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GEOLOGY OF THE CENTRAL MAGDALENA MOUNTAINS,
SOCORRO COUNTY, NEW MEXICO

by

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STATEMENT BY AUTHOR

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ABSTRACT

The Magdalena Mountains of west-central New Mexico are a north-trending block-faulted mountain range situated within the Rio Grande graben of the Basin and Range physiographic province. Mapping in the central Magdalena Mountains was undertaken to determine the geology and tectonic history of the range.

The oldest strata exposed in the central Magdalena Mountains are Precambrian argillite and granite, which are unconformably overlain by upper Paleozoic sedimentary rocks. Mesozoic strata were deposited but were subsequently eroded. Uplift during the Laramide orogeny was followed by extensive erosion and leveling during the Eocene Epoch. Volcanism began during the Oligocene Epoch with the deposition of volcanoclastic sediments, lava flows, and ash flows of the Datil Group. Movement along a N. 80° W.-trending, steeply dipping fault zone in Early Oligocene time resulted in uplift of the northern portion of the Magdalena Mountains and caused 2.5 miles of strike slip displacement of the strata. The emplacement of ash flows separated by caldera fill deposits followed the formation of the N. 80° W.-trending fault zone. The source areas for the Hells Mesa Formation ash flow and possibly the Sawmill Canyon formation ash flow are at the southern limit of the study area. The Timber Peak rhyolite ash flow is the youngest volcanic unit and its source area lies in the northern San Mateo Mountains, southwest of the Magdalena Mountains.

Following the emplacement of the Datil Group, the Magdalena area was faulted and tilted along a north-northwest-trending zone which localized the emplacement of dikes and stocks dated at 28 to 30.5 m.y. The Late Oligocene north-northwest-trending structures also served as the conduit for the hydrothermal solutions which formed limestone replacement deposits adjacent to the fault zones. The ancestral Magdalena Mountains were a topographic high during the Miocene Epoch, and supplied detritus to the adjacent lowlands. By Late Miocene time the Magdalena area was nearly completely buried by its own debris. Block faulting began during Late Miocene time and resulted in 5000 feet of structural relief between the Magdalena Mountains and the surrounding basins.

Zinc-lead mineralization in the basal Mississippian limestone is genetically and spatially related to the Oligocene stocks. Pyrometasomatic replacement and mineralization in the Linchburg and North Baldy Peak mines along Late Oligocene, north-northwest-trending structures may be related to a known buried stock underlying the area. Both mineralization and alteration progressively decrease to the south of the Linchburg-North Baldy Peak area. The spatial association of dike rocks, particularly the white rhyolite dikes, to exposed stocks suggests the presence of a buried stock underlying a portion of North Fork Canyon where sills, dikes, and plugs are very common. The potential mineralization either in the stocks, or in the wall rock surrounding the stocks, makes the Linchburg-North Baldy Peak and North Fork Canyon areas favorable for buried ore deposits.

INTRODUCTION

Although the geology of the Magdalena mining district is generally well understood (Loughlin and Koschmann, 1942), little is known about the geology and tectonic development of the Magdalena Mountains themselves. The lack of geologic information regarding the mountain mass into which the ore deposits have been emplaced leaves many problems unsolved. These include 1) definition of the Paleozoic stratigraphy, 2) studying the Tertiary Datil volcanics and locating the source areas for the ash flows, 3) determining guidelines for mineral exploration and evaluating the mineral potential of the area south of the Magdalena mining district, including the location of possible base-metal-associated stocks, and 4) interpreting the tectonic history of the Magdalena Mountains and establishing their relationship to the Rio Grande graben and the Basin and Range physiographic province.

Stratigraphy, structure, and magmatic intrusion in the central Magdalena Mountains were studied to determine the geologic history and tectonic development of the range. The central area provides exposures of the stratigraphic sequence from the Precambrian to the Holocene. Extensions of structure from the Magdalena mining district have been studied, the results of which have been utilized to outline the geologic history of the Magdalena Mountains. Although less concentrated than that of the Magdalena mining district at the present surface, the mineralization in the central part of the mountains reveals many of the same controls and alteration.

Location and Accessibility

The Magdalena Mountains are located in Socorro County, New Mexico, approximately 17 miles west of Socorro (Fig. 1). The area studied is the central portion of the Magdalena Mountains extending 6 miles north-south from ½ mile north of North Baldy Peak to approximately 1½ miles south of South Baldy Peak and 5 miles east-west, thus covering 30 square miles (Figs. 2 and 3). The central Magdalena Mountains are also referred to as the Water Canyon area after the major northeast-trending drainage that transects the area. The mapped area slightly overlaps the southeastern corner of the Magdalena mining district, which is also called the Kelly mining district. The area lies within the Magdalena 15-minute topographic quadrangle, and the Molino Peak and South Baldy 7½-minute topographic quadrangles.

Access to the area is by the Water Canyon road turnoff from U.S. Highway 60 (Fig. 3). Starting at the campgrounds in Water Canyon, the road is unpaved and climbs approximately 9 miles to the crest of the Magdalena Mountains on which is situated Langmuir Laboratory. Jeep trails offer access up North Fork and Copper Canyons. North Baldy Peak is also accessible by four-wheel drive vehicles along the crest road, which starts at the abandoned mining town of Kelly.

Topography and Drainage

Physiography of the central Magdalena Mountains is characterized by steep slopes and precipitous relief. A narrow, 6-mile-long north-trending crestal ridge transects the area. North Baldy Peak, at 9858 feet, and South Baldy Peak, the highest peak in the Magdalena Mountains, at 10,783 feet, are located along this crestal ridge. Steep slopes of

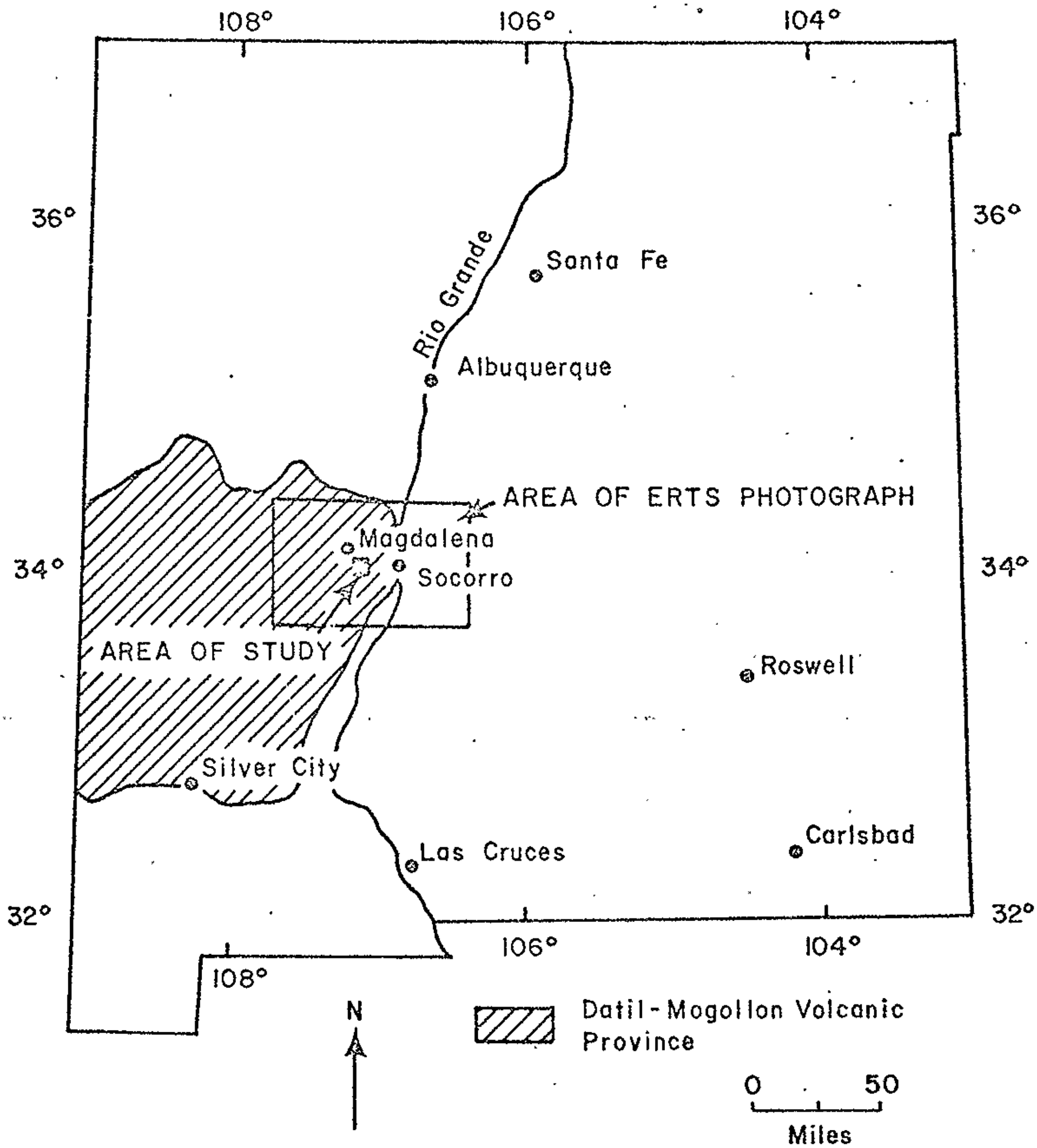

Figure 1. Index map showing the location of the central Magdalena Mountains, Socorro County, New Mexico.

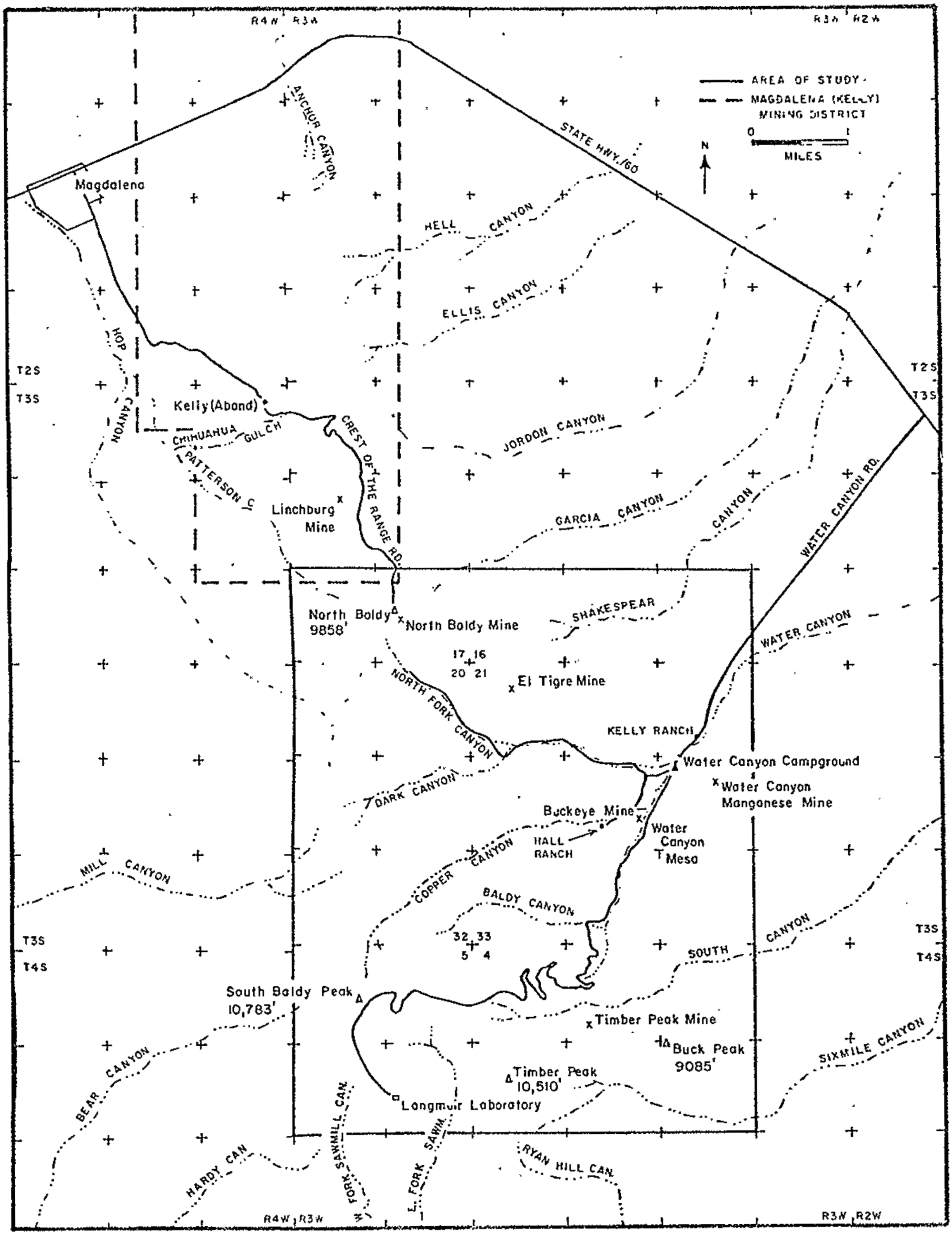

Figure 3. Landmarks and drainage systems of the central and northern Magdalena Mountains.

almost 2000 feet per mile extend to the west of this crestal ridge, whereas gentler slopes of less than 1000 feet per mile extend to the east. The lowest elevation in the region mapped, 6458 feet, is in the northeast corner of the area at the mouth of Water Canyon.

The area studied contains numerous steep-sided canyons. Water Canyon is the major drainage in the area, with North Fork Canyon, Copper Canyon and Baldy Canyon serving as its tributaries (Fig. 3). Other major drainages include South Canyon, Sixmile Canyon, Ryan Hill Canyon, Sawmill Canyon, Mill Canyon, Hop Canyon and Patterson Canyon. No permanent streams exist in the area. Runoff is mainly during the rainy months of July, August and September.

Purpose and Scope

A detailed study of the central Magdalena Mountains was undertaken for the following reasons:

The stratigraphic section present in the Magdalena Mountains is well exposed in the central portion of the range. As the stratigraphic and structural relationships are more clearly discernable in the central area than in the Magdalena mining district, an accurate interpretation of the stratigraphic and structural geology of the range can be made. A study of the Datil Group exposed in the study area would aid in the understanding of the volcano-tectonic history of the Datil-Mogollon volcanic field.

The Magdalena mining district, located in the northwest portion of the range, was a major producer of lead, zinc, and copper. The possibility of buried stocks in the southern portion of the district as postulated by Loughlin and Koschmann (1942) and Titley (1958), and the southward extension of the main ore zone can be assessed from the results of work in the central Magdalena Mountains.

The Magdalena Mountains are located near the juncture of the Colorado Plateau Province, the Basin and Range Province, and the Rio Grande graben. The addition of field data from the central Magdalena Mountains would allow the interpretation of stratigraphic, structural, and temporal relationships between these provinces, and assist in the placement of the range into a particular physiographic province.

Method of Investigation

Eleven months of field work during the spring and summer months of 1970, 1971, and 1972 were spent in the Magdalena Mountains. Reconnaissance mapping was done in the northern and southern Magdalena Mountains, detailed mapping was confined to the central portion of the range. The geologic map of the present study overlaps with the southeastern corner of the Magdalena mining district, as mapped by Loughlin and Koschmann (1942) and extends southward into the central portion of the range (Fig. 3). Aerial photographs, enlarged to a scale of approximately 500 feet to the inch, were used as a base for plotting the field data. The results have been transferred to a 1" = 2,000' composite map consisting of portions of the Magdalena 15-minute quadrangle, and the Molino Peak and South Baldy Peak 7½-minute quadrangles (Fig. 4, in pocket).

Previous Work

The early literature describing the Magdalena Mountains was primarily concerned with the mineralization in the Magdalena mining district and dealt little with the geology or tectonic development of the range. Early workers such as Jones (1904) and Gordon (Lindgren, Graton, and Gordon, 1910), provided a brief account of the general geology of the Magdalena mining district and noted the occurrences and characteristics of ore deposits. Lindgren, and others, (1910, p. 258) referred to the central portion of the Magdalena Range as the Silver Mountain or the Water Canyon district and discussed the mining activity in the area.

Wells (1918, p. 69-75), in his description of the manganese deposits in the Water Canyon district, described the geology of the central Magdalena Mountains. Lasky's (1932, p. 33-54) study of the mineral deposits in the Magdalena mining district also included a general discussion of the geology of Water Canyon and Hop Canyon. In both reports only a cursory description of the stratigraphy and structure was given.

Loughlin and Koschmann's (1942) description of the geology and ore deposits of the Magdalena mining district is one of the major contributions to the geology of the Magdalena Mountains. They considered the range to be within a southeast extension of the Basin and Range physiographic province. Loughlin and Koschmann (1942) admitted this placement was based on meager data covering a small portion of the Magdalena Mountains and considered any conclusions tentative until a much larger area has been investigated.

Two additional studies of the central Magdalena Mountains have been made. A portion of the Water Canyon area was studied by Kalish

(1953); and the geology around Langmuir Laboratory was described by Stacy (1968). Because of errors in describing the volcanic stratigraphy in their respective areas, they did not contribute to the understanding of the regional volcanic stratigraphy or tectonic development of the range.

Brown (1972) presented data on the volcanic stratigraphy and tectonics of the southern Bear Mountains, located north of the Magdalenas (Fig. 2). He redefined and expanded the Datil Group as described by Tonking (1957). Brown (1972) suggested that the southern Bear Mountains are a Basin and Range feature developed as a response to the opening of the Rio Grande rift.

A study of the San Mateo Mountains southwest of the Magdalena Mountains by Deal and Rhodes (in press) will aid in the correlation of similar volcanic units between the two ranges. The San Mateo Mountains consist essentially of mid-Tertiary volcanic rocks, ranging in composition from andesite to rhyolite. In the Mt. Withington area of the northern San Mateo Mountains, Deal and Rhodes (in press) describe a cauldron 30-40 km. in diameter which they consider to be the source area for the A. L. Peak Formation and the Potato Canyon Formation. These formations are lithologically and stratigraphically similar to units present in the Magdalena Mountains. Deal and Rhodes (in press) describe the San Mateo Mountains as an eastward dipping block which was tilted during post-volcanic tectonism related to the opening of the Rio Grande rift.

A compilation report on the field work currently in progress in the Magdalena-Tres Montosa area (Chapin, and others, in preparation) will add greatly to the level of understanding of the regional geology of the area as well as its mineral potential. Furthermore, contributions to the regional geology of the Datil-Mogollon volcanic province (Fig. 1) by Elston (1972), Elston, Bikerman, and Damon (1968), and Elston, Coney, and Rhodes (1970) will add to the understanding of the Tertiary volcano-tectonic framework of the Mogollon Plateau area.

GEOLOGY

The stratigraphic units exposed in the central Magdalena Mountains can be divided into four main groups according to the rock type and age. These include Precambrian argillite and granite; Mississippian to Permian limestone, shale, and sandstone; mid-Tertiary volcanic, intrusive, and sedimentary rocks; and talus, pediment gravels, and alluvial deposits of Quaternary age. A generalized columnar section of the pre-Cenozoic stratigraphic sequence is presented in Figure 5 and the Cenozoic stratigraphic sequence in Figure 8. The area has undergone at least 5 separate periods of faulting and tilting since Precambrian time resulting in the formation of unconformities, fault blocks, and complex surface geology.

The bedrock units crop out in a semi-domal configuration south of the Precambrian rocks exposed in the northeast portion of the study area (Fig. 4). Paleozoic and Cenozoic formations, dipping southwest to southeast, become progressively younger south of the Precambrian exposures. The Miocene Popotosa Formation, the youngest Tertiary unit, caps the crest between South Baldy Peak and Langmuir Laboratory. Farther to the north, in the Magdalena mining district, Precambrian rocks form the east slope of the range; sedimentary rocks, steeply dipping to the west, cover most of the west slope; and Oligocene volcanic rocks form the foothills.

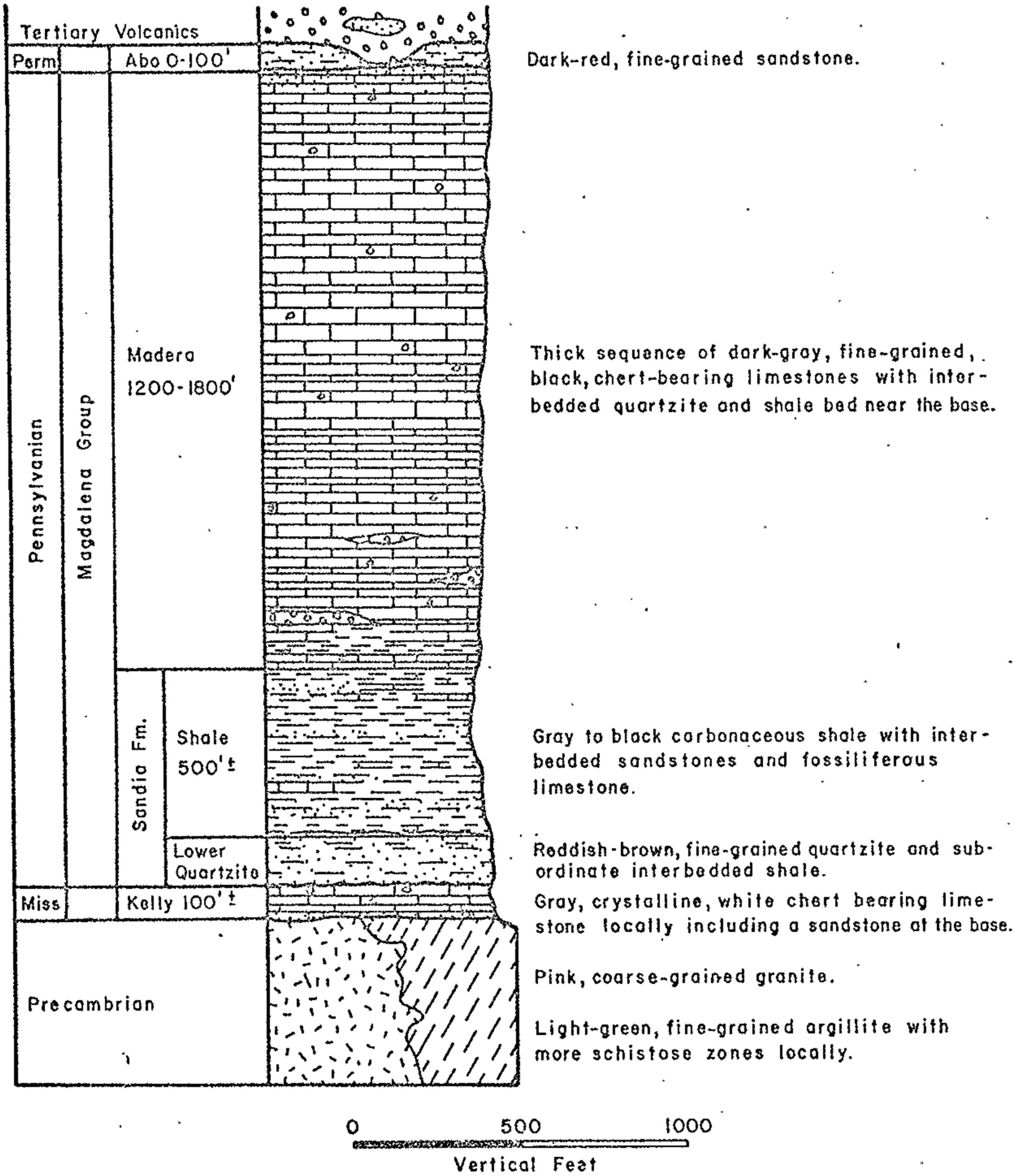

Figure 5. Pre-Cenozoic stratigraphy of the central Magdalena Mountains.

