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Geology of the Water Canyon-
Jordan Canyon Area,
Socorro County, New Mexico

by

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Abstract

The Water Canyon-Jordan Canyon area is located on the eastern flank of the northern Magdalena Mountains and consists almost entirely of Proterozoic and Tertiary rocks. The Proterozoic section comprises nearly 15,000 feet (4570 m) of thickly interbedded fine-grained clastic and volcaniclastic sedimentary rocks and felsic tuffaceous rocks. Mudflows of tuffaceous material fill large channels. Other mudflows are found within the fine-grained clastic sequence and consist primarily of clasts of siltstone in a siltstone matrix. Structures found within the fine-grained clastic rocks include large-scale cross bedding, soft-sediment deformation, ripple cross laminations, and scour-and-fill structures indicative of a fluvial to deltaic environment of deposition. The western portion of the thesis area contains part of a caldera which may have been the source for the felsic tuffaceous rocks.

This supracrustal succession shows greenschist facies metamorphism and has been intruded by; 1) the metagabbro of Garcia Canyon which contains roof pendants of the supracrustal rocks, 2) the Magdalena granite of batholithic size, and 3) diabase dikes.

Tertiary rocks in the thesis area are primarily igneous intrusions that were emplaced along preexisting structural zones. The Water Canyon stock is the largest of these bodies and was intruded along the North Fork Canyon fault zone. Dikes of monzonite to quartz monzonite and rhyolite form a nearly orthogonal grid in the eastern and southern portions of the area; they intrude faults formed by the collapse of the North Baldy caldera and by extension elated to the Rio Grande rift. Mafic dikes are concentrated in the North Fork Canyon-Water Canyon area and may reflect the roof zone of a buried intrusion.

Proterozoic structural features include part of a caldera and roof pendants of the supracrustal succession in the metagabbro of Garcia Canyon. The jumbled nature of these pendants accounts for the variations in bedding and foliation in the Proterozoic section.

The study area is bounded on the south by the North Fork Canyon fault zone, which probably represents the ring-fracture zone of the North Baldy caldera. This zone is represented by two major faults, a quartz monzonite intrusion, a zone of jumbled blocks of Paleozoic rocks, and numerous landslide blocks; an anomalously thick section of Hells Mesa Tuff is present to the south of this zone. Down-to-the-east normal faults related to rifting are found in the eastern portion of the study area and dip at varying degrees to the east.

Significant mineralization is limited to the North Fork Canyon fault zone and, in particular, to the intersection of this zone with the Proterozoic-Paleozoic contact.

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Introduction

Geographic Setting

The area of study lies on the eastern slope of the Magdalena Mountains between North Fork and Water Canyons on the south and Jordan Canyon on the north. The area is approximately twenty-five miles west-northwest of Socorro, New Mexico, and can be reached by traveling west on US60 from Socorro. The location is shown in figures 1 and 2. Access to the study area is principally by way of the Water Canyon road.

Elevations in the area range from 6500 feet (2170 m) at Water Canyon to over 9500 feet (3170 m) near North Baldy. Fieldwork is somewhat limited at the higher elevations in the winter but is possible year-round at lower elevations.

Geologic Setting

The Magdalena Mountains are a geologically complex fault block located within the Rio Grande rift in central New Mexico. The northern section of the range dips to the west and consists of Proterozoic, Paleozoic, and Tertiary rocks. Only Tertiary rocks crop out in the southern portion of the range. The study area is located within the Proterozoic rocks found on the eastern slope of the range. These

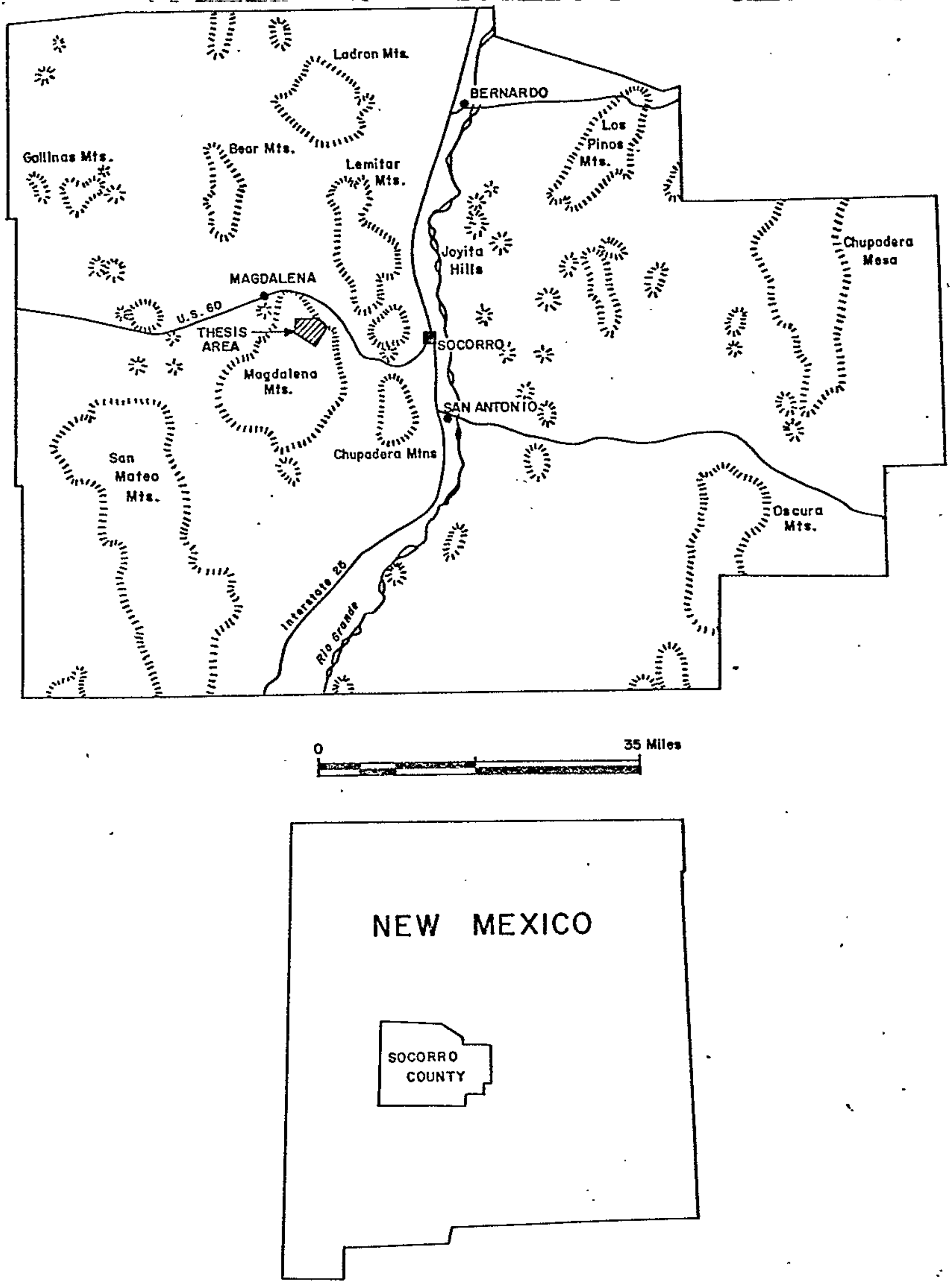

Figure 1: Location map of the Water Canyon-Jordan Canyon area in relationship to major mountain ranges in Socorro county.

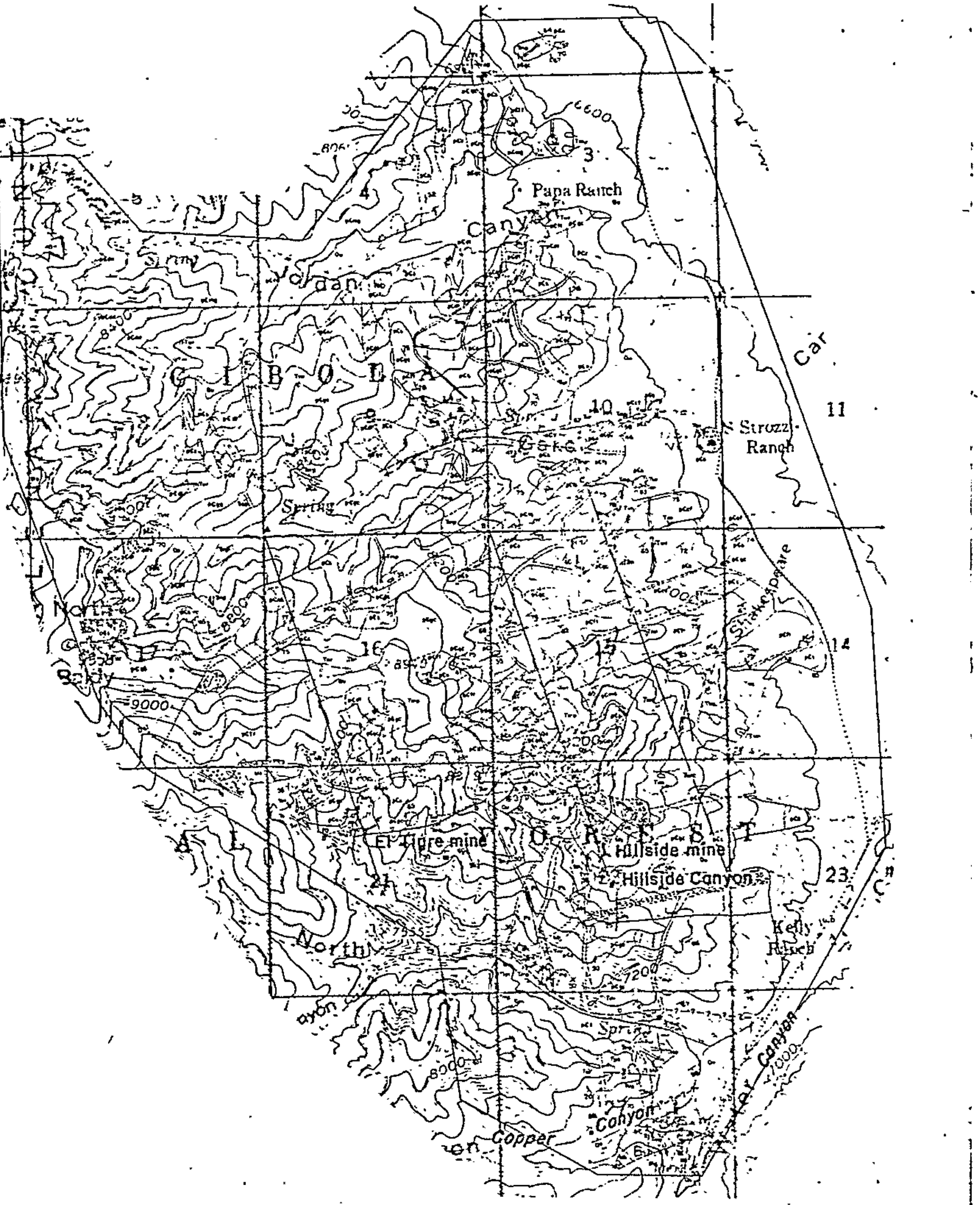

Figure 2: Location of the study area in the northern Magdalena Mountains and important geographic features.

Proterozoic rocks are primarily siltstones, sandstones, and argillites with interlayered felsic volcanic units. This section has been intruded by a gabbroic pluton (~1.5 b.y.B.P.,White,1977), a granite batholith (~1.3 b.y.B.P.,White,1977), and diabase dikes. Mississippian and Pennsylvanian sedimentary rocks overlie the Proterozoic rocks and are found along the western and southern borders of the study area.

A complex Tertiary volcanic section is in fault contact with the Proterozoic rocks in the southern portion of the study area. The Tertiary rocks consist primarily of ash-flow tuffs, andesite flows, and andesitic-latitic volcaniclastic sedimentary rocks. Several ash-flow tuff cauldrons are present within the central and southern portions of the range. The northern margin of the northernmost of these cauldrons is well exposed on North Baldy (fig. 2). The Proterozoic-Tertiary contact in the southern portion of the study area may be an eastward extension of this cauldron margin (Chapin and others,1978). North of this margin, the Proterozoic section has been extensively intruded by Tertiary stocks and dikes.

Since Oligocene time, the Magdalena Mountains have been broken by numerous faults related to the Rio Grande rift (Chapin,1971). One of these faults, the eastern range-bounding fault of the northern Magdalena Mountains, shows evidence of late Quaternary movement and marks the eastern boundary of the study area.

Statement of Problems and Objectives

The objectives of this thesis are: 1) to determine the lithologic composition, stratigraphic relationships, distribution, thickness, intrusive relationships, and structural trends of the Proterozoic rocks; 2) to delineate Tertiary intrusives and related metamorphism, alteration, and mineralization, and 3) to evaluate the nature of the boundary between the Proterozoic and Phanerozoic rocks in the North Fork Canyon area.

