band approximately one mile wide which is roughly parallel to the northern margin of the Sawmill Canyon cauldron.

The andesitic lavas and an interbedded laharic breccia, two rhyolite lavas, and a distinctive ash-flow tuff were mapped separately. In addition, two outcrops of volcaniclastic sedimentary rocks along the northern Sawmill Canyon cauldron margin, and two small outcrops of ash-flow tuff just south of Langmuir Laboratory were also mapped.

<u>andesitic lavas</u> In the northern study area, extensive exposures of andesitic to dacitic lavas occur but no vents for these lavas were identified. The major outcrops of the andesitic lavas occur: immediately south of Langmuir Laboratory (NW corner, sec. 18, T.4S., R.3W.); on the west flank of South Baldy in the vicinity of Hardy Springs (secs. 12 and 13, T.4S., R.4W.); and along the wet flank of Timber

Ridge and at the head of the East Fork of Sawmill Canyon (secs. 5 and 8, T.4S., R.3W.).

South of Langmuir Laboratory, in the northwest corner of section 18, T.4S., R.3W., dominantly andesitic lavas are exposed over a minimum topographic interval of 1400 feet in a thin band between exposures of A-L Peak Tuff. The andesites are conformably overlain by the upper unit of Sixmile Canyon. The common lava that crops out in this area is a dark-gray to grayish-green aphanitic andesite. It is usually extremely uniform in appearance and in places exhibits columnar jointing. Towards the top of the section, the andesite becomes porphyritic and vesicular; minor porphyritic zones also occur throughout the section. Where porphyritic, phenocrysts of plagioclase about 1.0 mm in length make up as much as 20 percent of the rock; also present are about one percent euhedral to rounded magnetite phenocrysts. The groundmass is made up of plagioclase microlites, finely disseminated magnetite, and minor pyroxene. In one specimen, magnetite made up 15 to 20 percent of the groundmass. The plagioclase phenocrysts and groundmass are largely replaced by clay minerals and calcite.

A similar lava crops out in the vicinity of Hardy Spring, although here it contains about 2 percent quartz phenocrysts that average 0.7 to 1.0 mm in diameter. In thin section, the quartz phenocrysts are surrounded by reaction rims of pyroxene (?) that have been completely replaced by clay minerals and calcite. Phenocrysts of pyroxene (?), also replaced by clay and calcite, make up approximately 5 percent of the rock. Magnetite occurs as subhedral phenocrysts that range in size from 0.05 mm to 0.3 mm. Also present are small unoriented patches of secondary quartz probably unrelated to emplacement of the lava.

In the East Fork of Sawmill Canyon are a variety of aphanitic to porphyritic andesites that range in color from gray to grayish blue. Autobrecciated flow tops and bottoms with minor amounts of volcaniclastic sediments are common. The phenocryst content ranges from 0 to 30 percent and consists of: euhedral to subhedral plagioclase (0.5 to 1.0 mm); euhedral to subhedral pyroxene, probably augite; and euhedral to rounded magnetite grains (0.05 to 0.25 mm). The matrix is composed of plagioclase microlites, finely disseminated magnetite and trace amounts of augite.

A distinctive lava that crops out on the east side of Timber Ridge at about the 8800 foot elevation (secs. 8 and 17, T.4S., R.3W.) is a light-bluish-gray andesite that has 5 to 10 percent euhedral to subhedral augite phenocrysts that range in size from 0.1 mm to 0.3 mm; much of the augite exhibits glomeroporphyritic texture. The groundmass consists of altered plagioclase microlites and minor amounts of augite.

Above this andesite is a medium- to light-gray dacite which crops out semi-continuously along Timber Ridge.

It contains about 35 percent phenocrysts: 20 percent plagioclase about 3 mm long; 5 to 10 percent alkali feldspar; 5 percent euhedral to subhedral pyroxene; and approximately 1 percent biotite. The groundmass and phenocrysts are almost completely altered to clay minerals.

The lower unit of Sixmile Canyon also crops out in an east-trending band, southwest of Langmuir Laboratory (south sec. 7, T.4S., R.3W.). This sequence is of particular interest because the lower unit of Sixmile Canyon is anomalously thin here and the upper unit of Sixmile Canyon is apparently absent. The exposures are very poor in this area, however it appears that the lower unit of Sixmile Canyon overlies the A-L Peak. Here, it is composed largely of andesite flows, with interbedded andesitic laharic breccias, tuffaceous sedimentary rocks and minor ash-flow tuff. Andesitic laharic breccia crops out along the Hardy Canyon Trail and consists of small, angular to rounded andesite fragments, usually less than 1 cm in diameter, in a dark-green to black fine-grained matrix. An excellent exposure of ash-flow tuff occurs along the Hardy Canyon Trail at about the 9400 foot elevation (southeast sec. 7, T.4S., R.3W.). <The Hardy Canyon Trail is mislocated on the South Baldy 7 1/2-minute quadrangle map.> The tuff is pale green, well bedded and forms a cliffy outcrop that dips 26 to 45 degrees to the southwest. It contains approximately 20 percent phenocrysts which consist of 10 percent plagioclase (largely replaced by potassium-rich clays and calcite), 5 percent quartz and 5 percent sanidine. Pumice makes up approximately 15 percent of the rock. There appear to be two distinct blocks, although they may be separated by a fault. The tuff may be equivalent to the tuff and sedimentary rocks interval within the lower unit of Sixmile Canyon discussed below.

rhyolite lavas The intermediate lavas thin abruptly to the south where the lower unit of Sixmile Canyon is dominated by rhyolite lavas. Extensive talus and slide blocks from the overlying upper unit of Sixmile Canyon and tuff of Lemitar Mountains obscure much of the rhyolite lavas. There are two distinct rhyolite flows usually separated by andesite and a tuff and sedimentary rocks interval.

The lower rhyolite lava is pale red purple to grayish pink and is typically flow banded and crystal poor. In the southeast part of the area, the lower rhyolite has a thick autobrecciated top that forms a prominent ridge on the south side of Black Bear Canyon. Its thickness is approximately 300 feet. In outcrop the lavas weather to small blocky talus and form steep slopes with occasional small cliffs.

The phenocryst content is variable but is generally between 5 and 15 percent. Sanidine phenocrysts range in maximum dimension from 0.3 to 2.0 mm and are often altered to clay minerals; some appear perthitic. Quartz occurs as embayed crystals about 1.0 mm in diameter; sanidine is two to three times as abundant as quartz. Euhedral to subhedral magnetite grains about 0.1 mm in diameter make up one half to one percent of the lava.

The upper rhyolite is likely correlative with the rhyolite lava flow described by Osburn (1978) in the upper reaches of Sixmile Canyon (secs. 10, 11, 14, and 15, T.4S., R.3W.). In this study area, the lavas are pale pink to grayish pink and often have a mottled appearance. They weather to small cliffs and steep, rubble-covered slopes. Lithic fragments of brown and gray aphanitic andesite are abundant locally and may make up as much as 5 percent of the rock. Good exposures of a lithic-rich portion of the lava can be seen in the vicinity of Hardy Spring (north central sec. 13, T.4S., R.3W.).

In thin section, the lava contains 20 to 40 percent phenocrysts of sanidine, quartz and biotite. The groundmass is spherulitically devitrified and stained with hematite; this gives the lava its mottled appearance. Sanidine occurs as euhedral to subhedral crystals that average 1.0 mm in largest diameter, although some are as large as 6.0 mm. Sanidine is usually altered to clay minerals but when unaltered, the larger crystals exhibit light-blue chatoyancy. A few percent of rounded and embayed quartz phenocrysts that average 0.5 mm in diameter and 1 to 2 percent biotite make up the remainder of the phenocrysts.

<u>tuff and sedimentary rocks interval</u> Above the lower rhyolite, a thin interval of ash-flow tuff and sedimentary rocks crop out along the west flank of Timber Ridge and in the Hardy Spring area. In both localities the tuff and sedimentary rocks pinch out to the north. This interval provides an important stratigraphic marker horizon in the lower unit of Sixmile Canyon. The thickness of the tuff and sedimentary rocks is variable but seldom exceeds 60 feet. The tuff exhibits a prominent, thin bedding which weathers to cliffy outcrops and platy talus. It is characteristically grayish yellow green; locally on Timber Ridge, the pumice is a distinctive grayish green. Sandstones and conglomerates are often present above the tuff. Excellent exposures of sandstone, 10 to 20 feet thick, that are dominated by andesitic debris occur immediately south of Hardy Spring.

In thin section, the tuff has 20 to 25 percent phenocrysts and 10 to 15 percent pumice. Sanidine is the dominant phenocryst with about 1 percent quartz and plagioclase. The groundmass has been replaced by clay minerals and chlorite which often concentrate in the pumice.

<u>sedimentary rocks</u> In the northeast corner of the study area, two exposures of coarse volcaniclastic sedimentary rocks are in apparent depositional contact with the Hells Mesa Tuff along the northern Sawmill Canyon cauldron margin. The strike and dip of these alluvial deposits are variable and

thickness estimates are difficult to obtain. However, just north of the road to Langmuir Laboratory, the volcaniclastic rocks are exposed over a minimum topographic interval of 400 feet. They weather to steep slopes and the blocks of lava could be mistaken for outcrop. No outcrops of this lava have been found in the unit of Sixmile Canyon; however cobbles and boulders of it are found in the float along the cauldron margin to the east. Osburn (1978, oral commun.) reports that clasts of a similar lava occur in coarse heterolithic breccias in the unit of Sixmile Canyon that are found dipping into the cauldron. A similar lava is reported beneath the flow-banded member of the A-L Peak in the area west of North Baldy (Krewedl, 1978). This porphyritic lava is lithologically identical to the lava found within the megabreccia blocks described previously. It is characterized by glomeroporphyritic plagioclase phenocrysts, biotite laths, and euhedral pyroxene (?) that has been replaced by magnetite.

It is likely that this distinctive lava is older than the unit of Sixmile Canyon, perhaps a portion of the unit of Hardy Ridge, and that it was incorporated in breccia and sedimentary rocks deposited near the walls of the Sawmill Canyon cauldron following its collapse.

<u>upper unit of Sixmile Canyon</u> Above the lower unit of Sixmile Canyon is a distinctive sequence of an ash-flow tuff capped

with a sandstone and an interval of andesite. Locally, minor tuffs and sedimentary rocks occur at the base. The ash-flow tuff is correlative with Osburn's (1978) tuff and sandstone intervals in the unit of Sixmile Canyon and Stacy's (1968) tuffaceous unit. Outcrops of the upper unit of Sixmile Canyon are restricted to the interior of the Sawmill Canyon cauldron (Chapin and others, 1978). The upper unit of Sixmile Canyon is conformably overlain by the Tuff of Lemitar Mountains. An apparent angular unconformity exists between A-L Peak and the upper unit of Sixmile Canyon. The regional dips of the A-L Peak are 45 to 55 degrees to the east while that of the upper Sixmile Canyon is 20 to 35 degrees. The angular relationship between the lower unit of Sixmile Canyon and the A-L Peak Tuff cannot be accurately determined although there appears to be a gradual flattening of dip throughout the lower Canyon. This angular relationship persists to the south and east (D. Petty, S. Roth, 1978, oral commun.).

The upper unit of Sixmile Canyon crops out along Timber Ridge, near Hardy Spring, and immediately south of Langmuir Laboratory. The upper unit of Sixmile Canyon has an average thickness of 500 to 600 feet in the study area; it thickens considerably to the south (D. Petty, S. Roth, 1978, oral commun.). In this study the upper unit has been divided into three map units: upper and lower tuff of Caronita Canyon and an overlying andesite interval.

<u>tuff of Caronita Canyon</u> The upper unit of Sixmile Canyon is dominated by a strongly zoned, moderately to densely welded ash-flow tuff, informally named the tuff of Caronita Canyon for exposures in the southeastern Magdalena Mountains (Chapin, 1979, oral commun.). The tuff of Caronita Canyon forms steep cliffy outcrops and weathers to extensive talus slopes; it forms the prominent cliff along the west flank of Timber Ridge at about the 9600 foot elevation. The tuff of Caronita Canyon consists of a lower and upper member that are welded together. Locally preserved at its base are thin volcaniclastic rocks and poorly welded ash-flow tuffs that were not mapped separately.

Good exposures of the sedimentary rocks can be seen on Timber Ridge, just north of Timber Peak at about the 10,150 foot elevation. Here, medium-grained sandstones are interbedded with tuffaceous strata and have a combined thickness of 150 feet. Just south of Langmuir Laboratory, in the extreme northeast corner of sec. 18, T.4S., R.3W., are excellent exposures of volcaniclastic rocks and poorly welded, lithic-rich ash-flow tuffs. They pinch out to the northwest along the contact with andesite of the lower unit of Sixmile Canyon. One poorly welded, lithic-rich tuff forms a distinctive cliffy outcrop and is interbedded with volcaniclastic rocks. In places, lithic fragments make up more than 50 percent of the tuff and range in size from microscopic to 3 to 4 cm. Another exposure of a similar, poorly welded tuff crops out at the extreme southern edge of the study area on Timber Ridge (9100 feet) and was mapped separately.

lower member The lower member of the tuff of Caronita Canyon varies in thickness from about 80 feet at the northern end of Timber Ridge to 150 feet at the southern end. The lower member is typically grayish red purple, moderately welded, and has less than 5 percent lithic fragments. The base is light gray to pale blue, poorly to moderately welded and contains 10 to 15 percent lithic fragments of aphanitic andesite and flow-banded rhyolite. Much of the lower member exhibits a prominent eutaxitic foliation.

In thin section, the lower tuff of Caronita Canyon contains 5 to 10 percent plagioclase phenocrysts, 1 to 2 percent small rounded quartz grains, and 1 to 2 percent biotite. The plagioclase has been replaced by clay minerals that often have been plucked from thin sections during preparation. Pumice fragments are characterized by spherulitic devitrification.

upper member Welded to the lower member of the tuff of Caronita Canyon is a crystal-rich, densely welded ash-flow tuff. It has a thickness of 80 to 100 feet at the north end of Timber Ridge and near Hardy Spring; at the southern edge of the study area it is about 200 feet thick. In places, the upper member exhibits thick bedding with bedding planes 6 inches to 2 feet apart. Hand specimens are grayish pink to very light gray and are characterized by coppery biotite and large (up to 4 mm), often bipyramidal, quartz phenocrysts.

In thin section, the phenocryst content varies from 25 percent at the base to 40 percent near the top. Sanidine is approximately 1.5 times as abundant as quartz; the latter occurs as large, slightly rounded crystals that average 2 mm in longest dimension or as small rounded fragments that average 0.3 mm in diameter. One to two percent euhedral rounded magnetite grains make up the remainder of the phenocrysts.

Overlying the upper member of the tuff of Caronita Canyon is an interval of pinkish-gray to pale-red finely laminated sandstone, 10 to 50 feet thick, which was not mapped separately. The sandstone is seen throughout the study area and to the south and east (Osburn, 1978; Petty, 1978, oral commun.). The sandstone exhibits fine laminations (1 to 3 mm) that are the result of alternating coarse and fine layers; the bedding is thick (0.1 to 1 meter). In thin section, the sandstone consists of poorly sorted quartz and feldspar grains with local concentrations of magnetite grains.