Precambrian Rocks

The oldest rocks in the mountain range are Precambrian argillite and granite. Although no radiometric age determinations have been made on the rocks, a Precambrian age may be inferred from a combination of several lines of evidence. This evidence includes the deposition of Mississippian limestones upon a subhorizontal granite and argillite surface suggesting a long period of erosion; pre-Mississippian regional metamorphism as evidenced by the lack of it in the post-Devonian or Tertiary rocks; and according to Loughlin and Koschmann (1942), structural similarity to Precambrian rocks elsewhere in New Mexico.

The Precambrian terrain consists predominately of argillite. Precambrian granite is limited to a circular outcrop east of North Baldy Peak. According to Loughlin and Koschmann (1942, p. 9-11) in the Magdalena mining district, the Precambrian granite is more common relative to the argillite in the Precambrian terrain.

Argillite

Distribution and Occurrence. Argillite crops out in the northern portion of the study area, and is best exposed east of North Baldy Peak, where Mississippian limestone unconformably overlies Precambrian rocks. The argillite is bounded on the south by the N. 80° W.-trending North Fork Canyon fault zone and to the east by a N. 35° W. fault zone. The argillite also crops out in sec. 18, T. 3S., R. 3W., in a highly silicified horst block within a north-northwest-trending fault zone. Correlative rocks in the Magdalena Range have been called greenstone schist in Lindgren, and others (1910, p. 243-244), argillite and schist by Loughlin and Koschmann (1942, p. 7-8), and greenstone by Kalish (1953, p. 6-8).

The argillite is the oldest rock in the area. It is intruded by the Precambrian granite, which contains many inclusions of the argillite. The intrusion of the granite appears to have had no alteration effect on the argillite. The argillite generally strikes N. 45° E. and dips 40-60° southeast. The contact of the argillite with the overlying Mississippian limestone is a prominent angular unconformity that generally strikes north and dips 25° to 35° to the west.

Minor amounts of mica schist are included under the general heading of argillite. Loughlin and Koschmann (1942, p. 8) state that the rocks become more schistose in the north end of the range. The increase of schist to the north could reflect either a regional metamorphic zonation, a lateral stratigraphic facies change of the rock before metamorphism, or a difference in stratigraphic or structural levels exposed in the north and central portion of the range.

Lithology. The argillite is typically light gray-green and weathers to a buff or gray. It is fine grained and has a distinctive siliceous appearance. Thin light-to-dark-green bands generally less than 1 cm. thick and rarely over 3 cm. thick are common in the argillite. The argillite weathers into small, angular fragments that cover considerable portions of the Precambrian terrain.

In thin section, the major minerals are quartz and sericite, and minor amounts of chlorite, magnetite, and orthoclase. Subround grains of quartz as large as 2 mm. in diameter are imbedded in a fine-grained quartz, sericite, and chlorite groundmass. Fine-grained laminae curve around the coarser quartz grains, which are elongate parallel to the bedding.

A pebble conglomerate in the argillite is exposed from place to place in the study area, and is well exposed in North Fork Canyon just east of the contact with the Kelly Limestone in sec. 22, T. 3S., R. 3W. (Fig. 4). Elongate pebbles, 1 cm. to 3 cm. in length, are parallel to the bedding and are cemented in a fine-grained matrix.

Granite

Distribution and Occurrence. In the central Magdalena Mountains, Precambrian granite crops out east of North Baldy Peak in sec. 17, T. 3S., R. 3W. (Fig. 4) and covers a much smaller surface area than the argillite. The predominance of the argillite in the study area suggests that the east slope of the range may not be entirely composed of granite as speculated by Loughlin and Koschmann (1942, p. 10), based on their study in the Magdalena mining district, and underscores the need for more mapping in the northeast portion of the range.

The younger age of the granite relative to the argillite is demonstrated by the intrusive relationship of the granite and the numerous inclusions of argillite in the granite. Small dikes of granite cut the argillite east of North Baldy Peak and are truncated at the basal contact of the Kelly Limestone. These dikes are generally less than 10 cm. wide and commonly parallel the argillite layers.

Lithology. The Precambrian granite is characterized by its pink color and fine-to-medium-grained texture. Microscopic examination shows microperthitic orthoclase and quartz to be the essential minerals. Micrographic intergrowth of quartz and orthoclase is common. The orthoclase is subhedral, fresh, and ranges as long as 4 mm. in length. Oligoclase composes less than 5 percent of the rock. Green biotite is a distinctive mineral that occurs as clusters with other minerals, in veinlets, and interstital to quartz and feldspar. Magnetite is commonly associated with the biotite. Apatite and zircon are minor constituents.

Paleozoic Rocks

Rocks of Early and Middle Paleozoic age are not present in the central Magdalena Mountains. The first record of deposition on the Precambrian surface is the Mississippian Kelly Limestone. The Pennsylvanian Sandia Formation and Madera Limestone and the Permian Abo Formation constitute the remainder of the Paleozoic section in the central Magdalena Mountains.

Mississippian Kelly Limestone

Mississippian strata in the Magdalena Mountains lie unconformably upon a gently undulating surface of truncated Precambrian argillite and granite (Fig. 6). The Mississippian limestone in central New Mexico is considered by Kottlowski (1965) to be a thin remnant of the original total section owing to erosion during Late Mississippian time.

The Mississippian section in the Magdalena mining district was originally named the Graphic-Kelly Limestone by Herrick (1904) after the two leading mines. Lindgren, and others (1910) renamed the Mississippian the Kelly Limestone after the town of Kelly. Armstrong (1958) divided the Mississippian of west-central New Mexico, including the Magdalena

Figure 6. Precambrian argillite (PC) contact with the Mississippian Kelly Limestone (M) located east of North Baldy Peak.

Mountains, into the Calosa Formation of Early Osagian age and the Kelly Limestone of Late Osagian age on the basis of the faunal assemblage. The entire Mississippian strata in the central Magdalena Mountains are designated the Kelly Limestone since the stratigraphic section is too thin to be subdivided on the scale of mapping (1" = 2,000') used in this study.

Distribution and Occurrence. The Kelly Limestone unconformably overlies the Precambrian from the crest of the range at North Baldy Peak southward across the North Fork Canyon fault zone, where it is displaced 2.5 miles to the east in Water Canyon (Fig. 4). A small outcrop of the Kelly Limestone is exposed between the two parallel north and south faults composing the transverse North Fork Canyon fault zone in sec. 21, T. 3S., R. 3W. approximately $\frac{1}{4}$ of a mile west of the El Tigre mine. The Kelly Limestone crops out as steep cliffs along the crest of the range because the uppermost portion of the limestone is silicified. In the Water Canyon district, south of the N. 80° W.-trending North Fork Canyon fault zone, the Kelly Limestone does not crop out as resistant ridges because of its lack of silicification.

The Kelly Limestone dips from 20° to 45° W., and varies in strike from northwest to northeast owing to the folding of the strata in the Water Canyon area. The resulting anticlines and synclines give the Kelly Limestone a sinuous outcrop pattern in the Water Canyon district. Where the dip is gentler, or the overlying rocks have been removed, the width of the exposures of the Kelly Limestone broadens considerably. The importance of the Kelly Limestone as the major ore-bearing horizon in the Magdalena mining district is reflected by the numerous prospect pits, which outline the exposures of the limestone in the Water Canyon area. The southernmost exposure of the Kelly Limestone is at the Buckeye mine in sec. 27, T. 3S., R. 3W., (Fig. 4) at the junction of Water Canyon and Copper Canyon at which place it is truncated by the Water Canyon fault zone and is dropped into the subsurface on the east side of the fault.

Lithology. The Kelly Limestone is a light bluish-gray, medium-to-coarse-grained crinoidal limestone. White to gray chert bands are present, particularly towards the top of the formation. The thickness varies from 80 to 100 feet, which is thinner than the 130 feet thickness reported by Loughlin and Koschmann (1942) in the Magdalena mining district. Locally, at the base of the Kelly Limestone, a zone, up to 8 feet thick, contains quartz, feldspar and argillite fragments as long as 5 cm. embedded in a fine-grained calcite matrix. This basal zone is the equivalent of the Calosa Formation as described by Armstrong (1963).

Loughlin and Koschmann (1942, p. 14-16) were able to subdivide the Kelly Limestone into a lower and upper limestone by the "silver pipe" member, a bed of fine-grained, argillaceous dolomitic limestone, which they describe as the most reliable marker horizon in the district. However, the "silver pipe" member was recognized only in a few places in the Water Canyon area and could not be used for mapping purposes.

Pennsylvanian Magdalena Group

The Pennsylvanian System is represented by the Magdalena Group, which was named after the Magdalena Mountains by Gordon (1907). The Magdalena Group rests unconformably upon the Mississippian Kelly

Limestone and consists of the Sandia Formation and Madera Limestone. The total thickness of the Pennsylvanian section in the central Magdalena Mountains is 2350 feet.

Sandia Formation. The Sandia Formation was originally named by Herrick (1899) after the Sandia Mountains, Bernalillo County, New Mexico. It is composed predominately of shale with lesser amounts of limestone and quartzite, and forms the lower half of the Magdalena Group.

The total thickness of the Sandia Formation in the Water Canyon area is 550 feet, which compares with the 600 feet measured by Loughlin and Koschmann (1942) in the Magdalena mining district. The Sandia Formation appears to thicken very rapidly northward as evidenced by the 2300 feet of section reported in Lindgren, and others (1910) at the north end of the Magdalena mining district.

Loughlin and Koschmann (1942, p. 16-18) subdivided the Sandia Formation into six members which, beginning with the oldest, are designated lower quartzite, lower limestone, middle quartzite, shale, upper limestone, and upper quartzite members. However, as noted by Loughlin and Koschmann (1942), the members vary considerably in thickness and some are lenticular and locally absent. The lower limestone, middle quartzite, upper limestone, and upper quartzite members are particulary noted for their thinness or absence in parts of the Magdalena mining district. In the central Magdalena Mountains, the division of the Sandia Formation into six members was not possible. Rather, for mapping purposes, the formation was divided into two members, a lower quartzite member containing minor amounts of shale and an upper shale member containing minor amounts of limestone and quartzite.

The Sandia Formation is characterized by the abundance of shale; medium-to-coarsely-crystalline limestone containing brachiopods, bryozoan, and algae; and the fine-to-medium-grain, cross-bedded, reddish-brown quartzite. The highly variable lithology of the Sandia Formation contrasts with the uniform fine-grained limestone of the Madera Limestone.

Lower quartzite member; The lower quartzite member persistently overlies the Kelly Limestone in the central Magdalena Range. The contact is structurally conformable, but does represent a hiatus from Late Mississippian to Early Pennsylvanian time. Thickness of the lower quartzite member varies from 100 to 150 feet. Characteristic features of the lower quartzite member include a fine-to-medium-grain size, round quartz grains, and cross-bedding. Reddish-brown, silty shale is present locally. Fauna are lacking, but Loughlin and Koschmann (1942, p. 17) describe some Pennsylvanian plant remains in the lower quartzite member.

Shale member; The shale member, which makes up the greater portion of the Sandia Formation, is approximately 400 feet thick in the Water Canyon area. The shale member includes the lower limestone, middle quartzite, shale, upper limestone, and upper quartzite members from Loughlin and Koschmann's (1942) study of the Sandia Formation in the Magdalena mining district. Shale is dominant throughout, but is locally interbedded with limestone and quartzite beds. The contact between the lower quartzite member and the shale member in some places is gradational, but the two members are commonly separated by a mottled, coarsely crystalline limestone, 2 to 8 feet in thickness, with abundant Productus brachiopods and bryozoans.

The shale is a dark-gray to black fissile rock. It is carbonaceous, and contains several thin, interbedded, lenticular layers of quartzite and limestone. The limestones are bluish-gray, medium-to-coarsely crystalline and fossiliferous, containing brachipods, bryozoans, and algae. The quartzites are brown to gray and fine grained.

Madera Limestone. The Madera Limestone overlies the Sandia Formation in the central Magdalena Mountains. Gordon (1907) adopted the name Madera Limestone for the dark-blue limestone conformably overlying the shaly Sandia Formation in Socorro and Bernalillo counties.

The true thickness of the Madera Limestone in the Magdalena mining district is difficult to estimate because of faulting and removal of the upper portion by erosion. Loughlin and Koschmann (1942) estimated the Madera Limestone to be at least 600 feet and a maximum of 1000 feet thick. Kottlowski (1963) considered that the formation included strata only as young as Missourian and predicted the Madera Limestone to be much thicker. Recent drilling approximately 1 mile west of North Baldy Peak penetrated an apparently unfaulted section of Madera Limestone, 1800 feet thick. The outcrop of the Madera Limestone in the central Magdalena Mountains further support the 1800 foot thickness.

Distribution and occurrence; The Madera Limestone is exposed in sec. 18 T. 3S., R. 3W. as the continuation of the Paleozoic exposures southward from the Magdalena mining district (Fig. 7). North Baldy Peak

Figure 7. West dipping Pennsylvanian Sandia Formation (S) and Madera Limestone (M) in North Fork Canyon.

is capped by a thin remnant of Madera Limestone. The N. 80° W.-trending North Fork Canyon fault zone has displaced the Madera Limestone east into Water Canyon area where it is well exposed in North Fork Canyon and Copper Canyon. An isolated horst block of Madera Limestone and basal Spears Formation of the Datil Group is exposed in secs. 20 and 29, T. 3S., R. 3W. south of North Baldy Peak near the head of North Fork Canyon. The uplifted block of Madera Limestone occurs in a north-trending outcrop of approximately 6500 feet in length and 300 to 600 feet in width. The Madera Limestone horst is a continuation of a north-northwest-trending zone of uplifted blocks of Precambrian rocks, which extend from the Magdalena mining district into the central Magdalena Mountains.

Lithology; The Madera Limestone is a blue-gray, fine-grained limestone that contains black chert nodules. Fusilinids, brachiopods, and solitary corals occur throughout the formation. A few thin beds of white to greenish-gray quartzite are present near the base. The upper beds are mottled, shaley, and are stained reddish by the overlying Abo Formation.

The lower 300 feet of the Madera Limestone contain bluish-gray shale and white to gray, medium-to-coarse-grain quartzite beds very similar to the Sandia Formation. The contact between the Sandia Formation and the Madera Limestone is gradational and is placed arbitrarily upon the dominance and greater thickness of the fine-grained limestone with a subsequent decrease in the shale and quartzite beds. The remainder of the Madera Limestone is a very uniform, fine-grained micrite.

Permian Abo Formation

Distribution and Occurrence. The Abo Formation is the youngest Paleozoic unit in the Magdalena Mountains and overlies the Madera Limestone with a slight angular unconformity. The only exposure of the Abo Formation in the study area is at the head of Patterson Canyon, northwest of North Baldy Peak (Fig. 4). In the Water Canyon area, all the Abo Formation was removed prior to the deposition of the Oligocene volcanics.

Lithology. The Abo Formation has a maximum thickness of 100 feet at the head of Patterson Canyon. The formation consists of dark-red, fine-to-coarse-grained sandstone and minor amounts of interbedded red sandy shale. Cross-bedding, ripple marks, and mud cracks are common. Locally, limestone pebbles apparently derived from the underlying Madera Limestone are in the basal beds of the Abo Formation. No fossils were found, but Loughlin and Koschmann (1942, p. 21) describe some Permian plant fossils from the formation in the Magdalena mining district.

Cenozoic Rocks

Oligocene volcanic rocks were deposited in angular unconformity on Paleozoic sedimentary rocks in the central Magdalena Mountains. Dikes and stocks intruded the area following the cessation of volcanism. Sedimentary processes became dominant during Miocene time with the deposition of the Popotosa Formation.

Tertiary Volcanic Rocks

Lava flows, ash flows, and volcanoclastic sedimentary rocks belonging to the Oligocene Datil Group cover the largest area in the central Magdalena Mountains. The volcanic rocks dip 20°-25° southwest to southeast from the Paleozoic-Precambrian core (Fig. 4).

The Datil period of volcanism lasted from 37.1 m.y. to 30.5 m.y. as determined by age dating by various workers (Burke and others, 1963; Smith and others, in press; Weber, 1971). The combined thickness of the volcanic rocks in the central Magdalena Mountains is a maximum of 12,000 feet and on the average dips 10°-15° less than the subjacent Paleozoic sedimentary rocks. Figure 8 is a generalized composite stratigraphic column of the Tertiary sequence in the central Magdalena Mountains.

The need to define the stratigraphic sequence of the Datil Group has existed since Winchester (1920) first named the Datil Formation as interbedded volcanics and sedimentary rocks outcropping in the Datil Mountains, 36 miles west of Magdalena. Loughlin and Koschmann's (1942) interpretation of the volcanic sequence in the Magdalena mining district was hampered by the complex structure and alteration in the area, making any correlation of their work in this study difficult.

Tonking (1957) who studied the Puertecito quadrangle, 15 miles north of Magdalena, divided the Datil Formation into three members: in ascending order, the Spears Member, the Hells Mesa Member, and the La Jara Peak Member. Weber (1971, p. 35) recognized the complexity of the Datil and raised it to group status and the Spears, Hells Mesa and the La Jara Peak Members were elevated to formational status. The La Jara Peak Formation has since been shown to be a post-Datil event based on structural evidence (Chapin, and others, in preparation) and a K-Ar date of 23.8 m.y. (Chapin 1971-a).

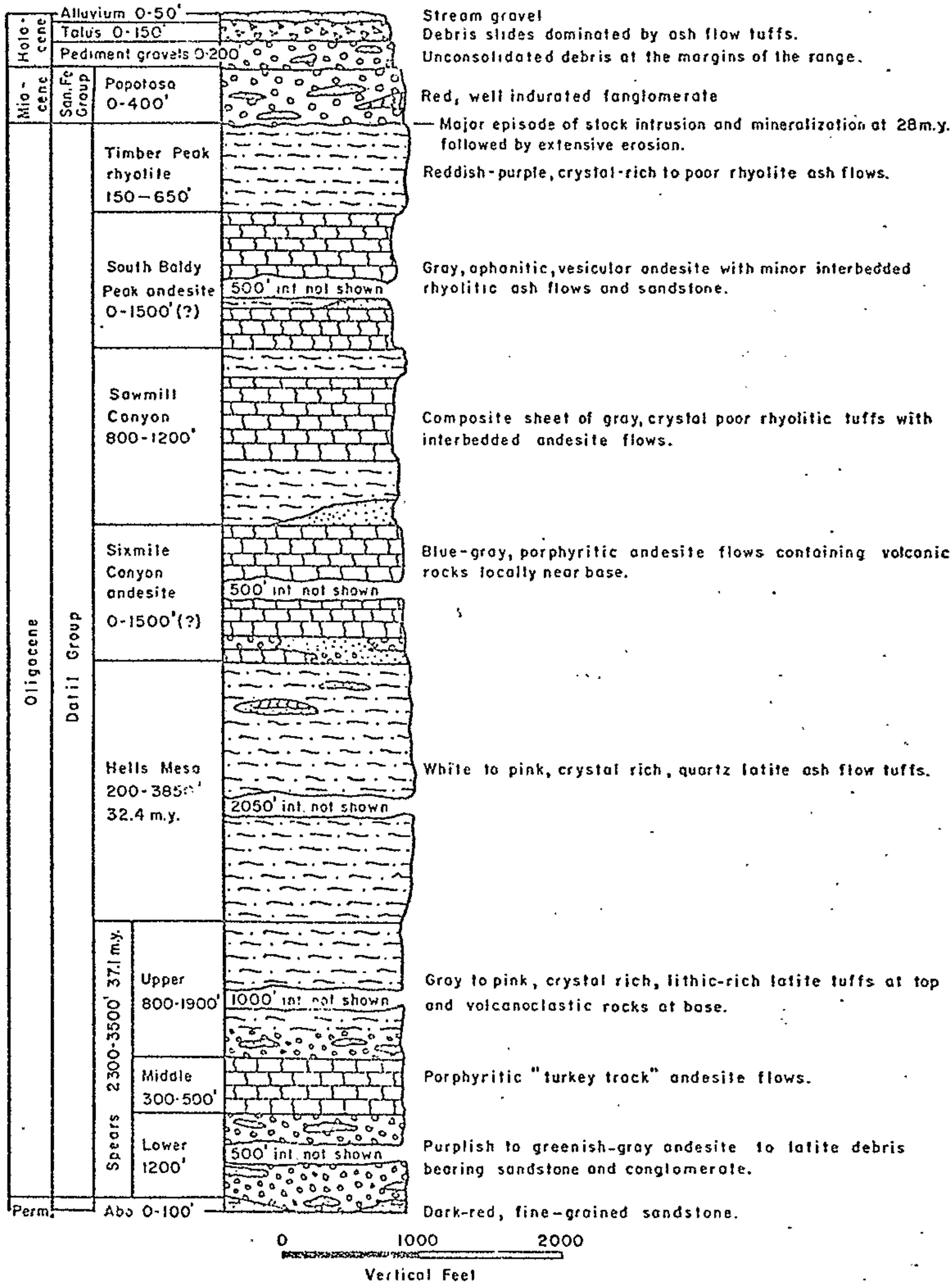

Figure 8. Cenozoic stratigraphy of the central Magdalena Mountains.

A study by Brown (1972) of the volcanic rocks in the southern Bear Mountains, 3 miles north of Magdalena, permitted the subdivision of Datil Group into 13 separate units totaling approximately 4000 feet in thickness. Figure 9 is a correlation chart of equivalent units described by Brown (1972) north of the Magdalena mining district, Loughlin and Koschmann's (1942) effusive sequence in the Magdalena mining district, and the units used in the present study from the central Magdalena Range.