Methods of Investigation

The area was mapped at a scale of 1:12000 on an enlarged section of the Magdalena 15-minute quadrangle. Mapping was done during the fall of 1977 and the spring of 1978. Air photos in the U.S. Forest Service series 4-13-71 at a scale of 1/12,000 were used to locate the eastern range-bounding fault. Seventy thin sections of rocks from the study area were analyzed petrographically. Some thin sections were stained for potassium with sodium cobaltinitrite. Rock names are from the classification chart by Travis (1955).

Previous Investigations

Previous to this investigation, many authors have dealt with the geology in this area. Lindgren and others

(1910) first wrote of the area in U.S. Geological Survey Professional Paper 68 The Ore Deposits of New Mexico. Lasky (1932), in his report on the ore deposits of Socorro county, mentions the study area in his descriptions of the Kelly and Water Canyon mining districts. The most comprehensive study was that by Loughlin and Koschmann (1942) in their professional paper on the Kelly mining district. They mapped and described an argillite-greenstone unit, a gabbro, a felsite, a granite, and diabase dikes, in order of decreasing age. Kalish (1953) mapped the southern portion of the study area and divided the Precambrian rocks into granite and argillites. Kalish mentions the presence of pebble conglomerates and the probability of interbedded tuffs and lavas in the argillites. Krewedl (1974) mapped in the southern portion of the study area and used the same units for the Precambrian as did Kalish. Park (1976) mapped the Precambrian and Tertiary rocks around the Papa Ranch in considerable detail (1:15,625). Park`s Precambrian units consisted of metasedimentary rocks, a gabbro, a pink granite, and diabase dikes. The western border of the study area was mapped by Blakestad (1978) and Iovenetti (1977) using the same units as Loughlin and Koschmann (1942).

The three most recent papers concerning the Precambrian rocks of the Magdalena Range deal principally with geochemistry. White (1977) dated (Rb/Sr whole rock) and determined initial Sr87/Sr86 ratios on two plutons which he called the Magdalena Gabbro and the Magdalena Pluton (the metagabbro of Garcia Canyon and the Magdalena granite in this report). Whole-rock and trace-element geochemistry are presented by Condie and Budding (1979). Their report includes a stratigraphic section of the Precambrian rocks from the Water Canyon area. Condie and Budding describe numerous scattered occurences of Precambrian rocks in southern and central New Mexico and interpret their tectonic setting to be a continental rift system. Chapin and others (1978) describe the complex mid-Tertiary history of the Magdalena Mountains, including the numerous cauldrons to the south of the study area and the down-to-the-east normal faults found throughout the area.

Acknowledgments

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PRECAMBRIAN ROCKS

Precambrian rocks make up approximately 80 % of the study area. About 75% of these rocks consist of a monotonous section of siltstones, argillites,and sandstones. Total thickness of the section is unknown as the rocks have been broken into at least five blocks with different orientations (fig. 3). The largest of these blocks consists of nearly 8000 feet (2438 m) of sedimentary and volcanic rocks. Several moderately thick units of felsic volcanic rocks, believed to be tuffs, are interbedded with the fine-grained clastic sedimentary rocks. Neither a top nor a bottom of this section is exposed. All the supracrustal rocks in the study area have tentatively been assigned to the Proterozoic.

The above mentioned blocks appear to be roof pendants in the gabbro of Garcia Canyon, a sill-like body which intruded the sedimentary rocks at approximately 1500 m.y.B.P. (White,1977). The Magdalena granite intruded the Precambrian supracrustal succession in the northern portion of the study area at approximately 1300 m.y.B.P. (White,1977) and now makes up a majority of the eastern slope of the Magdalena Mountains. The last Proterozoic igneous event in the study area is the intrusion of diabase dikes. The dikes are inferred to be of Proterozoic age as they intrude the Magdalena granite but not the Paleozoic sedimentary rocks.

Figure 3: Location and attitudes of the larger structural blocks of Proterozoic supracrustal rocks.

Metamorphism of Proterozoic rocks in the study area is of upper greenschist facies; original Proterozoic textures and both volcanic and sedimentary structures are visible.

Proterozoic Supracrustal Rocks

A thick section of interbedded fine-grained clastic sedimentary rocks and felsic volcanic rocks is found in the study area. These units occur in at least five structural blocks, each with different but internally consistent attitudes (fig. 3). The largest of these blocks contains a section nearly 8000 feet (2438 m) thick; if this section can be continued south of the Water Canyon stock the total section would be nearly 15000 feet (4572 m) thick. All of the blocks are bounded by faults, intrusions, or younger sedimentary rocks; neither a base nor a top of the Proterozoic section is exposed (fig. 4). Thinly interbedded sandstone-siltstone-argillite is the most abundant rock type, followed, in decreasing order of abundance by: 1) several types of felsic tuffs, 2) a thick, interbedded sequence of felsic tuffs and siltstones, 3) reworked tuffs, and 4) debris flow deposits (appendix 1).

Limited descriptions of these units are given by previous authors. Loughlin and Koschmann (1942) give the most complete description of the fine-grained clastic rocks which they called argillite"greenstone" and schist. They describe these rocks as being composed predominantly of quartz and sericite. Kalish (1953) mapped and described a greenstone in Water Canyon which he believed to be about 800 feet (246 m) thick. His greenstone consists mainly of quartz, chlorite, and muscovite. Krewedl (1974) described the

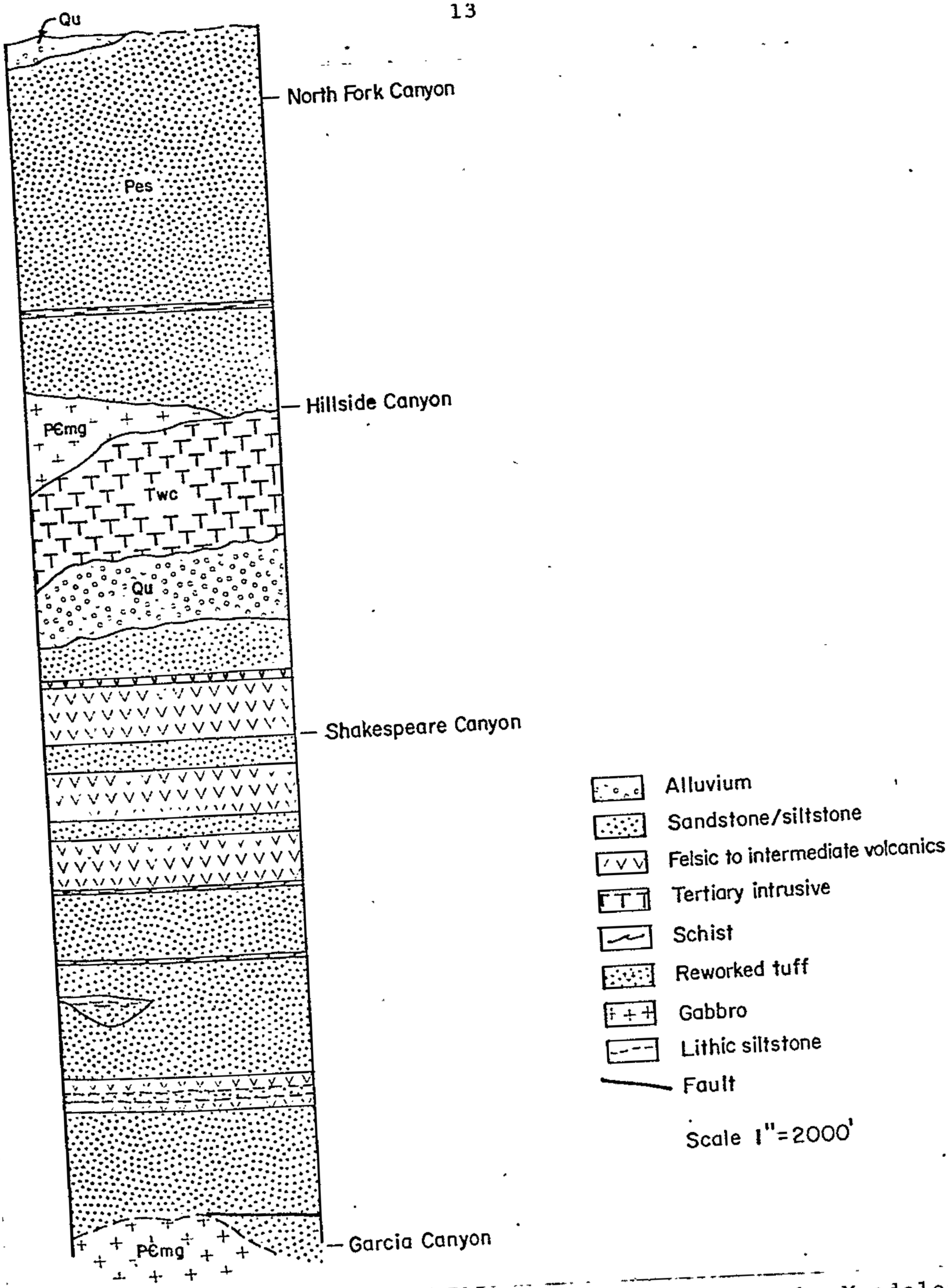

Figure 4: Proterozoic stratigraphic section in the Magdalena Mountains.

same units as Kalish (1953) and, similarily, did not map individual lithologies. Park (1976) did not differentiate the sedimentary or igneous rock types on his map in the Papa Ranch area. Condie and Budding (1979) measured a section of interbedded siltites, quartzites, argillites, metatuffs, phyllites, diabase sills, and conglomerates in Water Canyon. Their section is approximately 5400 feet (1648 m) thick. Uranium-lead dating reported by Stacy (1979, oral commun.) indicates an age of 1680-1700 m.y. for the supracrustal rocks in central New Mexico.

The Proterozoic rocks will be described as they occur in the stratigraphic section (fig. 4).

Fine-Grained Clastic Sedimentary Rocks

Interbedded sandstones, siltstones, argillites, and to a minor extent, shales are the most abundant and widespread rock types found in the area. These units are somewhat variable and range from thick (1 m), massive siltstones to thinly interbedded or laminated siltstone-sandstone-argillite units. The thickest section of siltstone is found west of the Kelly Ranch (sec.22,27,T.3 S.,R.3 W.) where it is greater than 3500 feet (1075 m) thick. This clastic sedimentary unit makes up nearly two-thirds of the contiguous Proterozoic section in the Magdalena Mountains and, if the section can be continued south of the Oligocene Water Canyon stock, may represent nearly three-quarters of the section (fig. 4).

Metamorphic grade for these rocks is low and belongs to the greenschist facies. In one thin section, abundant secondary biotite and garnet indicate upper greenschist facies. Original structures and textures are visible in outcrops along Copper Canyon (sec.27), North Fork Canyon (sec.27,28) and north of Garcia Canyon (sec.29).

Siltstones are found throughout the section interbedded with felsic tuffs, tuffaceous sandstones, and debris-flow deposits (appendix 1). In the largest structural block, siltstones occur at both the top and the bottom of the section. Siltstones are generally thick and appear compositionally homogenous, both laterally and stratigraphically. One interval can be traced from the rhyolite of North Baldy to the Quaternary cover at the edge of the range, a distance of nearly two miles (3.2 km).

Contacts of the siltstones with the other supracrustal rocks are generally obscured. In the siltstone-tuff unit, where contacts are visible, they range from sharp to gradational over 2-3 feet (1 m). The effects of intrusive rocks are variable and are discussed later.

Previous literature concerning the siltstones is terse except for the discussion by Loughlin and Koschmann (1942). The prevailing lithology in the area of their investigation is an argillite. Their unit is a light-greenish-gray, fine-grained to microgranular, thin-bedded, quartz-sericite rock. Kalish (1953) and Krewedl

(1974) use the same terminology to describe somewhat coarser units found within this study area.

Outcrops of siltstone are generally low, blocky, and well-jointed; they are best exposed in gullies. The primary colors are light tan, white, green, and greenish gray. Original structures are visible in outcrop and well-preserved for rocks of this age in central New Mexico. Structures in the sedimentary rocks are best observed in the creek bed in Copper Canyon. Most evident is large-scale trough cross-bedding (fig. 5). Cross-bedded features may be as much as 10 feet (3 m) across and have an amplitude of 20 inches (50 cm). Smaller cross-bedding may result from scour-and-fill sedimentation. Both types of cross-bedding are present in Copper Canyon and indicate a transport direction perpendicular to the attitude of the beds. This direction is approximately from the east when the rocks are rotated to the horizontal.

Soft sediment deformation is the next most noticable structure and is most evident in the argillaceous intervals (fig. 6). Planar laminations and ripple cross laminations are widespread throughout the study area. Laminations as thin as one millimeter are common in the argillites (fig. 7). Crude grading is apparent in a few outcrops. Grains in graded beds may range in size from silt to pebbles, and grading may show an upward increase in size or the grains may grade from coarse to fine to coarse again.

Figure 5: Large scale cross-bedding in siltstone unit from North Fork Canyon.