<u>andesite interval</u> Throughout most of the study area, a sequence of andesite flows overlies the sandstone of the tuff

of Caronita Canyon and underlies the tuff of Lemitar Mountains. Along Timber Ridge, the andesites thin to the south and are no longer present at the southern end of the study area. Osburn (1978) noted similar lavas below the tuff of Lemitar Mountains in Sixmile Canyon (sec. 12, T.4S., R.3W.; unsurveyed). Typical exposures of these andesites consist of conspicuous, colluvium-covered, grassy benches between the overlying tuff of Lemitar Mountains and the underlying tuff of Caronita Canyon. Excellent exposures can be found just north of Timber Peak where the andesites are approximately 160 feet thick.

In hand specimen, the andesites vary in color from brownish gray to greenish black. Most of the flows are porphyritic with as much as 10 percent small, oxidized, pyroxene phenocrysts in an aphanitic groundmass. Autobrecciated flow tops and bottoms and scoriaceous zones are common.

In thin section, the groundmass is composed of plagioclase, clinopyroxene and magnetite microlites. Phenocrysts of clinopyroxene, olivine (?) and magnetite account for 15 to 20 percent of the rock. Euhedral olivine (?) phenocrysts make up 3 percent of the rock and average about 0.5 to 1.0 mm in diameter. The olivine (?) phenocrysts are partly to completely altered to serpentine (?) and iddingsite; in places they appear to be partially replaced by pyroxene. The clinopyroxene phenocrysts range in diameter from 0.3 to 1.0 mm and make up approximately 10 percent of the rock; they are often zoned and occasionally show twinning. The optical properties of the clinopyroxene are consistent with those of augite. Euhedral to rounded magnetite phenocrysts, approximately 0.1 to 0.3 mm in diameter, account for 1 to 2 percent of the rock. In most specimens, the groundmass is altered to clay minerals, calcite, and hematite; individual phenocrysts cannot be discerned.

Locally, thin lenses of sandstone fill channels developed on top of the andesites. They are typically grayish-red, fine-grained sandstones comprised mainly of angular quartz and feldspar grains.

The unit of Sixmile Canyon is an accumulation of lavas, sediments, and ash-flow tuffs that were deposited on top of the A-L Peak following collapse of the Sawmill Canyon cauldron. The facies relationships within the unit of Sixmile Canyon suggest that the lower member buried the topographic relief developed during collapse of the cauldron. The lower member consists of mafic lavas that flowed into the cauldron from the north, rhyolite lavas that flowed in from the south, and coarse sediments and breccias that were deposited adjacent to the cauldron wall. The upper unit of Sixmile Canyon was deposited on subdued topography as indicated by the relatively uniform thickness of the tuff of Caronita Canyon and the widespread occurrence of a uniform sandstone at the top of the tuff of Caronita Canyon.

How much of a depression remained following deposition of the unit of Sixmile Canyon is not known; however, as will be discussed later, the Sawmill Canyon cauldron has influenced the thickness and distribution of the overlying tuff of Lemitar Mountains in the study area.

Tuff of Lemitar Mountains

Following filling of the Sawmill Canyon cauldron with the unit of Sixmile Canyon, the tuff of Lemitar Mountains was deposited over most of the Socorro-Magdalena area. The tuff is a distinctive, compositionally zoned, multiple-flow, simple cooling unit, rhyolite ash-flow tuff which has been dated at 27.0 +/- 1.1, 26.3 +/- 1.0, and 28.8 +/- 0.7 m.y. by the K-Ar technique on biotite (Chapin, unpublished data). The tuff of Lemitar Mountains, formerly tuff of Allen Well, has been described in detail by several authors: Simon (1974) described samples from the Crouch drill hole in the Silver Hill area (the unit was misidentified as tuff of La Jencia Creek due to its presence in a paleovalley); Osburn (1978) described a measured section of the lower part of the tuff of Lemitar Mountains in the eastern Magdalena Mountains; and R.M. Chamberlin (1978, oral commun.) has described a measured section in the Lemitar Mountains. The reader seeking detailed petrographic information is referred to these studies.

The Tuff of Lemitar Mountains is divided into two members: 1) a moderately crystal-poor lower member and 2) a crystal-rich upper member. Both members are believed to have been erupted from the Socorro cauldron (Chapin and others, 1978, fig. 4), the western margin of which is not clearly defined. There appears to be no sharp break between cauldron facies tuff of Lemitar Mountains described by Osburn (1978) and Chamberlin (in progress) and the outflow (?) equivalent in the southern Magdalena Mountains (D. Petty, 1978, oral commun.). This relationship is suggestive of "trap-door" subsidence, hinged down to the east, of the Socorro cauldron.

The influence of the Sawmill Canyon cauldron on deposition of the tuff of Lemitar Mountains can be clearly seen in this study area where there are two domains of tuff of Lemitar Mountains: 1) within the limits of the Sawmill Canyon cauldron there is a normal succession of the lower and upper members overlying the upper unit of Sixmile Canyon; and 2) outside of the cauldron there is little or no lower tuff of Lemitar Mountains present and the upper member rests unconformably on the unit of Hardy Ridge. In the latter case, the base of the upper member often exhibits primary laminar flow structures and is locally lithic rich.

<u>lower member</u> The lower tuff of Lemitar Mountains crops out almost exclusively within the limits of the Sawmill Canyon cauldron; however, one small exposure occurs outside of the

cauldron in the south-central portion of sec. 24, T.4S., R.4W. The lower member overlies andesites of the upper unit of Sixmile Canyon in the northern part of the study area and the upper tuff of Caronita Canyon to the south. The best exposures are along Timber Ridge where the lower member has an approximate minimum thickness of 400 feet. In the vicinity of South Baldy thickness estimates are hindered by poor outcrops with extensive talus, locally intense silicification, and closely spaced faults. Here, minimum thickness estimates range from 250 to 400 feet. Osburn (1978) found the thickness of the lower member to be variable, from 200 feet on Buck Peak to 820 feet in Sixmile Canyon. Petty (1979) reports similar variation in thickness of the lower member to the east and south of this study area. The lower tuff of Lemitar Mountains typically weathers to steep cliffs and extensive talus slopes.

Osburn (1978) described a measured section of the lower tuff of Lemitar Mountains in which he defined four distinct zones on the basis of outcrop pattern, degree of welding, total phenocryst content, pumice and lithic fragment content, and color. In general, this zonation was observed in this study area, although lesser thicknesses and poor exposures hindered accurate correlations. The lower tuff of Lemitar Mountains is moderately phenocryst-poor (8 to 25 percent range) and typically contains approximately 12 percent sanidine, quartz, plagioclase, and biotite.

Sanidine, the most abundant mineral, is an average of 1.0 mm in longest dimension and exhibits alteration textures which are not completely understood at this time. Small lenses of potassic clay minerals in a perthitic-like relationship with the sanidine are present and may represent alteration of exsolved albitic feldspar. In places, clay minerals have almost completely replaced the sanidine phenocrysts. Quartz occurs as anhedral grains approximately 0.6 mm in diameter. Small amounts of plagioclase phenocrysts are present in some thin sections but these are usually replaced by clay minerals. Trace amounts of reddish-brown biotite and magnetite are also present.

A distinctive slope-forming zone at the base of the lower tuff of Lemitar Mountains (Osburn, 1978) is not everywhere present in this study area. This zone is light colored, poorly to moderately welded, pumiceous, and locally contains as much as 15 percent andesitic and rhyolitic rock fragments. Where present, the basal zone varies in thickness from 10 to 40 feet. Excellent exposures can be found at the northern end of Timber Peak at about the 10,400 foot elevation. In thin section, the basal zone of the lower tuff of Lemitar Mountains contains approximately 6 percent sanidine, 4 percent quartz, and less than 1 percent each of biotite and plagioclase.

Overlying the lower zone is a zone that makes up most of the outcrop in this study area. It is typically grayish red and weathers to angular, cliffy outcrops. This zone is characteristically pumice-poor and contains approximately 10 to 12 percent phenocrysts of sanidine and quartz.

Above this main zone, the lower tuff of Lemitar Mountains gradually increases in both pumice and phenocryst content over an interval of approximately 10 to 40 feet. in the upper portions of the lower member, the contrast of light-gray pumice in a pale-red matrix gives the tuff a streaked appearance. The contact with the consistently phenocryst-rich upper member was mapped when the phenocryst content reached approximately 25 percent, usually accompanied by the appearance of pink blotches and crystal-rich pumice. The uppermost lower tuff of Lemitar Mountains contains 15 to 20 percent sanidine, 4 to 6 percent plagioclase and about 3 percent quartz.

<u>upper member</u> Throughout most of the Socorro-Magdalena area and this study area, the upper tuff of Lemitar Mountains is welded to the lower member. Excellent exposures of the upper member occur in road cuts just west of Langmuir Laboratory at an elevation of about 10,500 feet. In the southwestern portion of the study area, the upper Lemitar rests unconformably on the unit of Hardy Ridge. In this area, the upper Lemitar exhibits features such as flow-banding, flow folding, and gas cavities all of which suggest primary welding in a laminar boundary layer (Chapin and Lowell,

1979). Maximum deposited thickness of the upper tuff of Lemitar Mountains is uncertain since it is unconformably o erlain by the Popotosa Formation or by intermediate lavas; however, as much as 600 feet of upper Lemitar are present throughout the study area.

The upper tuff of Lemitar Mountains is phenocryst-rich and varies in color from moderate to light red. It typically weathers to steep talus-covered slopes and small cliffy outcrops. The average phenocryst content is 30 to 35 percent. In the southeast corner of sec. 24, T.4S., R.4W., the upper 50 to 100 feet of the upper tuff of Lemitar Mountains is pinkish gray to buff in color and appears hydrothermally bleached; this zone weathers to distinctive benches. The phenocryst content of this zone may be as much as 50 percent and is characterized by 10 to 15 percent large (up to 4 mm) quartz crystals and coppery biotite. Osburn (1978) noted a similar zone which was locally preserved at the top of the upper tuff of Lemitar Mountains.

The upper one-half to one-third of the upper Lemitar cannot be consistently distinguished in hand specimen or thin section from the Hells Mesa Tuff when stratigraphic control is missing. On the west side of Hardy Ridge (secs. 13, 24, T.4S., R.4W.) where the Hells Mesa Tuff is in apparent fault contact with the upper Lemitar, it is virtually impossible to tell the two units apart. If some unambiguous means of distinguishing the two units is discovered, the contacts in this area should be re-examined. This problem may be further complicated by the discovery to the south (Osburn, 1979, oral commun.) of upper tuff of Lemitar Mountains in apparent depositional contact with Hells Mesa Tuff.

Pumice in the upper tuff of Lemitar Mountains is usually not prominent. Exceptions are just above the lower contact where light-colored crystal-rich pumice are common and near the top of the unit where stringers of light-gray to brown, phenocryst-rich pumice are common. The phenocryst assemblage in the upper tuff of Lemitar Mountains consists of sanidine, plagioclase, quartz, and biotite with trace amounts of fayolite (?) and magnetite. Sanidine, the most abundant phenocryst, varies from 15 to 20 percent of the rock. It usually occurs as broken, euhedral to embayed crystals that average 1.0 to 1.2 mm in longest dimension. Perthitic exsolution lamellea are preferentially altered to clay minerals; the nature of the exsolution phenomena is extremely variable even on the scale of one thin section.

Plagioclase varies from less than one percent to three percent at the top of the lower tuff of Lemitar Mountains to a maximum of about 10 to 12 percent three quarters of the way up in the upper Lemitar. The upper one quarter of the upper tuff of Lemitar Mountains is marked by a drop in the plagioclase content to less than 5 percent. The plagioclase is often highly embayed and is typically almost completely altered to sericite and various clay minerals. This alteration has destroyed albite twinning in most specimens, although in one sample, plagioclase with preserved albite twinning was found in a glomeroporphyritic clot 3.5 mm in diameter.

Quartz phenocrysts are euhedral to anhedral and frequently rounded and embayed. Quartz comprises 1 to 3 percent of the rock in the lower two-thirds of the upper member; in the upper one-third, quartz makes up as much as 15 percent of the rock. One to two percent reddish-brown to light-green biotite occurs in varying stages of alteration to magnetite and hematite. Trace amounts of magnetite phenocrysts approximately 0.5 mm in diameter also occur. The groundmass of the upper tuff of Lemitar Mountains is usually devitrified to fine-grained aggregates of quartz and alkali feldspar; irregular patches of vapor-phase quartz are also common. in some specimens, especially towards the base, the original vitroclastic texture of the tuff is well preserved.

Throughout the study area, the upper tuff of Lemitar Mountains is pervasively altered; the nature and degree of alteration varies considerably. Within the approximate limits of the Sawmill Canyon cauldron, plagioclase has been completely repaced by clay minerals and alkali feldspar; the clays are usually plucked during thin section preparation. This type of alteration has been discussed in detail by Osburn (1978) and Chapin and others

(1978) and is believed to be the result of alkali metasomatism. Outside the limits of the cauldron, in the southwest portion of the study area, plagioclase has been altered to sericite but albite twinning is preserved. Very near the margin, but outside, some of the plagioclase phenocrysts have been partially altered to sericite and some to potassium-rich clays. Sanidine is altered to both sericite and potassium-rich clay, but is in general less altered than the plagioclase.

In the southwestern portion of the study area, the upper tuff of Lemitar Mountains locally exhibits primary welding characteristics. Where the base of the upper tuff of Lemitar Mountains rests on the unit of Hardy Ridge a conspicuous zone of lithic-rich tuff with abundant gas cavities occurs (figure 11). The tuff megascopically appears to be poorly welded but in thin section has highly flattened and deformed glass shards indicating moderate to dense welding. This zone varies in thickness from 10 to 50 feet. Elsewhere in this area, the upper tuff of Lemitar Mountains exhibits local zones of flow banding, flow folding, and ramp structures (figure 12).

One of the best exposures of these features is in the extreme southeastern corner of section 14 and the northeast corner of section 23, T.4S., R.4W. Here, the upper tuff of Lemitar Mountains appears to have been deposited in a paleovalley. Recognition and interpretation of many of the

Figure 11. Lithic-rich base of the upper tuff of Lemitar Mountains with abundant gas cavities. Cross sections of the gas cavities are short, flattened, ellipses.