Spears Formation. The deposition of Spears Formation, the lowermost unit of the Datil Group, represent the beginning of volcanic activity in the Magdalena area in Early Oligocene time. Burke and others (1963) obtained a 37.1 m.y. K-Ar date on biotite in a latite tuff breccia in the Joyita Hills, 30 miles east of the Lemitar Mountains. The Spears Formation is considered by Chapin, and others, (in preparation) to be stratigraphically equivalent to the latite-tuff breccia in the Joyita Hills based on lithologic and stratigraphic similarity.

The Spears Formation unconformably overlies the Madera Limestone in the central Magdalena Mountains. Only locally at the head of Patterson Canyon does the Spears Formation overlie the Abo Formation.

The Spears Formation is composed of volcanoclastic sedimentary rocks, volcanic ash flows, and lava flows. It can be divided into 3 mappable members. The middle member, which is a distinctive porphyritic lava flow or "turkey track" porphyry, separates the otherwise monotonously thick sequence of epiclastic rocks. The tuff of Nipple Mountain, which is a member of the Spears Formation exposed in the southern Bear

	Central Magdalena Mountains Krewedl (1974)	Magdalena Mining District Loughlin and Koschmann (1942)		Southern Bear Mountains Brown (1972)
	Popotosa Formation			Fanglomerate of Dry Lake Canyon La Jara Peak Formation
Datil Group	Timber Peak rhyolite South Baldy Peak andesite			
Datil Group			Hells Mesa Formation	Tuff of Allen Well Andesite flows
Datil Group	Sawmill Canyon formation	Banded rhyolite	Hells Mesa Formation	Upper tuff of Bear Springs
Datil Group			Hells Mesa Formation	Andesite flows Lower tuff of Bear Springs
Datil Group	Sixmile Canyon andesite		Hells Mesa Formation	Porphyritic andesite flows
Datil Group	Hells Mesa Formation	Rhyolite porphyry sill	Hells Mesa Formation	Tuff of Goat Spring
Datil Group	Spears Formation: Upper member	Upper latite Lower andesite Lower latite tuff	Spears Formation	Upper member
Datil Group	Spears Formation: Middle member		Spears Formation	Porphyritic andesite flows
Datil Group	Spears Formation: Lower member	Purple andesite	Spears Formation	Lower member

Figure 9. Correlation chart of equivalent Tertiary volcanic and sedimentary units used by workers in the southern Bear Mountains and the Magdalena Mountains.

Mountains (Brown, 1972), is not present in the central Magdalena Mountains. Brown (1972) reports that the Spears Formation is of variable lithology, from dominantly fine-grained fluvial rocks at Hells Mesa, in the Bear Mountains, to a thick section of lava flows and ash flow tuffs overlying relatively thin volcanic conglomerates in the southern Bear Mountains. These lithologic variations are also present in the central Magdalena Mountains. In North Fork Canyon, the Spears Formation consists of 3500 feet of conglomerate, sandstone, lava flows and latitic ash flows. Further to the south, the latitic ash flows decrease in thickness, but still overlie a thick volcanoclastic section.

Lower member; The lower member of the Spears Formation consists of volcanic siltstone, sandstone, and conglomerate as much as 1200 feet in thickness. The lower member contains no ash or lava flows and is the equivalent of Loughlin and Koschmann's (1942) Purple Andesite in the Magdalena mining district (Fig. 9).

Field exposures of the lower Spears Formation reveal a monotonous sequence of well-indurated, volcanoclastic sedimentary rocks containing no marker horizons that can be used for correlation purposes or stratigraphic position. Attitude determinations can be taken only from the finer-grained layers. The color varies from a grayish-purple in the rocks of Patterson Canyon on the northwest to a greenish-gray in the rocks of North Fork Canyon and Copper Canyon. Grayish-purple is the most common color and represents the fresh, generally more conglomeratic portion of the lower Spears Formation. The greenish-gray color is due to replacement of the ferromagnesian minerals to chlorite and epidote.

Conglomerate predominates in the sequence and contains unsorted and subrounded porphyritic latitic to andesitic clasts averaging 10 cm. in length (Fig. 10). The phenocrysts in the clasts uniformly consist of chalky white to gray feldspar and dark-green hornblende in a siliceous, aphanitic groundmass. Subrounded fragments of the distinctively red Abo Formation and Madera Limestone as long as 1 meter are common in the basal portion. Imbrication directions taken from clasts of Abo Formation within the unit indicate a direction of transport from the southwest.

Viewed microscopically, the clasts are similar mineralogically and consist of as much as 40 percent plagioclase, sanidine, and hornblende phenocrysts. The crystals are as long as 1.5 mm. and are subhedral to euhedral. The groundmass is a fine-grained aggregate of feldspar, hornblende, biotite, quartz, apatite and magnetite.

Middle member; The middle member of the Spears Formation is a blue-gray to reddish-gray vesicular, "turkey track" porphyry, andesite flow. The middle Spears Formation overlies the volcanoclastic lower Spears Formation throughout the central Magdalena Mountains. The extrusion of the andesite flows represents the oldest Cenozoic volcanism in the Magdalena area.

The middle Spears Formation is mapped separately because of its distinctiveness, its maximum 500 feet thickness, and its usefulness as a marker horizon in separating the lower and upper Spears Formation. Only one "turkey track" porphyry occurs within the Spears Formation in the central Magdalena Mountains, separating the volcanoclastics of the lower Spears Formation from the volcanoclastic and latitic ash flows of the

Figure 10. Lower Spears Formation containing clasts of Abo Formation (A) Paleozoic limestone (L) and porphyritic andesite (PA).

upper Spears Formation. A "turkey track" andesite flow within the Spears Formation is also exposed in the Bear Mountains (Brown, 1972; Tonking, 1957) and is equivalent to the middle member. Similar flows have been described in southeastern Arizona by Cooper (1961) who suggested that the "turkey track" porphyry be used as a guide for the correlation of Miocene rocks.

Viewed microscopically, the andesite flow is characterized by abundant euhedral phenocrysts of plagioclase (An_{55}) as long as 10 mm. in diameter in a fine-grained felty groundmass of plagioclase and magnetite (Fig. 11). The plagioclase commonly shows clay alteration. Calcite, epidote, chlorite, and silica are present in altered zones adjacent to faults or intrusions. The vesicles commonly are filled with secondary calcite or silica. Magnetite oxidized to hematite gives the characteristic reddish stain to the rock.

Upper member; A sequence of interbedded conglomeratic mud flows and latitic ash flows overlies the andesite flows of the middle Spears Formation and is in angular unconformity with the overlying Hells Mesa Formation. The lithology of the upper Spears Formation varies along its strike. South of North Baldy Peak, the upper Spears Formation is composed of volcanoclastics and some latitic ash flows. Further to the south in Baldy Canyon, the latitic ash flows dominate over the volcanoclastics and some latitic ash flows. Latitic ash flows become more dominant higher in the stratigraphic section of the upper Spears Formation in the central Magdalena Mountains.

The apparent thickness of the upper Spears Formation as measured from the geologic map and cross sections (Fig. 4) also varies

Figure 11. Photomicrograph of a porphyritic andesite from the middle Spears Formation.---Plagioclase (P) phenocrysts and calcite (C) filled vesicles in a fine-grained, iron-stained, groundmass of feldspar and magnetite. Crossed nicols, X 3.

considerable. At North Baldy Peak the upper member is at a maximum thickness of 1700 feet, but thins rapidly to a more consistent 700 feet southward.

The conglomeratic mud flows are best exposed in the southernmost exposures of the upper Spears Formation in secs. 33 and 34, T. 3S., R. 3W. They are very similar to the conglomerates of the lower Spears Formation, being purple-gray, and containing subrounded clasts of the underlying andesite flows as well as latitic ash flows. The clasts range from 1 cm. to 12 cm. and locally as long as 1 meter in length. The conglomerate exhibits neither sorting nor stratification.

The latitic ash flows are compact, welded, crystal and lithic-rich tuffs. The ash flows are characterized by an overall grayish-brown color, chalky white feldspars, and red-brown to grayish-red, subrounded lithic fragments. The tuffs contain few pumice fragments. Quartz crystals generally are absent, but become increasingly more common towards the top of the section though never exceeding 3 percent by volume of the rock.

Petrographically, feldspar and hornblende phenocrysts, composing as much as 40 percent of the ash flow in the upper Spears Formation, are in an aphanitic, argillized matrix (Fig. 12). Plagioclase, varying from An_{30} to An_{36}, dominates over sanidine. Hornblende ranges to as much as 5 percent and has been replaced by magnetite. The feldspars are subhedral to euhedral, and range in size from 0.2 mm. to 2 mm. but average 0.5 mm. The groundmass is glassy, with little devitrification, and shows a general alteration to clay or calcite. Flow banding is exhibited by the phenocrysts and the groundmass. Accessory minerals

Figure 12. Photomicrograph of a latite from the upper Spears Formation.--Plagioclase (P), sanidine (S) and hornblende (H) crystals in a glassy matrix. Crossed nicols, X 3.

include biotite, quartz, apatite, and clinopyroxene. The latitic lithic fragments, which are generally less than 3 cm. in length, contain crystals of plagioclase, less than 0.1 mm. long in a fine-grained, siliceous matrix.

The contact of the upper Spears Formation with the overlying Hells Mesa Formation can be easily placed on the basis of contrasts in color and lithology between the two formations and increase in the steepness of the slope, which is underlain by Hells Mesa Formation. Brown (1972, p. 17) reported that a distinctive hematite-stained conglomerate provides a useful marker bed at the top of the Spears in the southern Bear Mountains. This conglomerate is not present in the central Magdalena Mountains. A 0.5 meter thick regolith, developed at the top of the Spears Formation, is present only in the south portion of the study area and represents subaerial weathering before deposition of the Hells Mesa Formation. The actual contact in many places is obscured owing to the mantling by debris from the Hells Mesa Formation.

Hells Mesa Formation. The Hells Mesa Formation of the Datil Group is a thick sequence of quartz latite ash flow tuffs. Burke and others, (1963) obtained a K-Ar date from biotite of 32.4 m.y. from a sample taken from the basal portion of the Hells Mesa Formation exposed in Joyita Hills northeast of the Magdalena Mountains. Tonking (1957, p. 29-30, 56) originally named the Hells Mesa a member of the Datil Formation after a conspicuous landform at the eastern edge of Bear Mountain (secs. 7 and 26, T. 1N., R. 4W.). Weber (1971) raised the Datil to group status making the Hells Mesa a formation. The Hells Mesa Formation was mistakenly identified, by Loughlin and Koschmann (1942,

p. 33-35) in the Magdalena mining district and Kalish (1953, p. 26-27) in the Water Canyon area, as a rhyolite porphyry sill (Fig. 9). Brown (1972, p. 18-50) divided the Hells Mesa Formation into 7 members in the southern Bear Mountains (Fig. 9). Regional mapping in the Magdalena district (Chapin, and others, in preparation) resulted in redefining Brown's (1972) Hells Mesa Formation. In this study the Hells Mesa Formation is the equivalent of Brown's (1972, p. 19-30) lowest member of the Hells Mesa Formation, the tuff of Goat Spring (Fig. 9), on the basis of continuous exposure from the Bear Mountains to the Magdalena Mountains.

The Hells Mesa Formation covers a surface area greater than 10 square miles in the central Magdalena Mountains. The formation is exposed in a wide crescent shaped pattern beginning near North Baldy Peak, southeast to South Canyon, and then northeast to the western slopes of Water Canyon Mesa east of the Water Canyon campground (Fig. 4). It forms steep, talus-mantled slopes in the higher elevations and makes up the crest of the range for over 3 miles between North Baldy Peak and South Baldy Peak. Distinctive white cliffs near North Baldy Peak and a pronounced nearly vertical, fault escarpment on the east side of Water Canyon are composed of the Hells Mesa Formation.

The Hells Mesa Formation is a multiple flow, simple cooling unit of crystal-rich, quartz latite tuff. The formation is distinguished by its gray color, pink sanidine, white plagioclase and round quartz eyes embedded in a microgranular groundmass. Weathered cavities as long as 1 foot in the poorly welded, upper portions of the Hells Mesa Formation along the crest of the range in sec. 30, T. 3S., R. 3W. give the rock a pitted texture. As much as 2 percent of the rock is made up of lithic fragments. The rock weathers into angular, blocky boulders, forming extensive talus slopes. Slopes developed on the Hells Mesa Formation are steeper than those developed on the underlying Spears Formation.

The thickness of the Hells Mesa Formation varies considerably within a short distance. At the northernmost exposure west of North Baldy Peak the formation is approximately 200 feet thick. However, 3 miles south of North Baldy Peak in Copper Canyon and Mill Canyon, the formation is 3850 feet thick. The later figure is a maximum thickness that may include repetition of the strata by unrecognized normal faulting.

The Hells Mesa Formation is a densely welded, gray tuff everywhere in the central Magdalena Mountains except west and southwest of North Baldy Peak. The formation is white and poorly welded to the west and southwest of North Baldy Peak, becoming grayer and densely welded farther to the south.

Thin volcanoclastic conglomerates and minor "turkey track" porphyry andesite flows are interbedded with the Hells Mesa Formation ash flow tuffs in an area between North Baldy Peak and 2.5 miles south of North Baldy Peak. The epiclastic sedimentary rocks contain fragments very similar to the Spears Formation and the andesite flows resemble the middle member of the Spears Formation. They appear to be restricted to the upper portion of the Hells Mesa Formation and are limited in aerial extent from North Baldy Peak to the north side of Copper Canyon and Mill Canyon (Fig. 4).

Furthermore, the Hells Mesa Formation overlies the lower member of the Spears Formation west of North Baldy Peak in sec. 18, T. 3S., R. 3W. on the upthrown side of the N. 80° W.-trending North Fork Canyon fault zone (Fig. 4). There is no middle or upper Spears Formation underlying the Hells Mesa Formation on the north side of the North Fork Canyon fault zone. On the downthrown side of the North Fork Canyon fault zone, the Hells Mesa Formation overlies the upper Spears Formation.

Because of the lack of pumice, lithic fragments, megascopic foliation, attitudes on the Hells Mesa Formation are difficult to obtain. The blocky, debris-mantled slopes of the Hells Mesa Formation make it difficult to find outcrops. Attitudes are determinable where lithic fragments are more abundant or the rock is poorly welded.

The attitudes obtained indicate that an angular unconformity exists between the upper Spears Formation and the Hells Mesa Formation. The disparity in dip is very pronounced south of North Baldy Peak in sec. 20, T. 3S., R. 3W. where the upper Spears Formation dips as much as 49° west while the Hells Mesa Formation only dips 10° west (Fig. 4). The formations approach structural conformity farther to the south as the disparity in dips becomes less.

Viewed microscopically the quartz latite of the Hells Mesa Formation is distinctly porphyritic, phenocrysts making up from 20 to 50 percent of the rock (Fig. 13). Phenocrysts of sanidine, plagioclase, quartz, and minor hornblende are commonly broken and show partial resorption along their edges. The crystals range in size from 3 mm. to less than 0.1 mm. The groundmass has devitrified to microgranular cristobalite, glass, and feldspar.

Figure 13. Photomicrograph of a quartz latite from the Hells Mesa Formation.--Plagioclase (P), sanidine (S), and quartz (Q) crystals in fine-grained groundmass of cristobalite, glass, and feldspar. Crossed nicols, X 3.

Sanidine is the most abundant feldspar and varies from 10 to 30 percent of the rock. The sanidine is subhedral to euhedral, varies from 2 mm. to 0.1 mm. and averages around 1 mm. in size. The sanidine generally is fresh, but locally shows clay or hemátite alteration. In the more intensely altered zones, sanidine is replaced by calcite, and more rarely by chlorite or epidote. Many of the grains appear to have been broken and partly resorbed during emplacement of the ash flow sheet.

Plagioclase phenocrysts make up from 5 to 20 percent of the rock. The plagioclase is subhedral to euhedral, but is slightly smaller in size than the sanidine, ranging from 0.1 mm to 1.5 mm., with an average of 0.8 mm. The plagioclase is andesine, An_{32} to An_{36}. The grains show incipient to almost total replacement by clay and sericite. Calcite, chlorite, or epidote replacement of the plagioclase occurs generally near fault zones or intrusive bodies. The plagioclase phenocrysts are also broken or resorbed, but not to the same degree as the sanidine grains.

Quartz composes from 5 to 15 percent of the rock. The rounded grains are as much as 3 mm. in size averaging around 1.2 mm., which is slightly greater than the feldspars. Quartz is fresh and shows rare breakage, as demonstrated by cavities and holes that are filled with cristobalite and glass.

The ferromagnesian minerals, represented by hornblende and biotite, never comprise more than 2 percent of the rock. The biotite is fine grained and subhedral. The hornblende is euhedral and as much as 1 mm. in length. Alteration to chlorite, magnetite, and, less commonly, calcite is present in most grains. The minor accessories are magnetite, apatite, and zircon.

Lithic fragments in the Hells Mesa Formation are light brown pieces of porphyry less than 4 cm. long. Alteration in the form of chlorite, calcite and clay give the fragments a greenish color.

The groundmass, which is generally highly argillized, of the quartz latite is commonly devitrified to cristobalite and feldspar. Flow banding of the groundmass around the phenocrysts is only slightly developed and can only be observed microscopically.

Volcanoclastic sedimentary rocks interbedded in the upper portion of Hells Mesa Formation are restricted to within a 2.5 mile area south and southeast of North Baldy Peak. At North Baldy Peak the sedimentary rocks are approximately 30 feet thick, and become progressively thinner to the south. The boulder-size clasts at North Baldy Peak grade to sand-size clasts at the southern limit of exposure in sec. 31, T. 3S., R. 3W.

Sixmile Canyon Andesite. The Sixmile Canyon andesite is a thick sequence of blue-gray, amygdaloidal, porphyritic andesite flows with local, interbedded sedimentary rocks near the base. The Sixmile Canyon andesite is the equivalent of Brown's (1972, p. 46-47) porphyritic andesite flows. The plagioclase phenocrysts average 0.8 mm. in length, which is slightly smaller than the average of the plagioclase phenocrysts in the middle Spears Formation. Volcanoclastic conglomerate and mud flow breccia at the base of the Sixmile Canyon andesite are a heterolithic composite of quartz latite, latite and andesite fragments with no obvious sorting or bedding. They are exposed only in South Canyon northwest of Buck Peak.

An isolated outcrop of finely laminated limestone is exposed east of Timber Peak in sec. 9, T. 4S., R. 3W. The stratigraphic position of the limestone is difficult to determine because of the talus and plant coverage, but it appears to be interbedded with the andesites. The limestone outcrop is small, covers an area of 50 feet by 15 feet, and is not exposed anywhere else in the study area. In thin section, the limestone contains laminae of subround quartz grains less than 0.1 mm. in length interbedded with micritic limestone. No fossils or organic material are present.

A thin section of typical andesite reveals phenocrysts of plagioclase composing as much as 60 percent of the rock, embedded in a felty, fine-grained matrix of plagioclase with lesser amounts of pyroxene and magnetite (Fig. 14). The euhedral plagioclase phenocrysts are labradorite (An_{57}), which are as much as 3 mm. in length but average 0.8 mm. The grains have undergone alteration to clay, sericite, and calcite. The pyroxene is as much as 2 mm. in size, averaging 0.5 mm., and is altered to magnetite, chlorite, and calcite.

<u>Sawmill Canyon Formation</u>. The Sawmill Canyon formation is a multiple flow, compound cooling unit consisting of crystal-poor, rhyolitic ash flow tuffs interbedded with andesite flows and a basal volcanoclastic sandstone. The unit crops out in a discontinuous band on the western and southern flanks of the study area from west of North Baldy Peak, south to Sawmill Canyon and east to Sixmile Canyon (Fig. 4). It overlies the Hells Mesa Formation to the north and the Sixmile Canyon andesite to the south. The Sawmill Canyon formation is lithologically

Figure 14. Photomicrograph of an andesite from the Sixmile Canyon andesite.--Plagioclase (P) crystals in a fine-grained groundmass of feldspar, magnetite and pyroxene. Crossed nicols, X 3.

similar to the tuffs of Bear Springs and the tuff of Allen Well in the southern Bear Mountains (Brown, 1972, p. 31-49).

Deal and Rhodes (in press) describe a 2100 foot thick section of rhyolitic ash flows in the A. L. Peak area of the northern San Mateo Mountains that they consider to be the source area for at least part of the A. L. Peak Formation. The Sawmill Canyon formation in the central Magdalena Mountains is a sequence of gray, crystal-poor ash flow tuffs that are lithologically and stratigraphically similar to the A. L. Peak Formation exposed in the San Mateo Mountains. Exposures from the San Mateo Mountains to the Magdalena Mountains are not continuous due to Late Cenozoic block faulting, downdropping the Mulligan Gulch area (Fig. 2), and subsequent cover of the volcanic rocks by Quaternary sediments. Fission track dates from sphenes (Smith and others, in press) place the age of the A. L. Peak Formation from the San Mateo Mountains at 31.8 m.y. ± 1.7 m.y. Age dating of the Sawmill Canyon formation from the Magdalena Mountains will be necessary in order to definitely correlate with the A. L. Peak Formation of the San Mateo Mountains. Therefore, the Sawmill Canyon formation in the central Magdalena Mountains is tentatively correlated with the A. L. Peak Formation of the San Mateo Mountains until their equivalency can be established.

The Sawmill Canyon formation is poorly exposed in the central Magdalena Mountains with the best outcrops occurring on the ridge between Hop Canyon and Patterson Canyon, west of North Baldy Peak in sec. 18, T. 3S., R. 3W. The thickness of the Sawmill Canyon formation in the central Magdalena Range is from 800 to 1200 feet. The unit thickens considerably in Sawmill Canyon and at the head of Ryan Hill Canyon, south of the study area.

The Sawmill Canyon formation west of North Baldy Peak in sec. 18, T. 3S., R. 3W. contains 125 feet of dark-gray volcaniclastic sedimentary rocks that were at least partly derived from the underlying Hells Mesa Formation. The sand-size fragments of quartz, lithic fragments, and feldspar are well bedded and show cross-bedding and graded bedding. Minor channeling into the Hells Mesa Formation suggests a fluvial origin. In Sixmile Canyon west of Buck Peak (Fig. 3), similar sedimentary rocks are also at the base of the Sawmill Canyon formation overlying the Sixmile Canyon andesite. The sandstone contains quartz, feldspar, and a variety of lithic fragments embedded in a fine-grain, iron-stained, quartz-rich matrix.

Fine-grained andesite flows, 50 feet thick, overlie the volcanoclastic rocks in sec. 18, T. 3S., R. 3W. Samples of the andesite flows contain phenocrysts of plagioclase as much as 1 cm. in length in a matrix of fine-grained plagioclase, pyroxene, and magnetite. Minor silica veinlets cut the andesite. The andesite flow is overlain by a crystal-poor, quartz-poor, highly foliated ash flow that is 200 to 500 feet thick. The ash flow is gray and is moderately to densely welded with flattened pumice that gives the rock a strong foliation pattern (Fig. 15). Total crystal content is less than 10 percent. The phenocrysts are euhedral sanidine less than 2 mm. in length with minor amounts of quartz or plagioclase. Lineation due to the elongation of pumice or flow folds around phenocrysts or pumice fragments is well developed. The rock weathers to gruss.