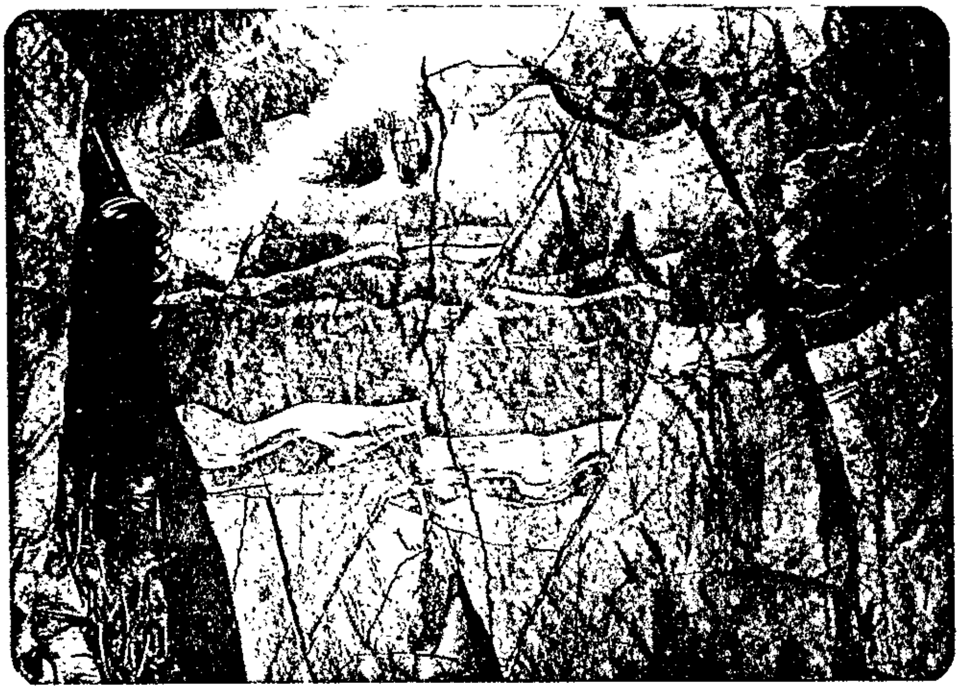

Figure 6: Soft sediment deformation in siltstones and argillites in Copper Canyon.

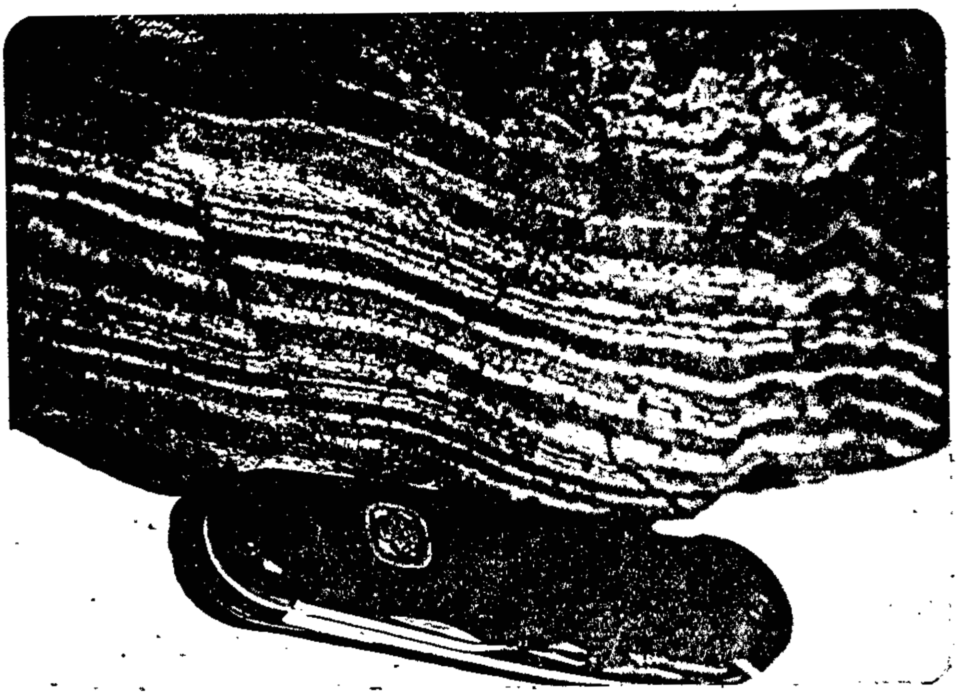

Figure 7: Thinly laminated argillite from Garcia Canyon.

Fine-grained clastic sedimentary rocks are interbedded with debris flow (mudflow) and traction current deposits in Copper Canyon. These deposits show several depositional features including pebble imbrication and rip-up clasts. Fine-grained beds found between lithic sandstones often contain a few pebble-size fragments. These deposits are described below under lithic sandstones.

Handspecimen analysis of the siltstones reveals little because the rocks are extremely fine-grained. Minerals identified at this scale include quartz, feldspar, and magnetite which gives the rock an occasional salt and pepper appearance.

Most of the rocks called siltstone in this section are actually quartzites or feldspathic, argillaceous sandstones and siltstones. Some garnet-bearing quartzites and sandstones are also present. Grain size ranges from very fine sand to silt.

Quartz is by far the most abundant mineral and comprises at least 50-60% of the rock. The samples labeled argillaceous may contain as much as 30% of a mixture of fine-grained clays and/or micas and chlorite. In one thin section, these minerals support the quartz grains (i.e. matrix supported). Another thin section shows partial calcite cementing which is believed to be a secondary cement, as the section shows several quartz-calcite-magnetite veins. Additional trace and accessory minerals include biotite, magnetite, monazite, and zircon. Grains in the quartzite units are subrounded and grains in the siltstone units are subangular. In thin section, most samples are well-sorted; few show graded bedding. The thinnest lamination seen in thin section is approximately 1 mm thick. Lateral variations are difficult to assess due to lack of outcrop. A biotite-garnet schist of unknown thickness is found in the siltstones west of the Strozzi Ranch (sec.10,T.3 S.,R.3 W.). This schist does not differ from the siltstones in either outcrop or handspecimen. Foliation caused by the planar orientation of fine-grained biotite is seen only in thin section. In thin section, garnet porphyroblasts to 0.4 millimeters make up less than 5% of the rock. Fine-grained biotite comprises as much as 20% Of the rock.

Thick, fine-grained clastic sequences are common in Proterozoic successions (Long,1978). Long (1978) suggests that it is often difficult to determine the environment of deposition of these sequences due to lack of fossils and a lack of comparable sections in modern sequences. Due to the above mentioned problems, interpretation of Proterozoic clastic sedimentary sections is strongly dependant on bedding types and sedimentary structures (Long,1978). Table 1 compares sedimentary structures and bedding types found in the Magdalena Mountains with modern fluvial systems, Proterozoic fluvial systems, flysch deposits (appendix 1), modern abyssal plain deposits, modern near-shore marine deposits, and modern deltaic sediments.

Table 1

Comparison of sedimentary structures and bedding types in 1) the Magdalena Mountains (this report), 2) modern fluvial systems (Reineck & Singh, 1975), 3) Proterozoic fluvial systems (Long, 1978), 4) flysch deposits (Dzulynski & Walton, 1965), 5) modern abyssal plain deposits (Reineck & Singh, 1975), 6) modern nearshore marine deposits (Selley, 1970; Reineck & Singh, 1975), and 7) modern deltaic deposits (Selley, 1970; Reineck & Singh, 1975).

x - characteristic; r - rare

bedding type and sedimentary structures	Magdalena Mountains	Modern Fluvial	Proterozoic Fluvial	Flysch Deposits	Abyssal Plains Deposits	Nearshore Marine	Deltaic Deposits
large-scale X-bedding	x	x	x			x	x
ripple X-lamination	x	x	x	x	x-r	x	r
soft-sediment deformation	x	x		r			
planar laminations	x	x		x	x	x	x
scour & fill X-bedding	x	x	x	x			
graded bedding	r			x	x-r		x
traction current features	x	x				x	x
debris-flow deposits	x	x	x				r
channel-fill deposits	x	x	x	r		r	x-r
rip-up structures	r	x	x				
mud-chip deposits	x-r	x	x	x	x	r	
conglomerates	r	x				r	
total thickness - X000 ft.	x	r	x	x	x	x-r	x
poor sorting	x-r	x-r		x			
interbedded fine- and coarse-grained rocks	r			x	x-r	x-r	x
rippled bedding		x		x	x	x	x
bioturbation				x-r	x	x	x

Table 1 indicates that the most likely environment of deposition for the Proterozoic sedimentary rocks in the Magdalena Mountains is a fluvial one. The area is believed to represent a distal fluvial or deltaic environment because of the paucity of high-energy sedimentary features and rocks, e.g. conglomerates and rippled bedding. The scarcity of shales and the presence of numerous typical fluvial sedimentary structures and bedding types are indications that the area does not represent a true deltaic environment. The term fluvial-deltaic seems to best describe the evidence for the environment of deposition.

Interbedded Tuffs, Tuffaceous Sandstones, and Clastic Sedimentary Rocks

A 435-foot (133 m) sequence of interbedded felsic tuffs, tuffaceous sandstones, and siltstones were mapped as one unit. This sequence is unique as member rock types are considerably thinner than in the remainder of the Proterozoic section (fig. 4). There are at least eleven members in the sequence which include rhyolitic ash-flow tuffs and tuffaceous sandstones. The thickest member is nearly 100 feet (30 m) thick, but most average 10-20 feet (3-6 m). The unit is best exposed in an arroyo west of the Strozzi Ranch (sec.10,T.3 S.,R.3 W.). Previous work on this unit is limited to Park's map which shows the unit as a metasedimentary rock.

This sequence of interbedded siltstones, tuffs, and tuffaceous sandstones occurs approximately 1400 feet (427 m) above the base of the exposed section. Contacts with the overlying and underlying siltstones are sharp (fig. 8). The unit is continuous over a strike length of nearly two miles (3.2 km) and is distinctive enough to be considered a marker horizon.

This volcaniclastic-siltstone sequence forms low, blocky outcrops. Outcrops are generally most prominent along steep slopes or in gullies. Color varies with rock type; siltstones and tuffaceous sandstones are tan to light gray, and rhyolite tuffs and tuffaceous sandstones are generally tan.

Handspecimen and thin-section descriptions are similar to those for the thicker units described later in this section and the reader is referred to those descriptions for more detail on the rocks. Tuffs in this sequence show flow or compaction foliation, and white lenticular streaks that are probably relict pumice (fig. 10). The lower part of the lowermost tuff member also contains fragments of siltstone to six inches (15 cm) in length. Lateral petrographic variations are difficult to assess due to the lack of outcrop.

Although this sequence of volcaniclastic rocks and siltstones is unique to the section, it is important to note that there are no new rock types within the sequence. The

Figure 8: Sharp contact between a siltstone and a rhyolitic tuff from the interbedded siltstone-tuff unit west of the Strozzi Ranch. White patches in the tuff are probably relict pumice fragments.

environment of deposition probably did not change; individual volcanic events were of shorter duration.

Tuffaceous Sandstones and Siltstones (Reworked Tuffs)

Sandstones and siltstones with minor amounts of plagioclase and blue quartz crystals are found stratigraphically above some of the tuffs. These were mapped as reworked tuffs (plate 1). In the study area, these rocks make up a minor portion of the section. Tuffaceous siltstones and sandstones are found primarily in the Papa Ranch area (sec.3,4,T.3 S.,R.3 W.) and south of Shakespeare Canyon (sec.14,T.3 S.,R.3 W.). Most contacts with the surrounding supracrustal rocks are obscured; however, south of Shakespeare Canyon where a majority of the section is exposed, contacts appear to be gradational. The best example of a reworked tuff is a siltstone containing blue quartz eyes and plagioclase crystals found west of the Strozzi Ranch (sec. 10) (fig. 9). This unit has not previously been described in the study area.

In handspecimen, the reworked tuffs are light-tan to yellow, fine-to medium-grained sandstones, siltstones, and quartzites containing crystals of quartz and plagioclase. The quartz and plagioclase grains occasionally show an imbrication (fig. 10).

In thin section, the essential minerals in the tuffaceous siltstones and sandstones are quartz and a white

Figure 9: A tuffaceous siltstone from the interbedded siltstone-tuff unit found west of the Strozzi Ranch. The photo shows crystals of quartz and feldspar in a silt size matrix. The crystals probably eroded from tuffs.

Figure 10: Photomicrograph of the tuffaceous siltstone from west of the Strozzi Ranch showing imbricated plagioclase crystals in a siltstone matrix.

mica. Accessory minerals in order of decreasing abundance are altered plagioclase, biotite, limonite, magnetite, and hematite. Bedding is usually massive but may be graded. Grain size of the matrix averages 0.02 millimeters. Grain size of the plagioclase and quartz crystals is variable but ranges to 0.5 millimeters. Plagioclase grains are generally moderately altered; quartz grains occasionally show a mosaic texture.

The tuffaceous siltstones and sandstones are believed to be reworked tuffs because of their stratigraphic position above tuff beds. Also, the crystals found within the reworked units are similar to phenocrysts found in the tuffs.