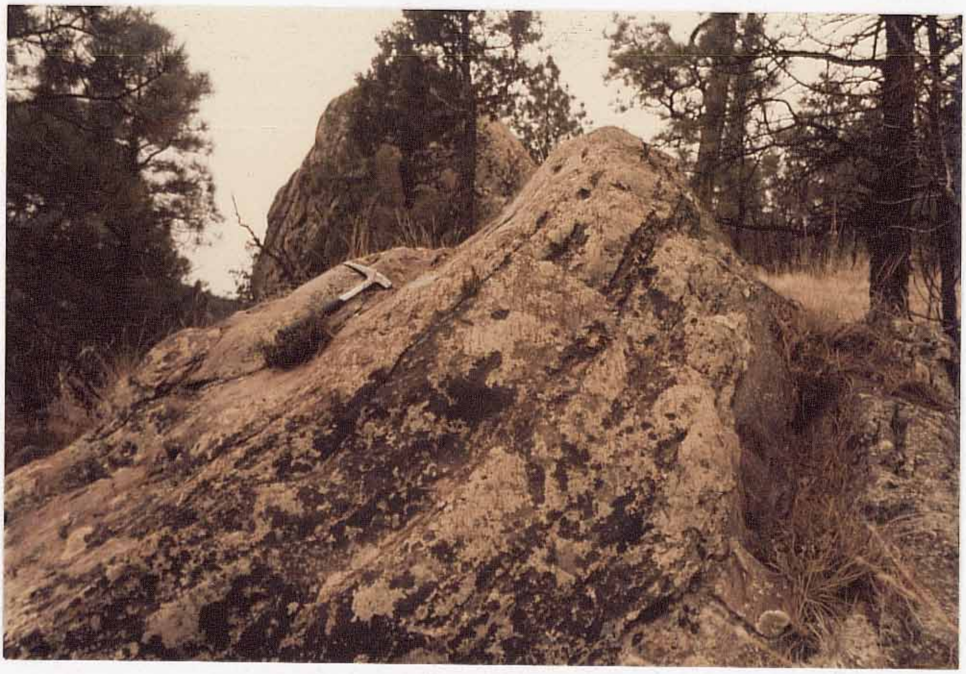


Figure 12. Outcrop of densely welded upper tuff of Lemitar Mountains showing ramp structure. Foliation dips to the left.

features in this paleovalley was greatly enhanced by a paper written by Chapin and Lowell (1979) that provides detailed descriptions and interpretations of structures present in an ash-flow tuff that was deposited in a paleovalley in central Colorado.

The small outcrop of upper tuff of Lemitar Mountainsin sections 14 and 24 are believed to occur in an east-trending paleovalley. If the regional dip of 25 to 30 degrees to the east is removed from the measured attitudes along the southern margin of the outcrop of upper tuff of Lemitar Mountains, the tuff is found to have primary foliation dips to the north. Thus, the southern outcrop edge is believed to represent the valley wall and the primary dips are toward the presumed valley axis. Chapin and Lowell (1979) argue convincingly that primary foliation dips such as those observed along the southern margin of the paleovalley are probably not produced by secondary compaction. They calculate that secondary compaction cannot produce foliations steeper than about 22 degrees. After correcting for post-depositional regional tilting, dips as steep as 40 to 45 degrees are commonly observed along the paleovalley wall. These dips are the result of primary welding in a laminar boundary along the wall of the valley.

The preservation of large rod-shaped gas cavities in the vicinity of the valley wall (figure 13) also argue against much secondary compaction. These gas cavities are lineated parallel to the axis of the valley like those described by Chapin and Lowell (1979). These elongate cavities are present only along the southern margin of the valley; as one traverses north towards the valley axis, the cavities disappear and the tuff has a prominent flow lineation defined by thin, light-colored streaks and by highly compressed pumice. This streaky eutaxitic foliation is defined by a combination of foliation planes, pumice, and collapsed gas cavities. Some individual flow planes can be traced for as much as 8 feet. The gas cavities may have formed when the volume of escaping volatiles became too great for storage on flow planes and pockets of gas formed (Chapin and Lowell, 1979).

Also present in the upper tuff of Lemitar Mountains in this paleovalley are intricate recumbent folds with axes parallel to the valley axis. They are best exposed about 100 meters from the southern margin of the outcrop. These are interpreted as having formed when the tuff, which was deposited along the oversteepened sides of the valley, slumped towards the valley bottom. Throughout the zone of folding, the strong east-west lineation of the tuff remains constant. In places, zones of recumbent folding are overlain by undisturbed planar foliation and the whole unit is welded together. Chapin and Lowell (1979) describe similar features in the Wall Mountain Tuff of central Colorado.

The distribution of the tuff of Lemitar Mountains and the features observed in the paleovalley are of particular interest because primary welding features have not been observed in the tuff of Lemitar Mountains in other localities and the areal distribution of these features may be of importance in reconstructing its environment of deposition. It should be noted that the mineralogical zonation of the upper tuff of Lemitar Mountains, as described above, is present throughout the study area. This indicates that the tuff with the anomalous features is equivalent to the more "normal" upper tuff of Lemitar Mountains and that differences in the environments of deposition caused the textural variations. The most important variables responsible for the observed primary welding features were probably emplacement temperature and the amount of gas entrained in the ash flows (Chapin and Lowell, 1979).

The southwestern portion of the study area appears to have remained structurally high during collapse and filling of the Sawmill Canyon cauldron because the A-L Peak Tuff, the unit of Sixmile Canyon, and most of the lower tuff of Lemitar Mountains were not deposited there. The surface of this structurally high block may have possessed considerable topographic relief. The lower tuff of Lemitar Mountains filled most of the remaining depression of the Sawmill Canyon cauldron and only small amounts of it were deposited outside of the cauldron. The upper member was then erupted onto the relatively smooth upper surface of the lower member within the cauldron and flowed over the western Sawmill Canyon cauldron margin. As the upper member flowed over the margin onto a dissected block of the unit of Hardy Ridge, the tuff was probably channeled into existing valleys. This concentrated flow may have conserved heat and allowed hotter emplacement temperatures. The rough topography may also have caused enough air to become incorporated in the ash flow so that gases expressed during primary welding exceeded the volume of gas that could be incorporated along flow planes, thus forming cavities. The observations that most of these cavities occur near the base of the upper member and along the margins of paleovalleys support this.

Tuff of South Canyon

The tuff of South Canyon was the last major ash-flow tuff erupted in the Socorro-Magdalena area. It is a multiple-flow, simple cooling unit, rhyolite ash-flow tuff (Chapin and others, 1978). In the Magdalena Mountains, the tuff of South Canyon usually overlies basaltic andesite lavas that overlie the tuff of Lemitar Mountains (Chapin and others, 1978). Osburn (1978) described a measured section 620 feet thick in the eastern Magdalena Mountains (SW 1/4, sec. 30, T.3S., R.3W.) for which the tuff is named. The tuff of South Canyon has been dated at 26.2 +/- 1.0 m.y. (Chapin, unpublished data) and at 25.8 +/- 1.0 m.y. (Bochman and Mehnert, 1978) by the K-Ar method on biotite. The source area for the tuff is poorly understood at this time; Chapin and others (1978) suggested that it was erupted from the Hop Canyon cauldron located west of this study area.

The tuff of South Canyon crops out discontinuously throughout the eastern and southern Magdalena Mountains and in the Lemitar Mountains. Petty (1979) reports a maximum of about 400 feet in the southern Magdalena Mountains and Allen (1978, oral commun.) reports a maximum of 300 feet in the area southwest of North Baldy. The only outcrop of the tuff of South Canyon in this study area occurs just east of the summit of South Baldy where approximately 150 feet of tuff is exposed on a fault block. Here, the base of the tuff is poorly exposed; however, at about the 10,040 foot elevation along the road to Langmuir Laboratory, a small outcrop of reddish-brown sandstone is found beneath the tuff. The outcrop area above the tuff of Lemitar Mountains and below the tuff of South Canyon is obscured by colluvium; the gentle slope is suggestive of an andesite interval. Osburn (1978) reports basaltic andesite in this stratigraphic position in the eastern Magdalena Mountains.

Osburn (1978) described the tuff of South Canyon in detail and subdivided it into three zones: a lower, poorly-welded, crystal-poor zone; a lithophysal zone; and an upper pumiceous "streaked" zone. The reader seeking detailed petrographic information is referred to his study. The tuff of South Canyon in this study area is likely equivalent to Osburn's upper streaked zone. Here the tuff of South Canyon is grayish red to pale red and weathers to angular blocks. Light-gray to pink pumice, 2 to 5 cm long, make up from 10 to 20 percent of the rock and give it a pronounced eutaxitic foliation. The tuff contains approximately 20 percent phenocrysts of sanidine and quartz in roughly equal proportions.

Quartz occurs as euhedral to subhedral, occasionally embayed, phenocrysts that average 1.0 mm in diameter. Sanidine occurs as subhedral to euhedral tabular crystals approximately 1.0 mm in length. Exsolution lamellae within the sanidine are commonly altered to potassium-rich clays. Also noted were less than 1 percent relict phenocrysts that have been completely replaced by clay minerals. These phenocrysts closely resemble altered plagioclase phenocrysts in the tuff of Lemitar Mountains. One to three percent lithic fragments of aphanitic andesite also occur.

The obvious lack of tuff of South Canyon in this study area is likely the result of a combination of erosion, faulting, and lack of deposition. The top of the unit elsewhere in the Socorro-Magdalena area is usually eroded and greater thicknesses may have been present.
Large-displacement, down-to-the-west faults along the western

part of the study area have not exposed the stratigraphic interval which contains the tuff of South Canyon. Thus the tuff may be present beneath the intermediate lavas in sections 10 and 12 (T.4S., R.4W.). On South Baldy, where the intermediate lavas overlie the tuff of Lemitar Mountains, the tuff of South Canyon was probably not deposited. Further mapping to the west is needed to determine the areal extent and thickness of the tuff of South Canyon in the western Magdalena Mountains.

Intermediate Lavas

Above the tuff of Lemitar Mountains is a sequence of intermediate composition lavas that range mineralogically from andesite to quartz latite. These lavas crop out in scattered localities near the summit of South Baldy and in a band along the west side of the range (secs. 1, 12, 13, 14, T.4S., R.4W.). Locally (sec. 24) poorly welded ash-flow tuffs, volcaniclastic sedimentary rocks, and laharic breccias overlie the lavas. The stratigraphic position of this sequence of lavas and tuffs with respect to the tuff of South Canyon cannot be unambiguously determined in this study area. However, the following lines of evidence from this study area and the surrounding areas suggest that the lavas may be younger than the tuff of South Canyon: 1) along the western flank of the range the lavas are conformably overlain by laharic breccias of the lower Popotosa Formation which contain abundant clasts of the tuff of South Canyon; 2) Osburn (1979, oral commun.) reports very similar intermediate lavas above the tuff of South Canyon to the southwest of this study area; 3) on Water Canyon Mesa, Osburn (1978) reports scattered outcrops of similar intermediate lavas above the tuff of South Canyon; and 4) Simon (1973) described 100 feet of variable porphyritic lavas, now believed to be above the tuff of South Canyon, in the Silver Hill area.

In this study area thickness estimates for the lavas range from 100 feet on South Baldy to 300 feet along the western flank of the range. Two types of lavas were mapped within the intermediate lavas. These are: 1) aphanitic andesites that are similar to basaltic andesites found above the tuff of Lemitar Mountains elsewhere in the Socorro-Magdalena area; and 2) a sequence of variable porphyritic lavas which overlie and are interbedded with the aphanitic andesites. Local ash-flow tuffs and volcaniclastic sedimentary rocks were also mapped in this interval.

<u>andesitic lavas</u> The summit of South Baldy is composed of approximately 400 feet of andesitic lava which is in apparent depositional contact with the tuff of Lemitar Mountains. Multiple flows of grayish-red to brownish-gray aphanitic andesite are marked by autobrecciated flow tops and bottoms. Excellent exposures of the andesites can be seen along the road to Langmuir Laboratory at an elevation of about 10,500

feet. Scoriaceous zones are common and vesicles are usually filled with clay minerals and calcite. The andesite weathers to steep rubbly slopes.

In thin section, the andesite is composed mainly of plagioclase microlites (0.2 mm in longest dimension) which have been partially replaced by clay minerals. About one percent altered plagioclase phenocrysts also occur. Relict phenocrysts of pyroxene and/or amphibole (0.2 to 0.6 mm in diameter) make up 5 to 7 percent of the rock. About 10 to 15 percent finely disseminated magnetite, now largely oxidized, makes up the remainder of the rock.

Dark-gray to grayish-red-purple aphanitic andesites are in depositional contact with the upper tuff of Lemitar Mountains along the western edge of section 24, T.4S., R.4W. Similar lavas crop out in the northwest corner of section 24 where they are overlain by the porphyritic lavas; the contact between the two is interbedded through an interval of about 6 meters. Aphanitic andesites also crop out in a band in sections 1 and 12 (T.4S., R.4W.). Here they are overlain by laharic breccias and pebble conglomerates of the Popotosa Formation. Locally, channels filled with andesitic sandstone are found in the andesite. Two large outcrops of the tuff of Lemitar Mountains are found within this outcrop of andesite. These outcrops probably represent exhumed topographic highs of the tuff of Lemitar Mountains.

In thin section, these lavas are similar to the andesite on the summit of South Baldy but are intensely altered. A few relict pyroxene (?) phenocrysts altered to magnetite are visible but, in general, all that can be seen are remnants of plagioclase microlites; most of the plagioclase has been replaced by clay minerals and sericite.

porphyritic lavas Southwest of the summit of South Baldy is a north-trending rectangular outcrop of porphyritic lavas in fault contact on two sides with the upper tuff of Lemitar Mountains. This relationship suggests that pre-lava faults may have influenced the deposition of the lavas as was reported by Osburn (1978). Stacy (1968) mapped this outcrop as the Mohawk Peak rhyolite. It varies from grayish red purple to medium dark gray in color. The lava is often vesicular and locally becomes scoriaceous near the erosional top of the outcrop.

In thin section, the lava varies in phenocryst content from 2 to 5 percent with alkali feldspars, quartz, plagioclase, relict pyroxene (?) and magnetite present. In more phenocryst rich specimens, quartz makes up 1 to 5 percent of the rock. It occurs as rounded, often deeply embayed, grains that are as much as 4.0 mm in diameter.

Alkali feldspar occurs as euhedral to rounded and embayed phenocrysts that average about 2.0 mm in length. Many of the alkali feldspar phenocrysts are surrounded by reaction rims, now replaced by clay minerals. The alkali feldspar phenocrysts range in degree of alteration from fresh to complete replacement by clay minerals. Many of the alkali feldspars exhibit perthite-like textures; this texture may be the result of alteration. Minor amounts of plagioclase phenocrysts are also seen. Some of the plagioclase appears to have been replaced by alkali feldspar but intense alteration obscures the relationship.

Relict pyroxene (?) phenocrysts make up 5 to 8 percent of the lava; they have a short, stubby habit with hexagonal cross sections. The rims of these phenocrysts are completely replaced by magnetite and the cores by a brown, moderately birefringent, fibrous mineral which may be uralite. Glomeroporphyritic clots as much as 3 mm in diameter of alkali (?) feldspar and relict pyroxene are seen occasionally. The groundmass consists of simple or Carlsbad-twinned plagioclase microlites, which have been altered to clay minerals and sericite, and about 10 to 15 percent finely disseminated magnetite.