Figure 15. Photomicrograph of a rhyolite from the Sawmill Canyon formation.--Sanidine (S) crystals in a fine-grained, highly foliated groundmass. Crossed nicols, X 3.

A dark-gray, fine-grained to prophyritic andesite flow unit, 400 to 600 feet thick, overlies the ash flows. The aphanitic flows are compact with an abundance of small, red hematitized phenocrysts of pyroxene. The porphyritic flows are vesicular and contain up to 50 percent plagioclase phenocrysts as long as 3 mm. The uppermost ash flow unit of the Sawmill Canyon Formation is a foliated rhyolite containing as much as 15 percent crystals of quartz, sanidine, plagioclase and biotite. Limited exposures and weathering of the ash flow to nearly vertical cliffs make any detailed study difficult.

South Baldy Peak Andesite. The South Baldy Peak andesite consists predominately of vesicular, fine-grained andesite flows, and minor interbedded ash flows and epiclastic sediments. The unit crops out at South Baldy Peak, the highest peak in the Magdalena Range. The exposures are restricted to the southwestern portion of the study area, in Sawmill Canyon, where talus slopes and complex faulting make any interpretation of the stratigraphy difficult. The thickness of the South Baldy Peak andesite may be a maximum of 1500 feet. This thickness, however, could represent an exaggerated thickness because of normal faulting in the Sawmill Canyon area. The stratigraphic position of the South Baldy Peak andesite can be seen south of Langmuir Laboratory, at which place it overlies the Sawmill Canyon formation. At the northern limit of exposure in Baldy Canyon the andesite flows are in fault contact with the Hells Mesa Formation. The Timber Peak rhyolite overlies the South Baldy Peak andesite.

The aphanitic, dark-gray andesite flows are best exposed at South Baldy Peak and on the slopes west of Timber Peak. The andesites contain vesicles, which commonly are filled with calcite or quartz. Phenocrysts of plagioclase crystals, and pyroxenes converted to hematite, are present, but they are rare.

Isolated exposures of ash flows and sandstone interbedded with andesite crop out south and east of Langmuir Laboratory in Sawmill Canyon. Large talus cones derived primarily from the overlying Timber Peak rhyolite prevent the lateral correlation or determination of stratigraphic position of the ash flows and sandstone within the South Baldy Peak andesite.

The sandstone of the South Baldy Peak andesite is white to pink, well bedded, ranges from 2 to 12 cm. thick and is resistant to weathering. Angular to rounded sand-size grains ranging from 0.02 mm. to 4 mm. in length comprise the sandstone. Quartz is generally the major constituent, but lesser amounts of feldspar and light-colored, fine-grained rock fragments are also present.

Ash flows are less common than the sandstone with which they are interbedded. The ash flows are reddish-brown to gray and contain phenocrysts of feldspar, quartz and biotite in a microgranular dense groundmass. A prominent foliation pattern is developed by the alignment of flattened pumice and lithic fragments.

In thin section, the andesite consists of irregular interwoven microlites of plagioclase (Fig. 16). Euhedral plagioclase rarely reaches 0.5 mm. in length, averaging approximately 0.2 mm. Magnetite varying as much as 10 percent of the rock is present interstitially and as alteration products of pyroxene. The vesicles are commonly filled with calcite, chlorite or quartz.

Figure 16. Photomicrograph of an andesite from the South Baldy Peak andesite.--Fine-grained plagioclase, pyroxene, and magnetite and calcite-filled (C) vesicle. Crossed nicols, X 3.

Timber Peak Rhyolite. The Timber Peak rhyolite represents the youngest volcanic rock in the study area. It caps the highest elevations in the central Magdalena Range, and forms a crescent shaped outcrop pattern beginning at the ridge 1 mile west of North Baldy Peak, south to Langmuir Laboratory, east to Timber Peak and Buck Peak, and north to Water Canyon Mesa (Fig. 4, in pocket). The unit overlies the Sawmill Canyon formation to the north in Hop Canyon and the South Baldy Peak andesite to the south at Langmuir Laboratory. The Popotosa Formation unconformably overlies the Timber Peak rhyolite at Water Canyon Mesa and near Langmuir Laboratory.

The Timber Peak rhyolite is tentatively correlated with the Potato Canyon Formation exposed in the San Mateo Mountains (Deal and Rhodes, in press) based on lithologic similarity and stratigraphic position. Late Cenozoic block faulting and cover by Quaternary sediments prevent direct correlation by continuous outcrops between the San Mateo Range and the Magdalena Mountains. An age date of 30.3 m.y. ± 1.6 m.y. by fission track from sphenes has been obtained from the Potato Canyon Formation in the San Mateo Mountains (Deal and Rhodes, in press), but no dating has been done on the Timber Peak rhyolite in the Magdalena Mountains.

The Timber Peak rhyolite in the central Magdalena Mountains is a multiple flow sequence of compactly welded rhyolitic ash flows. The rock is characterized by its grayish-red-purple color, "moonstone" sanidine, bronze-colored biotite, and foliation. The foliation is the result of bands of light-colored, coarse-grained mixtures of cristobalite and feldspar surrounded by finer-grained, reddish-purple layers of glass. The formation varies from a crystal-poor to crystal-rich tuff with quartz, sanidine, and biotite being the most common phenocrysts. Fine-grained andesite flows locally interfinger with the tuff at the northwest limit of exposure of the Timber Peak rhyolite in sec. 18, T. 3N., R. 3W. The total thickness of the Timber Peak rhyolite in the central Magdalena Mountains is as much as 650 feet and may be considerably thicker in the Water Canyon Mesa area.

Viewed microscopically, the Timber Peak rhyolite is composed primarily of a cristobalite and sanidine matrix and 20 to 40 percent phenocrysts (Fig. 17). Sanidine and quartz are the dominant crystals and compose as much as 38 percent of the rock with biotite and traces of plagioclase making up the remainder of the phenocrysts. The phenocrysts range in size from less than 0.1 mm. to 1.5 mm. and average approximately 0.8 mm. The crystals are subrounded and broken. Lithic fragments are rare, but consist of rocks composed of intergrowths of cristobalite and feldspar. Some of the sanidine exhibits a perthitic texture and locally forms spherulites. Inclusions of South Baldy Peak andesite are present locally near the base of the unit. Biotite is in various stages of alteration to magnetite. The feldspars as a whole are fresh, but locally are altered to clay and minor sericite. Excellent flow banding is displayed by the bands of hematized glassy zones alternating with light colored, coarser-grained zones of cristobalite and feldspar.

Tertiary Intrusive Rocks

The oldest Tertiary intrusive rock is a volcanic neck, which intruded the Hells Mesa Formation during Oligocene time. Following the

Figure 17. Photomicrograph of a rhyolite from the Timber Peak rhyolite.--Individual flow bands consisting mainly of sanidine (S) and quartz (Q) are distinguished by the presence or absence of hematized groundmass. Crossed nicols, X 3.

emplacement of the Timber Peak rhyolite, the youngest unit in the Datil Group, the Magdalena area underwent a period of extensional faulting along a north-northwest trending structural zone. Stocks and dikes intruded the north-northwest-trending fault zone during Late Oligocene in the central Magdalena Mountains as well as in the Magdalena mining district. The stocks are monzonite to granite in composition and have been dated as ranging from 28 to 30.5 m.y. in age (Weber, 1971). The dike rocks can be classified into three major types, which in order of decreasing age are: 1) mafic 2) latite-monzonite, and 3) white rhyolite. The aplite dikes reported by Loughlin and Koschmann (1942, p. 40) in the Magdalena mining district were not found in the central Magdalena Mountains.

Dikes are spatially associated with stocks in the Magdalena Mountains. The mafic dikes in the Magdalena mining district are concentrated within 1 mile of the exposed stocks (Chapin, personal communication). The latite-monzonite dikes/stock association is best illustrated in the central Magdalena Mountains where the dikes are abundant adjacent to the Water Canyon stock (Fig. 4). White rhyolite dikes are restricted to the Nitt and Anchor Canyon stocks in the Magdalena mining district (Loughlin and Koschmann, 1942, Plate 2), and die out beyond the southern limits of the exposed stocks.

<u>Volcanic Neck</u>. A topographically prominent rhyolitic volcanic neck crops out in sec. 33, T. 3N., R. 3W. (Fig. 4). The volcanic neck intrudes and extends 90 feet above the exposed surface of the Hells Mesa Formation. The rhyolite is composed of quartz phenocrysts in a fine-grained, highly foliated matrix. Excellent columnar jointing is

exhibited by the volcanic neck and outward-dipping attitudes of the foliation are present near the base changing to nearly vertical dips at the top. The neck is crudely cylindrical and has a maximum diameter of 900 feet. No radial dikes are associated with the volcanic neck.

An age of Middle Oligocene or younger is suggested by cross-cutting relationships and possible Hells Mesa Formation inclusions in the volcanic neck. Gray to black, fine-grained volcanic fragments are present. The volcanic fragments are as long as 3 cm., subrounded, and are most common near the base of the volcanic neck, becoming rare towards the top. The alignment of the more elongate fragments provides the rock with a flow structure. The intruded Hells Mesa Formation shows very little disruption, distortion or compaction. No thermal effects were noticed surrounding the neck.

Mafic Dikes. Fine-grained mafic dikes in the central Magdalena Mountains were intruded along a north-northwest-trending fault zone before and after the emplacement of the Late Oligocene stocks. The mafic dikes are equivalent in composition to the lamprophyre dikes in the Magdalena mining district (Loughlin and Koschmann, 1942, p. 43), where the dikes are most abundant within and near exposed stocks.

The mafic dikes are most common within a 1 mile radius of the exposed stocks in the Magdalena mining district. The area of most abundant mafic dikes in the central Magdalena Mountains is in sec. 21, T. 3S., R. 3W. (Fig. 4) on the north side of North Fork Canyon. This is also the area of the greatest concentration of latite-monzonite dikes and white rhyolite dikes.

The mafic dikes range in width from 2 to 20 feet and are generally less than 200 feet long. The average trend is N. 10° W. but varies from N. 5° E. to N. 45° W.; the dips are from 70° east to vertical. Topographically, the dikes are depressed slightly owing to their more rapid weathering relative to the surrounding country rock. The wall rocks adjacent to the dikes are characteristically bleached and are rarely silicified. Goethite staining and goethite-calcite veinlets in the mafic dikes, extending locally some 30 feet into wall rocks, are a common occurrence, particularly in the North Fork Canyon area.

In hand specimen, the mafic dike rocks are dark green, fine grained, rarely porphyritic, and contain as much as 10 percent magnetite. The oxidation of the magnetite to goethite has resulted in a rusty brown stain on the weathered surfaces. Plagioclase grains are present in the slightly coarser samples. The porphyritic varieties contain phenocrysts consisting of plagioclase, pyroxene, hornblende, and biotite. Quartz is present in some dikes.

Viewed microscopically, the groundmass consists predominately of felty plagioclase microlites with interstitial magnetite, pyroxene, and apatite (Fig. 18). Alteration of the plagioclase to clay and the pyroxene to calcite and chlorite is common. The phenocrysts are as much as 3 mm. in length and euhedral. The labradorite phenocrysts are altered to clay, sericite, and calcite. The ferromagnesian phenocrysts are totally to partially replaced by calcite, chlorite, or magnetite.

Latite-Monzonite Dikes. Porphyritic latite-monzonite dikes are the next youngest in the central Magdalena Mountains and cut the mafic dikes at a number of localities in North Fork Canyon. The

Figure 18. Photomicrograph of a mafic dike of andesitic composition.--Plagioclase (P) crystals with lesser amounts of pyroxene and magnetite in a fine-grained matrix. Crossed nicols, X 3.

latite-monzonite dikes are spatially associated with the Water Canyon stock, becoming less abundant with increased distance from the stock (Fig. 4). The latite-monzonite dikes crop out from 3 miles south of the Water Canyon stock in Copper Canyon and Water Canyon to 2.5 miles north of the stock in Garcia Canyon and Jordan Canyon. The dikes are exposed 2 miles west of the Water Canyon stock, which is bordered on the east by the N. 35° W.-trending fault zone and the Water Canyon fault zone. Latite-monzonite dikes as well as white rhyolite and mafic dikes are present in the northeast portion of the Magdalena Mountains.

The latite-monzonite dikes intrude the Late Oligocene north-northwest-trending fault zone and some of the dikes crop out continuously for over 1 mile in North Fork Canyon. The dikes are sinuous, dipping 70° east to vertical. The thickness of the dikes varies from 25 to 75 feet. The outcrop breadth of some of the dikes adjacent to the Water Canyon stock is greater than 75 feet. Many of the latite-monzonite dikes stand out in relief by as much as 30 feet above the surrounding country rock, especially in North Fork Canyon. Silicification, argillization, and limonite staining of the intruded country rock are sporadic and limited to a few feet from the dike.

A large isolated latite-monzonite dike crops out in the northwest portion of the study area in sec. 18, T. 3S., R. 3W. at the head of Patterson Canyon and continues N. 10° E. to Chihuahua Gulch in the Magdalena mining district. The intrusion was originally mapped as a sill by Loughlin and Koschmann (1942). However, the nearly vertical intrusion cross-cuts both the Spears Formation and the Paleozoic sedimentary rocks substantiate and therefore must be considered a dike. The dike is as wide as 300 feet and is truncated on the south by a north-trending Late Cenozoic fault.

Hand specimens of the latite-monzonite dikes are characterized by their grayish-green color weathering to a yellow brown; by phenocrysts of feldspar commonly over 10 mm. in length; by chloritized biotite and hornblende; by rounded, glassy, quartz grains; and by a fine-to-medium-grained matrix. The rock weathers to spheroidal forms, different from the blocky character of the weathered white rhyolite dikes. Quartz is present interstitially and as subround discrete grains and composes as much as 5 percent of the rock. Some orthoclase is graphically intergrown with the quartz. Magnetite is commonly oxidized to limonite and gives the rock a yellow-brown color.

In thin section, the texture of the latite-monzonite dikes is porphyritic, with a groundmass that varies from felty in the latitic types to a fine phaneritic in the monzonitic types (Fig. 19). The phenocrysts are orthoclase, plagioclase, or clinopyroxene composing as much as 20 percent of the rock. Orthoclase crystals are as long as 30 mm., subhedral, and commonly show normal zoning and resorption along their boundaries. Alteration of the orthoclase includes both clay and sericite, and is generally not as intense as in the plagioclase grains. The andesine phenocrysts are as much as 4 mm. in length, euhedral, and show strong alteration to clay, sericite, and calcite. Augite, which occurs in the latitic varieties both as phenocrysts and as a component of the groundmass, is as much as 3 mm. in length and generally highly altered to calcite, chlorite, and magnetite. The feldspars compose

Figure 19. Photomicrograph of a latite-monzonite dike of monzonitic composition.--Orthoclase (O), plagioclase (P), and quartz (Q) in a chloritized groundmass. Crossed nicols, X 3.

approximately 80 percent of the rock with plagioclase in excess of potash feldspar. Biotite, which alters to chlorite and magnetite, is the dominant ferromagnesian mineral in the monzonitic varieties making up to 15 percent of the rock. Accessory minerals include zircon, apatite and euhedral sphene as long as 2 mm.

White Rhyolite Dikes. White rhyolite dikes are the youngest intrusions in the central Magdalena Mountains. They cut the mafic and latite-monzonite dikes as well as the Water Canyon stock. The white rhyolite dikes also intrude the Late Oligocene, north-northwest-trending fault zone, locally using the same conduits as the mafic or latite-monzonite dikes. The white rhyolite dikes have been described in the Magdalena mining district (Loughlin and Koschmann, 1942, p. 43-44) where they occupy the roof zones of the exposed stocks. The dikes are common in the central Magdalena Mountains where they are localized primarily along north-northwest-trending faults, and the N. 80° W.-trending North Fork Canyon fault zone (Fig. 4). The white rhyolite dikes exhibit, as well, a northeast-trending zone beginning north of South Baldy Peak and extending to the Water Canyon stock as defined by a number of short, sinuous, north-trending dikes.

The most prolific white rhyolite diking in the central Magdalena Mountains is in North Fork Canyon, particularly in secs. 21 and 28, T. 3S., R. 3W. (Fig. 4). In North Fork Canyon, the white rhyolite intrusions have penetrated parallel to the bedding of the strata or crop out as circular plugs. Parallel dike swarms are exposed almost continuously from North Baldy Peak to the southern limit of mapping at the head of Ryan Hill Canyon, a distance of 6 miles. North of the study area in the

Magdalena mining district, the white rhyolite dikes are rare, but three north-northwest-trending dikes have penetrated the exposed stocks in the northern part of the district. The white rhyolite dikes range from 10 to 200 feet in width and commonly stand out as "chinese wall", topographic features rising as much as 75 feet above the terrain. The resistance to erosion generally is the result of the high silica content of the white rhyolite dikes such as the dike which intruded the North Fork Canyon fault zone which contains 76 percent silica.

The white rhyolite dikes are distinguished in the field by their grayish-white color; by a compact, fine-grained, locally flow banded texture (Fig. 20); by round quartz grains; and by feldspar phenocrysts. Pyrite is present, commonly as much as 0.3 percent. Weathering of the pyrite produces limonite psuedomorphs and a yellow-brown stain on the rock. Phenocrysts of quartz and feldspar, up to 2 cm. long, make up as much as 20 percent of the white rhyolite dikes.

In thin section, the white rhyolite dikes have a distinctive porphyritic to glomeroporphyritic texture in a compact, microgranular groundmass (Fig. 21). The phenocrysts are generally orthoclase and quartz and compose 10 to 20 percent of the rock. The orthoclase is subhedral to euhedral, as much as 1.5 mm. in length, and shows weak to moderate alteration to clay and sericite. Graphic intergrowths with quartz are common. Quartz is subround, as much as 2 mm. in length, and shows minor resorption along its edges. Minor subhedral to euhedral plagioclase of An_8 to An_{12} composition also forms phenocrysts as large as 1 mm. The plagioclase is altered to clay and sericite. The

Figure 20. Highly flow-banded white rhyolite dike exposed in sec. 21, T. 3S., R. 3W.

Figure 21. Photomicrograph of a white rhyolite dike.--Orthoclase (O) and quartz (Q) phenocrysts in a fine-grained groundmass. Crossed nicols, X 3.

groundmass is a fine-grained mixture of quartz and feldspar and is highly sericitized. Silicification is also a common alteration effect.

Hydrothermal alteration and mineralization, which followed the emplacement of the white rhyolite dikes, are spatially related to the intrusions. Alteration includes the silicification of the dikes, silication of the adjacent country rock, and mineralization in the intruded rocks and on the walls of the dikes. Silicification of the dikes primarily is seen in the northern part of the study area. Silication and lead-zinc-copper mineralization in the Kelly Limestone adjacent to a white rhyolite dike occurs in the North Baldy Peak area. Gold in gold-bearing pyrite occurs on the walls of the white rhyolite dikes at the divide between Mill Canyon and Copper Canyon. The presence of white rhyolite dikes in mineralized areas has previously been reported by Loughlin and Koschmann (1942) in the Magdalena mining district and by Titley (1958) in the Linchburg mine.

Water Canyon Stock. The Water Canyon stock is located on the north side of the mouth of Water Canyon, 2.5 to 3 miles east of North Baldy Peak in secs. 14, 15, 22, and 23, T. 3S., R. 3W. (Fig. 4). The dimensions of the stock are 3700 feet east-west by 3000 feet north-south. The stock is exposed due to Late Cenozoic block faulting along the N. 35° W. marginal fault zone and the N. 25° E. Water Canyon fault zone. Kalish (1953, p. 8) considered the stock to be a Precambrian granite similar to the basement rocks exposed in the Magdalena mining district.

An age date obtained by the author and Charles Chapin of the New Mexico Bureau of Mines supports a Late Oligocene age for the stock. The K-Ar date was obtained from biotite in a sample taken from the center of the Water Canyon stock. The date of 30.5 m.y. ± 1.2 m.y. corresponds closely with the dates on the exposed stocks in the Magdalena mining district and suggests a major episode of stock intrusion from 28.0 to 30.5 m.y. affecting the central and northern Magdalena Mountains.

Field data supporting a Late Oligocene age for the Water Canyon stock are as follows. The stock is compositionally similar to the Nitt and Anchor Canyon stocks in the Magdalena mining district, which have been dated at 28.0 and 28.3 m.y., respectively (Weber and Bassett, 1963). The stock does not intrude Paleozoic sedimentary rocks or the Oligocene volcanic rocks, but latite-monzonite dikes, which are compositionally similar and genetically related to the Water Canyon stock, penetrate the entire stratigraphic section. The North Fork Canyon fault zone, which is Early Oligocene in age, has been truncated by the Water Canyon stock. Furthermore, the gray to buff color and the rounded-terrain of the Water Canyon stock is in contrast to the pink to red color and angular terrain of the Precambrian granite.

A mafic dike cuts the Water Canyon stock. The mafic dike is the grayish-green type commonly found in the central Magdalena Mountains. The felty groundmass as well as the few phenocrysts of plagioclase have been altered to carbonate, chlorite, or epidote. A white rhyolite dike also has intruded the Water Canyon stock.

There is no apparent alteration of the Precambrian country rock surrounding the stock, possibly reflecting the unreactive nature of the argillite. The only mineralization present is along a N. 40° W.-trending silicified zone that cuts the stock with minor lead, zinc and copper.

There is minor mineralization in the Kelly Limestone adjacent to the Water Canyon stock.

The Water Canyon stock is a fresh, coarse-grained, buff to pink quartz monzonite porphyry with a well-developed north-trending joint system. Epidote commonly is developed along these joint surfaces. Numerous inclusions of Precambrian argillite are in the stock, particularly along the contact. The stock is fine-grained adjacent to the Precambrian contact. Microscopically, the quartz monzonite consists primarily of orthoclase, plagioclase (An_{25} to An_{33}) and quartz. Hornblende and biotite are the common ferromagnesian minerals with minor pyroxene. The rock has a porphyritic texture with phenocrysts of orthoclase as long as 5 cm. The orthoclase shows zoning and only minor alteration to sericite or carbonate.

Buried Stocks. Field evidence suggests the presence of buried stocks underlying the Linchburg-North Baldy Peak area and the North Fork Canyon area in secs. 21 and 28, T. 3S., R. 3W. Each area is discussed and evidence is presented supporting the assertion of the presence of the buried stocks.