Valley-Fill Deposits

Several lobate outcops valley-fill material are found in siltstone sequences in the northeast portion of the study area (sec.3,10,T.3 S.,R.3 W.). A majority of these units are believed to represent debris flows (Appendix 1); however, the upper portions contain siltstones, shales, and tuffs. The total outcrop area of these channel- fill deposits is less than 0.25 square miles (0.65 sq km). The largest outcrop lies south of the Papa Ranch in section 10. Valley-fill deposits have not been previously described; Park (1976), and Condie and Budding (1979) mapped the units but did not distinguish them from the felsic tuffs or from the

Magdalena granite. These rocks are assigned to the Proterozoic because they contain a slight mineral alignment believed to be a Proterozoic foliation, and because they are found solely within Proterozoic rocks in the Magdalena Mountains.

Outcrops of the valley-fill deposits are generally low and blocky. Weathered surfaces are often limonite stained and a grus-like soil is commonly formed. In handspecimen, the rock appears bleached and has numerous conspicuous blue quartz and feldspar crystals (fig. 11). These crystals are believed to be reworked from tuffs due to the pelitic nature of the groundmass of the unit in which they are found (a debris flow) and the large percentage of quartz present in the rock. Quartz content may be as much as 55%, an unreasonably high number if the crystals were phenocrysts in an igneous rock. Clasts of fine-grained clastic and mafic rocks make up a trace amount of the unit. Feldspars with poikilitic magnetite are also seen.

Thin sections show the rock to contain medium-sized grains of quartz and potash feldspar in a medium sand to silt sized matrix. The essential minerals are quartz, white micas, and potash feldspar representing 50-55, 20-25, and 15-20 percent of the rock, respectively. Staining with sodium cobaltinitrite showed some of the micas to be muscovite or sericite. Minor amounts of plagioclase, perthitic potash feldspar, and magnetite are also present.

Figure 11: Handspecimen of a debris-flow deposit showing the abundant crystals of quartz and feldspar floating in a fine grained matrix of quartz, feldspars and sericite.

Biotite, limonite, and clasts of fine-grained sedimentary rocks are present in trace amounts. Quartz crystals are often strained and many feldspar crystals are broken. The outcrop of channel-fill material south of the Papa Ranch is the most intensely altered of the units. This outcop is bleached and contains limonite stains along fractures.

Valley-fill deposits in the Proterozoic terrane of the Magdalena Mountains have previously been mapped as igneous rocks (Park,1976; Condie and Budding,1979). The unit was interpreted as channel fill deposits in this study because: 1) they contain too much quartz (50-55%) to be an igneous rock (Cox and others,1979), 2) their shape is suggestive of a channel and they dip nearly conformable to bedding (plate 1), 3) their sides truncate bedding of older strata, 4) rounded rock and argillite fragments are present, 5) the units are finely interbedded near the top with siltstones and shales (fig. 12), and 6) the pelitic nature of the debris flow portion; clays (now sericite) make up a major portion (30%) of the unit. A majority of the unit is interpreted as a mudflow deposit as outcrops lack stratification, crystals are matrix supported, margins of the unit are well defined, and the outcrops lack grading and are poorly sorted (Reineck and Singh,1975).

Valley-fill deposits are important in the interpretation of the clastic sedimentary sequence in the Magdalena Mountains. Channels other than these were not

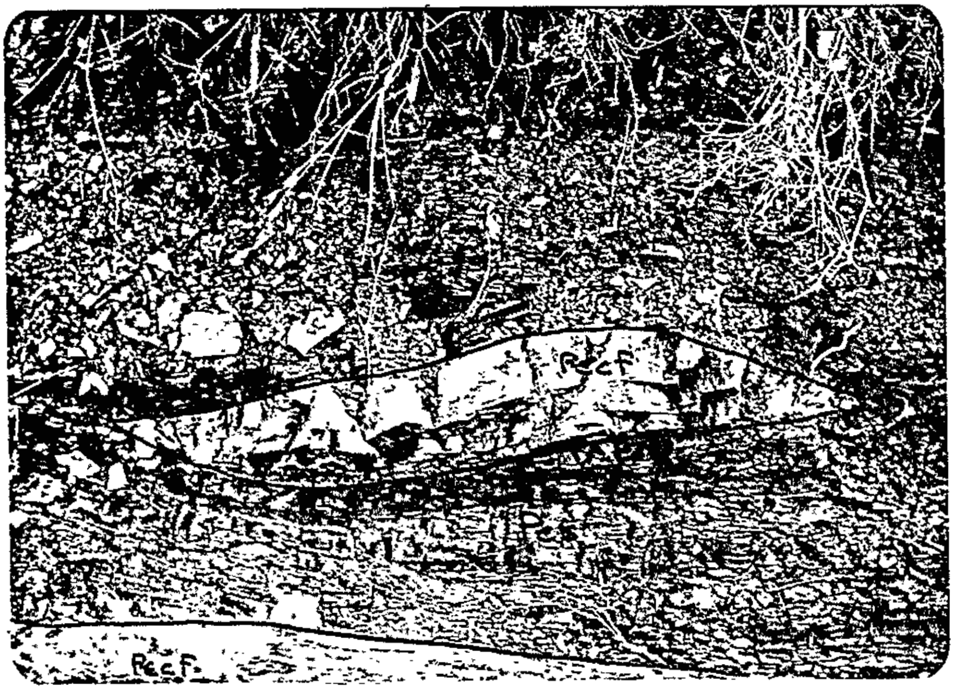

Figure 12: Photo showing a small debris flow deposit interbedded with siltstones. This deposit is located in the upper portions of the large channel-fill deposit west of the Strozzi Ranch.

recognized in the section and yet are important features in fluvial-deltaic environments (Rieneck and Singh, 1975).

Felsic Tuffs

Felsic tuffs make up approximately 10 to 15 percent of the Precambrian succession in the Magdalena Mountains (plate 1). The study area contains three sections of felsic volcanic rocks: 1) several isolated blocks of rhyolite north of the Papa Ranch (sec.3,4,T.3 S.,R.3 W.) and (sec.33,34,T.2 S.,R.3 W.) that represent at least 500 feet (152 m) of section, 2) a thick section northwest of the El Tigre mine (sec.16,17,T.3 S.,R.3 W.) that contains at least 1450 feet (442 m) of tuffs, and 3) a section of interbedded siltstones and tuffs found in and around Shakespeare Canyon (sec.15,T.3 S.,R.3 W.). The last area contains three separate tuffaceous intervals that measure 630 feet (192 m), 630 feet (192 m) and 775 feet (236 m), respectively, from the lowermost to the uppermost tuff. Felsic tuffs throughout the area are best exposed in gullies and on ridges.

These felsic tuffs are quartz-rich and are not readily altered or metamorphosed. Some of the feldspars present are altered to clays and/or white micas, and a small metamorphic aureole around the Water Canyon stock is visible in the tuff units. This aureole is only weakly developed in the tuffs and is expressed by the formation of spotted hornfels (see metamorphic section). In all cases, the glass shards have devitrified and recrystallized to quartz and feldspars.

The tuffaceous intervals in each of the three areas contain features characteristic of modern ash-flow tuffs. These features are best seen in the southernmost exposure in the Shakespeare Canyon area. Here, quartz eyes and feldspar phenocrysts are conspicuous along with numerous streaky features that are probably relict pumice (fig. 13). Compaction and/or flow foliation is also apparent.

No previous work has been done on these felsic tuffaceous units in the Magdalena Mountains. Condie and Budding (1979) mention the possibility of tuffs in their measured section. Condie (1976) mapped and discussed Proterozoic felsic volcanic rocks of a similar composition in the Sierra Ladrones.

The felsic tuffs from the three areas listed above cannot be correlated. The rhyolite tuff north of the Papa Ranch is extensively intruded by the gabbro of Garcia Canyon. It is in apparent depositional contact with an overlying sandstone/siltstone interval to the west and is covered by Quaternary deposits of the La Jencia basin on the east. The tuff found northwest of the El Tigre mine is exposed along strike for about 0.5 miles (0.8 km) within a structurally complex area. It is bordered on the south by the North Fork Canyon fault zone, on the east by Quaternary cover and a dacitic rock, on the west by Quaternary cover and the

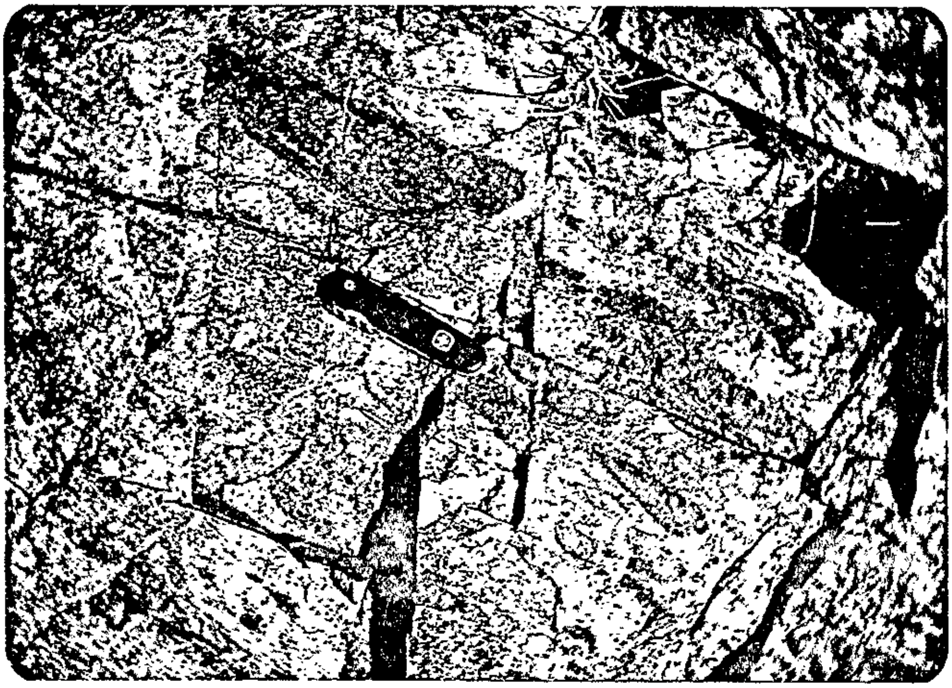

Figure 13: View of foliation surface with numerous black lenticular features which are relict pumice. They range in size to 17 inches (43 cm). Note the conspicuous lineation parallel to the knife. This lineation is radial with respect to a caldera in the southwestern portion of the study area. The streamlined, tear-drop shape of some of the pumice indicates eastward transport, away from the caldera. This tuff outcrops south of Shakespeare Canyon.

rhyolite of North Baldy, and on the north it is underlain by a sill of the gabbro of Garcia Canyon. The eastern contact of this unit is believed to represent a Proterozoic fault zone which now separates this section from the interbedded siltstones and tuffs found to the east. This fault zone has been used in Tertiary times as a plumbing system for rhyolitic and monzonitic magmas.

The felsic tuffs found in the Shakespeare Canyon area are continuous along strike for nearly 1.5 miles (2.4 km). These tuff units are interbedded with sandstone-siltstone units in the middle of the section (fig. 4). This area is covered by Quaternary deposits of the La Jencia basin on the east and is in contact with the above mentioned Proterozoic fault zone on the west. This portion of the section has been extensively intruded by the gabbro of Garcia Canyon, the Water Canyon stock, and several varieties of Tertiary dikes.

The felsic tuffs do not crop out extensively and few contact relationships were observed. The southernmost tuffaceous interval in the Shakespeare Canyon area appears to be in gradational contact with the overlying clastic sedimentary rocks. Contacts with dacitic rocks are difficult to determine as the dacite and the felsic tuffs are not readily distinguishable in the field. The dacitic rocks are istinguished from the felsic tuffs by feldspar ratios, a weaker foliation, and lack of relict pumice.

Outcrops of felsic tuffs vary in color, shape, and structures present. The felsic tuff north of the Papa Ranch is gray and weathers along joint surfaces to form blocky outcrops. A few small, white, streaky features probably represent relict pumice but little foliation is present. The tuff unit northwest of the El Tigre mine forms brown to dark-brown blocky outcrops that appear massive. The felsic tuffs in the Shakespeare Canyon area range from nearly black to light tan. These generally form more rounded outcrops than the felsic tuffs in other areas and contain more structures. Relict pumice fragments and well-preserved flow and/or compaction foliation is common, especially in the upper two intervals (fig. 14). The basal portion of the owermost tuff in the interbeddeb tuff-siltstone unit contains numerous clasts of the underlying siltstone.

The felsic tuffs show a greater resemblance to each other in handspecimen than in outcrop. All samples contain conspicuous blue quartz eyes and feldspar phenocrysts; nearly all samples contain relict pumice fragments. The northern-most rhyolite is the most massive in handspecimen. This unit contains large (approx. 10 cm) white lenticular streaks in the northern block (sec.34) and small (< 3 cm) green chlorite-rich lenticular features in the southern block (sec.3). Both features are probably relict pumice. The tuff found near the El Tigre mine shows a weak to moderate foliation in handspecimen and is reddish brown in color. The

Figure 14: An outcrop of felsic tuff from the interbeddeb tuff-siltstone unit showing broken phenocrysts and relict pumice fragments (white streaks).

two uppermost intervals of tuffs in the Shakespeare Canyon area are well-foliated, light tan in color, and often contain numerous, conspicuous, chlorite-rich relict pumice fragments (fig. 15). The lowermost interval of tuff is dark gray to nearly black and has a more weakly developed foliation. A small exposure of a felsic tuff on the north side of Garcia Canyon, in the center of section 9, contains phenocrysts of feldspar measuring as much as 6.5 mm long.