A distinctive porphyritic lava crops out in the northeast corner of section 23, T.4S., R.4W. As much as 30 percent light-colored feldspar phenocrysts, as much as 1.0 cm in length, contrast strongly with a pale-red to light-gray groundmass. The lava is in fault contact with the tuff of Lemitar Mountains along the southern margin of the paleovalley described above. The contact relationships with the unit of Hardy Ridge are uncertain but may be partly intrusive. Flow foliations in the lava are quite variable. The significant difference in elevation between the two outcrops of upper tuff of Lemitar Mountains in section 23 suggests that considerable down-to-the-north relief existed during deposition of both the tuff of Lemitar Mountains and the porphyritic lavas. Thus, the lavas may have been locally preserved against a steep escarpment and scallop in the unit of Hardy Ridge. Locally, the lava contains abundant fragments, as much as 20 cm in diameter, of aphanitic andesite. The lava forms steep cliffs and ledgy outcrops.

Similar lavas with smaller and fewer phenocrysts crop out in the northwest corner of section 24, T.4S., R.4W. Here the porphyritic lavas overlie and are interbedded with the aphanitic andesites described above. In general, the lavas have smaller and fewer phenocrysts northward from section 23.

In thin section, the porphyritic lava contains phenocrysts of quartz, plagioclase, relict amphibole (?), biotite, and alkali feldspar. Quartz occurs as large (up to 4 mm) embayed phenocrysts. Often, the quartz phenocrysts are fractured and partly disaggregated so that a large phenocryst may be surrounded by many smaller fragments. Quartz makes up 3 to 8 percent of the rock.

Plagioclase feldspar is the most abundant phenocryst and makes up about 10 percent of the lava. The plagioclase is usually altered to sericite and clay minerals and often has a pockmarked or sieve texture. In many samples, alteration is so complete that no relict twinning is visible. The plagioclase occasionally occurs as glomeroporphyritic clots with rounded and corroded edges.

Alkali feldspar phenocrysts make up from one to five percent of the lava and are only slightly altered to sericite and clay minerals. One phenocryst measured 1.0 cm in longest dimension. Some of the phenocrysts exhibit concentric zoning (?) and an indistinct wavy extinction; others have unmixing textures. Osburn (1978) interpreted similar features in the Water Canyon Mesa lavas to be indicative of secondary potassium feldspar that had replaced plagioclase. It is possible that the "alkali feldspar phenocrysts" in this lava are the result of secondary replacement of plagioclase.

Two to three percent euhedral to subhedral amphibole (?) now replaced by magnetite also occur. Biotite in varying stages of alteration to magnetite makes up about one percent of the lava. The groundmass is composed of plagioclase microlites that are largely replaced by clay minerals and sericite.

ash-flow tuff and volcaniclastic sedimentary rocks In the northwest corner and along the western margin of section 24, T.4S., R.4W. poorly welded, lithic-rich ash-flow tuffs, laharic breccias, and volcaniclastic sedimentary rocks crop out. Lithic fragments of aphanitic andesite, phenocryst-poor rhyolite lavas, and a distinctive, phenocryst-rich ash-flow tuff are common in this interval. The ash-flow tuff fragments are very similar to the upper tuff of Lemitar Mountains. The thickness of the tuffs and volcaniclastic rocks is a maximum of about 200 feet in the northeast corner of section 24. They weather to rubble-covered slopes and ledgy outcrops.

In thin section, the tuffs are made up of 10 to 15 percent phenocrysts of quartz, plagioclase, and alkali feldspar. Quartz occurs as embayed phenocrysts and varies from 3 to 5 percent of the tuff. The original vitroclastic texture of the groundmass has been completely destroyed by devitrification.

Popotosa Formation

In the Socorro-Magdalena area, the basal unit of the Santa Fe Group consists of laharic breccias, conglomerates, sandstones, and playa mudstones. This assemblage was named the Popotosa Formation by Denny (1940) for exposures along Arroyo Popotosa, southwest of the Ladron Mountains. The Popotosa Formation was deposited as alluvial fans in a broad sedimentary basin which spanned the Rio Grande rift in the Socorro region during the interval from about 26 m.y. to 7 m.y. ago (Chapin and Seager, 1975).

Source regions for much of the Popotosa Formation were the Colorado Plateau and the Ladron Mountains to the north and the Gallinas, Magdalena, and San Mateo Mountains to the west and south.

K-Ar dates obtained on lava flows which overlie and are interbedded with the Popotosa Formation indicate that its deposition spanned the period from about 26 m.y. ago to about 7 m.y. ago (Chapin, 1978, oral commun.). In the east-central Magdalena Mountains, Osburn (1978) reports that the lower Popotosa Formation rests unconformably on Water Canyon Mesa lavas which have been dated at 20.0 +/- 0.8 m.y. In the western part of this study area (sec. 11, T.4S., R.4W.), rhyolite lavas of Magdalena Peak overlie and are interbedded in the Popotosa Formation. A sample of the interbedded lava has been dated at 18.0 +/- 0.8 m.y. (Chapin, unpublished data). The dacites of Deer Plot Tank intrude the Popotosa Formation in the extreme southwestern portion of the study area (SW 1/4, sec. 23, T.4S., R.4W.); these lavas have not been dated.

Bruning (1973) divided the Popotosa Formation into fanglomerate and playa facies. Chapin and others (1978) subsequently divided the Popotosa Formation into lower and upper members. The lower member is characterized by intertonguing mudflow deposits, conglomerates and minor lacustrine deposits; the upper member, in the Socorro area, is dominated by mudstones, siltstones, and sandstones.

In this study, the Popotosa Formation was informally divided into three map units: 1) lower laharic breccias; 2) interbedded conglomerates and sandstones; and 3) fine-grained, laminated, sandstones and siltstones. The laharic breccias and conglomerates are probably correlative with Chapin and others' (1978) lower member and the laminated siltstones and sandtones may be correlative with their upper member.

laharic breccias Laharic breccias crop out in two fault-bounded, north-trending strips near the summit of South Baldy. Here, they were deposited on the upper tuff of Lemitar Mountains and the "intermediate lavas". The laharic breccias occur as rubble-covered surfaces that have been highly disturbed by frost action; they are a maximum of about 350 feet thick.

On the west side of the range, laharic breccias crop out in a north-trending band (secs. 1, 12, T.4S., R.4W.) and form very steep, rubble-covered slopes. Here they are a maximum of of 500 feet in thickness. The laharic breccias were deposited on andesites and "intermediate lavas". In Bear Canyon (sec. 1, T.4S., R.4W.), the lower contact of the Popotosa Formation is observed to be gradational over one meter, from andesitic rubble to matrix-supported clasts of andesite.

In outcrop, the laharic breccias vary from pale reddish brown to grayish red and are so well indurated that joints and fractures break through the clasts. The breccias consist of an assortment of clasts from the underlying lavas and tuffs in a matrix of clay to sand-sized particles. Average clast size varies from cobble to boulder and some blocks of the tuff of South Canyon are as much as 2 meters in diameter. The most common clast lithologies are tuff of South Canyon, aphanitic andesites, and porphyritic intermediate lavas. In places, the laharic breccias exhibit crude bedding with individual beds approximately 5 cm in thickness; however, internal stratification is usually not present.

conglomerates and sandstones The majority of the Popotosa Formation in this study area consists of interbedded conglomerates and sandstones. They crop out extensively in the west-central portion of the study area and have a maximum thickness of about 800 feet. The lavas of Magdalena Peak and associated ash-flow tuffs overlie the conglomerates and sandstones in the northern part of the outcrop area. Along the eastern edge of section 11 (T.4S., R.4W.), lavas of Magdalena Peak are interbedded in the Popotosa Formation. Excellent exposures of the conglomerates and sandstones can be seen along Bear Canyon (secs. 1, 11, T.4S., R.4W.).

The conglomerates and sandstones are well indurated and typically weather to ledgy outcrops and colluvium covered slopes. They are both usually dark reddish brown to moderate red in color. In general, clast size decreases with stratigraphic height; clasts sizes range from cobbles to coarse sand. Clast lithologies are dominated by andesitic lavas and ash-flow tuffs, including the tuff of South Canyon and tuff of Lemitar Mountains. Pebble imbrications in the conglomerates indicate that much of it was derived southwest of the study area.

sandstones and siltstones. In the southwestern portion of the study area (sec. 24, T.4S., R.4W.), fine-grained sandstones and siltstones overlie the tuff of Lemitar Mountains. The laharic breccias and conglomerates are not found in this area. Small amounts of similar sandstones were observed near the top of the conglomerate section in the northern part of the study area suggesting that they are the youngest of the preserved Popotosa Formation in the study area.

Just south of Deer Plot Tank (sec. 23), a sequence of well-sorted, fine-grained, laminated sandstones and siltstones is preserved in a narrow graben; this sequence is a minimum of 800 feet thick. The sandstones and siltstones vary in color from dark reddish brown to grayish pink; they are usually well indurated although some horizons are very friable.

The distribution of lithologies within the Popotosa Formation in this study area indicates structural control of their environments of deposition. South of Hardy Canyon, on the structural block which is largely made up of the unit of Hardy Ridge overlain by the upper tuff of Lemitar Mountains (secs. 23, 24, T.4S., R.4W.), the laharic breccias and conglomerates of the Popotosa Formation are not found. This relationship suggests that this structural block was high during deposition of these strata. The presence of at least 800 feet of finely-laminated sandstones and siltstones, indicative of a stable, low-relief environment of deposition, suggests the burial of topography by this latest Popotosa. Thus it seems likely that a structural zone, roughly coincident with Hardy Canyon separated a basin to the north from a highland to the south. The basin was filled with conglomerates and sandstones and the whole area was then blanketed with fine-grained basin-floor deposits. The southern margin of this basin is coincident with the proposed southern margin of the Magdalena cauldron and is probably related to it.

Lavas of Magdalena Peak

In the northwest portion of the study area, a sequence of rhyolitic lavas and minor ash-flow tuffs overlies conglomerates and sandstones of the Popotosa Formation. Just south of the town of Magdalena are excellent exposures of similar lavas with which the lavas in this area are tentatively correlated. The rhyolite lavas in this study area are part of a large field of rhyolites which crop out along the west flank of the Magdalena Mountains, from Magdalena Peak on the north to Alameda Spring on the south. Weber (1957) provides detailed petrographic descriptions and chemical analyses for rhyolites from the Stendel Perlite deposit north of the study area (secs. 14, 23, T.3W., R.4S.).

Samples of the lavas of Magdalena Peak from the Stendel Perlite deposit and the type locality have been dated at 14.0 +/- 0.7 m.y. (Weber and Bassett, 1963) and 13.1 +/- 0.5 m.y. (Chapin, Jahns, and others, 1978) respectively. A sample of a rhyolite lava from this study area which is interbedded in the Popotosa Formation has been dated at 18.0 +/- 0.8 m.y. (Chapin, unpublished data). This lava has been tentatively correlated with the lavas of Magdalena Peak although its age suggests that it may represent an older sequence of lavas which do not crop out elsewhere in this study area.

A commonly observed outcrop sequence in the lavas of Magdalena Peak is: 1) well-indurated conglomerates and sandstones of the Popotosa Formation overlain by 2) thin, discontinuous lenses of poorly welded, locally reworked, lithic-rich ash-flow tuff overlain by 3) highly vesicular "froth" rhyolite lava which grades upward into 4) alternating layers of porphyritic lava and vitrophyre. Excellent exposures of this sequence can be seen in Bear Canyon at an elevation of 8000 feet.

tuff interval Thin discontinuous lenses of poorly welded ash-flow tuff are commonly found at the base of the rhyolite lavas. Similar tuffs, which are locally waterlaid, are found in several large outcrop blocks in sections 1 and 2, T4S., R.4W. Here, the contacts between the lavas and tuffs are not well exposed. However, where exposed, the lava has nearly vertical foliation and the contacts are marked by abundant silicification and intrusive jasperoid veinlets. These relationships suggest that the lavas may be locally intrusive.

The tuff is white to gray brown in color and contains dark reddish-brown lithic fragments that range in diameter from 0.05 to 1.5 cm. Lithic fragments make up from 5 to 20 percent of the rock. The tuff often contains large, equidimensional (up to 5.0 cm) yellowish-gray pumice fragments. The tuff is crudely bedded and, in places where it has been reworked, exhibits graded bedding.

In thin section, the tuff contains phenocrysts of quartz, alkali feldspar, plagioclase and biotite; the relative amounts of phenocrysts are highly variable. Quartz is usually the most abundant and occurs as both rounded and embayed phenocrysts as well as angular fragments; quartz makes up 2 to 5 percent of the rock. Alkali feldspar comprises 1 to 5 percent of the tuff; it occurs as euhedral to subhedral phenocrysts which range from 0.2 to 1.5 mm in longest dimension. Plagioclase feldspar occurs in trace amounts and occurs as tabular crystals 1 to 2 mm in length.

rhyolite flows The lavas of Magdalena Peak are massive, porphyritic flows. Mineralogically, the lavas vary from quartz latite to rhyolite; chemically, however, they are rhyolites (Weber, 1957). The rhyolites are often partially vitric and interlayered vitrophyres are characteristic. The contact between devitrified lava and vitrophyre is gradational. The basal portions of individual flows, including the vitrophyres, are often autobrecciated. The total thickness of the lavas is difficult to estimate because of the possibility of unrecognized faulting, but it is a minimum of 500 feet. Ramp structures and convoluted flow banding are found locally but, in general, the lavas dip to the west at 10 to 20 degrees. The lavas weather to flat-topped hills with very steep slopes. Outcrops are characterized by abundant opaline silica which fills fractures and cavities.

In hand specimen, the lavas vary in color from light greenish gray to grayish orange pink or light brown. Phenocrysts of feldspar, hornblende, biotite, and quartz are visible. Vitrophyre layers range in color from black to dark bluish gray and various hues of red.

In thin section, the rhyolites commonly have a devitrified groundmass and spherulitic textures are sometimes preserved. The vitrophyres have both perlitic and spherulitic textures. Plagioclase is the most abundant phenocryst and makes up 7 to 10 percent of the rock; it exhibits albite, Carlsbad, and pericline twins and is often strongly zoned. The plagioclase occurs as rounded phenocrysts which average 1.0 to 1.5 mm in length and as glomeroporphyritic clots as much as 5 mm in diameter.

Quartz comprises a trace to 5 percent of the rock; it occurs as rounded and embayed phenocrysts which average 1 to 2 mm in diameter. In some samples, coarse aggregates of secondary quartz fill fractures and cavities. Alkali feldspar is not present in some samples and, where present, seldom exceeds 2 percent. The alkali feldspar occurs as anhedral, corroded phenocrysts which average 1 to 1.5 mm in longest dimension. Hornblende comprises 1 to 2 percent of the rhyolite and occurs as euhedral to subhedral phenocrysts which average 1.5 mm in length; it has often been partially replaced by magnetite. Biotite occurs as lath-shaped phenocrysts about 1.0 mm in length and makes up 0.5 to 1 percent of the rock.