The presence of a buried stock underlying the Linchburg mine area in the southern portion of the Magdalena mining district has been previously predicted. Loughlin and Koschmann (1942, p. 32, 48, 105) noted the extensive silicification of Precambrian argillite and Paleozoic limestone along fault zones and the high temperature mineral assemblage in the Linchburg mine as suggestive of a stock underlying the area. Austin (1960, p, 16) considered the abundance of scheelite in the vicinity of the Linchburg mine along the north-northwest-trending Young

American fault zone as strongly suggestive of a stock underlying the area. Titley (1958) studied the skarn mineral assemblage adjacent to the north-northwest-trending faults in the Linchburg mine and suggested that the area is underlain by a buried stock. A similar skarn-type alteration and silicification is present at North Baldy Peak southeast of the Linchburg mine in the study area.

Mafic, latite-monzonite, and particularly white rhyolite dikes are spatially associated with the exposed stocks and may be further evidence for buried stocks in the Magdalena Mountains. Titley (1958) described a white rhyolite dike in the Linchburg mine, and the writer has mapped white rhyolite dikes in the North Baldy Peak area, suggesting the possibility of a buried stock.

The Linchburg-North Baldy Peak area is within a north-northwest-trending zone of horst blocks extending from the Magdalena mining district into the central Magdalena Mountains. Loughlin and Koschmann (1942) called this zone of horsts the main ore zone as it contained the greatest concentration of metals in the Magdalena mining district. Horst blocks of Precambrian argillite uplifted against Paleozoic sedimentary rocks outline the main ore zone in the Magdalena mining district and this zone of horsts continues south-southeastward. In the central Magdalena Mountains a long, narrow block of Madera Limestone and lower Spears Formation has been uplifted within the Hells Mesa Formation and the upper Spears Formation and is a continuation of the horst blocks from the Magdalena mining district.

The presence of a buried stock underlying the Linchburg-North Baldy Peak area has been verified recently by the release of information previously held confidential by mining companies (Chapin, and others, in preparation). Drill holes and a crosscut in the Linchburg mine penetrated the outermost portion of an igneous rock. Little is known of the size or shape of the intrusion, but it is similar in texture and composition to the exposed stocks, and suggests that it is part of the same magmatic event. According to Chapin and others (in preparation), the intrusion exposed in the crosscut in the Linchburg mine is a quartz monzonite porphyry containing argillized plagioclase phenocrysts and fresh, rounded grains of potash feldspar and quartz in a granophyric matrix of potash feldspar and quartz. Chlorite and calcite alteration are common in the intrusion. The presence of disseminated pyrite and sparse copper mineralization in the Linchburg stock differs from the exposed stocks in the Magdalena Mountains.

Another stock may underly the North Fork Canyon area in secs. 21, and 28, T. 3N., R. 3W. approximately 1.5 miles southeast of North Baldy Peak. The proposed existence of the stock is based primarily on the large number of dikes in the North Fork Canyon area, differing from the Linchburg mine area where dikes are rare at the surface. Nowhere in the Magdalena mining district or in the central Magdalena Mountains is the diking as prolific as in the North Fork Canyon area.

White rhyolite dikes as well as mafic and latite-monzonite dikes are present in North Fork Canyon. White rhyolite sills and plugs are locally present in North Fork Canyon. The intrusive rocks are exposed in numerous stream channels suggesting that the Paleozoic sedimentary rocks and the Tertiary volcanic rocks exposed on the surface are only a thin veneer overlying a larger intrusion at depth. In all directions from the area of greatest intrusion in the south half of sec. 21, T. 3S., R. 3W., the exposed intrusions decrease in number and occurrence. South of sec. 21, T. 3S., R. 3W. a few latite-monzonite and white rhyolite dikes trend north-northwest for 3 miles (Fig. 4).

Dike rocks are spatially associated with the exposed stocks in the Magdalena Mountains. The existence of the recently verified buried stock in the Linchburg-North Baldy Peak area was suggested by the white rhyolite dikes as well as the high temperature mineralization and alteration present in the area. Intense faulting may have allowed the movement and concentration of magma from a distant source area. The abundant diking in North Fork Canyon, and particularly the white rhyolite dikes, may suggest a buried stock underlying secs. 21 and 28, T. 3S., R. 3W. Furthermore, the white rhyolite dike swarms exposed to the southern limits of mapping may suggest a larger intrusion underlying the central Magdalena Mountains.

Tertiary Sedimentary Rocks

Popotosa Formation. The prominent red cliffs that form the east wall of Water Canyon for more than 1.5 miles are made up of Miocene sedimentary rocks of the Popotosa Formation. Kalish (1953, p. 22) called this unit a rhyolite agglomerate in the Water Canyon Mesa area. Also, much of the flat, rubbly area between South Baldy and Langmuir Laboratory is underlain by the Popotosa Formation. Stacy (1968, p. 42) called the rock between South Baldy Peak and Langmuir Laboratory a laharic breccia. The Popotosa Formation lies unconformably on the Timber Peak rhyolite and represents the beginning of Tertiary sedimentation in the central Magdalena Mountains following Late Oligocene faulting and intrusion. Denny (1940) originally described the Popotosa Formation as a basal unit of the Sante Fe Group which was deposited in middle Miocene to Pliocene time.

The Popotosa Formation is not present in the Magdalena mining district. In the southern Bear Mountains, the Popotosa Formation is interbedded with the upper one-third of the La Jara Peak Formation, a unit which Chapin (1971-a) dated at 23.8 m.y. The Popotosa Formation in the southern Bear Mountains consists of siltstones and mud flow breccias composed mainly of detritus from the La Jara Peak Formation. Brown (1972, p. 66) called the unit the fanglomerate of Dry Lake Canyon (Fig. 9), a facies of the Popotosa Formation (Bruning, 1973). In the southern part of the Puertecito quadrangle, north of the Magdalena Mountains, Tonking (1957, p. 34) designated the extensively exposed series of poorly sorted volcanic-rich siltstone, sandstone, and conglomerate as the Popotosa Formation.

According to Bruning (1973, p. 107) the deposition of the Popotosa Formation began about 24 m.y. during the emplacement of the upper third of the La Jara Peak Formation. Deposition of the Popotosa Formation continued locally in the Socorro, New Mexico area to approximately 11 m.y. as dated by a trachyandesite flow and associated tuffs overlying the Popotosa Formation on Socorro Peak (Burke and others, 1963). The Popotosa Formation is overlain by 14 m.y. rhyolite flows (Weber and Bassett, 1963) west of the central Magdalena Mountains indicating deposition of the Popotosa Formation ceased earlier in the Magdalena area.

Kottlowski, Weber, and Willard (1969) considered the Santa Fe Group of central New Mexico to have formed under a similar depositional environment to the Gila Conglomerate of southwestern New Mexico and southeastern Arizona. Both rock units resulted from erosion of the existing highlands and deposition in adjacent basins. The age of the Gila Conglomerate as determined by vertebrate fossils from lake beds south of Benson, Arizona is Late Pliocene to Early Pleistocene (Heindl, 1962).

The Popotosa Formation in the central Magdalena Mountains is an alluvial fan deposit consisting of well indurated sandstone, conglomerate, and breccia. Exposures of the Popotosa Formation are limited to the Water Canyon Mesa (Fig. 22) and to the area between South Baldy Peak and Langmuir Laboratory.

No clasts of La Jara Peak Formation, Paleozoic sedimentary rocks, or Precambrian argillite and granite have been found in the Popotosa Formation of the central Magdalena Mountains. In the central Magdalena Mountains the Popotosa Formation is red to reddish-brown and is composed of angular to subrounded clasts of Datil volcanic rock, primarily the Timber Peak rhyolite. The clasts range in size from less than 1 inch to over 2.5 feet and are cemented by an iron-stained, siliceous groundmass. The rock has a vuggy or frothy texture and contains cavities as much as 9 feet in diameter in Water Canyon Mesa. The Popotosa Formation is approximately 400 feet thick at Water Canyon Mesa, but thins rapidly eastward within 0.5 miles to a depositional pinchout on the Timber Peak rhyolite surface. At the crest of the range between South Baldy Peak and Langmuir Laboratory, the Popotosa Formation forms a thin veneer of blocky fragments.

Figure 22. Well indurated and conglomeratic Popotosa Formation exposed at Water Canyon Mesa.

In the Water Canyon Mesa area, a thin, reddish-black, vesicular lava flow is interbedded with the Popotosa Formation. Minor plagioclase and pyroxene phenocrysts are in the aphanitic groundmass. The lava flow is exposed only in a few stream beds and cannot be traced laterally.

The size, shape, and composition of the detritus composing the Popotosa Formation varies from place to place. Between South Baldy Peak and Langmuir Laboratory the Popotosa Formation contains subround to angular fragments as much as 2.5 feet in length of Timber Peak rhyolite, the South Baldy andesite, and minor Sawmill Canyon formation. All of these volcanic units crop out in the adjacent area. In the Water Canyon Mesa area, the clasts in the Popotosa Formation are much more heterolithic and variable in size and roundness.

Rocks similar to the Popotosa Formation crop out 3 miles southwest of South Baldy Peak in the Mule Shoe Ranch area. The clastic rocks southwest of South Baldy Peak are not as coarse or angular as the Popotosa Formation at the crest of the range. The lithology of the fragments in the clastic rocks southwest of South Baldy Peak is more heterolithic and does not contain as many clasts of South Baldy Peak andesite and Timber Peak rhyolite as the Popotosa Formation at the crest of the range. The clastic rocks in the Mule Shoe Ranch area are interbedded with Late Oligocene volcanic rocks approximately 29-30 m.y. in age and are considered correlative with the Bear Trap Canyon Formation described by Deal and Rhodes (in press). 26 m.y.

Quaternary Sediments

The Quaternary sediments of the central Magdalena Mountains consist of pediment gravels, talus, and alluvium. The unconsolidated sediments cover large areas, particularly in the South Baldy Peak-Langmuir Laboratory area, concealing the underlying geology.

Pediment Gravel. Poorly consolidated material mapped as pediment gravel is exposed on the eastern flank of the Magdalena Range and in a considerable portion of Water Canyon. The pediment gravel includes gently sloping alluvial fans on the margins of the range that dip eastward into the Snake Ranch Flats (La Jencia Basin), and the boulder-covered slopes in Water Canyon.

The bedrock areas demonstrably influence the type of debris found in the pediment gravels. To the north and west of Water Canyon, Precambrian argillite, Oligocene volcanic rocks, and Paleozoic sedimentary rocks predominate in the gravel. To the south and east of Water Canyon eroded material from the Popotosa Formation and Oligocene volcanic rocks make up the debris.

Where the pediment gravel is only a thin veneer covering the underlying formations, windows of possible bedrock are present. A good example is the Water Canyon manganese mine on the east slopes of Water Canyon (Fig. 4) that was developed in the Timber Peak rhyolite and is surrounded by pediment gravels. Whether such an exposure is bedrock or a slumpblock from higher elevations is difficult to determine.

Talus. Material mapped as talus includes debris slides and landslides that are extensively developed at the higher elevations, particularly in the southern portion of the study area. Large blocks of Timber Peak rhyolite, over 300 feet in length, slump down steep, unstable slopes. Rock glaciers, some up to 0.5 mile in length, cover considerable portions of the slopes in South, Sixmile, Sawmill, Hardy, Bear, Mill, Hop, and Patterson Canyons (Fig. 3).

Clasts of ash flow tuffs derived for the most part from the Hells Mesa Formation and the Timber Peak rhyolite are the main constituents of the talus. The Timber Peak rhyolite supplied material to the talus cones covering many of the southern and western slopes of the range. House-size blocks of Timber Peak rhyolite around Langmuir Laboratory have slumped into Sawmill Canyon. Talus covered, westward-dipping slopes between North Baldy Peak and South Baldy Peak are composed of Hells Mesa Formation.

Alluvium. Alluvium comprises Holocene stream gravels that have been deposited in the major drainages cutting bedrock, talus, and pediment gravels. In Water Canyon west of Water Canyon Mesa, the stream has been entrenched into an older stream terrace. Intermittent runoff still supplies material, which is deposited in the valleys today.

STRUCTURE

Interpretation of the structures in the Magdalena Mountains has been hampered by a lack of field data. Reconnaissance mapping and traverses were made outside the central Magdalena Mountains in order to better understand the structure of the range. The additional data available from Brown (1972) in the southern Bear Mountains, the compilation study by Chapin and others (in preparation) of the Magdalena-Tres Montosas area as well as Loughlin and Koschmann's (1942) study on the Magdalena mining district allow for a better understanding of the local and regional structures.

Structural features in the central Magdalena Mountains can be considered under five major headings: Precambrian and Paleozoic structure, Laramide structure, Early to Middle Oligocene faults, Late Oligocene faults, and Late Cenozoic block faults. Each type has been influential in the structural history of the central Magdalena Mountains and is discussed separately.

Precambrian and Paleozoic Structure

The Precambrian argillite in general strikes northwest and dips steeply to the east. No folds are present in the argillite. The Precambrian granite cross cuts the dip of the argillite. Granite dikes generally less than 2 feet wide fill northeast-trending fractures and commonly intrude parallel to the bedding of the argillite.

Mississippian strata unconformably overlie the Precambrian. The Mississippian-Pennsylvanian contact is a conformable surface that shows no structural disruption. Unconformities in the Pennsylvanian sedimentary rocks are reported by Loughlin and Koschmann (1942, p. 56) in the Magdalena mining district. Loughlin and Koschmann (1942) stated there is an angular unconformity between the Madera Limestone of Pennsylvanian age and the Abo Formation of Permian age in the Magdalena mining district.

The Paleozoic strata strike northwest and dip 10° to 30° west near North Baldy Peak but change to a west-trending strike and a southward dip of 30° to 55° at their southern limit of exposure in the central Magdalena Mountains. A series of upright anticlines and synclines with northwest to northeast trends are developed in the Paleozoic sedimentary rocks in the central Magdalena Mountains (Fig. 23, in pocket). Folds are also present in the Oligocene Spears Formation. North Fork Canyon and Copper Canyon occupy the hinge zone of anticlines and are separated by topographic ridges which are structural synclines. Spacing between the anticlines is approximately 1 mile. The structures plunge approximately 30° to the west beneath the unfolded Hells Mesa Formation.

Folds in the Paleozoic rocks and the Oligocene Spears Formation are restricted to the central Magdalena Mountains and are not present in the Magdalena mining district (Loughlin and Koschmann, 1942, p. 57). Spatially, folds in the Paleozoic rocks are limited to North Baldy Peak and to the south in the central Magdalena Mountains. The folds are developed on the downthrown side and south of the N. 80° W.-trending North Fork Canyon fault zone, along which oblique slip movement occurred.

Laramide Structure

The term "Laramide" has been applied to a period of large-scale, crustal disturbances during which many of the mountains and basins of the Rocky Mountain region were formed. Wilmarth (1938, p. 1149) defined the Laramide as beginning in Late Cretaceous time and ending in Early Tertiary time. As more structural data accumulate, it is increasingly evident that orogenic events presently ascribed to the Laramide did not begin nor end simultaneously in all parts of the Rocky Mountains. The limits and scope of the Laramide orogeny in west-central New Mexico can best be defined in terms of the time following the deposition of the Cretaceous Mesa Verde Group and before the deposition of the Eocene Baca Formation.

The Laramide uplift appears to have the shape of an elongate dome or anticline whose axis trends north-northwest in the Magdalena area. Loughlin and Koschmann (1942, p. 57) noted the general change in strike of the west-dipping pre-volcanic rocks, from N. 30° E. in the Granite Mountain area north of the Magdalena mining district to N. 15° W. in the main portion of the Magdalena mining district. At the southern limit of exposure in the central Magdalena Mountains, the Paleozoic rocks strike east-west and dip south. The east-dipping limb of the Paleozoic strata has been dropped into the subsurface by Late Cenozoic block faulting.

Early to Middle Oligocene Faults

A N. 80° W.-trending fault zone of Early Oligocene age is exposed from North Baldy Peak east to Water Canyon paralleling the north side of North Fork Canyon (Fig. 23). The fault zone dips from steeply to the south to vertical. The North Fork Canyon fault zone is composed of two west-trending, parallel, normal faults with the south side down.

The strike-slip component of apparent !! offset along the North Fork Canyon fault zone is determined by the Kelly Limestone, which is truncated at North Baldy Peak and crops out 2.5 miles to the east in the Water Canyon area. The strike-slip displacement along the north fault of the North Fork Canyon fault zone is greater than the south fault. The dip-slip component of offset across the North Fork Canyon fault zone is 1400 feet as measured by the difference in elevation of the Kelly Limestone at North Baldy Peak and in Water Canyon.

The North Fork Canyon fault zone is covered by younger volcanic rocks west and south of North Baldy Peak. The northern fault of the North Fork Canyon fault zone is exposed in the west half of sec. 18, T. 3S., R. 3W. at the south fork of Patterson Canyon (Fig. 4). Erosion has removed the younger volcanic rocks and exposed the Spears Formation and the fault zone. To the west the North Fork Canyon fault zone is truncated by a Late Cenozoic, north-trending block fault. Mapping by Wilkinson (Chapin, and others, in preparation) in the Tres Montosas area of the Gallinas Range, approximately 10 miles west of Magdalena, has resulted in the recognition of a west-northwest-trending fault zone, which may be a westerly continuation of the North Fork Canyon fault zone.

The North Fork Canyon fault zone developed before the deposition of the Hells Mesa Formation and after the emplacement of the Spears Formation. The Spears Formation was truncated by the North Fork Canyon fault zone whereas the Hells Mesa Formation overlaps the North Fork Canyon fault zone west and south of North Baldy Peak. Furthermore, dikes related to the Late Oligocene intrusions, which affected the entire Magdalena Mountains, were intruded across as well as along the North Fork Canyon fault zone.

Following the emplacement of the Hells Mesa Formation, a west-trending, south-dipping, normal fault developed from South Baldy Peak east to South Canyon (Fig. 23). Evidence for the existence of the South Canyon fault is based on topography, displacement of strata, and alteration adjacent to the fault. North of the fault in South Canyon, the Hells Mesa Formation is exposed and truncated against the younger Sixmile Canyon andesite. Pyrite and quartz veinlets occur in the Hells Mesa Formation adjacent to the South Canyon fault but are not present in the Sixmile Canyon andesite. The South Canyon fault is truncated by a north-trending, Late Cenozoic block fault to the east and is covered by the Timber Peak rhyolite.

The South Canyon fault was reactivated between South Baldy Peak and Timber Peak after the emplacement of the Sawmill Canyon formation. The displacement of strata is evidence for the second period of faulting. Hells Mesa Formation north of the fault is truncated against South Baldy Peak andesite on the south. The South Canyon fault west of South Baldy Peak is covered by Timber Peak rhyolite.

Late Oligocene Faults

Following the emplacement of the Datil Group, the central Magdalena Mountains were cut by a set of north-northwest-trending faults of Late Oligocene age (Fig. 23). These faults trend from N. 10° E. to N. 30° W. with a dominant trend of N. 10° W. The north-northwest-trending faults dip at angles from 60° E. to nearly vertical with normal, down to the east movement. Offset along the faults varies from 0 to 200 feet. The faults are present in a north-northwest-trending zone as wide as 4 miles in the central Magdalena Mountains.

The recognition of the north-northwest-trending faults is difficult in volcanic rocks, particularly the Hells Mesa Formation, due to the lack of marker horizons with which to determine offset. North-northwest-trending dikes aid in the recognition of the north-northwest-trending fault zone into which they intrude.

The mafic, latite-monzonite, and white rhyolite dikes show a dominant north-northwest trend. The N. 10° W. alignment is particulary well demonstrated by the white rhyolite and latite-monzonite dikes, some of which crop out continuously for over 1 mile as in secs. 17, 20, and 29, T. 3S., R. 3W. (Fig. 4). White rhyolite dikes aligned with the north-northwest-trending fault zone are exposed almost continuously for a length of 6 miles in the central Magdalena Mountains.

A north-northwest-trending horst block consisting of Madera Limestone and lower Spears Formation has been uplifted within the Hells Mesa Formation and the upper Spears Formation (Fig. 23). The horst block is approximately 6500 feet long (north-south) and 300 to 600 feet wide. The horst block is exposed south of North Baldy Peak in secs. 17 and 20, T. 3S., R. 3W.

Another north-northwest-trending horst consisting of Precambrian argillite is exposed in sec. 18, T. 3S., R. 3W. (Fig. 23). This block is a continuation of a horst mapped in the Magdalena mining district and is part of an intermittant series of north-northwest-trending horsts exposed from the southern limit of the Nitt stock through the Linchburg-Grand Ledge area (Loughlin and Koschmann, 1942, Plate 2).

The north-northwest-trending faults continue north and south of the central Magdalena Mountains. The faults extend southward into Sawmill Canyon and Ryan Hill Canyon, both of which have a pronounced north-northwest topographic trend. The north-northwest-trending faults continue northward into the Magdalena mining district as expressed by horsts and faults along which the Kelly Limestone has been mineralized. Replacement deposits in the Kelly Limestone along north-northwest-trending faults occur in the Linchburg mine and the North Baldy Peak mine, 4 miles south of the exposed stocks in the Magdalena mining district. Also, dikes and the Nitt and Anchor Canyon stocks in the Magdalena mining district have a north-northwest orientation.

In the southern Bear Mountains north of the Magdalena Mountains, Brown (1972) recognized the continuation of the north-northwest-trending faults, which have cut the area into a number of westward tilted blocks progressively stepped down to the east. Tonking's (1957) map of the Puertocito quadrangle shows the north-northwest-trending faults continuing northward from Brown's area.

Late Cenozoic Block Faults

The major uplift of the central Magdalena Mountains occurred along Late Cenozoic block faults. Movement occurred along three major fault zones (Fig. 23); the N. 25° E.-trending Water Canyon fault zone, the N. 35° W.-trending boundary fault zone on the northeast side of the Magdalena Range, and a north-trending fault zone on the west side of the

Magdalena Range. The north-trending fault zone, bordering the west side of the central Magdalena Mountains, caused large, down to the west displacements, and forms the east border of the Mulligan Gulch graben. Movement along the N. 35° W.-trending fault zone, bordering the northeast side of the central Magdalena Mountains, caused down to east displacement and formed the Snake Ranch Flats graben. The N. 25° E. Water Canyon fault zone separates the upthrown Precambrian to Tertiary rocks to the northwest from the downthrown Tertiary rock at Water Canyon Mesa to the southeast.

The north-trending fault zone on the west side of the central Magdalena Range is distinguished by the alignment of springs, displacement of strata, silicified fault zones, and steep slope gradients. Two parallel faults make up the north-trending fault zone bordering the west side of the range. The east fault lies within the study area, but the west fault is 0.5 mile outside the study area. The easternmost fault of the north-trending fault zone continues northward from the central Magdalena Mountains passing through the town of Kelly and continues along the east flank of Granite Mountain (Chapin, and others, in preparation). Displacement of strata along this fault in sec. 18, T. 3S., R. 3W. is estimated to be from 1000 to 1500 feet.