Thin-section analysis of the felsic tuffs shows the essential minerals to be quartz (25-30%) and potash feldspar (10-30%). Thin sections of the lowermost tuff in the Shakespeare Canyon area are mineralogically quartz-latite in composition and contain nearly equal amounts (10%) of potash feldspar and plagioclase phenocrysts. The other samples are determined by thin section analysis to be rhyolites. Accessory minerals include magnetite, biotite, and occasionally hornblende. Secondary minerals include limonite, chlorite, and sericite as alteration products after the feldspars. Zircon, sphene, and apatite occur in trace amounts. Sphene most often occurs surrounding magnetite. Magnetite is often altered to limonite and the two minerals are, in large part, responsible for the color of the rock. One relict pumice fragment was viewed in thin section. The fragment consists of fine-grained chlorite, magnetite, biotite, and quartz. No relict textures are preserved in the fragment; many fragments contain phenocrysts of quartz. The biotite, magnetite, and chlorite are probably not primary and most likely replaced the pumice during alteration associated with an intrusion. Texturally, all felsic tuffs are porphyritic, holocrystalline and show a vitroclastic texture (compaction foliation and broken phenocrysts) (fig. 15). Foliation varies from well-to poorly-developed. Phenocrysts are rounded and corroded in nearly all samples, and show a distinct alignment in several thin sections.

These felsic porphyries are probably ash-flow tufts. Evidence which supports this interpretation includes outcrop pattern; the occurrence of broken quartz and feldspar phenocrysts; relict pumice fragments; compaction foliation; and the lack of obvious flow features in the units. This author found no way to correlate the tuff intervals in the three areas mentioned. The blocks found north of the Papa Ranch lack stratigraphic control and the proposed Proterozoic fault zone between the tuff in the El Tigre area and those in the Shakespeare Canyon area makes correlation difficult. Certain characteristics of the tuff near the El Tigre mine, such as its thickness, lack of pumice, weak foliation, and proximity to a fault zone suggest that the tuff may have puddled in a depression. This felsic tuff shows many similarities to the Hells Mesa Tuff which puddled in the North Baldy caldera and is presently exposed in the upper portions of Water Canyon (Krewedl,1974; Chapin,personal commun.,1977). The tuff northwest of the El Tigre mine

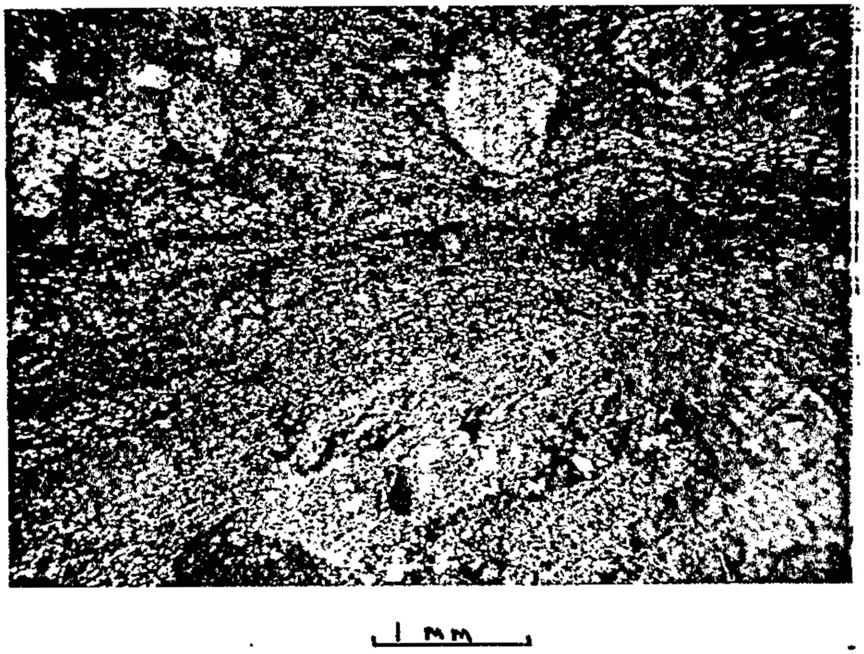

Figure 15: Photomicrograph of a felsic tuff from Shakespeare Canyon showing well developed pyroclastic texture with broken phenocrysts and compaction foliation.

resembles the Proterozoic felsic tuff sequence of the Sierra Ladrones which is approximately 5900 feet (1800 m) thick (Condie,1976).

Intermediate Porphyritic Rocks

Proterozoic porphyritic rocks of intermediate composition crop out throughout the study area in small irregular bodies. Mineralogically these rocks are dacites. At least nine separate outcrops of dacite are found; the largest (0.12 sq mi, 0.3 sq km) is in Jordan Canyon (sec.8,T.3 S.,R.3 W.). Determining whether the dacite is intrusive or extrusive is difficult due to the lack of outcrops, poor exposure of contacts, and varying petrographic characteristics. The dacite mapped southwest of the Papa Ranch shows the problems concerning origin. Here, a small contact aureole and cross-cutting relationships (plate 1) indicate an intrusive rock; a vitroclastic texture and a conformable contact on the west side suggest an extrusive rock.

Previous literature concerning the dacite is somewhat limited. Loughlin and Koschmann (1942) mapped and described a felsite found in several places on the west side of the range. They were unsure as to the exact nature of the rock and suggested that it may be an aporhyolite (devitrifed rhyolite) or possibly a dacite. The felsite (Loughlin and Koschmann,1942) is a silicous, dark, porphyritic rock with quartz, orthoclase, and oligoclase phenocrysts. Park's (1976) and Condie and Budding's (1979) maps of the Papa Ranch area include all felsic Proterozoic igneous rocks as one unit. Kalish (1953) and Krewedl (1974) did not differentiate the dacitic rocks on their maps.

The dacite has been assigned to the Proterozoic as it does not outcrop in the Phanerozoic terrane and, in places, has a conformable contact with the Proterozoic sedimentary rocks. Due to uncertainties as to the genesis of the dacite, stratigraphic relationships are unknown. Outcrops of the dacite appear as xenoliths in the gabbro of Garcia Canyon in sections 8 and 9 (plate 1); in this case, the dacite is presummed to be older than the gabbro.

The dacite forms blocky, dark, massive outcrops. The rock weathers to small angular chips rather than a grus, as is characteristic of other intrusive units in this area. In handspecimen, the rock is generally dark, porphyritic, and massive. The color varies from tan to nearly black. Darker samples contain larger amounts of opaque minerals, primarily magnetite and pyrite. Feldspar and quartz eyes in a ratio of 3 to 1 are the primary phenocrysts. The matrix is often silicified. A few small xenoliths of a dark, fine-grained rock are seen.

In thin section, the groundmass of the rock is noticeably rich in quartz. Plagioclase is also abundant in the groundmass and is usually altered to a white mica or clay plus epidote and calcite. Secondary minerals include biotite, magnetite, epidote, and a white mica (sericite). The magnetite is often altered to hematite or limonite. K-feldspar, zircon, pyrite, and apatite are found in minor to trace amounts. All thin sections show porphyritic textures. The groundmass has a seriate texture in which crystals range from fine to coarse grained. A majority of the sections show a weak- to moderately well-developed vitroclastic texture with broken phenocrysts and weak compaction foliation (fig. 16). Variations found in thin section are the proportion of feldspar to quartz phenocrysts, the total number and size of phenocrysts, texture, and the amount of opaque minerals in the matrix.

This unit was called a dacite using the classification of Travis (1955). The rock may have been more potash-rich than a dacite and similar to the felsite of Loughlin and Koschmann (1942); however, alteration makes determination of the original feldspar composition difficult.

The origin of the dacite is questionable but two possibilities are likely. They are: 1) the dacite is an intrusive, or 2) it is a tuff that outcrops as xenoliths and jumbled blocks in the gabbro of Garcia Canyon.

Evidence for an intrusive dacite is found primarily southwest of the Papa Ranch. This evidence includes cross-cutting relationships with the siltstones (plate 1) and the formation of a small area of spotted hornfels (see

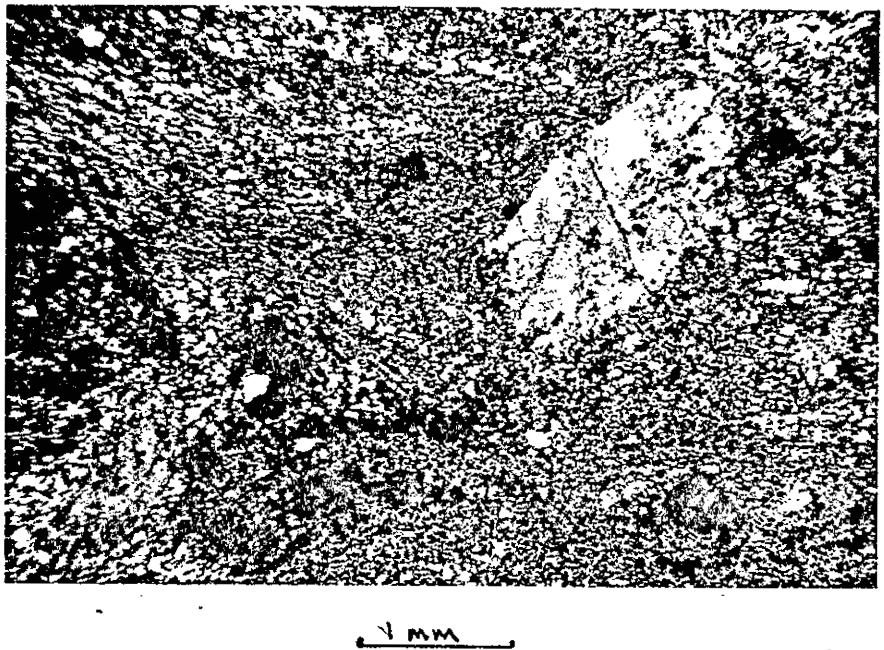

Figure 16: Photomicrograph of dacite showing a well-developed vitroclastic texture with broken phenocrysts and compaction foliation. This sample is from an outcrop completely surrounded by gabbro in Garcia Canyon.

metamorphic section) in the siltstones west of the dacite. North of the El Tigre mine, the dacite is found along a possible conduit, the inferred north-northwest-trending Proterozoic fault zone (see structure section). Here, a lack of a vitroclastic texture is suggestive of an intrusive origin. Furthermore, contact relationships reported by Loughlin and Koschmann (1942) from the Germany mine in the Kelly district support an intrusive relationship.

Direct evidence for an extrusive dacite includes an observed vitroclastic texture with broken phenocrysts, compaction foliation, and possible relict pumice. This texture is found in a majority of the outcrops; however, a few outcrops may contain portions with and without a vitroclastic texture. In these cases, textural evidence concerning origin is inconclusive. Additional evidence for an extrusive dacite is found southwest of the Papa Ranch. Here, the dacite has a nearly conformable contact with the Proterozoic siltstones.

Indirect evidence for an extrusive origin for the dacite is twofold. Outcrops of the dacite are generally surrounded by the gabbro of Garcia Canyon, suggesting that the outcrops are xenoliths in the gabbro and hence a portion of the supracrustal succession into which the gabbro intruded. Secondly, intermediate to felsic intrusions usually require a preexisting plumbing system for which there is little evidence.

Within the scope of this report the problem of the origin of the dacite seems unresolvable. It is possible that there are both intrusive and extrusive dacites, but not in the same outcrop as is found southwest of the Papa Ranch and north of the El Tugre mine. I feel the evidence points more to an extrusive origin for the dacite, and for this reason the unit is located in the supracrustal rock section of this report.

Matrix-supported conglomerates

Matrix-supported conglomerates interbedded with thick siltstone-sandstone sequences are found in three parts of the study area; 1) the largest, in and north of North Fork Canyon (sec.22,T.3 S.,R.3 W.), 2) the thickest, in Copper Canyon (sec.27,T.3 S.,R.3 W.), and 3) north of the Papa Ranch (sec.34,T.2 S.,R.3 W.). Float of matrix-supported conglomeratesis also found in section 10 and 15. Both Kalish (1954) and Krewedl (1974) mention, but do not describe, the matrix-supported conglomerates.