The lavas of Magdalena Peak are part of the bimodal suite of rhyolitic to rhyodacitic and basaltic lavas that were erupted in the Socorro-Magdalena area over the interval from about 20 m.y. to 7 m.y. ago. These lavas are much younger than the major ash-flow tuff cauldrons in the area. Much of this suite of rhyolite and basalt is in close proximity to the transverse shear zone (figure 4) which suggests that this structure has controlled their emplacement (Chapin and others, 1978). The lavas of Magdalena Peak are also located very close to the western margin of the Magdalena cauldron and their eruption was also likely controlled by this structure.

Tertiary Intrusive Rocks

Tertiary intrusive rocks are found throughout most of the study area; they are concentrated in the central portion of the area and are absent from the northwest quarter of the area. The most prominent of these are the dacites of Deer Plot Tank which intrude the Popotosa Formation in the southwestern corner of the study area (SW 1/4, sec. 23, T.4S., R.4W.). Also present are "white rhyolite" and andesitic dikes which intrude most of the units older than the Popotosa Formation.

In the SW 1/4, NW 1/4, sec. 23 (T.4S., R.4W.), two outcrops of colluvial breccia, within the Popotosa Formation, consist of fragments of white rhyolite intrusive rock in a muddy matrix. These outcrops, downfaulted to the east, suggest that the Popotosa was at least locally deposited on these intrusives.

<u>dacites of Deer Plot Tank</u> A porphyritic dacite lava crops out in the southwestern corner of section 23 (T.4S., R.4W.). More extensive outcrops of the lava are found southwest of the study area. Excellent exposures of the lava are found where a stream has cut a steep-walled canyon through the center of the outcrop. At the southern end of this canyon, abundant veinlets of jasperoid cut the lava. Contacts with the Popotosa Formation are steep and highly silicified which suggest that the lavas are intrusive. The lavas of Deer Plot Tank weather to steep, talus-covered slopes and cliffs.

In hand specimen, the lava is pale red purple to white and is often flow-banded. It contains 10 to 20 percent phenocrysts of feldspar, quartz, and biotite. The feldspars may appear chalky in hand specimen or, in some cases, only skeletal remains are present. Several percent dark to coppery biotite can also be seen in hand specimen.

In thin section, the lava contains 10 to 20 percent phenocrysts of quartz, altered plagioclase, sanidine (?), and biotite. Quartz occurs as euhedral to embayed phenocrysts that average about 0.5 mm in diameter and make up 10 to 20 percent of the rock.

Plagioclase feldspar phenocrysts, 0.5 to 1.0 mm in longest dimension, makes up about 5 percent of the lavas; most have been highly altered although albite twinning was observed in a few phenocrysts. Clay minerals and an optically continuous mineral, which may be alkali feldspar, have replaced the plagioclase in most samples. These secondary minerals have often been plucked out during thin section preparation. In some specimens, small, inward-growing quartz crystals line cavities where plagioclase phenocrysts once existed.

Biotite makes up 3 to 5 percent of the rock and occurs as lath-shaped phenocrysts which are aligned subparallel to the flow structure. Some of the biotite, which occurs within highly altered phenocrysts, appears to be secondary. The groundmass of the lava has been replaced by clay minerals and silica indicating intense hydrothermal alteration.

white rhyolite intrusives White rhyolite dikes are very common in the northern Magdalena Mountains (Blakestad, 1978; Allen, 1979; Sumner, in progress). These dikes are thought to be related to the numerous Tertiary granitic plutons in the northern Magdalenas. In this study area and to the south and east, the dikes are much less common and often appear to be related to small domal intrusions (Osburn, 1978; Petty, 1979; Allen, 1979; Roth, in progress).

The majority of the dikes in this area, and elsewhere in the Magdalenas, intrude north-trending faults. The dikes are typically less than 15 meters in thickness; however, in the southwestern part of the area, the outcrops are suggestive of a larger intrusive body. The dikes are often highly fractured and jointed and weather to platy talus. Silicification is common within several feet of intrusive contacts.

In hand specimen, the white rhyolites are white to light gray in color. Most are porphyritic although some are strongly flow-banded and aphanitic. In thin section, rounded phenocrysts of quartz and sanidine, which average about 1.0 mm in diameter, make up 15 to 20 percent of the rock. In a few specimens, trace amounts of biotite and plagioclase are found.

The source for most of the white rhyolite dikes in the central portion of the study area is probably an intrusive center marked by a white rhyolite dome just south of the study area in Sawmill Canyon. A crude radial pattern of dikes has been observed about this intrusive (Roth, oral commun., 1978). In the southwestern part of the area (NW 1/4, sec. 23, T.4S., R.4W.), an elliptical outcrop of white rhyolite surrounded by pediment gravels and an outcrop of a lithic-rich variety of white rhyolite are suggestive of a larger body. These white rhyolite dikes are intruded along the hypothesized southern margin of the Magdalena cauldron.

mafic dikes A few thin, fine-grained, mafic dikes occur in the central part of the study area. The dikes are typically a distinctive green color and are usually deeply weathered. They are usually found parallel to white rhyolite dikes along a common structure.

In thin section, the dikes consist of plagioclase microlites with about 5 to 10 percent plagioclase phenocrysts and less than 5 percent relict pyroxene (?); the plagioclase is largely altered to sericite and the pyroxene (?) to chlorite. Trace amounts of magnetite are also present.

Tertiary-Quaternary Deposits

<u>piedmont gravels</u> Extensive westward-sloping piedmont deposits of unconsolidated gravels are found along the western flank of the Magdalena Mountains. The deposits consist of coalescing alluvial fans derived largely from the western flank of the Magdalena Mountains. They have been partially dissected and thicknesses in excess of 5 meters have been observed in arroyos. Immediately to the west of the study area (sec. 22, T.4S., R.4W.), the gravels rest unconformably on conglomerates of the Popotosa Formation.

The gravels consist of cobble to sand-sized clasts of ash-flow tuffs and andesitic lava; the tuff of Lemitar Mountains is the most common clast lithology. Large blocks of the tuff of Lemitar Mountains are often found protruding from these surfaces and are believed to be large talus blocks which have come to rest on the alluvial fans.

Quaternary Deposits

<u>alluvium</u> Stream sediments in active drainages were mapped as alluvium. The largest areas are in stream beds which dissect the rhyolite and Popotosa Formation terrane in the northwest corner of the area and along Sawmill Canyon where a perennial stream flows.

<u>talus/colluvium</u> Active talus slopes, rock glaciers, and stabilized colluvium cover large portions of the study area. The prominent talus slopes on the west side of the range and along the East Fork of Sawmill Canyon are composed chiefly of the tuff of Lemitar Mountains which forms steep cliffs above the talus. Colluvium covers gentler slopes and grades into piedmont gravels. In general, talus/colluvium was mapped only where important geologic contacts or faults were obscured.

<u>terrace gravels of unknown age</u> Along the west flank of the West Fork of Sawmill Canyon are several outcrops of unconsolidated gravels. In the southernmost outcrop, the gravels are in excess of 100 feet thick (figure 15). They are typically preserved on remnants of old terraces as much as 250 feet above the present canyon floor. Similar terraces with minor amounts of gravels preserved are also seen along the East Fork of Sawmill Canyon. Below these terraces, the canyon walls are much steeper and reflect a period of rapid

down-cutting. This period may be at least in part due to the capture of the ancestral Rio Grande in middle Pleistocene time.

The gravels consist of rounded to subrounded cobbles and boulders of locally derived volcanic rocks in a matrix of coarse to fine sand. The clast lithologies are dominated by the tuff of Lemitar Mountains, Hells Mesa Tuff, andesite, and the Popotosa Formation.

landslide deposits Along the eastern side of Sawmill Canyon and just south of Langmuir Laboratory several large landslide blocks have been mapped. The blocks are slices of the unit of Sixmile Canyon which have moved down slope along low angle detachment faults. Internal stratigraphy is preserved within the fault slices; however, they are characterized by highly variable strike and dips and rubbly outcrops.

The fault slices became detached and moved down slope under the influence of gravity due to the low strength of the poorly welded tuffs and sedimentary rocks which occur at their stratigraphic base. The age of this faulting is not known; however, the blocks on the east flank of Sawmill Canyon appear to rest on Quaternary talus deposits.

STRUCTURAL GEOLOGY

Regional Structure

The structural development of the Magdalena Mountains reflects three distinct periods of regional tectonic activity: 1) Laramide uplift and erosion; 2) Oligocene calc-alkaline volcanism; and 3) regional extension and block-faulting related to the Rio Grande rift.

Laramide uplift and erosion During Late Cretaceous to middle Eocene a regional compressional stress field gave rise to large north-trending uplifts in the Socorro-Magdalena area. The area of the present day Magdalena Mountains lay on the flank of a major north-trending uplift (Loughlin and Koschmann, 1942; Chapin and others, 1978). In middle Eocene time (approximately 45 m.y. ago), relaxation of compressional stresses brought an end to uplift; erosion leveled topography and formed a regional surface of low relief (Epis and Chapin, 1975). In the northern Magdalena Mountains area, erosion of the Laramide uplift exposed Late Paleozoic rocks and sediments which were shed northward into the west-trending Baca Basin to form the Baca Formation of Eocene age (Chapin, 1978; and oral commun., 1979).

Oligocene volcanism About 37 m.y. ago calc-alkaline volcanic rocks were erupted onto the late Eocene regional erosion surface. In Colorado and New Mexico these eruptions began the construction of the well known San Juan and Datil-Mogollon volcanic fields. In the Socorro-Magdalena area, the Spears Formation marks the base of the Datil-Mogollon field. The Spears Formation consists of andesitic to latitic breccia complexes and quartz latite ash-flow tuffs (Chapin and others, 1978). Between 32 and 26 m.y. ago, at least five overlapping cauldron complexes formed in the Socorro-Magdalena area and blanketed the Spears Formation with thousands of feet of ash-flow tuffs and intercalated andesitic lavas.

A major feature of the Rio Grande rift in New Mexico and Colorado are a series of northeast-trending basement lineaments (Chapin and others, 1978); the lineaments have had a major influence on the tectonic and magmatic history of the rift. As the Rio Grande rift opened, it broke en echelon across these lineaments and basins on either side developed opposing symmetries (Chapin and others, 1978). The lineaments are acting as incipient transform faults which connect en echelon segments of the rift. The portions of the lineaments connecting the ends of basins were subjected to a scissors-like torque in the brittle near surface rocks and to transverse shear at depth (Chapin, 1978). Some of these transverse structures have been the site of extensive volcanic activity. The Socorro transverse shear zone of Chapin and others (1978) is one of these lineaments and the five overlapping cauldron complexes recognized in the Socorro-Magdalena area lie on or near this shear zone, as do Miocene and Pliocene rhyolite domes and flows.

Regional extension Between 32 and 27 m.y. ago, a regional, extensional, stress field reactivated the southern Rocky Mountains which is a north-trending zone of weakness that developed during late Paleozoic and early Tertiary orogenies. This extension marks the beginning of the Rio Grande rift (Chapin and Seager, 1975). Chapin (1978) divided the rift into three segments, each with its own structural style and history. The Socorro-Magdalena area is within the southern segment of the rift which has undergone the most extension and is wider than the two northern segments. The rift bifurcates near Socorro and a weaker arm (San Augustin rift) extends southwestward into Arizona (Chapin, 1971). The Socorro-Lemitar Mountains and the Magdalena Mountains lie in a triangular area between the San Augustin arm and the main rift. Much of this triangular area is characterized by closely spaced, subparallel normal faults which have undergone progressive rotation of as much as 60 degrees (Chamberlin, 1978; Osburn, 1978). Chamberlin (1978) termed this kind of faulting "domino-style" faulting and related it to shallow levels of ductile horizontal extension within the crust during periods of high heat flow. Domino-style faulting was common in the Lemitar Mountains and the

Magdalena Mountains from about 29 to 20 m.y. ago and again from 12 to 7 m.y. ago and was accompanied by local silicic volcanism. During periods of lower heat flow and lower rates of extension (20 to 12 m.y. ago, and 7 m.y. ago to present), faulting occurred along widely spaced normal faults with little or no rotation of fault blocks (Chamberlin, 1978).

Broad epiorogenic uplift disrupted the basins of the Rio Grande rift betwen 7 and 4 m.y. ago and formed much of the present day topography which is characterized by steep mountain ranges and narrow basins (Chapin, 1978). Epiorogenic uplift has continued since 4 m.y. ago but at a much reduced rate. The majority of structure in this study area is the result of interaction between the Socorro transverse shear zone, cauldron structures, and extensional faulting. (Figure 14 shows the location of cauldron structures, faults, and the Socorro shear zone in this study area.)

Local Structure

<u>ash-flow tuff cauldrons</u> During the period from about 32 to 25 m.y. ago, at least five major ash-flow tuff cauldrons were formed in the Magdalena and San Mateo Mountains area (Chapin and others, 1978). Portions of three of these cauldrons are exposed in this study area, the North Baldy, Sawmill Canyon, and Magdalena cauldrons.

North Baldy cauldron The North Baldy cauldron was formed about 32 m.y. ago during the eruption of the Hells Mesa Tuff. The cauldron was centered in the Magdalena Mountains although its full areal extent is not well known. Two remnants of the North Baldy cauldron are exposed in this study area; both occur along the margin of the Sawmill Canyon cauldron.

In the northeast corner of the area, a minimum of 1000 feet of gently dipping cauldron-facies Hells Mesa Tuff is exposed; this is part of an outcrop belt that extends northward to North Baldy. In the south-central and southwest parts of the study area (sec. 19, T.4S., R.3W.), Hells Mesa Tuff and the unit of Hardy Ridge are exposed; the unit of Hardy Ridge represents cauldron fill (largely rhyolitic) of the North Baldy cauldron.

Sawmill Canyon and Magdalena cauldrons The majority of this study area is located within the Sawmill Canyon and Magdalena cauldrons which were formed between 32 and 28 m.y. a o with the eruption of the A-L Peak Tuff. This study suggests that the Sawmill Canyon and Magdalena cauldrons are a composite structure and are joined near the summit of South Baldy. Chapin and others (1978) believe that the flow-banded member of the A-L Peak was erupted from the Magdalena cauldron and the pinnacles member from the Sawmill Canyon cauldron. The similarity of the A-L Peak in this area to the rlow-banded member complicates this interpretation. However, the presence of the same members of the unit of Sixmile Canyon in both cauldrons suggests that collapse in the Magdalena and Sawmill Canyon cauldrons was approximately contemporaneous.

The northern margin of the Sawmill Canyon cauldron is well exposed in the northeast corner of the study area where it can be traced eastward towards Buck Peak (Osburn, 1978; Petty, 1978). Due north of the Langmuir Laboratory road (sec. 5, T.4S., R.3W.), the exposed margin is a near vertical contact between cauldron facies Hells Mesa Tuff on the north and andesite and sedimentary rocks of the unit of Sixmile Canyon on the south; further to the west, down-to-the-west normal faults juxtapose the upper tuff of Lemitar Mountains against Hells Mesa Tuff.