The Water Canyon fault zone consists of two parallel normal faults dropping blocks down to the east. The faults trend N. 25° E. in Water Canyon and control the drainage pattern. The west fault dies out to the southwest in sec. 3, T. 4S., R. 3W. The east fault is continuous from Water Canyon to the head of Ryan Hill Canyon at the southern limit of mapping. Aerial photographs indicate that this fault may continue south into Ryan Hill Canyon and into the southern portion of the range.

The Miocene Popotosa Formation is truncated and exposed on the downthrown side of the Water Canyon fault zone. Furthermore, the Popotosa Formation contains only fragments of the Datil volcanics, and not of Paleozoic or Precambrian rocks presently exposed on the northwest and upthrown side of the Water Canyon fault zone. This suggests that the Paleozoic and Precambrian rocks were not exposed during the time of Popotosa sedimentation, and that present day exposure is due to Late Cenozoic uplift along the Water Canyon fault zone after the deposition of the Popotosa Formation.

The amount of displacement along the Water Canyon fault zone is greatest at the mouth of Water Canyon and decreases southward. At the mouth of Water Canyon in sec. 14, T. 3S., R. 3W., Precambrian rocks are exposed on the upthrown side, and Tertiary rock are exposed on the downthrown side. Farther to the south, as in sec. 3, T. 3N., R. 3W., Tertiary rocks of different age are in fault contact. The stratigraphic displacement at the mouth of Water Canyon is in excess of 3000 feet.

The northeast portion of the central Magdalena Mountains is bordered by a N. 35° W.-trending fault zone, which has dropped the adjoining Snake Ranch Flats down to the east. Sanford (1968), on the basis of gravity studies, interpreted the Snake Ranch Flats to be a northwest-trending structural depression probably resulting from normal step-faulting and possible tilting along a northwest-trending fault zone. The presence of scarplets cutting alluvial fans as evidenced in the field, and particularly from aerial photographs, indicate movement has been continuing. Aerial photographs also indicate the N. 35° W.-trending fault zone appears to truncate the N. 25° E. Water Canyon fault zone and continues to the southeast forming the eastern boundary of Water Canyon Mesa.

The displacement on the N. 35° W.-trending fault zone is difficult to determine and varies depending on the location where the estimate is made. North of Water Canyon, Precambrian rocks are exposed on the upthrown side of the N. 35° W. fault zone at the northern end of the range, whereas from Water Canyon south, Tertiary volcanic and sedimentary rocks are exposed on the upthrown side of the N. 35° W. fault zone. The area north of Water Canyon was also uplifted by the Water Canyon fault zone. The best estimate of displacement for the N. 35° W.-trending fault zone should be made south of the Water Canyon fault zone. As alluvium covers the strata on the downthrown side of the N. 35° W. trending fault zone, the exact displacement is indeterminate, but probably exceeds 2000 feet.

REGIONAL ALTERATION

Alteration in the central Magdalena Mountains is dependent upon the composition of the host rock, and is closely confined to intrusive contacts along which altering solutions were able to migrate. Alteration is of the same type as found in the Magdalena mining district, but is not as intense nor as widespread. Five types of alteration are present in the central Magdalena Mountains; propylitization, silicification, lime-silicate, argillization, and sericitization. Hematite alteration, which is so striking in the southern Magdalena mining district (Loughlin and Koschmann, 1942), is rarely present in the central Magdalena Mountains. Variations in distribution, controls, and importance to mineralization will be discussed under each type of alteration.

Rock exposed within and along the Late Oligocene, north-northwest-trending structural zone reveal the greatest amount and development of alteration. Along this zone two areas have undergone the major alteration in the central portion of the range (Fig. 24, in pocket). One area to the north is adjacent to the Magdalena mining district and overlies one known buried intrusion in the Linchburg-North Baldy area and a postulated buried stock in the North Fork Canyon area. Alteration dies out southward but increases in intensity in the southernmost part of the study area in sec. 33, T. 3S., R. 3W., and secs. 4 and 5, T. 4S., R. 3S. at the intersection of the north-northwest-trending zone with the transverse South Canyon fault zone.

Propylitization

Propylitic alteration occurs over a wide area and at great distances from known areas of mineralization. Calcite, chlorite, and epidote characterize propylitic alteration. Pyrite is rarely present. Propylitic alteration in the central Magdalena Mountains is best developed in the Spears and Hells Mesa Formations within the north-northwest-trending structural zone. Calcite veinlets with geothite are present locally in the Paleozoic rocks, particularly in the area overlying the postulated North Fork Canyon stock.

The Spears Formation, consisting of sedimentary rocks, andesite flows, and latitic ash flows, is the most susceptible to propylitic alteration. Feldspar and ferromagnesian minerals in the Spears Formation are commonly altered to calcite and locally to epidote or chlorite. Propylitic alteration is particularly common adjacent to a fault zone or an intrusive contact. The alteration of the Spears Formation is not as intense as described by Brown (1972) in the southern Bear Mountains or in the Magdalena Mining district, where the pervasive propylitization led Loughlin and Koschmann (1942) to believe that four separate but laterally equivalent units existed (Fig. 9). The lower Spears Formation, normally purple in color, is a greenish gray where propylitically altered. The middle or "turkey track" member of the Spears Formation appears to be very reactive to altering solutions, probably because of its vesicular or porous nature and chemical composition. Calcite, epidote, and chlorite are common alteration products of plagioclase and ferromagnesian minerals of the middle Spears Formation throughout the study area.

The upper Spears and the Hells Mesa Formation show propylitic alteration most commonly south and southeast of North Baldy Peak in secs. 17 and 20, T. 3S., R. 3W. (Fig. 24). The southernmost exposure of the Hells Mesa Formation, in secs. 3 and 4, T. 4S., R. 3W., has also undergone propylitic alteration. Chlorite and epidote occur in the more intense zones of alteration and give the ash flows of the upper Spears and Hells Mesa Formation a greenish tinge.

Silicification

The addition of silica to the country rock of the Magdalena Mountains is controlled by the proximity of the altered rocks to intrusions or fault zones. Silicification occurs either as partial to total replacement of the host rock or as veins. The jasperoid type replacement in the Kelly Limestone at North Baldy Peak and in the Magdalena mining district has undergone two periods of silicification. The first period was characterized by the massive replacement of the Kelly Limestone by silica, forming the jasperoid. The rock was later fractured, and then drusy quartz filled the fractures. No mineralization accompanied the massive replacement, but barite, fluorite, minor sulfides, and gold were introduced with the second stage of silicification.

Jasperoid replacement is restricted to the North Baldy Peak area and is a continuation of widespread silicification present in the southern Magdalena mining district (Loughlin and Koschmann, 1942). The uppermost portion of the Kelly Limestone is preferentially replaced by jasperoid along the crest of the range north of North Baldy Peak in sec. 17, T. 3S., R. 3W. and north of the North Fork Canyon fault zone. South of the North Fork Canyon fault zone and along the north-northwest-trending fault zone in sec. 20, T. 3S., R. 3W., the middle Spears Formation is totally replaced by jasperoid in a zone 150 feet east-west by 250 feet north-south (Fig. 24). Hematite accompanies the jasperoid alteration, but there is no mineralization present. The hematite association with silicification was also recognized by Loughlin and Koschmann (1942, p. 54) in the volcanic rocks of the southern Magdalena mining district. A horst block exposing Precambrian argillite, uplifted along the Grand Ledge fault (Loughlin and Koschmann, 1942) northwest of North Baldy Peak in sec. 18, T. 3S., R. 3W., is totally replaced by silica. The jasperoid replacement of the Precambrian argillite only occurs in the North Baldy Peak area. Loughlin and Koschmann (1942), Titley (1958), and Lovering (1962) stated that the jasperoid replacements in the Magdalena mining district were equivalent in time and origin to the lime-silicate alteration, but were farther away from the source of the fluids.

Silicification is also present in the Timber Peak mine area (secs. 4 and 5, T. 4S., R. 3W.) in the form of veinlets penetrating the upper Spears Formation and the Hells Mesa Formation (Fig. 24). Pyrite, locally as much as 0.5 percent, is found in the quartz veinlets. The area is within the north-northwest structural zone at its intersection with the east-west South Canyon fault. Silica veinlets cut only the Spears and Hells Mesa Formations on the upthrown side of the South Canyon fault and not the younger Sixmile Canyon andesite exposed on the downthrown side of the fault.

A second period of silicification is indicated by silica veins occurring along Late Cenozoic block fault zones. The main western boundary fault of the Magdalena Mountains is silicified in a number of localities along the western edge of the central Magdalena Mountains. The Popotosa Formation has been silicified adjacent to the Late Cenozoic fault south of South Baldy Peak, and the Hells Mesa Formation is replaced by silica along the Water Canyon fault zone.

Lime-Silicate

A small pyrometasomatic deposit developed in the Kelly Limestone is located 0.2 mile southeast of North Baldy Peak (Fig. 24). It is located at the intersection of the north-northwest-trending structural zone with the North Fork Canyon fault zone. The minerals present are diopside, andradite, quartz, allophane, galena, sphalerite, pyrite, minor chalcopyrite and malachite. A white rhyolite dike is the only intrusive present and appears to have preceded the alteration and the mineralization.

A pyrometasomatic deposit similar to the North Baldy Peak skarn is located in the Linchburg mine in the Magdalena mining district where Titley (1958) studied silication as a control of ore deposition. Titley (1958) determined the lime-silicate alteration to be spatially associated to fault zones that were the conduits for the mineralizing and altering solutions. Silicate and sulfide zones developed from a fault outward are: 1) 1-2 feet of intense silicification; 2) approximately 15 feet of garnetized limestone (andradite); 3) a wide transition zone of andradite, hedenbergite, sphalerite, and galena constituting the main ore bodies; 4) a narrower zone of pyroxenated limestone containing galena and sphalerite; and 5) a broad fringe of hematized limestone which generally gives way to marbleized limestone (Titley, 1958, p. 58-78). Zone 3 from the Linchburg mine most closely resembles the skarn deposit at the North Baldy Peak mine.

Argillization

Clay alteration of feldspar is common throughout the study area. Hypogene alteration of feldspar is generally restricted to rocks close to faults or intrusive contacts whereas supergene alteration occurs over a wider area. Local bleached or argillized zones are adjacent to fault zones or next to mafic or white rhyolite dikes at the surface.

The most intense argillic alteration is a zone 400 feet east-west by 750 feet north-south in sec. 21, T. 3S., R. 3W., 1.5 miles southeast of North Baldy Peak (Fig. 24). The northwest-trending zone is almost entirely within the middle Spears Formation. The presence of boxwork structures after pyrite as well as goethite staining of the rock indicate there was a high amount of iron sulfide present before oxidation. The acidic solutions resulting from the oxidation of the pyrite may have resulted in clay alteration of the rocks.

Sericitization

Sericite alteration of feldspar is common in the intrusive and volcanic rocks in the study area. The white rhyolite dikes, in particular, are characterized by a quartz-sericitic groundmass and quartz-sericite replacement of the feldspars. As much as 0.5 percent pyrite is associated with the quartz-sericite alteration. The association of white rhyolite dikes with the exposed stocks and the suggestion that they used the same conduits as the mineralizing and altering solutions would argue for the alteration to be hydrothermal.

ECONOMIC GEOLOGY

The study area overlaps by $\frac{1}{4}$ mile the southeast corner of the Magdalena mining district, which produced over $52 million in zinc, lead, copper and silver (Chapin and others, in preparation). Most of the production came from limestone replacement deposits in the Kelly Limestone adjacent to the southern exposure of the Oligocene stocks and adjacent to the Late Oligocene north-northwest-trending fault zone wherein lies the main ore zones. Most of the copper ore was produced from the northern part of the Magdalena mining district between the Nitt stock and the town of Kelly. Zinc-lead replacement deposits occur along the north-northwest main ore zone in the Linchburg mine, 2 miles south of any exposed stock.

The presence of a buried stock underlying the southern portion of the district has been predicted for many years (Loughlin and Koschmann, 1942, Titley, 1958, and Austin, 1960). One of the purposes for mapping in the central Magdalena Mountains was to better evaluate the possibility of the presence of a buried stock in the southern Magdalena mining district. The presence of another mineralizing center in the southern portion of the district would make limestone replacement deposits or a porphyry copper deposit definite targets for exploration.

Mineral Occurrence

Although mining interest in the central Magdalena Mountains began in 1869 (Jones, 1904, p. 126), there has been only minor mineral production. Smith (private report, 1953) reported as of 1952 only a total of 784 tons of ore, which included 0.21 oz. of Au/ton, 2.26 oz. of Ag/ton, 0.81 percent Cu, 7.09 percent Pb, and 39 percent Zn, being produced from the central Magdalena Mountains. In recent years there has been virtually no mining. The occurrence of mineralization in the central Magdalena Mountains has been briefly described by Wells (1918, p. 71-74) and Lasky (1932, p. 46-53), who called it the Water Canyon mining district.

Mineralization present can be divided into four genetic types: 1) zinc, lead and copper, 2) gold, 3) manganese, and 4) barite and fluorite. The Water Canyon stock is barren of mineralization as are the rocks in contact with the intrusion.

The base metal deposits of zinc, lead, copper and silver occur as limestone replacement deposits, primarily in the Kelly Limestone along fault zones. The reputation of the Kelly Limestone as the ore-bearing horizon in the Magdalena mining district resulted in numerous, mostly non-productive prospect pits in the Kelly Limestone throughout the central Magdalena Mountains.

Mineralization and alteration in the central Magdalena Mountains are best developed in the North Baldy Peak area. The North Baldy Peak mine located on the southeast shoulder of North Baldy Peak in sec. 17, T. 3S., R. 3W., (Figure 24, in pocket) is developed in an andradite-diopside skarn of the Kelly Limestone with associated zinc, lead, and copper sulfides. No estimate of the tonnage produced is available, but the extent of the workings would indicate production was minor. The skarn occurs at the intersection with the northern fault of the North

Fork Canyon fault zone and a north-northwest-trending fault, which is occupied by a white rhyolite dike.

The El Tigre mine is located in sec. 21, T. 3S., R. 3W. (Fig. 24), approximately 1 mile southeast of North Baldy Peak. The mine was a small scale operation developed along the southern fault of the North Fork Canyon fault zone. There is no skarn alteration present but silicified fault zones at the contact of the Madera Limestone with the Precambrian argillite are present. Mineralization consists of galena, sphalerite, barite, and rarely chalcopyrite. White rhyolite and latite-monzonite dikes are common in the area but no major intrusive body is exposed.

The southernmost exposure of any appreciable amount of mineralization is found in the Buckeye mine developed in the Kelly Limestone and located on the divide between Copper Canyon and Water Canyon in sec. 27, T. 3S., R. 3W. (Fig. 24). Southeast of the Buckeye mine, the Kelly Limestone is truncated and downthrown on the east side of the Water Canyon fault zone. According to Smith (private report, 1953), small pockets of ore confined to the Kelly Limestone were produced along fault zones in the Buckeye mine. Silicification of the limestone is the only alteration present. There is only one record of shipment in 1917 of 53 tons containing 0.02 oz. Au/ton, 2.79 oz. Ag/ton, and 5.57 percent copper. No other records of shipments can be traced directly to the Buckeye mine although minor production may have continued. Except for the Water Canyon stock located 1.5 miles to the north and local white rhyolite and latite-monzonite dikes, there are no major intrusions in the mine area.

South of the Paleozoic exposures, base metal mineralization is almost absent. Local traces of malachite are found along the north-northwest-trending faults, but, become absent in the southern part of the study area. Minor amounts of chrysocolla are found in prospect pits southwest of South Baldy Peak along fault zones.

Igneous intrusion and mineralization followed the emplacement of the Datil Group during Late Oligocene time. The stocks in the Magdalena mining district penetrated the volcanic rocks and may have risen to within 1000 feet of the surface. To the south the Water Canyon stock and the buried stocks underlying the Linchburg-North Baldy Peak area and North Fork Canyon stopped within the pre-volcanic rock surface. Erosion has uncovered both the stocks and the spatially associated mineralization in the Magdalena mining district. However, erosion has not uncovered the buried stocks in the central Magdalena Mountains where only sparse mineralization is present. Mineralization may be associated with buried stocks and exist in greater quantity with depth in the Paleozoic rocks underlying the volcanic rocks in the central Magdalena Mountains.

Gold and manganese occur in the south and east portion of the central Magdalena Mountains to the south and east of the zinc, lead, and copper mineralization. Siliceous gold veins are present at the crest of the range 3 miles south of North Baldy Peak in sec. 31, T. 3S., R. 3W. (Fig. 24). The gold occurs as a trace element and locally as specks less than 2 mm. in size within pyrite cubes that are on the silicified walls of a white rhyolite dike.

Reportedly, gold has also been mined from the Timber Peak mine in secs. 4 and 5, T. 4S., R. 3W., (Fig. 24) approximately 1.5 miles east-southeast of South Baldy Peak. According to Jones (1904, p. 127) gold and silver values were obtained in the early 1900's from limited production along fault zones. The mine is located at the intersection of the east-trending South Canyon fault and a north-northwest-trending fault. No visible mineralization is present but cross-cutting silica veinlets with pyrite oxidizing to goethite are present and restricted to the Hells Mesa Formation on the north side of the South Canyon fault. The lack of silica veinlets or goethite in the younger Sixmile Canyon formation on the south side of the South Canyon fault suggests that the silica and pyrite may have been introduced into the Hells Mesa Formation before the emplacement of the younger Sixmile Canyon volcanics.

The South Canyon fault developed after the extrusion of the Hells Mesa ash flow. Fumarolic activity associated with the terminal activity of the Hells Mesa ash flow eruption may have resulted in the emplacement of silica veinlets, pyrite, and possibly gold. It is difficult to determine whether the gold mineralization was introduced during the fumarolic activity along the South Canyon fault or during the main period of Oligocene mineralization along the north-northwest-trending structure. The mine workings are parallel to the north-northwest-trending structure suggesting that the gold mineralization was localized along the north-northwest-trending fault.

Manganese occurrences are common in the eastern and southern portion of the central Magdalena Mountains. A number of manganese mines developed along north-northwest-trending structures occur in the southern half of the range as well. A manganese mine located in sec. 26, T. 3S., R. 3W. (Fig. 24) of Water Canyon produced 854 tons of over 40 percent manganese from 1914 to 1918 (Wells, 1918, p. 72). The ore is mostly wad, but also contains some psilomelane and manganiferous calcite. The mine is developed in a block of Timber Peak rhyolite surrounded by Popotosa Formation debris fallen from the overhanging cliffs. The mineralization was emplaced along a Late Cenozoic northwest-trending fault that displaced the Popotosa Formation southeast of the Water Canyon mine. If this interpretation is correct, then the manganese mineralization is younger than the main period of Late Oligocene mineralization. The younger age corresponds with Pliocene dates for manganese mineralization obtained by Weber (1971) in the Luis Lopez manganese district located in the Chupedera Mountains, 10 miles east of the Magdalena Mountains. Only more detailed mapping and correlation of dated events will help to determine whether both areas were affected by the same period of manganese mineralization.

Barite occurs along fault planes throughout the central Magdalena Mountains. Barite is most common in the North Baldy Peak area where it is associated with minor amounts of fluorite. Minor amounts of barite occur along Late Oligocene faults and the walls of white rhyolite dikes south of the Paleozoic exposures. Barite veins, as wide as 3 feet, and quartz veinlets occur along the Water Canyon fault zone.

Controls of Mineralization

The factors which controlled mineralization in the central Magdalena Mountains were the same that affected the Magdalena mining district. A review of these factors is now presented in order to aid future mineral exploration.

The age of mineralization is Late Oligocene based on its association with the 28 to 30.5 m.y. stocks in the Magdalena Mountains. Mineralization, with the possible exception of manganese, was the last event to affect the area prior to the uplift of the Magdalena Mountains. Chapin (1971-a) reported a younger period of lead-silver mineralization cutting the 23.8 m.y. La Jara Peak Formation in the southern Bear Mountains. This second period of mineralization appears to be minor, and there is no evidence of it affecting the Magdalena Mountains.

Mineralization occurs primarily as limestone replacement deposits in the Mississippian Kelly Limestone, the first favorable horizon above the Precambrian rocks conducive to sulfide mineralization. The overlying Pennsylvanian quartzites, shales, and limestones locally contained minor ore and may have acted as a relatively impermeable capping forcing the solutions to move laterally through the Kelly Limestone.

The main structural control was the Late Oligocene, north-northwest-trending fault zone which controlled the emplacement of the Oligocene stocks and dikes and provided the conduits for the ascent of the hydrothermal solutions. The stocks intrude the north-northwest-trending fault zone and are not faulted by it. Intrusion into the north-northwest-trending zone caused the northerly alignment of the stocks in the Magdalena mining district (Loughlin and Koschmann, 1942, plate 2) and the N. 10° W. alignment of dike rocks, particularly the white rhyolite dikes that are common in the central Magdalena Mountains. The main ore zone containing zinc-lead mineralization in the Linchburg mine, 2 miles south of the exposed Oligocene stocks, parallels the north-northwest-trending structure. Other pre-existing structures such as the N. 80° W. North Fork Canyon structure appear to have aided in stock and dike emplacement.

The spatial association of the mineralization with the Oligocene stocks demonstrates the magmatic control of ore deposition. Future mineral exploration should be directed toward the finding of more stocks because of possible mineralization in the adjacent bedrock or in the intrusion itself.

Based on these controls certain guidelines can be used to define areas underlain by these stocks. The north-northwest-trending structural zone controlled the emplacement of the stocks and exploration should be carried out along this zone for potential buried stocks. White rhyolite dikes, because of their spatial association with exposed stocks in the Magdalena mining district (Loughlin and Koschmann, 1942, plate 2), may be surface indicators of buried stocks.

Alteration of the volcanic and sedimentary rocks can be ascribed to the exposed or postulated buried intrusions. Propylitic alteration is widespread in the Spears Formation in the Magdalena mining district but becomes more restricted along the north-northwest-trending structures in the central Magdalena Mountains. This decrease in alteration in the central Magdalena Mountains could signify distance from the source area or contrasting rock types. Jasperoid replacement of the Kelly Limestone is common in the Magdalena mining district but is present only in the North Baldy Peak area of the central Magdalena Mountains. The Precambrian argillite exposed in sec. 18, T. 3S., R. 3W.

is part of a north-northwest-trending horst block that is almost totally replaced by silica. This is the most complete alteration of the argillite anywhere in the Magdalena Mountains. Farther to the south, silica veins trending north-northwest cut the volcanics and locally totally replace them,(sec. 17, T. 3S., R. 3W., 0.5 mile southeast of North Baldy Peak, Fig. 24). Silicification becomes less common farther to the south.