Outcrops of matrix-supported conglomerates are best exposed in stream bottoms. The massive gray-green mudflow deposit in North Fork Canyon is easily spotted as it crops out near the road. This interval is nearly 40 feet (12 m) thick and contains primarily siltstone clasts as much as 5 inches (13 cm) long. The clasts are subrounded and comprise about 50% of the rock. Minor amounts of mafic and

Figure 17: The North Fork Canyon mudflow deposit showing clasts of siltstone and mafic igneous rocks. The photo also shows a preferred orientation to the clasts.

porphyritic rocks are present as clasts (fig. 17). The Copper Canyon mudflow deposit is about 40 feet (12 m) thick and has a majority of siltstone clasts. Clasts in this unit are subrounded and range in size to 5 inches (13 cm). These clasts make up about 50% of the rock (fig. 18). The unit differs from the North Fork Canyon mudflow deposit in that it is brown in color and contains numerous interbedded sandstone units (fig. 19). Also, the Copper Canyon mudflow deposit has a wider variety of clasts including quartzites, felsic tuffs, and granitic rocks.

In thin section, other differences between the two matrix-supported conglomerates are apparent. The matrix of the unit found in North Fork Canyon contains a clay or white mica, chlorite, quartz, biotite, and magnetite, in order of decreasing abundance. Matrix grains are subrounded to subangular and are generally less than 0.2 mm in size. The matrix of the Copper Canyon interval contains quartz, a white mica or clay, limonite, and a minor amount of feldspars. Grain size is less than 0.2 mm and grains are subangular to subrounded. An orientation of the clasts is visible in the North Fork Canyon mudflow deposit. The Copper Canyon mudflow deposit contains a greater percentage of fine-grained volcanic and mafic clasts, clasts containing feldspars, clasts of shattered quartz grains, and portions of the matrix consisting of a concentration of broken grains.

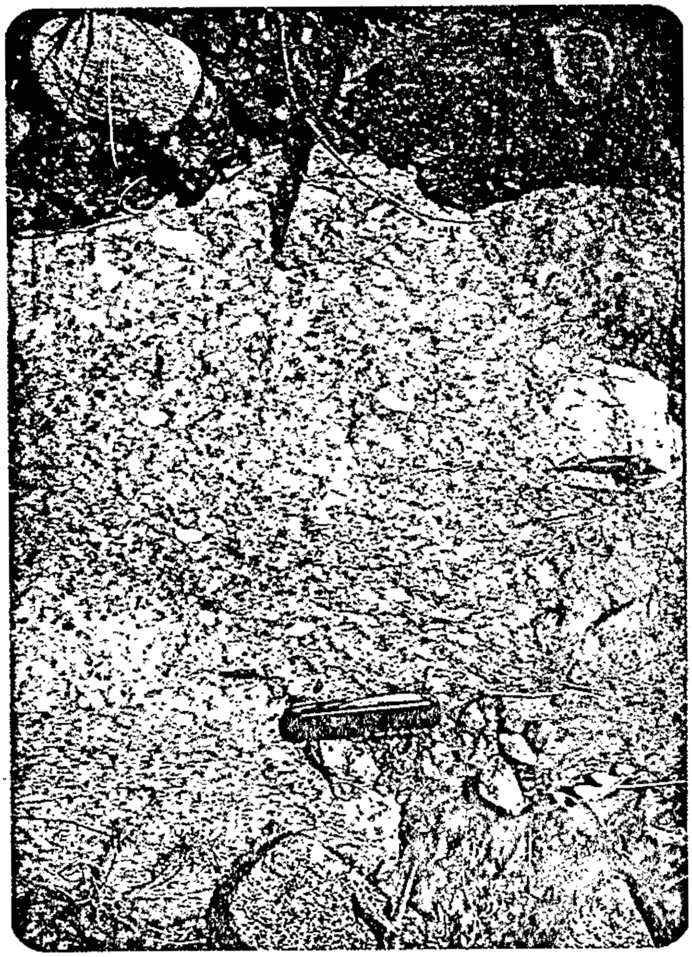

Figure 18: The Copper Canyon mudflow deposit showing a lack of sorting, bedding, and orientation of the clasts.

Figure 19: The Copper Canyon mudflow deposit shown interbedded with a sandstone interval. The photo shows approximately 12 inches (30 cm) of section.

Matrix-supported conglomerates and siltstone intervals are interpreted as mudflow or debris flow deposits because of internal characteristics, and, in the case of the Copper Canyon mudflow deposit, characteristics of the surrounding rocks. Internal characteristics found in all intervals in the mapped area and considered by Reineck and Singh (1975) as important features of mudflow deposits include: 1) abrupt well defined margins, 2) absence of grading, 3) lack of particle orientation except for an occasional vertical orientation of platy clasts, 4) poorly developed bedding, and 5) lack of sorting. In the Copper Canyon sequence, surrounding beds contain features suggestive of an alluvial fan deposit, an environment where mudflow deposits are likely to occur.

Proterozoic Intrusive Rocks

Proterozoic intrusive rocks underlie approximately 25% of the study area and nearly 60% of the eastern slope of the northern Magdalena Mountains. Four different intrusives were mapped: the rhyolite of North Baldy, the gabbro of Garcia Canyon, the Magdalena granite, and diabase dikes. A dacitic unit found in numerous scattered outcrops contains both intrusive and extrusive features and is of uncertain origin. The rhyolite of North Baldy is undated but is believed to be contemporaneous with the deposition of the supracrustal rocks. Volcanic rocks from central New Mexico have been dated at 1680-1700 m.y. (Stacy,1979,oral commun.). The oldest date on an intrusive rock from this area is 1517+-239 m.y. (Rb/Sr whole-rock, White,1977) on the gabbro of Garcia Canyon. Diabase dikes, believed to be the youngest Proterozoic igneous intrusion, have not been dated in the Magdalena Mountains but similar dikes have been dated elsewhere in the southwestern United States at 1.0 to 1.1 b.y. (Brookins,1978; Thorman,1979, oral commun.).

Two possible explanations for the intrusive activity are mentioned here and will be discussed in the conclusions section. First, the study area is at the intersection of two major structural lineaments: the northeast-trending Morenci lineament, and the west-northwest trending Capitan lineament (Chapin and others,1978). Both are believed to have been active during the Precambrian and may have leaked magmas then as they did in the Tertiary (Chapin and others,1978).

Secondly, the study area is within a tectonically and magmatically active region as evidenced by a caldera structure, felsic pyroclastic volcanism, and the abundance of volcanic and intrusive rocks in the Proterozoic of central New Mexico (Condie and Budding,1979). In such a setting, numerous intrusions are to be expected.

Rhyolite of North Baldy

An intrusive rhyolite found east of North Baldy (sec.17,T.3 S.,R.3 W.) is here informally termed the hyolite of North Baldy. This unit was mapped and described by Krewedl (1974) who inferred it to be the Precambrian granite of Loughlin and Koschmann (1942) (the Magdalena granite in this study). This author found the granite and the rhyolite to be texturally different. A Proterozoic age is assigned to this rhyolite because the rhyolite is not found intruding Phanerozoic rocks and it appears to be a vent for Proterozoic tuffs mapped in the area.

The rhyolite of North Baldy crops out in two lobes which cover approximately 0.12 square miles (0.33 sq km) on a ridge trending east from North Baldy (plate 1). Outcrops of the rhyolite are blocky; the unit forms cliffs on the south side of the ridge and a talus slope on the north side. In handspecimen, the rock is generally pink or pinkish gray and hard. Conspicuous within the rock are medium-grained quartz eyes, pink feldspars and green biotite. The rock is easily distinguishable from the Magdalena granite (fig. 20).

Thin section analysis shows the rhyolite to be porphyritic and strongly vitroclastic with broken phenocrysts and a weak to moderately well-developed flow foliation (fig. 21). Quartz and potash feldspar are the essential minerals comprising 50-60 and 10-15 percent of the rock, respectively. Less than 5% sodic plagioclase is present. Quartz and sericite make up the groundmass and green biotite fills fractures. Minerals found in trace amounts include apatite and zircon.

The rhyolite has a conspicuous vitroclastic texture evident by the broken and shattered phenocrysts (fig. 21). Shattering in the rock is also seen in outcrop as fragments of the rhyolite caught up in a later phase of the rhyolite (fig. 22). Further evidence for vitroclastic texture is expressed by a weak to moderate foliation. This foliation is generally perpendicular to bedding in the Proterozoic section and is expressed by an alignment of xenoliths and by variation in grain sizes.

The rhyolite of North Baldy probably represents the vent facies of a vitroclastic eruption. Several lines of evidence suggests this and include: 1) a vitroclastic texture in the unit, including shattered crystals and a foliation, 2)

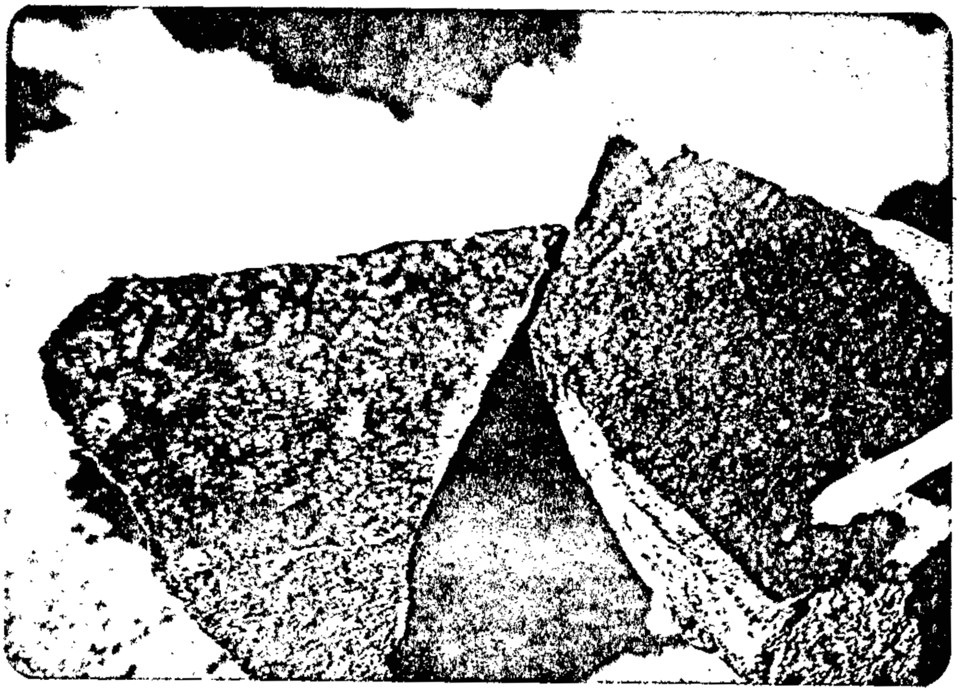

Figure 20: A comparison of the rhyolite of North Baldy (right) and the Magdalena granite (left). Differences between the two intrusions include color, texture, and the presence of quartz phenocrysts in the rhyolite.

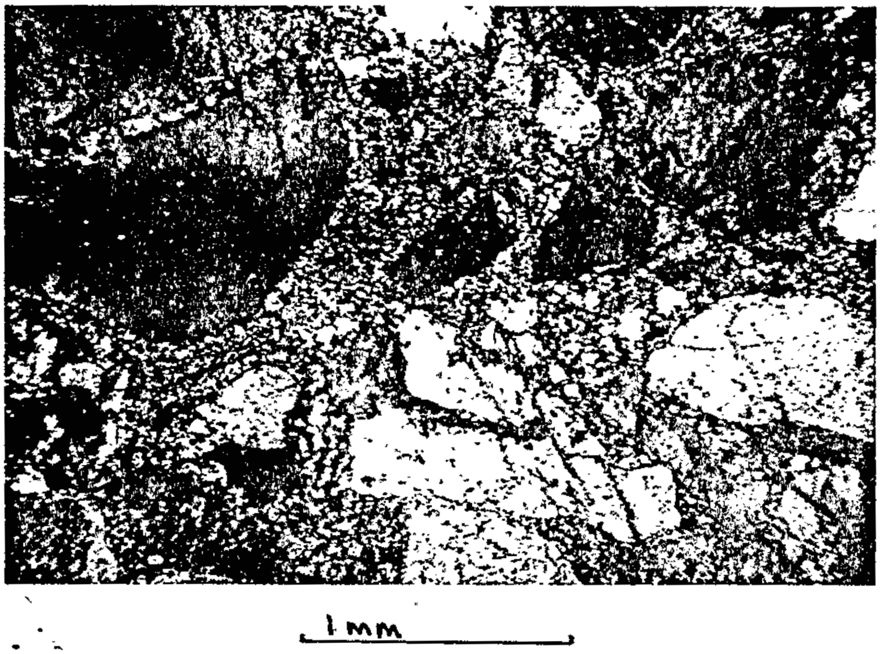

Figure 21: Photomicrograph of the rhyolite of North Baldy showing a vitroclastic texture. Numerous broken phenocrysts are seen and a small area of flow foliation is developed below the large quartz grain in the upper left corner.