The contact between the Hells Mesa Tuff and the unit of Sixmile Canyon is depositional and thus represents the topographic wall of the Sawmill Canyon cauldron. The large outcrops of volcaniclastic sedimentary rocks along the contact are interpreted as large blocks which fell from an unstable portion of the cauldron wall into the andesites of the unit of Sixmile Canyon. To the east of this study area, similar relationships are reported by Osburn (1978). In the western Magdalena Mountains, the Hells Mesa Tuff and the unit of Sixmile Canyon are in depositional contact along the western margin of the Magdalena cauldron (Allen, 1979).

The southwestern margin of the Sawmill Canyon cauldron can be traced along the west side of the West Fork of Sawmill Canyon and northwestward over the crest of Hardy Ridge. The margin is represented by a northwest-trending down-to-the-east fault with the unit of Hardy Ridge and the Hells Mesa Tuff on the west and cauldron facies A-L Peak Tuff on the east. This fault is poorly exposed, has little or no topographic expression, and dips steeply to the southwest. To the south of this study area, a large rhyolite dome has been intruded along the fault and has caused locally intense alteration of the A-L Peak Tuff. Just west of the crest of Hardy Ridge, the fault trends nearly due west; younger down-to-the-west faults have juxtaposed the upper tuff of Lemitar Mountains against the unit of Sixmile Canyon. Here, the Sawmill Canyon cauldron margin joins the southwest-trending Magdalena cauldron margin. Thus, the two cauldrons are joined in a narrow zone and form a crude dumbbell shape (figure 14).

Parallel to Hardy Canyon is a geologically complex zone which I believe to be an expression of the southern margin of the Magdalena cauldron. This southwest-trending zone has influenced the deposition of the major volcanic and sedimentary units younger than Hells Mesa Tuff. Rocks to the north of this zone are dominated by the Miocene lavas of Magdalena Peak, the Popotosa Formation and the unit of Sixmile Canyon. To the south, the upper tuff of Lemitar

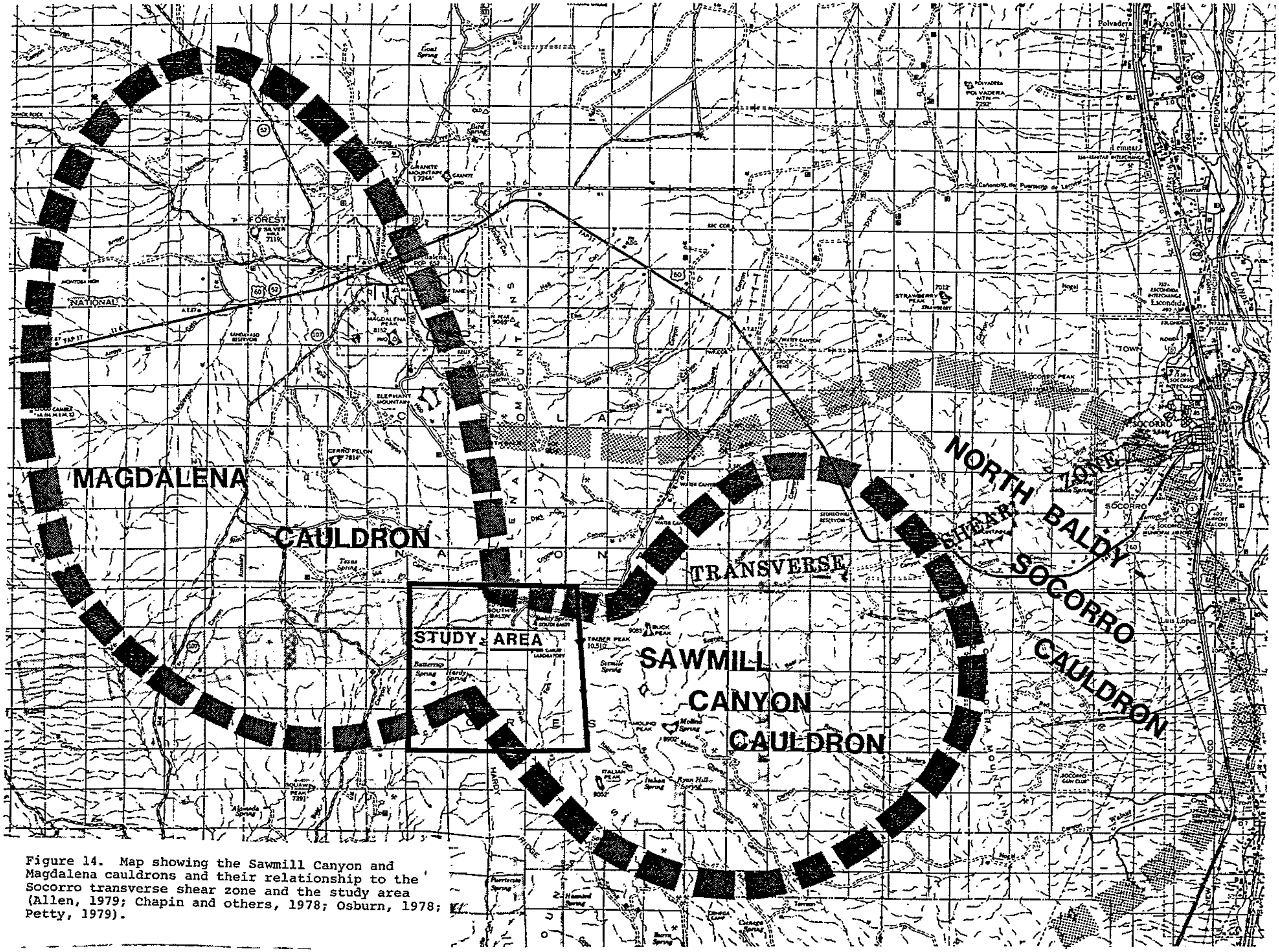


Figure 14. Map showing the Sawmill Canyon and Magdalena cauldrons and their relationship to the Socorro transverse shear zone and the study area (Allen, 1979; Chapin and others, 1978; Osburn, 1978; Petty, 1979).

Mountains and the intermediate lavas rest unconformably on the unit of Hardy Ridge. Thus, it appears that the southern block was structurally high following eruption of the A-L Peak Tuff. The absence of lower Popotosa Formation on this block suggests that it remained high during deposition of the Popotosa Formation. Another prominent feature of this zone is its irregular, scalloped appearance with intermediate lavas and tuff resting against a buttress of the upper tuff of Lemitar Mountains and the unit of Hardy Ridge (sec. 24, T.4S., R.4W.). Many of the rocks in the vicinity of this zone are highly silicified; numerous and closely spaced shear zones give the rocks a brecciated appearance. This zone has also localized several prominent white rhyolite intrusives as well as the intrusive lavas of Deer Plot Tank. Recent work to the southwest (Donze, in progress) has revealed more rhyolitic domes on the same trend as the structure in this area.

The Magdalena and Sawmill Canyon cauldrons are joined in a narrow zone about 2.5 miles long by 1 mile wide along the ridge crest between South Baldy and Langmuir Laboratory. This zone is characterized by a dramatic thinning of the unit of Sixmile Canyon and by closely spaced normal faults; thinning of the unit of Sixmile Canyon indicates that this block was structurally high following eruption of the A-L Peak Tuff from the Sawmill Canyon cauldron. To the east and west of this zone, the unit of

Sixmile Canyon has a minimum thickness of 2000 and 900 feet, respectively.

At least three explanations are possible to explain this zone between the Sawmill and Magdalena cauldrons: 1) it is a small resurgent block between the two cauldrons which rose during eruption of the unit of Sixmile Canyon; 2) it is a remnant of a septum between the cauldrons which formed when their topographic walls merged locally to form a narrow, low divide between the two depressions; and 3) it represents a block that was "caught" in a narrow zone and did not subside as much as the adjacent cauldrons.

Although this block may have been resurgently uplifted following collapse of the calderas, the small size of the block and its location within the cauldron complex is unlike the many well-documented resurgent calderas of the San Jan volcanic field in Colorado (Steven and Lipman, 1976). In the San Juan field, resurgence is generally a very broad scale feature centrally located within the calderas. The second hypothesis may not be fully evaluated as normal faulting has disrupted the original geometry of the cauldrons and the contact between the structurally high block and the thick cauldron fill to the west is not exposed. However, there is no evidence to support an expected thinning of the A-L Peak Tuff against the septum. The third explanation appears to be the simplest one and is preferred at this time. With inward-dipping ring fractures, it is possible that subsidence would not be able to proceed as rapidly or completely in the narrow zone between the cauldrons. Thus, a block could be "caught" between the major depressions and create a topographic high following eruption of the A-L Peak Tuff.

<u>extensional faulting</u> In this study area, most of the faults are north-trending, down-to-the-west normal faults. The domino-style of faulting characterized by block rotation, which has been documented in the Lemitar Mountains (Chamberlin, 1978) and the eastern Magdalena Mountains (Osburn, 1978; Petty, 1978) cannot be well documented in this study area. Typically, fault zones are obscured by talus and are poorly exposed. However, field relationships suggest that many of the faults dip toward the west; some are in a nearly orthoganol relationship with the volcanic strata.

The age of faulting in this study area cannot be well constrained. Extensional faulting related to the Rio Grande rift began between about 32 and 28 m.y. ago and has continued to the present (Chapin, 1978). In the Lemitar Mountains (Chamberlin, 1978) and eastern Magdalena Mountains (Osburn, 1978) north-trending faults have been documented prior to the eruption of the tuff of Lemitar Mountains. These fault planes have subsequently been rotated 25 to 60 degrees (Osburn, 1978; Chamberlin, 1978). Chamberlin (1978) has also noted that, in general, the dip of fault planes becomes shallower with increase in age. During the late Miocene and Pliocene (7 to 4 m.y. ago), the present-day Magdalena Mountains were uplifted along major north-trending, high-angle, normal faults; these faults have been superimposed on older faults. The closely spaced, near-vertical faults which characterized the crest of the range probably belong to this younger set of faults and intersect older, rotated faults at depth. Thus, the faults which were mapped in this study area are the result of successive generations of normal faults which have undergone variable amounts of rotation and been further modified by uplift and erosion. Interpretation of displacement on faults is further complicated by paleotopography created by cauldron collapse which has influenced the deposition of younger units.

Faulting in this study area has been strongly influenced by the Socorro transverse shear zone and by cauldron related structures. Near-surface manifestation of the Socorro shear zone consists of a complex intermeshing zone of normal faults of opposing sense, rather than strike-slip faulting (Chapin, 1978). In the Socorro-Magdalena area, the shear zone separates fields of tilted blocks which have undergone rotation and step faulting in opposite directions. In general, north of the shear zone fault planes have been rotated toward the east, strata dip towards the west, and step faulting is down-to-the-west; to the south, the reverse is true.

The Socorro shear zone passes through the northern part of this study area and a dramatic change in dip of the rocks is observed in sec. 6, T.4S., R.4W. In most of section 6, the tuff of Lemitar Mountains dips towards the west while to the south the dip is towards the east. In addition, a short segment of a down-to-the-east, east-dipping fault was mapped in the western portion of section 6. To the north of this study area, the beds consistently dip towards the west and the faults have down-to-the-west displacement along the margin of the Magdalena cauldron (Allen, 1979).

Another feature which may be related to the shear zone are two major springs which occur along it. Baldy Spring (SW corner, sec. 5, T.4S., R.3W.) is a perennial spring with a significant and relatively constant output of water. The spring is unusual because it occurs at an elevation of nearly 10,000 feet and thus has very little recharge area. Another spring occurs due west of Baldy Spring at an elevation of 8800 feet and produces a year-round supply of water for most of the Muleshoe Ranch. Two thermal springs near Socorro also occur along the shear zone. The coincidence of these large springs and the shear zone suggest that the rocks may be unusually fractured along the shear zone.

Cauldron structures have also had a major influence on the nature of faulting in the study area. For example, along the west flank of the East Fork of Sawmill Canyon a rotated, down-to-the-west fault with at least 3000 feet of displacement turns sharply to the west and joins the northern margin of the Sawmill Canyon cauldron. A possible explanation is that the great thickness of cauldron facies Hells Mesa Tuff, which occupies the crest of the range between North and South Baldy, behaved as a coherent block and resisted faulting. Alternatively, the fault may have followed the structural margin of the Sawmill Canyon cauldron for some distance before continuing on to the north.

The effect of the Sawmill Canyon-Magdalena cauldron margin on other faults can be seen in sec. 13, T.4S., R.4W., where the two cauldrons are joined. Here, the displacement on several large faults is offset and/or redistributed along the cauldron margin. A down-to-the-west fault from the north, which juxtaposes the lower tuff of Lemitar Mountains and A-L Peak Tuff, joins the west-trending cauldron margin fault and bends nearly 90 degrees. Original displacement on both faults is difficult to estimate; however, it is apparent that the displacement on one of the faults dies out.

The area immediately to the north and south of the southern Magdalena cauldron margin is characterized by east-west transverse faults which are subparallel to the cauldron margin. This type of faulting is not common in the rest of this study area or elsewhere in the Magdalena Mountains and is thought to be related to the cauldron margin.

ECONOMIC GEOLOGY

This study area is unusual in that it lacks the abundant prospects and mines which characterize much of the Socorro-Magdalena area. Most of the prospects in this area are located near the northeast-trending Sawmill Canyon cauldron margin.

The only mine located in this study area is the Copper Lode patented claim (P. Allen, oral commun., 1978) which is located on Baldy Ridge at the extreme northern end of the study area (sec. 6, T.4S., R.4W.). The mine is located along a north-trending white rhyolite dike which intrudes the ring fracture of the Sawmill Canyon cauldron margin. A shaft estimated to be a minimum of 100 feet deep was sunk along the dike, however there is no sign of economic mineralization in the mine dumps; the Hells Mesa Tuff in the vicinity of the dike is highly silicified. Numerous shallow prospect pits and short adits are common in the Hells Mesa Tuff along the cauldron margin, however no significant mineralization is visible.

Small amounts of copper mineralization (malachite?) are found in several localities within the andesite that caps South Baldy. Several shallow pits are present on the south flank of South Baldy and a 30-foot adit is located along a north-trending fault zone in the saddle due east of South Baldy. Small amounts of malachite (?) which occurs as fracture fillings may be found in the dumps of these prospects.

Hydrothermal veins formed largely of quartz and carbonate have been intruded along north-trending faults in the vicinity of South Baldy and immediately to the wet in sections 1 and 12 (T.4S., R.4W.). Typically, the veins consist of banded calcite and quartz with vugs which are filled with drusy minerals. The vein in section 1 and 12 has numerous small prospect pits dug on it, however there is no visible economic mineralization.

CONCLUSIONS

The contributions of this study to the geology of the Socorro-Magdalena area can be divided into stratigraphic and structural sections and are detailed below.

Stratigraphy

The rocks in this study area are predominantly Tertiary ash-flow tuffs, andesitic lavas, and rhyolite lavas. In general, the stratigraphic sequence in this study follows the stratigraphic framework established for the Socorro-Magdalena area (Chapin, 1974; Chapin and others, 1978). However, there are aspects of the stratigraphy which are unique to this study area and are as follows:

1) A sequence of distinctive, phenocryst-poor, flow-banded, rhyolite lavas, ash-flow tuffs, and minor andesite overlies cauldron facies Hells Mesa Tuff in the central portion of the study area. This sequence is here informally named the unit of Hardy Ridge and is considered to be cauldron fill of the North Baldy cauldron.