Silication is possibly another indicator of a buried stock. Pyrometasomatic deposits occur adjacent to north-northwest-trending structures in the Linchburg-North Baldy Peak area, 2 to 3 miles south of the exposed stocks in the Magdalena mining district. The pyrometasomatic deposit in the Linchburg mine north of the study area and a small skarn deposit on the southeast limb of North Baldy Peak suggest a possible local source for the altering solutions. Both deposits may be the result of hydrothermal solutions emitted from an intrusion underlying the Linchburg-North Baldy Peak area. East and south of the Linchburg-North Baldy Peak area silication is absent. However, silicification is present in these areas suggesting a greater distance from the source of the altering solutions.

Zinc-lead-copper-silver mineralization occurs predominately in the northwest portion of the Magdalena Mountains whereas gold and manganese are mainly in the central Magdalena Mountains. Any zoning model is complicated by the presence of multiple plutons, exposed or inferred, each of which could be the source for local hydrothermal solutions. Nonetheless, a general zonation does appear to be present. Most of the copper mineralization is adjacent to the exposed stocks in the Magdalena mining district with local, minor occurrences farther to the south in the central Magdalena Mountains. Zinc-lead occur in limestone replacement deposits as far south as the Buckeye mine in the central Magdalena Mountains. The areas of greatest concentration of lead-zinc mineralization are adjacent to the Oligocene stocks and in the Linchburg mine. Tungsten is anomalously high in the vicinity of the Linchburg mine (Austin, 1960) occurring as scheelite in the pyrometasomatic ores along a north-northwest-trending fault. Minor values of gold occur in the ore and jasperoid deposits in the Magdalena mining district. Gold also occurs in siliceous veins cutting volcanic rocks in the central Magdalena Mountains, peripheral to the major zinc-lead-copper deposits in the northwest portion of the range. Silver is associated with the galena in the Magdalena mining district. Manganese mineralization is peripheral to the Magdalena mining district cutting volcanic rocks in the eastern and southern foothills of the Magdalena Mountains. Some of the manganese may be younger than the main period of zinc-lead-copper mineralization and, therefore, may represent a separate period of mineralization.

Two different source areas for mineralizing fluids are definable on the basis of alteration and mineral assemblages. The northern area is adjacent to the Nitt stock in the Magdalena mining district where a pyrometasomatic mineral assemblage with associated sulfide minerals extends from the Linchburg mine to the North Baldy Peak area overlapping into the central Magdalena Mountains. The Linchburg-North Baldy Peak area is considered to be a continuation of the main ore zone from the Magdalena mining district. Fluids from a buried stock underlying the Linchburg-North Baldy Peak area rose along the north-northwest-trending faults mineralizing the Kelly Limestone much the same way as in the northern area adjacent to the Nitt stock.

GEOLOGIC HISTORY

Precambrian to Middle Cenozoic

The deposition of impure argillaceous and quartzose sediments during Precambrian time was followed by a regional metamorphism resulting in the formation of argillite in the Magdalena area. The low-grade metamorphism could have been at least in part due to the intrusion of a granite. Tilting of the metasediments to the northeast marked the end of Precambrian orogenic activity.

Isopach and facies maps drawn by Kottlowski (1965) show that during Early and Middle Paleozoic time, central New Mexico was a positive area. It is presumed that the extensive erosion and levelling of the Precambrian terrain took place during this time. A marine basin existed in southwestern New Mexico during the Early and Middle Paleozoic, but not until the Mississippian Period did shallow epicontinental seas transgress northward across the Magdalena area, depositing the Kelly Limestone (Armstrong, 1963). Following the deposition of the Kelly Limestone, Mississippian seas withdrew toward the south, allowing widespread erosion to occur during Late Mississippian to Early Pennsylvanian time.

The geography of west-central New Mexico changed greatly in Pennsylvanian time (Kottlowski, 1965). Seas transgressed from the north depositing marine limestone, quartzose sandstone, and shale of the Magdalena Group. The 2350 foot thickness of Magdalena Group in the central Magdalena Mountains suggests that the Lucero-San Mateo Basin was one large, north-trending channelway instead of two distinct basins separated in the Magdalena area as proposed by Kottlowski (1965). In Early Permian time, terrestrial sedimentation ensued with the deposition of red shale, siltstone and sandstone of the Abo Formation.

No sedimentary record of Mesozoic strata exists in the Magdalena Mountains. Lithofacies and isopach maps (Kottlowski, 1965) indicate that Late Permian, Triassic, and Late Cretaceous strata were deposited in the Magdalena area, but erosion during Mesozoic and Tertiary time has removed them.

The Magdalena area is situated on the northwest flank of a major Late Cretaceous-Early Tertiary uplift (Chapin, and others, in preparation). The outline of this major Laramide uplift is poorly known and is determined by locating areas where the Eocene Baca Formation overlies the Upper Cretaceous Mesa Verde Group. Using this evidence, present data indicate the major Laramide uplift is bordered to the north in the Joyita Hills, to the west in southern Gallinas Range, to the east in the Socorro Mountains and to the south on the southwest flank of the San Mateo Mountains (Chapin, and others, in preparation).

Uplift and tilting of the Magdalena area during the Laramide orogeny were followed by erosion and beveling of the area during Eocene time. The removal of the Abo Formation in the Water Canyon area and the variable thickness of the Madera Limestone resulted from erosion during Eocene time.

Cenozoic volcanism began in the Magdalena area during Early Oligocene time with the deposition of Spears Formation, the basal unit of the Datil Group, approximately 37 m.y. ago. The lower member is a volcanoclastic deposit consisting entirely of debris derived from latitic and andesitic flow rocks of the Mogollon Plateau volcanic province to the south and southwest. Imbrication directions taken from clasts of Abo Formation within the unit indicate a direction of transport from the southwest. The deposition of the porphyritic andesite flow, which is the middle member of the Spears Formation in the Magdalena area, represents a temporary break in the sedimentation process that was renewed again in the upper Spears Formation. The latitic volcanic rocks in the upper Spears Formation represent the first emplacement of ash flows upon the Magdalena area.

Following the deposition of the upper Spears Formation, a N. 80° W.-trending fault zone developed, called the North Fork Canyon fault, which uplifted the northern portion of the Magdalena Mountains by 1400 feet. The emplacement of the Hells Mesa Formation followed the formation of the North Fork Canyon fault. Quartz latite ash flows probably moved northward from a source located south of the study area and possibly overlapping the southeast portion of the central Magdalena Mountains in the area between Timber Peak and Buck Peak (Fig. 3). The Hells Mesa volcanics filled the paleovalley south of the North Fork Canyon fault zone, eventually covering the escarpment. The erosion of the Spears Formation on the upthrown side of the escarpment resulted in the deposition of volcanoclastic sediments between the individual ash flows of the Hells Mesa Formation.

The speculated source area of the Hells Mesa Formation between Timber Peak and Buck Peak, which is covered by younger volcanics, is based on the following observations. The rapid increase in thickness of the Hells Mesa ash flows southward, from less than 200 feet west of North Baldy Peak at sec. 18, T. 3N., R. 3W. to 3850 feet, three miles south of North Baldy Peak, may indicate proximity to the source in the southern portion of the study area. The extrusion of the voluminous ash flows occurred along ring fractures which developed into faults following the collapse of the roof overlying the Hells Mesa magma chamber. The South Canyon fault is considered to be a ring fault which truncates the Hells Mesa Formation and allows volcanoclastics and andesite flows of the Sixmile Canyon andesite to fill the collapsed caldera overlying the source area of the Hells Mesa Formation.

The lack of megascopic lineation in the Hells Mesa Formation exposed in the central Magdalena Mountains prevented flow directions to be determined. However, in the southern Bear Mountains, north of the Magdalena Mountains, Brown (1972) determined from flow structures that the source area for the Hells Mesa Formation may have been to the south of the town of Magdalena.

The Sixmile Canyon andesite was probably deposited in a caldera that formed by collapse along ring faults such as the South Canyon fault following the eruption of the Hells Mesa ash flow. The steep, unstable walls of the caldera underwent caving and avalanching, depositing and filling the caldera with volcanoclastic sediments. A shallow, calm lake of limited aerial extent formed during this time on the caldera floor depositing minor limestone. Most of the filling of the caldera, however, was the result of the deposition of andesitic flows. There is no evidence for resurgency in the Hells Mesa caldera.

Pyroclastic volcanism in the central Magdalena Mountains was renewed with the emplacement of the Sawmill Canyon formation, and was in part derived from a source area located in the northern San Mateo Mountains, southwest of the Magdalena Mountains (Deal and Rhodes, in press). In the Sawmill Canyon area of the central and southern Magdalena Mountains, the Sawmill Canyon formation is exposed over a large area and increases greatly in thickness. The dip of the Sawmill Canyon formation in Sawmill Canyon varies from 45° east to nearly vertical and the strike is generally north. The widespread aerial distribution, the great thickness, and the steep dips of the Sawmill Canyon formation could indicate another source area located in the southern Magdalena Mountains and overlapping into the southwestern portion of the central Magdalena Mountains between Langmuir Laboratory and Timber Peak (Fig. 3).

Following the emplacement of Sawmill Canyon formation, the South Canyon fault between Timber Peak and South Baldy Peak was reactivated and downdropped the area south of the fault. Andesite lava flows coupled with minor ash flow tuffs and volcanoclastic sedimentary rocks composing the South Baldy Peak andesite filled the depression south of the reactivated South Canyon fault. The South Baldy andesite may have been deposited in a caldera formed by the collapse of the roof overlying the Sawmill Canyon formation magma chamber located in the southwest portion of the central Magdalena Mountains and into the southern Magdalena Mountains.

The final pyroclastic event that effected the central Magdalena Mountains was the emplacement of the Timber Peak rhyolite, whose source area is in the Mt. Withington area of the northern San Mateo Mountains

(Deal and Rhodes, in press). During Late Oligocene time the central Magdalena Mountains were faulted and tilted along a north-northwest-trending zone along which dikes and stocks intruded. These stocks range in age from 28 to 30.5 m.y. giving a minimum age for the formation of the fault zone as well as the cessation of pyroclastic volcanism. Associated with the Oligocene igneous activity was the mineralization and alteration that affected the Magdalena mining district and the central Magdalena Mountains.

Late Cenozoic

The Late Cenozoic geologic history of the Magdalena Mountains can best be determined by the depositional and post-depositional history of the Popotosa Formation. The Popotosa Formation resulted from the erosion of the highlands, producing the bordering coarse-grained sediments of alluvial fan deposits intertonguing with the finer-grained sediments of playa deposits (Fig. 25). The original size and shape of the Popotosa Basin can be only partially reconstructed, but according to Bruning (1973, p. 108), it extended north-south at least 30 miles from the Magdalena Mountains to the Ladron Mountains and at least 35 miles in an east-west direction. The deposition of the Popotosa Formation began about 24 m.y. ago during the emplacement of the La Jara Peak Formation in the Bear Mountains and ceased in the Socorro Peak area before the extrusion of flows approximately 11 m.y. ago.

The original Popotosa Basin was modified by uplift of the ancestral Magdalena Mountains during the time of Popotosa deposition. Uplift of the ancestral Magdalena Mountains began after the emplacement of the

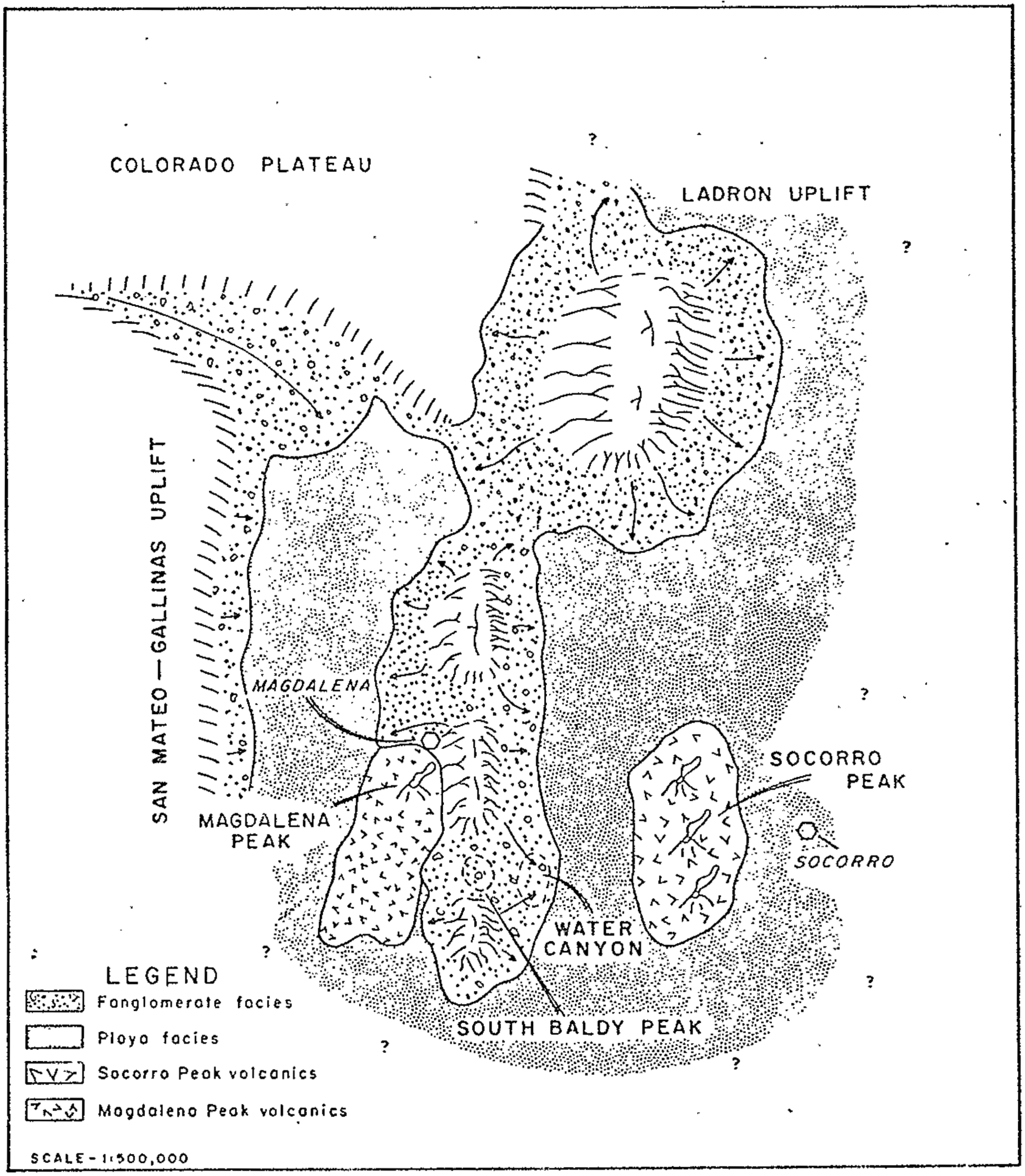

Figure 25. West-central New Mexico during Middle to Late Miocene time showing the distribution of volcanic rocks and facies of the Popotosa Formation according to Bruning (1973).

La Jara Peak Formation. Detritus derived from the dip slope of La Jara Peak Formation capping the north end of the Magdalena Mountains was shed north and west forming the distinctive fanglomerate of Dry Lake Canyon, a facies of the Popotosa Formation (Bruning, 1973, p. 94). A long period of erosion ensued until finally the Magdalena Mountains were buried beneath their own debris. Rhyolite lavas from a vent at Magdalena Peak overlie fanglomerates of the Popotosa Formation west of the Magdalena Mountains (Fig. 25). These 14 m.y. flows (Weber, 1971) suggest that degradation of the Magdalena Mountains occurred at least up until that time.

Following the deposition of the Popotosa Formation in Miocene time, west-central New Mexico underwent a tectonic adjustment after the cessation of volcanic activity in the Socorro Peak area about 11 m.y. (Fig. 26). The original Popotosa Basin was subsequently disrupted by a number of intrabasin horsts such as the Magdalena Mountains, the Bear Mountains, and the Socorro-Lemitar Mountains.

Uplift of the Magdalena Mountains may have begun shortly after the emplacement of the 14. m.y. Magdalena Peak rhyolitic lavas, and almost certainly after the 11 m.y. Socorro Peak lavas. The entire Popotosa Formation was removed from the northern Magdalena Mountains exposing Paleozoic and Precambrian rocks. The north end of the Magdalena Mountains was located at least as far north as Bear Springs canyon along the east side of the present Bear Mountains (Bruning, 1973) but was downfaulted north of U.S. Highway 60 along the San Augustin lineament (Fig. 26).

Continued uplift in Pliocene and Quaternary time has allowed the erosion of much of the Popotosa Formation in the central Magdalena

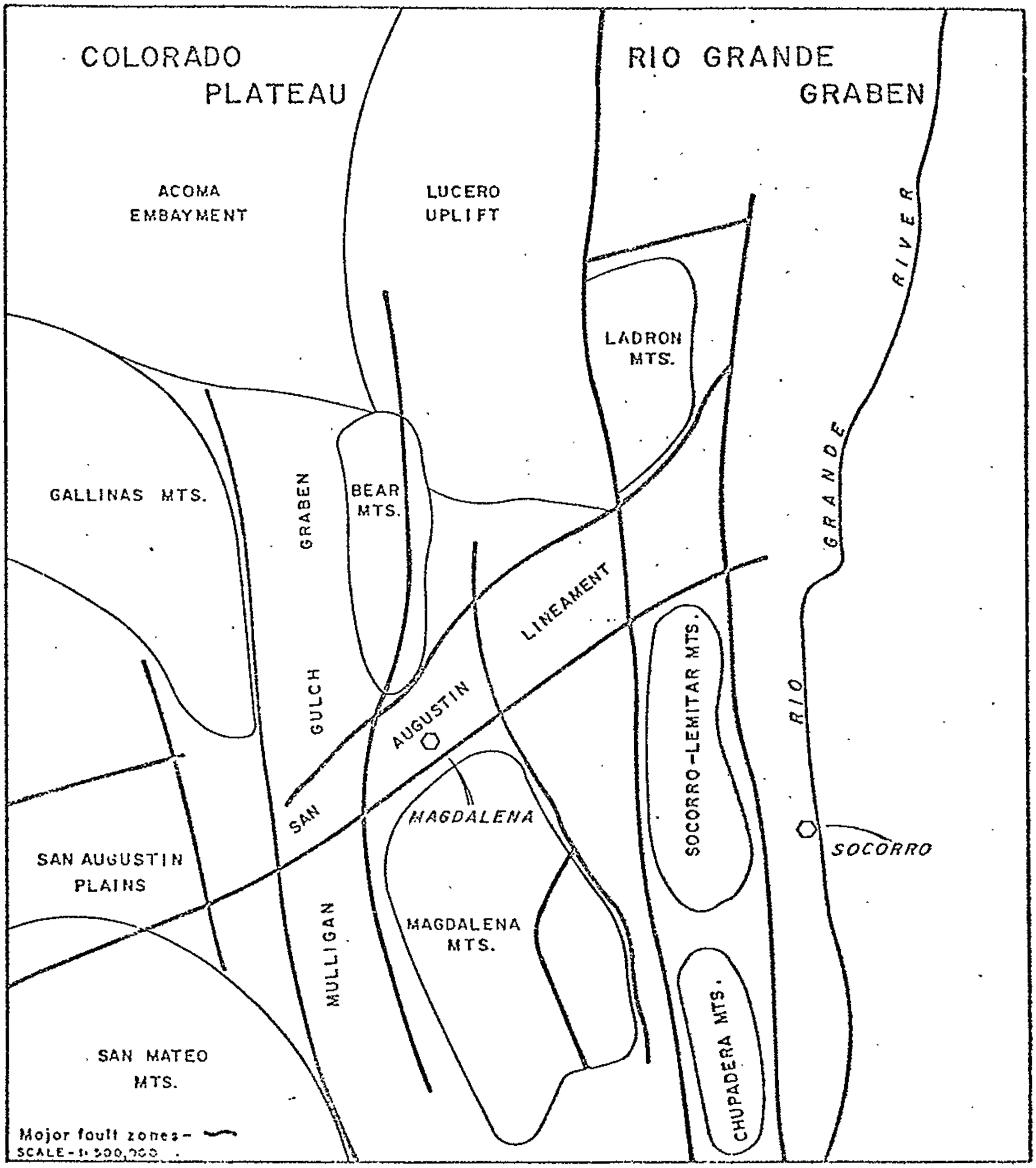

Figure 26. The major Late Cenozoic structural trends which influenced the formation of the Holocene physiography of west-central New Mexico.--Data outside the Magdalena area compiled from Bruning (1973) and Chapin, and others (in preparation).

Mountains. The fanglomerates, which crop out between South Baldy Peak and Langmuir Laboratory, and at Water Canyon Mesa, represent the remnants of the Popotosa Formation. The Popotosa Formation in the central Magdalena Mountains has been greatly reduced in volumne and aerial extent. Uplift of the Magdalena Mountains since Pliocene time along basin-range faults has been as much as 5,000 feet in elevation relative to the bordering basins.

LATE CENOZOIC TECTONIC SETTING

The purpose of a physiographic classification is the ready characterization of large areas for identification, comparison, and contrast. Such a classification is based on geologic structure and geomorphic stage. A physiographic classification that does not set an area into its correct structural or topographic setting defeats its purpose. If the physiographic province includes areas of strongly contrasting structures, it becomes misleading.

West-central New Mexico has been divided into the Colorado Plateau physiographic province and the Mexican Highland section of the Basin and Range physiographic province (Eardley, 1962). The Magdalena Mountains are located within the Basin and Range physiographic province and are adjacent to the eastern edge of the Colorado Plateau physiographic province. The Basin and Range province in west-central New Mexico is characterized by generally north-trending mountain ranges and basins forming a structural and topographic depression known as the Rio Grande graben.

Colorado Plateau

The Colorado Plateau province is located west and north of the Magdalena Mountains and occupies a rectangular area of almost 150,000 square miles within northwestern New Mexico, northeastern Arizona, southeastern Utah, and southwestern Colorado. The Colorado Plateau is characterized by flat-lying sedimentary rocks greater than 10,000 feet thick and is bordered on all sides by belts of Cretaceous and Early Tertiary folds and thrusts (Gilluly, 1963, p. 156).

Fitzsimmons (1959) differentiated the Colorado Plateau province of west-central New Mexico into the Lucero uplift, the Alcoma embayment, and the Mogollon slope (Fig. 27). The Mogollon slope is not a single geomorphic feature but is rather an area of individual ranges, including the Gallinas Mountains and the San Mateo Mountains.

All of west-central New Mexico underwent a similar tectonic development through the Middle Tertiary, including the emplacement of Oligocene volcanics and intrusives. Beginning in Late Cenozoic time, the present physiographic separation of west-central New Mexico resulted from the Colorado Plateau acting as a relatively stable crustal block while the Basin and Range province underwent differential movement and block faulting.