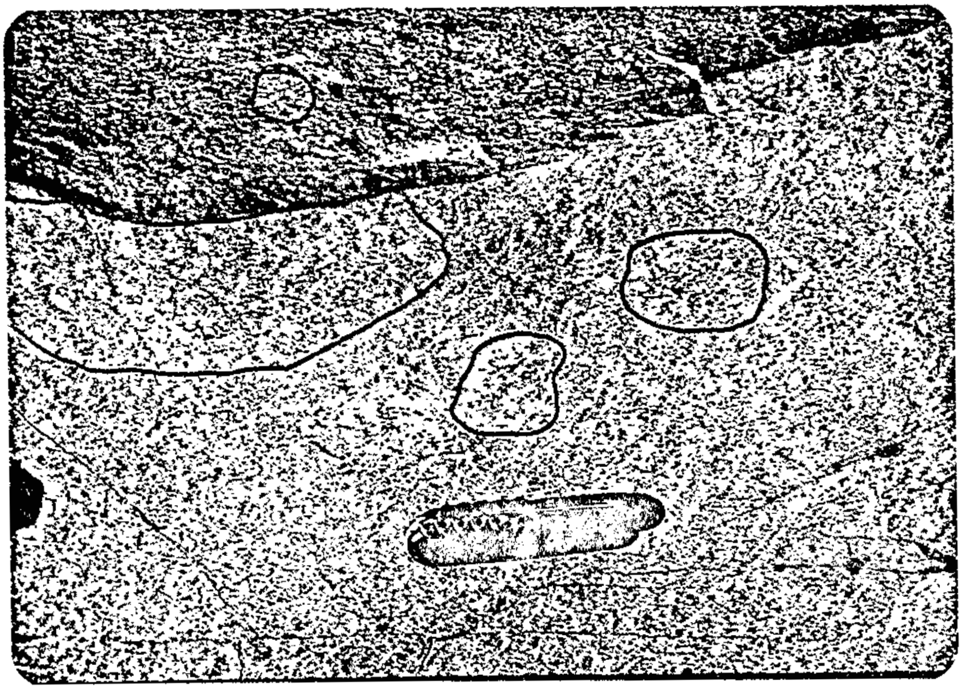

Figure 22: Fragments of rhyolite of North Baldy within the rhyolite of North Baldy indicating explosive disruption of the previously consolidated rhyolite. Fragments are not uniformily found throughout the unit.

foliation perpendicular to bedding of the tuff units in the Proterzoic section, 3) clasts of the rhyolite within the intrusive indicating explosive disruption of previuosly consolidated rhyolite, 4) a heterogeneous xenolith population, 5) the presence of copious amounts of vitroclastic volcanic rock nearby, 6) the presence of an inferred graben or caldera structure including an anomalously thick tuff sequence (to be discussed later), and 7) lineations on pumice from the eastern portion of the area which indicate a possible transport direction from the area of the vent (plate 1). The rhyolite also contains pervasive quartz veining (nearly stockworks) which may be related to a late stage venting or hydrothermal event.

Features inherent to the rhyolite of North Baldy, along with with features found nearby, indicate a volcanic source area in the western portion of the study area during the Proterozoic. An extrusive phase of the rhyolite of North Baldy was not confirmed.

Gabbro of Garcia Canyon

The gabbro of Garcia Canyon crops out throughout the Proterozoic terrane in the Magdalena Mountains in large irregular pods and in smaller sill-like bodies (plate 1). Contact relations are poorly exposed; however, the outcrop pattern, the holocrystalline nature of the intrusion, subophitic textures, and the lack of obvious extrusive characteristics indicate that the gabbro is intrusive. In general, the intrusion is mafic in composition; however, minor variations in composition do occur, e.g. sphene gabbro. The gabbro is altered or metamorphosed such that the clinopyroxenes are now amphiboles.

Loughlin and Koschmann (1942) were the first to map and describe the gabbro from fault blocks in the Kelly district. In that district, the gabbro is sill-like and metamorphosed to the upper greenschist facies (composed of plagioclase and uralitic hornblende). Crosscutting relationships found around the Germany mines in the Kelly District require that the gabbro be the oldest intrusive followed by the felsite of Loughlin and Koschmann (1942) and the Magdalena granite. This age relationship is supported by the Rb/Sr isotopic dates of White (1977). White (1977) first named the unit the Magdalena Gabbro and determined a preliminary Rb/Sr-whole-rock age of 1517+-239 m.y. Condie and Budding (1979) report the general characteristics of this gabbro and other gabbros and metadiabases in central New Mexico.

Three large irregular exposures of the gabbro are found in the study area: 1) the largest, between Jordan and Garcia Canyons (sec.8,9,T.3 S.,R.3 W.), 2) east of North Baldy (sec.16,T.3 S.,R.3 S.), and 3) north of the Kelly Ranch (sec.22,23,T.3 S.,R.3 W.) (plate 1). The sill-like nature of the unit is apparent in many places, but it is best shown southwest of the Papa Ranch, between Garcia and Jordan Canyons (sec.9,10,T.3 S.,R.3 W.). Here the map pattern suggests a conformable relationship. Attitudes of xenoliths of sedimentary rocks are similar to those found in the sedimentary units outside the gabbro. The pervasiveness of outcrop of the gabbro throughout the study area and its relationship to the five structural blocks (fig. 3) of Proterozoic sedimentary rocks suggests that the blocks are roof pendants in the gabbro.

Outcrops of the gabbro are generally low and rounded except in some stream beds and along steep slopes, as in Garcia Canyon (sec.9,T.3 S.,R.3 W.). The unit weathers to dark green to brown friable soil. A few outcrops in Garcia Canyon show foliation as do others near the contact with an intermediate tuff near the El Tigre mine (sec.16,T.3 S.,R.3 W.).

Distinguishing between the Proterozoic gabbro and Tertiary intermediate intrusions is often difficult in the field. Tertiary intrusions are distinguished by the presence of plagioclase phenocrysts, by the greater degree of weathering in the Tertiary rocks and, where possible, by crosscutting relationships.

In handspecimen, the gabbro is dark green, holocrystalline and massive. Grain size varies from fine to coarse. Recognizable minerals include plagioclase, chlorite, hornblende, magnetite, and occasionally pyrite.

The gabbro is often the most altered unit near Tertiary intrusions. At these contacts, alteration minerals include epidote, quartz, calcite, magnetite, limonite, and pyrite. Examples of this alteration assemblage can be seen north of the Kelly Ranch (sec.23,T.3 S.,R,3 W.).

Most of the rock is petrographically a gabbro (Travis,1955) although some samples contain as much as 10% quartz and may be termed quartz gabbros. One thin section contains nearly 10% sphene and is called a sphene gabbro.

Intense alteration makes determination of modal compositions in many thin sections difficult. The plagioclase is calcium-rich and is often altered to a mica and/or clays and calcite; the hornblende and clinopyroxenes are altered to chlorite and calcite. Plagioclase content seems to be somewhat variable but averages 40-50%; clinopyroxenes and hornblende comprise 1-3% and 40-50% of the rock, respectively. Accessory minerals include quartz, magnetite, biotite, tremolite, and sphene. Normal zoning in the plagioclase is suggested by the preferential alteration of the centers of the plagioclase grains to fine-grained micas, clays, and calcite. This preferential alteration would be expected if the centers contained more calcium than the rims.

Metamorphism and/or alteration of the original mafic mineral clinopyroxene to hornblende and tremolite is apparent. Reaction rims of hornblende on clinopyroxene and partial to complete replacement of clinopyroxene by fine-grained, oriented hornblende is seen in thin section (fig. 23). One section shows a pyroxene in which the rim is replaced by hornblende and the center is replaced by tremolite. These metamorphic minerals have in some cases been further altered to chlorite and calcite.

Textures in the gabbro are somewhat variable. The most pervasive texture is ophitic to subophitic in which the plagioclase crystals are partially or totally enclosed in pyroxene (now amphibole) crystals. This texture is sometimes conspicuous despite the high degree of alteration. A poikiolitic/poikioblastic texture is also present with grains of magnetite found in plagioclase and in the mafic minerals. Some magnetite grains have dendritic texture. The ophitic to subophitic textures are consistent with an origin for the gabbro as sills or as a small pluton (Carmichael and others,1974).

Defining the conditions under which the gabbro was altered and/or metamorphosed is somewhat difficult. Both the plagioclase and the mafic minerals have been replaced by an assemblage of minerals which can be produced by either metamorphism or alteration. The plagioclase in the gabbro may show normal zoning with an altered calcium-rich core. Alternatively, the plagioclase may have crystallized unzoned and calcium rich; the rims may have been changed during greenschist facies metamorphism to a lower An content (Deer,

Figure 23: Photomicrograph of the gabbro of Garcia Canyon showing complete replacement of the clinopyoxene by honblende on the rims and tremolite in the center. The hornblende shows a preferred orientation.

Howie, Zussman,1974). The unmetamorphosed calcium-rich core may have later been altered to calcite by deuteric alteration, hydrothermal fluids from later intrusions, or by supergene fluids.

The process of uralitization (replacement of pyroxene by amphiboles) can be attributed to either alteration or metamorphism. Deer and others (1963) appear undecided as to the cause of uralitization. They cite an example where the ratio of amphibole replacing pyroxene reflects a relative grade of metamorphism and hornblende is associated with higher grades of metamorphism (p.305,1963). Their final statement (p.308,1963) on the subject is inconclusive; they believe uralization may be associated with regional, contact, or metasomatic metamorphism.

The wide range of possible processes for the formation of the suite of minerals found in the gabbro and the large amount of igneous activity recorded in the study area (four Proterozoic intrusions and four Tertiary intrusions) makes determination of the time and method of alteration nearly impossible.

The nearest similar Proterozoic unit, the Lemitar gabbro, is located in the Lemitar Mountains approximately 12 miles (19.2 km) northeast of the study area. The geology of the Proterozoic rocks in the Lemitar Mountains has been described by Woodward (1973), Chamberlin (in prep.), and Mclemore (in prep.). The Lemitar gabbro, like the gabbro of

Garcia Canyon, intrudes Proterozoic metasedimentary rocks and is in turn intruded by a granitic pluton. From Woodward´s (1973) description, the Lemitar gabbro appears to be similar to the gabbro of Garcia Canyon except that the pyroxenes are completely replaced by hornblende and the plagioclase is more sodic in the Lemitar gabbro. Samples of the "gabbro" collected by Chamberlin and Mclemore are more felsic than Woodward´s description; most samples contain megascopic quartz.

Hornblende Chlorite Schist (Gabbro or Diabase)

Two thin chlorite schist units occur near the middle of the Proterozoic stratigraphic section (fig. 4). The rock is composed primarily of fine-grained plagioclase, hornblende, and chlorite, and is called a hornblende chlorite schist using the classification of Travis (1955). Deformation and/or alteration has been intense in some cases and the nature of the original rock is questionable. In one thin section, the rock appears to be a mylonite. In general, the unit is 10 to 20 feet (3-6 m) thick but thickens to approximately 100 feet (30 m) at the western end of its exposure. The schist is best exposed in gullies north of Shakespeare Canyon. This unit has not been described in previous literature.

The hornblende chlorite schists found west of the Strozzi Ranch (sec.10,T.3 S.,R.3 W.) are underlain by thick siltstone sequences and the upper schist is overlain by a dark, felsic tuffaceous rock on the west and by siltstones on the east. Contacts with the surrounding sediments appear conformable. The schists are continuous along strike for nearly a mile (1.6 km); they are cut off on the west by a Tertiary monzonite dike and are covered on the east by Quaternary deposits.

Few outcrops of the hornblende chlorite schist are seen. The schist weathers to a green, friable soil. Typical exposures of the unit are low rounded outcrops. In outcrop, the rock is dark green, fine-grained, and noticeably schistose. The schist appears compositionally homogeneous but has a variable texture. In handspecimen, one type is dense, dark green to dark grey, fine grained and contains chlorite and an amphibole. Thin section analysis shows that this type of schist contains plagioclase and hornblende of equal grain size (less than 0.2 mm) and is only weakly foliated. Other samples of the schist contain a well-foliated matrix made up of plagioclase and chlorite, which surrounds ragged porphyroblasts of hornblende. This type may be called a mylonite using the classification of Spry (1969) (fig. 24). In both cases, chlorite and magnetite are ubiquitous.