2) A thick, uniform, sequence (at least 2500 feet) of densely welded, flow-banded A-L Peak Tuff crops out in the central portion of this study area. The tuff is characterized by prominent, lineated pumice and secondary flow folds. The A-L Peak in this study area is thought to have been erupted from the Sawmill Canyon cauldron and may be

correlative with either the pinnacles or flow-banded members of the A-L Peak Tuff. Large blocks of older volcanic rocks are found within the A-L Peak Tuff and are interpreted as landslide deposits which fell from the wall of the Sawmill Canyon cauldron during its collapse.

3) The unit of Sixmile Canyon is a thick, heterogeneous assemblage of andesitic and rhyolite lavas, ash-flow tuffs, and volcaniclastic sedimentary rocks that filled the Sawmill Canyon cauldron following the eruption of the A-L Peak tuff. Andesitic lavas predominate in a narrow band parallel to the northern Sawmill Canyon cauldron margin and thin dramatically to the south; rhyolite lavas are common elsewhere in the cauldron. A distinctive sequence of rhyolite flows and interbedded volcaniclastic sedimentary rocks is found within both the Sawmill Canyon and Magdalena cauldron which suggests approximately contemporaneous collapse of both cauldrons.

4) The Sawmill Canyon cauldron influenced the deposition of the tuff of Lemitar Mountains in this study area. Two domains of the tuff are present: 1) within the Sawmill Canyon and Magdalena cauldrons a normal succession of lower and upper members is found overlying the unit of Sixmile Canyon. 2) Outside of the cauldrons there is little or no lower tuff of Lemitar Mountains present and the upper member rests unconformably on the unit of Hardy Ridge. The upper tuff of Lemitar Mountains outside of the cauldrons was

deposited on a structurally high block. Here, the tuff has well-developed primary welding features which have not been recognized in the upper tuff of Lemitar Mountains elsewhere in the Socorro-Magdalena area.

5) Intermediate lavas and minor ash-flow tuffs that are probably younger than the tuff of South Canyon occur in the western part of the study area. The lavas vary from aphanitic andesites to porphyritic quartz latites. Locally, the lavas are overlain by poorly welded lithic-rich ash-flow tuffs and volcaniclastic sedimentary rocks. This sequence is overlain by lower Popotosa Formation laharic breccias.

6) The distribution of lithologies within the Popotosa Formation indicate structural control of their environments of deposition. In general, laharic breccias and conglomerates were deposited in a depression which roughly coincides with the Magdalena cauldron. South of the cauldron margin, as much as 800 feet of finely laminated sandstones and siltstones were deposited on the upper tuff of Lemitar Mountains.

7) Rhyolitic lavas, tentatively correlated with the lavas of Magdalena Peak, overlie and are interbedded with the Popotosa Formation in this study area. A sample of an interbedded rhyolite lava from this area has been dated at 18.0 +/- 0.8 m.y. The lava is significantly older than samples of the lavas of Magdalena Peak from the type locality and the Stendel Perlite deposit.

Structure

The major structural features of this study area are the Magdalena and Sawmill Canyon cauldrons, the Socorro transverse shear zone, and north-trending extensional faults associated with the Rio Grande rift.

1) The northern topographic margin of the Sawmill Canyon cauldron is well exposed just north of the Langmuir Laboratory access road in the northeast portion of the study area. The topographic margin is marked by the unit of Sixmile Canyon in depositional contact with the Hells Mesa Tuff and by large blocks of older volcaniclastic sedimentary rocks which fell into the cauldron. The western margin of the Sawmill Canyon cauldron is represented by a steeply dipping fault between cauldron facies A-L Peak Tuff and Hells Mesa Tuff. Megabreccia deposits are found in the A-L Peak Tuff adjacent to the margin.

2) The Sawmill Canyon cauldron and the Magdalena cauldron are joined in a narrow zone near the summit of South Baldy and form a crude dumbbell shape. This zone probably did not subside as much as the adjacent cauldron and is characterized by a dramatic thinning of the unit of Sixmile Canyon.

3) The southern margin of the Magdalena cauldron is represented by a geologically complex zone, parallel to Hardy Canyon. This southwest-trending zone has influenced the deposition of the major volcanic and sedimentary units

younger than the Hells Mesa Tuff and has localized dacite to rhyolite intrusive rocks.

4) In the Socorro-Magdalena area, the Socorro transverse shear zone separates fields of tilted blocks which have undergone rotation and step faulting in opposite directions. The transverse shear zone passes through this study area in the vicinity of South Baldy. South of the shear zone, east-dipping strata, and down-to-the-west normal faults predominate; to the north, west-dipping strata and down-to-the-east normal faults are found.

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

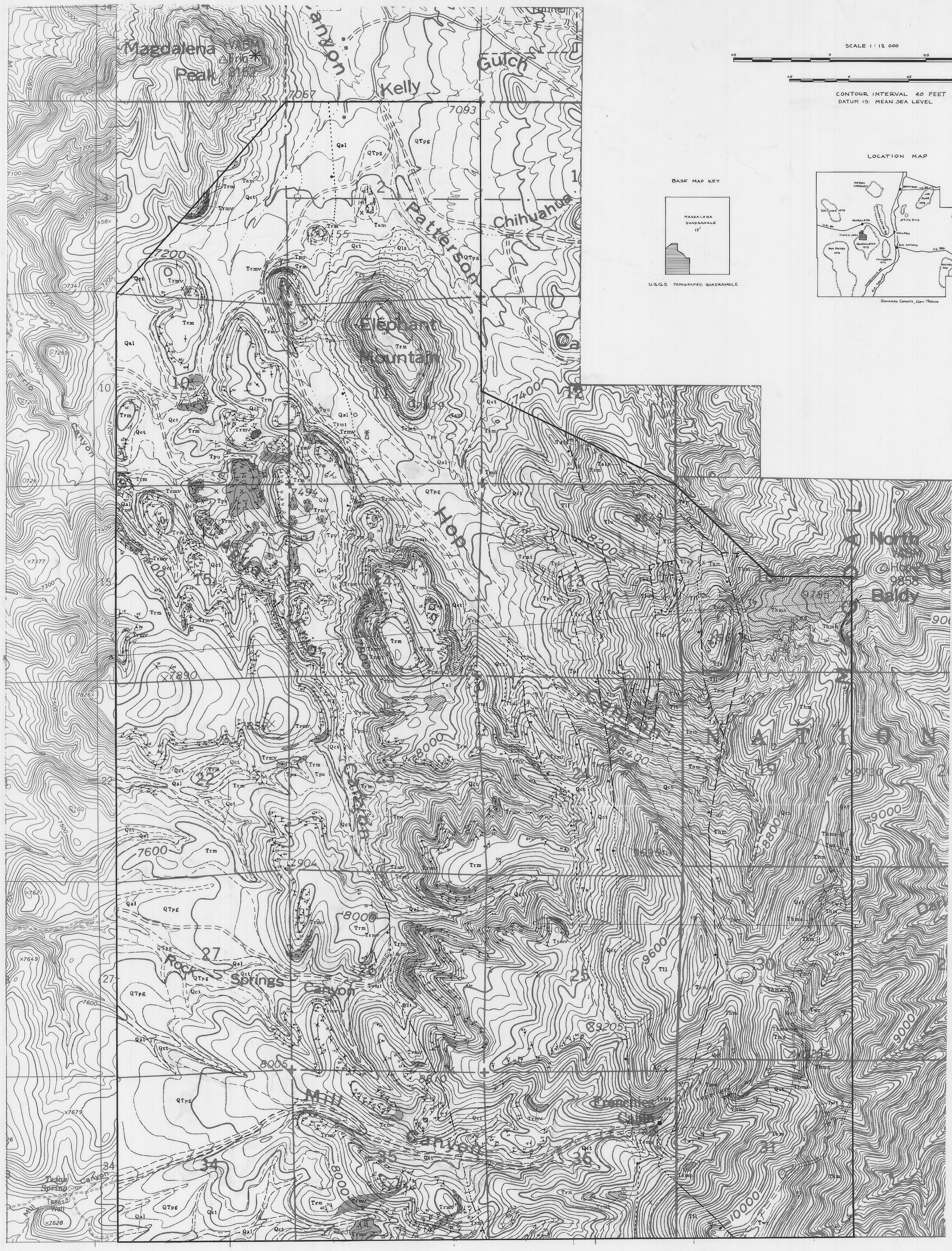
Adviser

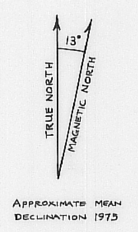
5/6/1980

Date

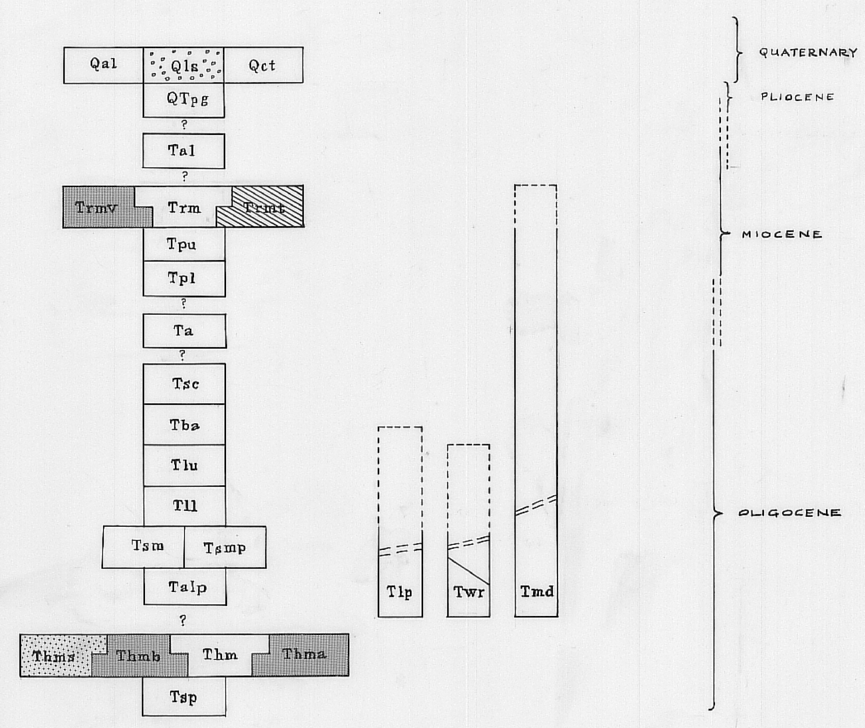
GEOLOGIC MAP AND SECTIONS OF THE WEST FLANK OF THE MAGDALENA MOUNTAINS SOUTH OF THE KELLY MINING DISTRICT SOCORRO COUNTY, NEW MEXICO

by
Philip Allen
1979





CORRELATION OF MAP UNITS



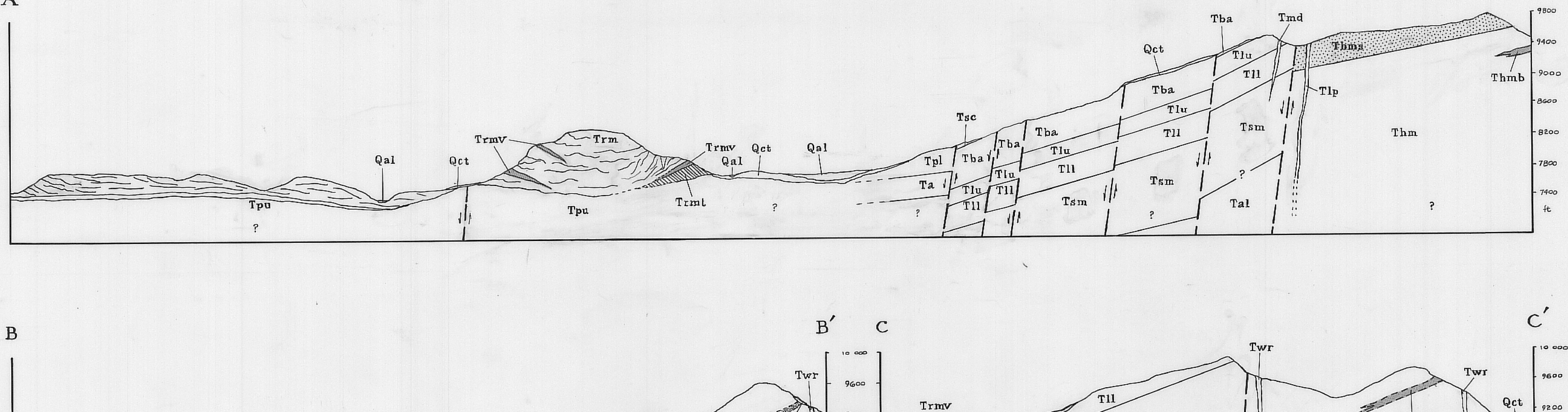
DESCRIPTION OF MAP UNITS

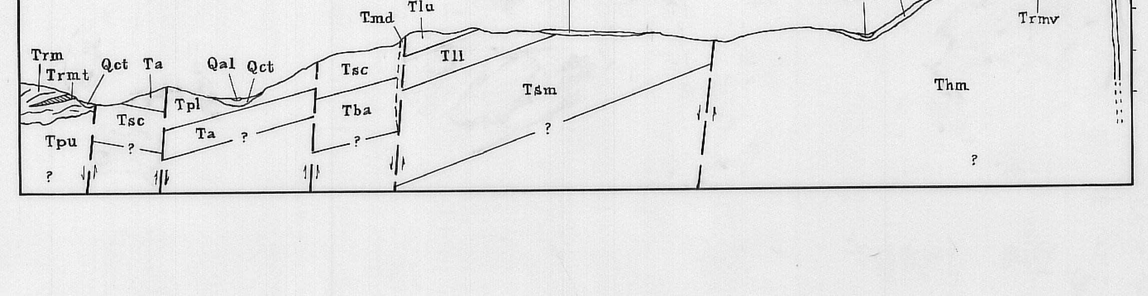
EXTRUSIVE AND SEDIMENTARY ROCKS

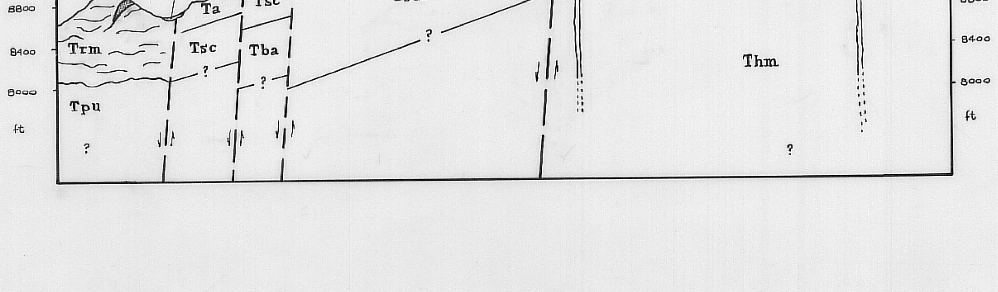
Qal	ALLUVIUM
Qls	LANDSLIDES
Qct	COLLUVIUM - TALUS
QTpg	PIEDMONT GRAVELS and older valley fill
Tal	ALLUVIUM
Trm	RHYOLITE OF MAGDALENA PEAK — Flow banded where foliation trends shown, undivided elsewhere. Locally includes: Trmv and Trmt
Trmv	Vitrophyre and perlite
Trmt	Tuffs
Tpu	POPOTOSA FORMATION — Upper member
Tpl	POPOTOSA FORMATION — Lower member
Ta	ANDESITE
Tsc	TUFF OF SOUTH CANYON
Tba	BASALTIC ANDESITE AND HORNBLENDE ANDESITE
Tlu	TUFF OF LEMITAR MOUNTAINS — Upper member
Tll	TUFF OF LEMITAR MOUNTAINS — Lower member
Tsm	UNIT OF SIXMILE CANYON — Locally includes: Tsmp
Tsmp	Latite porphyry
Talp	A-L PEAK TUFF — Flow-banded member
Thm	HELLS MESA TUFF — Locally includes: Thms, Thmb, and Thma
Thms	Sandstones and conglomerates
Thmb	Laharic Breccias
Thma	Andesites
Tsp	SPEARS FORMATION