Basin and Range Province

The Basin and Range province has become the type area for a structural pattern commonly called basin-range or fault-block structure. What is commonly referred to as the Basin and Range type of structures is actually only one of various types of structures found in the province. Mountain ranges resulting from structural anticlines with adjacent basins being structural synclines are also present. Domal intrusions formed other mountain ranges. Horst and graben type of structures characterized particularly by the Rio Grande graben occur within the Basin and Range province. From the diverse structure present,

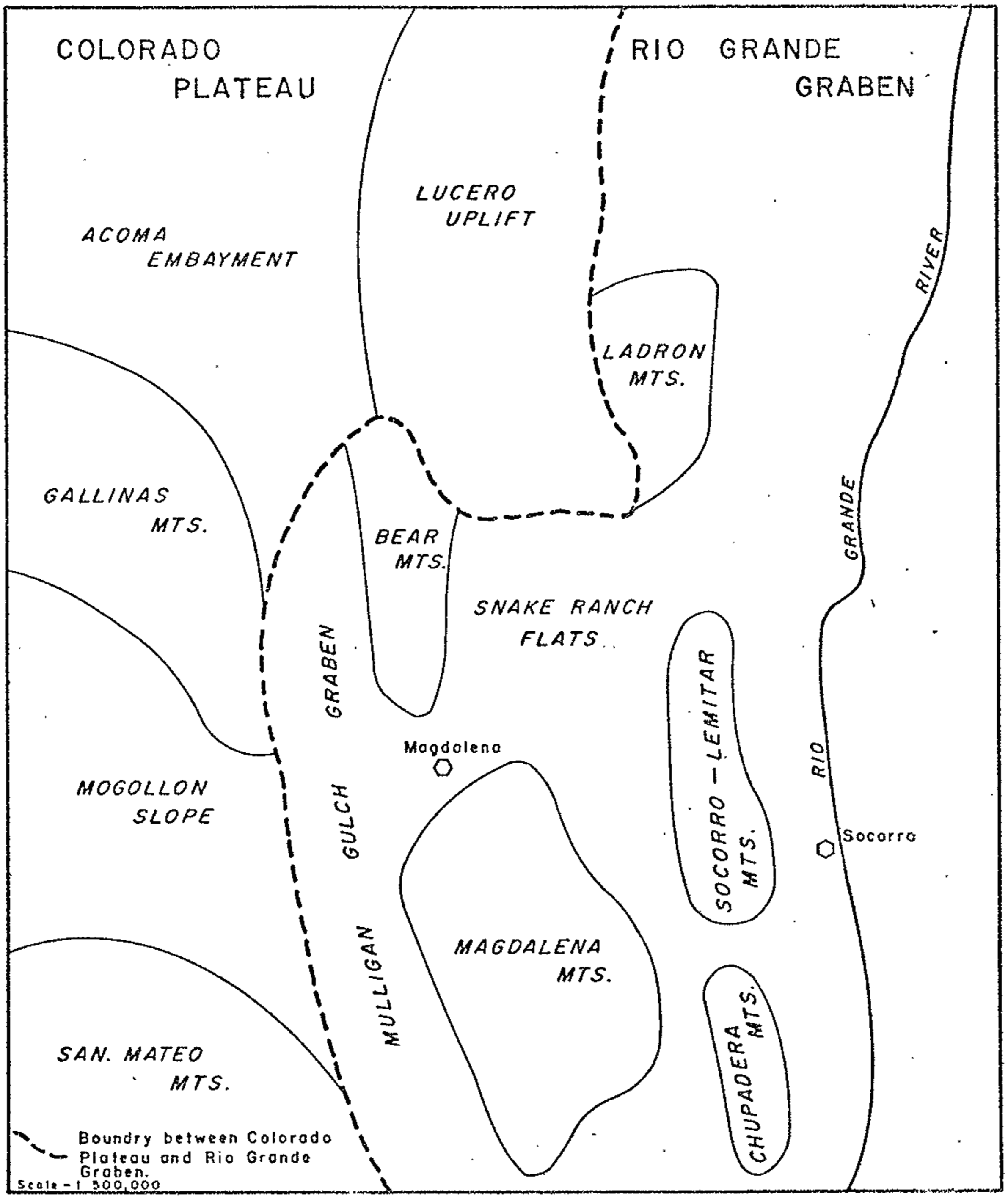

Figure 27. Major physiographic features within the Colorado Plateau and the Rio Grande graben of west-central New Mexico.--Data outside the Magdalena area compiled from Bruning (1973), Chapin, and others (in preparation) and Fitzsimmons (1959).

the term Basin and Range truly describes a gross physiographic aspect, and no general explanation of the structure is possible.

Historical Sketch

The origin of the Basin and Range topography and its structural implications have long been debated among geologist. King (1870) interpreted the mountains in Nevada and western Utah as erosional remnants of Late Jurassic folds. He assumed that the mountains of the Basin and Range province were similar to those in the Valley and Ridge province of the Applachian Mountains in appearance, but he attributed the differences in topography to different climate conditions under which the two mountain areas developed.

Gilbert (1874) concluded from the geomorphic evidence in Nevada and western Utah that the mountains are bordered on one or both sides by faults and have been raised and/or rotated above the intervening basins in relatively recent geologic time. He inferred that Basin and Range topography was caused directly by Late Cenozoic faulting, the effects of which are still manifest in the modern landscape. Davis (1903) supported Gilbert's theories and systematized observations for the recognition of an area's geomorphic stage of development.

The genesis of the mountain ranges in the Mexican Highland section of the Basin and Range province is equally controversial. Cserna (1969) considered the overwhelming majority of the mountain ranges in the north-central Chihuahua to be complex anticlines whereas the intermontane basins are synclines filled with Late Tertiary sediments. He noted that map evidence is scarce to prove the presence of faulted blocks. However, Tuan (1962) characterized the Basin and Range province of Arizona and New Mexico as faulted mountain ranges separated by structural troughs developed since post-Pliocene time. He suggested the presence of erosional surfaces in correlatable layers across the San Pedro River in southeastern Arizona and the Rio Grande in New Mexico indicate the tectonic instability and active uplift of the Basin and Range province.

Rio Grande Graben

The Rio Grande graben is the dominant feature of the Basin and Range province of west-central New Mexico. The Rio Grande graben is a structurally and topographic low area that divides New Mexico in half. It trends north-northeast for about 600 miles from northern Chihuahua, Mexico to north of Leadville, Colorado (Chapin, 1971-b). Block faulting characterizes the Rio Grande graben which consists of generally north-trending mountain ranges and basins arranged in an en echelon manner.

Bryan (1938) described the geology of the Rio Grande valley and noted the offset of the Miocene Sante Fe Group by Late Cenozoic faults. Kelley (1952) showed the depression to be a series of en echelon north-trending grabens along the course of the Rio Grande. In central New Mexico Kelley (1952) restricted the Rio Grande graben to a narrow constriction, which did not include the Magdalena Mountains.

Chapin (1971-b) noted that the south end of the Rio Grande graben appears to widen and splay out into the Basin and Range province of southern New Mexico and that the north end tapers to a narrow depression along the upper Arkansas Valley in Colorado. He suggested that the Rio Grande graben may represent a rift formed by crustal attenuation as the

Colorado Plateau moved west-northwestward away from the continental interior. Based on fossils in basal alluvial fill and K-Ar dates on interbedded volcanic rocks Chapin (1971-b) argued that block faulting began at least 18 million years ago.

Results of the author's study have established a basis for the placement of the Magdalena Mountains into the Rio Grande graben of the Basin and Range physiographic province. The Magdalena Mountains are a north-northwest-trending uplift formed by Late Cenozoic block faulting, approximately 14 m.y. ago. The renewal of uplift of the Magdalena Mountains in Holocene time is suggested by scarps in the pediment gravels on the northeast side of the range, the entrenched stream in Water Canyon, and the steep slopes and landslides. The horst is bounded on the northeast by Snake Ranch Flats, on the north-northwest by the Bear Mountains, and on the west by the Mulligan Gulch graben (Fig. 27). A topographic relief of 5,000 feet by the Magdalena Mountains is the greatest in west-central New Mexico.

Other prominent features in the Magdalena area included within the Rio Grande graben are the Bear Mountains, a westward tilted block uplifted by Late Cenozoic faulting (Brown, 1972). The Snake Ranch Flats has been downfaulted against the Bear Mountains and the Magdalena Mountains on the west and the Socorro-Lemitar Mountains on the east. Late Cenozoic sediments eroded from the neighboring uplifts have filled the basin (Debrine, Spiegel, and Williams, 1963). Mulligan Gulch graben separates the San Mateo Mountains and the Gallinas Mountains on the west from the Bear Mountains and Magdalena Mountains on the east (Chapin and others, in preparation). The graben was formed by Late Cenozoic faulting and contains sediments derived from the bordering uplifts.

CONCLUSIONS

Mississippian limestones unconformably overlie Precambrian argillite and granite in the Magdalena area. During Pennsylvanian time a thick sequence of quartzose sandstone, shale, and limestone were deposited in the Lucero-San Mateo Basin. Terrestrial sandstone and siltstone were deposited during Permian time.

Uplift and tilting of the Magdalena area during the Laramide orogeny was followed by leveling of the highlands during Eocene time. Erosion removed all of the Mesozoic strata and left only isolated remnants of the Permian strata.

Volcanism began approximately 37 m.y. and ceased 30.5 m.y. ago. Six distinct volcanic formations make up the Datil Group and consist of volcanoclastics, ash flows and lava flows. A source area for the Hells Mesa Formation ash flows may overlap the southeastern portion of the central Magdalena Mountains and a source area for the Sawmill Canyon formation may overlap the southwestern portion.

Following the emplacement of the youngest ash flow, the Magdalena area was faulted and tilted by a north-northwest-trending zone of Late Oligocene age. These faults played a major role in the emplacement of the Late Oligocene stocks, dikes, and served as the conduits for hydrothermal solutions, which altered or mineralized the adjacent county rock. The dikes and stocks may be the surface expressions of a much larger intrusion underlying the northern and central Magdalena Mountains.

Buried plutons including the North Baldy Peak-Linchburg stock may contain mineralization or replacement deposits adjacent to them. Possible buried stocks may be defined by alteration and mineralization, structural control, and diking, particularly the white rhyolite dikes.

The ancestral Magdalena Mountains were degraded during Miocene time until they were nearly or completely buried beneath their own debris. The Popotosa Formation in the Water Canyon and South Baldy Peak areas are remnants of alluvial fans that once covered a much wider area.

The Magdalena Mountains have been uplifted approximately 5,000 feet along bordering block faults. The Magdalena Mountains are within the Basin and Range physiographic province and are part of the Rio Grande graben of west-central New Mexico.

GEOLOGY OF THE CENTRAL MAGDALENA MOUNTAINS, SOCORRO COUNTY, NEW MEXICO

by

Dieter Anton Krewedl

A Dissertation Submitted to the Faculty of the

DEPARTMENT OF GEOSCIENCES

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DOCTOR OF PHILOSOPHY

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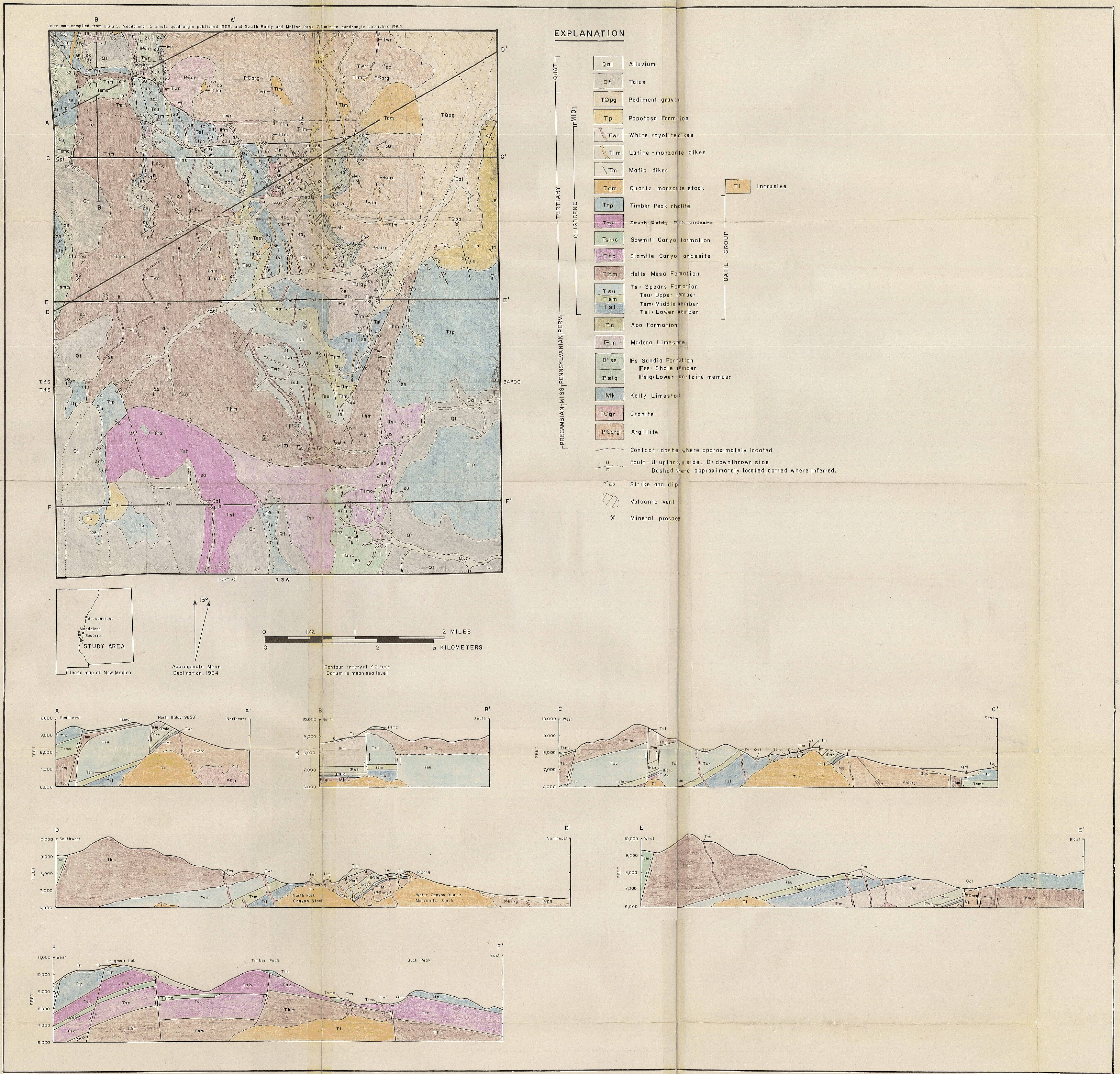

FIGURE 4 : GEOLOGIC MAP AND SECTIONS OF THE CENTRAL MAGDALENA MOUNTAINS, SOCORRO COUNTY, NEW MEXCO

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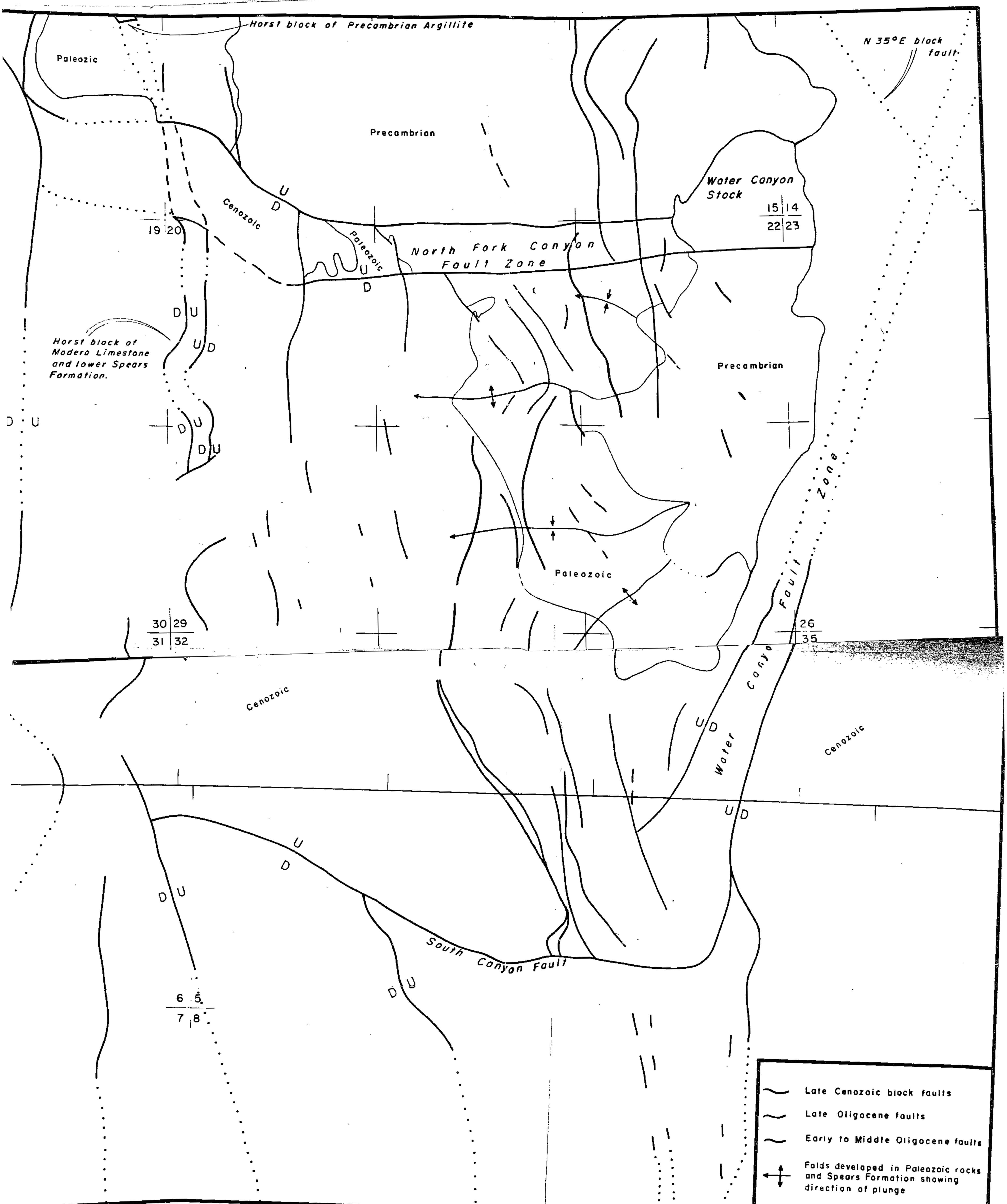

re 23: Generalized geologic map of the central Magdalena Mountains showing folds and faults developed during various periods.

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Base map compiled from U.S.G.S. Magdalena 15 minute quadrangle published 1959, and South Baldy and Molino Peak 7.5 minute quadrangle published 1965.

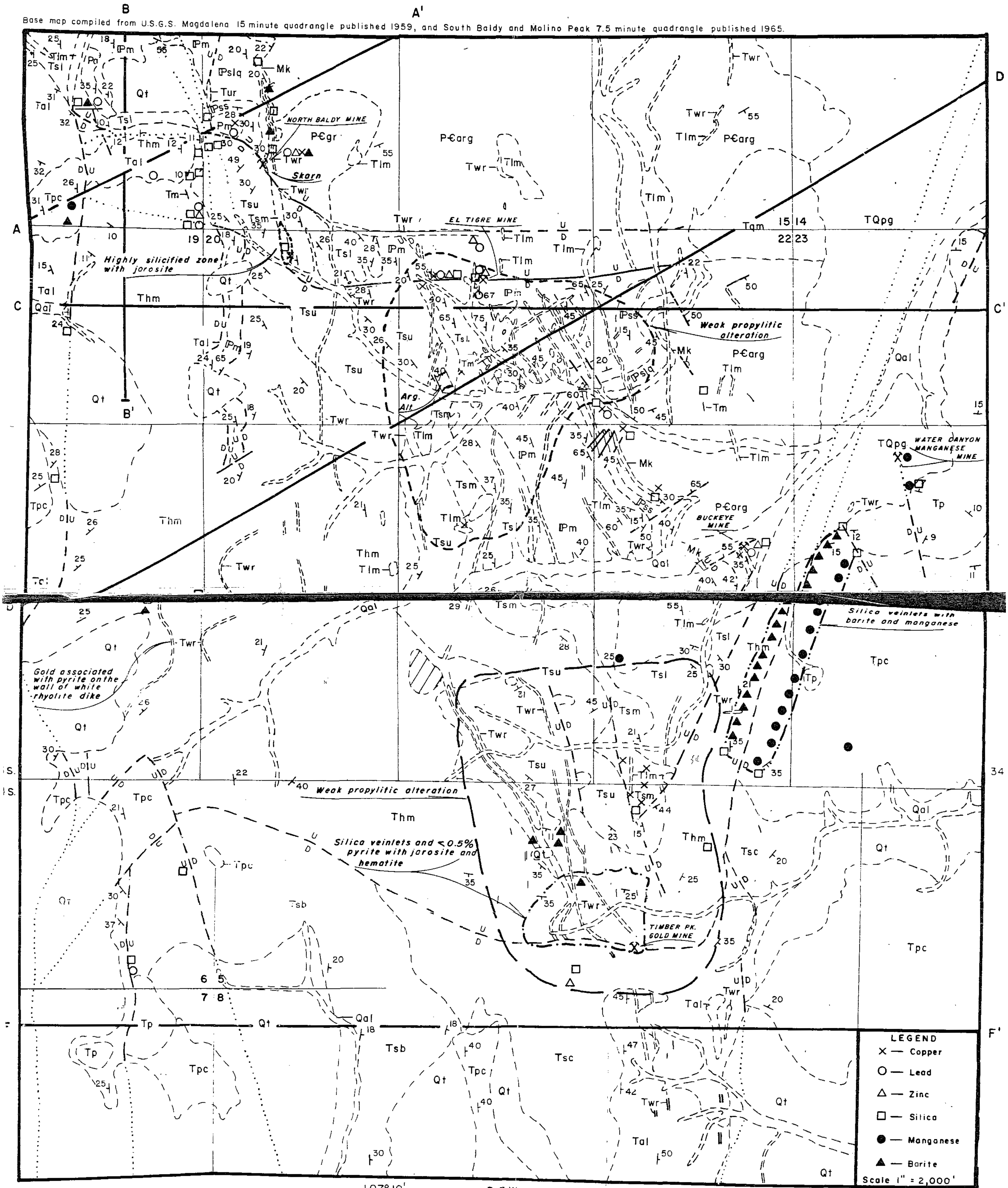

Figure 24: Alteration and mineralization in the central Magdalena Mountains.

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