INTRUSIVE ROCKS

Tlp	LATITE PORPHYRY OF MISTLETOE GULCH
Twr	WHITE RHYOLITE DIKES AND DOME
Tmd	MAFIC DIKES







SYMBOLS

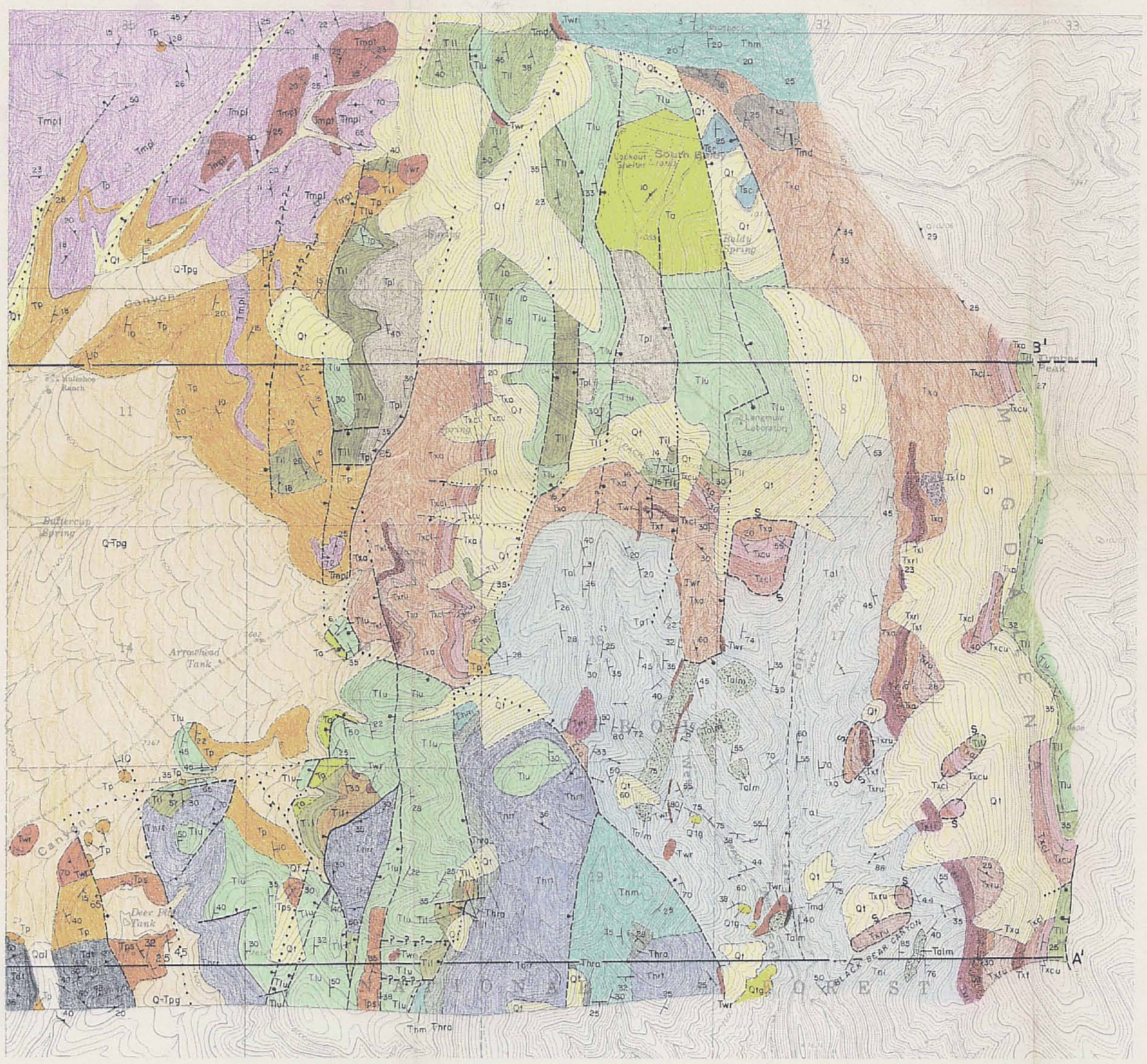
- CONTACT — Dashed where approximately located
- FAULT — Dashed where approximately, dotted where concealed, ball on downthrown block
- STRIKE AND DIP OF BEDS
- STRIKE AND DIP OF FLOW LAYERING (vertical)
- TRANSPORT DIRECTION
- VOLCANIC VENT
- SILICIFIED ZONE
- VEIN — Arrow shows inclination
- PROSPECT
- MINE — Includes adits, shafts, and large open pits

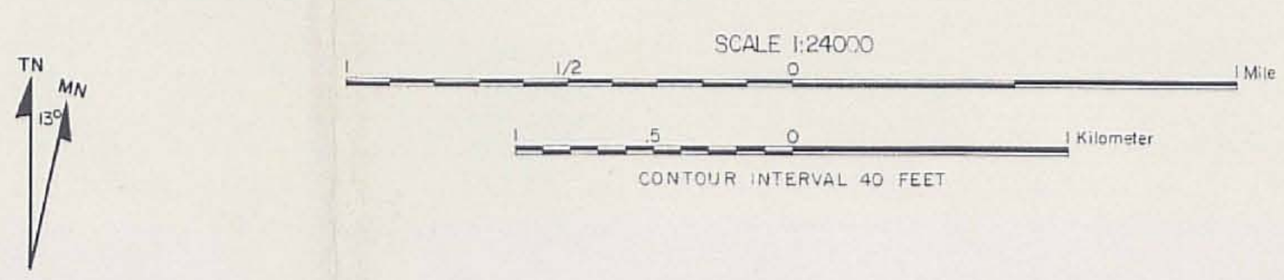
GEOLOGIC MAP AND SECTIONS OF THE WEST CENTRAL MAGDALENA MOUNTAINS, SOCORRO COUNTY, NEW MEXICO

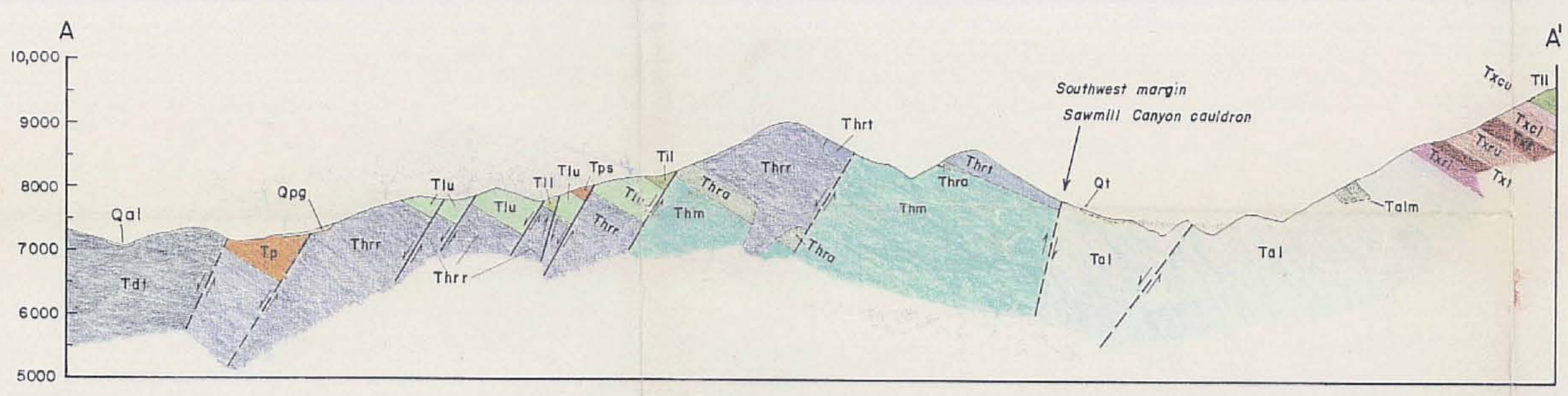
by

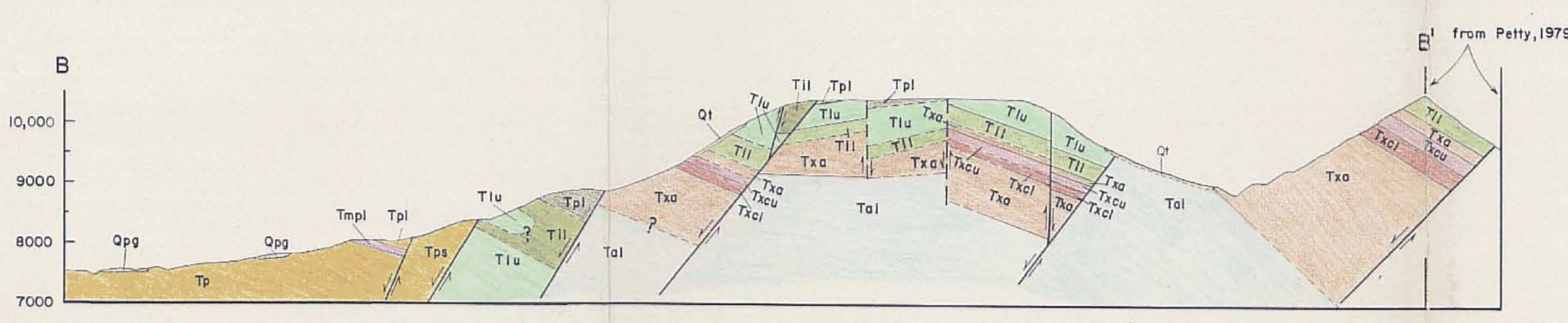
SAMUEL A. BOWRING

1980









EXPLANATION

PLIOCENE-HOLOCENE

- Qal — alluvium
- Qt — talus/colluvium
- Qtg — terrace gravels
- Q-Tpg — piedmont gravels

MIOCENE

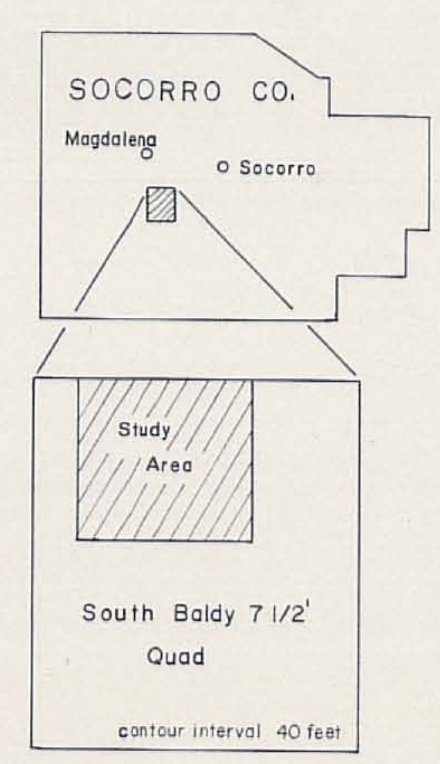
- Tmpl / Tmpt — *Lavas of Magdalena Peak:* flow-banded rhyolite lava (Tmpl), poorly welded ash-flow tuff (Tmpt)
- Tps / Tp / Tpl — *Popotosa Formation:* laharic breccias (Tpl), conglomerates (Tp), and finely laminated sandstones and siltstones (Tps)
- Tdt — *Dacite of Deer Pilot Tank*

OLIGOCENE

- Tilt / Til / Ta — *Intermediate lavas:* andesite (Ta) to porphyritic rhyodacite (Til), minor ash-flow tuffs and sedimentary rocks (Tilt).
- Tsc — *Tuff of South Canyon:* rhyolite ash-flow tuff
- Tlu / Tll — *Tuff of Lemitar Mountains:* upper crystal-rich, quartz-rich member (Tlu) and lower moderately crystal-poor member (Tll)
- Twr — white rhyolite dikes
- Tmd — mafic dikes
- Txa, Txcu, Txcl, Txs, Txt, Txru, Txrl, Txlb — *Unit of Sixmile Canyon:*
  - upper member: tuff of Caronita Canyon—lower crystal-poor member (Txcl) and upper crystal-rich member (Txcl)
  - lower member: andesitic lavas (Txa), laharic breccias (Txlb), lower crystal-poor rhyolite lava (Txrl), upper crystal-rich rhyolite lava (Txru), ash-flow tuff (Txt), and sedimentary rocks (Txs)
- Tal / Talm — *A-L Peak Tuff:* crystal-poor rhyolite, ash-flow tuff. Megabreccia blocks of older ash-flow tuffs and lavas (Talm).
- Thrr / Thrt / Thra — *Unit of Hardy Ridge:* crystal-poor, flow-banded rhyolite lavas (Thrr), andesite lavas (Thra), lithic-rich ash-flow tuff (Thrt)
- Thm — *Hells Mesa Tuff:* crystal-rich, quartz-rich ash-flow tuff.

SYMBOLS

- Contact — *dashed where approximately located*
- Epithermal quartz-carbonate veins
- Prospect pit
- 65 — Normal Fault — *dashed where approximately located, dotted where covered or inferred, bar and ball on downthrown block, arrow and number indicate dip direction and inclination of fault plane*
- Adit
- Shaft
- 25 — Strike and dip of bedding
- 82 — Strike and dip of flow foliation in lavas
- Trend of lineation
- Gravity slide block



STRUCTURAL FEATURES OF THE WEST CENTRAL MAGDALENA MOUNTAINS, SOCORRO COUNTY, NEW MEXICO

EXPLANATION

Normal Fault

dashed where approximately located, dotted where covere or inferred, bar and ball on downthrown block, arrow and number indicate dip direction and inclination of fault plane

Gravity Slide Block

Cauldron Margin

Transverse Shear Zone

2 of 2

OFR-120