The hornblende chlorite schist is a unique rock in the stratigraphic section due to the greater intensity of alteration/deformation that the unit records. The schist was

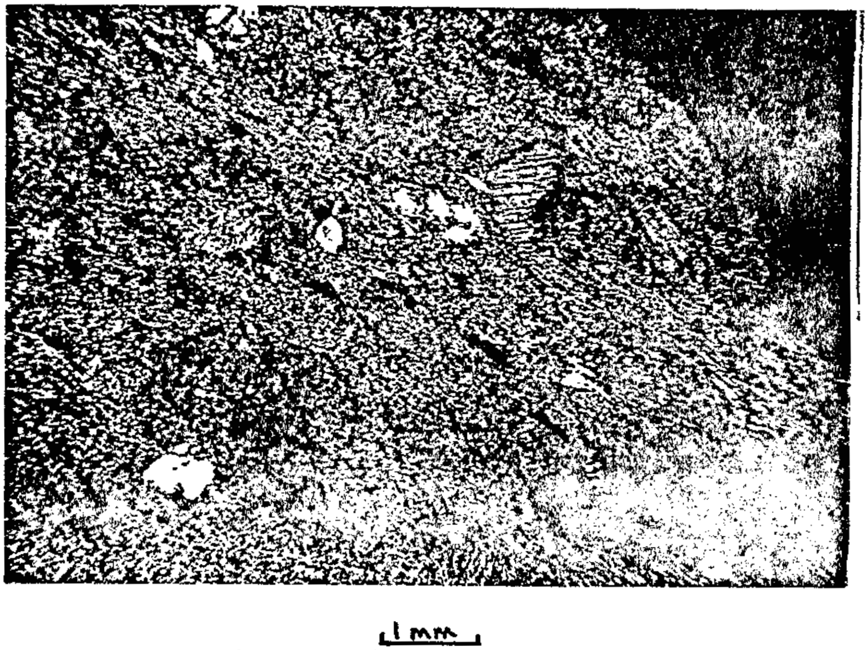

Figure 24: Photomicrograph of the hornblende-chlorite schist from west of the Strozzi Ranch showing a mylonitic texture.

probably a diabase sill rather than an extrusive basalt or a shaley sediment. Contacts with the surrounding supracrustal rocks suggest an intrusive origin because of slight cross-cutting relationships. Lack of layered quartz-rich zones rules against a shale origin; cross-cutting relationships rule against an extrusive origin. Contact effects from the injection of the sill are not seen, probably due to the unreactive nature of the host rocks and the lack of outcrops.

The true nature of the hornblende chlorite schist has been further concealed by what appears to be shearing along the western portion of the outcrop. The termination of two Tertiary dikes indicates a possible fault in this area. No fault evidence is seen in other rocks along strike of the inferred fault.

This hornblende chlorite schist is probably a diabase sills related to the gabbro of Garcia Canyon. The unusually thin and continuous outcrop supports this interpretation. The schistosity of the rock and Tertiary shearing along the outcrop tend to mask the origin of the unit.

Magdalena Granite

The Magdalena granite consists of pink micrographic granite which covers approximately eight square miles (21 sq km). North of Jordan Canyon, the granite comprises a majority of the eastern slope of the northern Magdalena Mountains. The intrusion of the Magdalena granite is believed to be part of a Proterozoic felsic intrusive event (~1400 m.y.) that occured in central New Mexico (White,1977).

Previous literature concerning the Magdalena granite is confusing. Four different intrusives or combination of intrusives have been called, or inferred to be, the Magdalena granite. These include: 1) the Magdalena granite; 2) the rhyolite of North Baldy; 3) the Tertiary Water Canyon stock; and 4) rhyolitic and dacitic rocks, debris flows, and tuffs in the Papa Ranch area (sec.4,T.3 S.,R.3 W.). Loughlin and Koschmann (1942) characterized the granite as having quartz micrographically intergrown with microperthite, and secondary green biotite. Kalish (1953) described the Water Canyon stock and assigned it a Precambrian age. His description of this unit is similar to the Magdalena granite, although he mentions a coarser grain size and larger orthoclase phenocrysts. An intrusive contact with the Kelly Limestone exposed in a prospect pit north of the Kelly Ranch (sec.22,T.3 S.,R.3 W.) requires that the Water Canyon stock be post-Mississippian. A K-Ar date on biotite from the Water Canyon stock yielded an age of 30.5+-1.2 m.y. (Chapin and others,1978). Krewedl (1974) inferred the rhyolite of North Baldy to be the granite of Loughlin and Koschmann (1942). His description of the rhyolite and the Magdalena granite are similar. This author found the units dissimilar; in outcrop, the rhyolite of North Baldy is darker and more silicious, and in thin section, is porphyritic, with a vitroclastic texture (broken phenocrysts and a flow foliation). The rhyolite also contains more quartz, and lacks the micrographic texture of the Magdalena granite. In this investigation, the rhyolite of North Baldy is considered to be a separate unit and is described in a proir section. Park's (1976) mapping in the northeast portion of the study area did not distinguish between the Magdalena granite, felsic quartz porphyries, and felsic tuffs found in the area. White (1977) named the granite described by Loughlin and Koschmann (1942) the Magdalena Pluton and determined a preliminary Rb/Sr whole-rock age of 1274 +-63 m.y. Condie and Budding (1979) present a short description and a whole-rock chemical analysis of the Magdalena granite.

In outcrop, the Magdalena granite weathers to blocky outcrops, especially along steep slopes. The granite also occurs sporadically along ridges and in gullies as more rounded outcrops. The pluton appears salmon-pink and spotted in outcrop, often with conspicuous green biotite. In the lower portions of Jordan Canyon (sec.4,T.3 S.,R.3 W.), several xenoliths of Proterozoic siltstone are found within the granite. A fine-grained border facies, as much as 50 feet (15 m) wide, is also occasionally developed in the Jordan Canyon area. This border facies is seen only where the granite intrudes siltstones.

In hand specimen, the Magdalena granite is a pink-to buff-colored, medium-grained holocrystalline rock composed of potash feldspar, plagioclase, quartz, and biotite. One sample collected west of the Papa Ranch is a distinctive granite porphyry. This porphyritic portion of the Magdalena granite contains phenocrysts of potash feldspar (60%), quartz (30%), and plagioclase (10%) and irregular patches of biotite in a fine-grained groundmass. This granite porphyry is not distinguished on the map.

The essential minerals in the granite are quartz, perthitic potash feldspar, and sodic plagioclase. The quartz and potash feldspar are micrographically intergrown showing a wormy texture in the center of the intergrown grains and well-developed cuneiform graphic textures towards the rims (fig. 25). Accessory minerals include magnetite and zircon. Secondary minerals including biotite, epidote, magnetite, and sphene are generally found in clusters. Also, epidote and a white mica replace some of the plagioclase. In general, the plagioclase in the granite is less altered than the plagioclase in the granite porphyry. The border facies is primarily fine-grained quartz, plagioclase, and biotite.

Several Proterozoic granitic intrusions are found nearby in the Sierra Ladrones, the Lemitar Mountains and in the Chupadera Mountains (fig. 1). Kottlowski (1960) mapped a Precambrian granite to granodiorite that intrudes a Precambrian gneiss/schist in the Chupadera Mountains. This

Figure 25: Photomicrograph of the Magdalena granite showing well developed micrographic texture.

granitic rock is coarser than the Magdalena granite and consists primarily of quartz, potash feldspar, plagioclase, and clusters of mafic/opaque minerals including biotite. The Polvadera granite intrudes the gabbro found in the Lemitar Mounatins. The Polvadera granite consists primarily of perthitic microcline, quartz, and biotite. Two granitic plutons are found in the Sierra Ladrones (Condie,1976). The older Capriote Pluton is heterogeneous, consists of potash feldspar (45-55%), sodium plagioclase (25-30%), and quartz (15-25%), and shows graphic textures (Cookro,1978). The younger Ladron Quartz Monzonite (Condie,1976) was dated by White (1977) at 1319+-51 m.y. (Rb/Sr whole-rock age). Cookro (1978) describes the quartz monzonite as a homogeneous, light-brown to pink, equigranular rock. The essential minerals in the unit are plagioclase, quartz, perthitic microcline, muscovite, and biotite.

The importance of granitic rocks of the Proterozoic of central New Mexico is made clear by an examination of geologic maps (Condie and Budding,1979). Granites and quartz monzonites cover a large portion of these terranes. Condie and Budding (1979) believe that these granitic intrusions are part of a plutonic event which occured throughout the mid-continent region of the United States between 1.5 and 1.3 b.y.B.P.

Diabase Dikes

Several diabase dikes intrude the Magdalena granite in the northwest portion of the study area. They are presumed to be of Proterozoic age as they do not intrude the Paleozoic section. Loughlin and Koschmann (1942) were the first to map and describe these diabase dikes which are more abundant north of the study area. Park (1976) mapped a few diabase dikes in the Magdalena granite near the Papa Ranch. Diabase dikes with a similar age relationship are described by Woodward (1973) in the Lemitar Mountains.

The dikes have a peculiar short and thick outcrop pattern. Outcrops weather to greenish-brown blocky boulders with moderately strong limonite staining along fractures. A fresh surface shows black to dark-gray, fine-grained rock. The rock contains traces of pyrite and the plagioclase is altered to a light-gray material. In thin section, the dike rocks are moderately to severely altered. A calcium-rich plagioclase and a pyroxene were probably the original essential minerals; these have now been partially altered to epidote, chlorite, and calcite. Accessory minerals are pyrite, magnetite, and biotite. Trace amounts of sphene are believed to be secondary after ilmenite.

Dikes of this approximate age are widespread in the southwestern United States. Thorman (1979, personal commun.) reported a date on a diabase dike from southwestern New Mexico at approximately 1100 m.y. and Brookins and others

(1978) report a date on mafic dikes in the Zuni Mountains of western New Mexico at approximately 1000 m.y. The intrusion of diabase sills and dikes in central Arizona, like the intrusion of diabase dikes in the Magdalena Mountains, is the last recognized Precambrian igneous event (Wilson, 1962).

PALEOZOIC ROCKS

Rocks of Paleozoic age within and bordering the study area are: the Mississippian Kelly Limestone, the Pennsylvanian Sandia Formation, and the Pennsylvanian Madera Limestone. These units are not emphasized in this study and were used primarily to define the extent of exposed Proterozoic rocks. The Paleozoic section is found in depositional contact with the Proterozoic rocks and is, in turn, unconformably overlain by the Oligocene Spears Formation.

Previous literature concerning Paleozoic rocks in the Magdalena Mountains is extensive as most of the ore in the Magdalena and surrounding districts is found in these units. For this reason, only brief descriptions of the units are provided here. Lasky (1932) described the Paleozoic section for Socorro County in _The Ore Deposits of Socorro County, New Mexico_. In that bulletin, the Kelly Limestone is called the Lake Valley Limestone, a name now restricted to the stratigraphically equivalent unit in southern New Mexico. Loughlin and Koschmann (1942) described the Paleozoic units and the mineralization and alteration in the Kelly district. Detailed stratigraphic sections, petrology and paleoenvironmental interpretations are provided by Siemers (1973,1978). Krewedl (1974) described the Paleozoic units and associated mineralization and alteration in the southern portion of the study area. Further work in the Kelly district was done by Blakestad (1977) and Iovenitti (1977).

Kelly Limestone

The Kelly Limestone is found in depositional contact with the Proterozoic rocks and is conformably overlain by the Pennsylvanian Sandia Formation. In the Magdalena area the Kelly is 0 to 90 feet (0 to 27.5 m) thick and is 64 feet (19.5 m) thick in North Fork Canyon (Siemers,1973). The Kelly forms the western boundary of the study area along the crest of the Magdalena Mountains (plate 1, Loughlin and Koschmann,1942; Iovenitti,1977; Blakestad,1977). In the Copper Canyon-North Fork Canyon area, the Kelly is found in depositional contact with the Proterozoic rocks and in fault contact with Proterozoic rocks along east-trending faults. Kelly Limestone is also found in fault blocks and/or landslide blocks south and west of the Water Canyon stock (sec.22,T.3 S.,R.3 W.). In the Magdalena Mountains, the Kelly consists of light-gray, thick-bedded, coarse-grained crinoidal biosparrites (Siemers,1973). The Kelly contains minor interbedded light-brown chert horizons in the study area.

Economically, the Kelly Limestone is the most important unit in the vicinity as it is the most receptive host rock for sulfide mineralization. The largest mines in the study area; the Buckeye, Hall-Lytton, and Hillside mines are found at the Kelly-Proterozoic contact or in the Kelly Limestone.

Sandia Formation

The Sandia Formation is the lower member of the Pennsylvanian Magdalena Group and is in gradational contact with the overlying Madera Limestone. In the study area, it is found in fault contact with the Proterozoic rocks in the southern portion of the study area and in fault or landslide blocks west of the Water Canyon stock (sec.22,T.3 S.,R.3 W.). In the Magdalena Mountains, the Sandia varies in thickness from 550 to 650 feet (168 to 198 m) (Siemers,1973). The Sandia is 554 feet (169 m) in North Fork Canyon (Siemers,1973). The unit is made up of gray-to-black, sandy, carbonaceous shales and siltstones, light-tan medium-to coarse-grained quartz sandstones, and gray medium-grained micritic limestone (Siemers,1973).

Madera Limestone

The Madera Limestone is the upper member of the Magdalena Group and is unconformably overlain by the Tertiary Spears Formation. The Madera ranges in thickness from 500 to 1500 feet (152 to 457 m) and is 763 feet (233 m) thick in North Fork Canyon (Siemers,1973). East of the El Tigre mine (sec.21,T.3 S.,R.3 W.) variations in attitudes suggest landslide or fault blocks along a major east trending fault separating Proterozoic and Phanerozoic rocks. The Madera is a thick homogeneous sequence of gray to black micrites with a few thin, coarse-grained sandstones (Siemers,1973). In the North Fork Canyon area, black chert is commonly found within the Madera.

The Madera Limestone is host to several small prospects in the North Fork Canyon area, the largest being the El Tigre mine.

TERTIARY ROCKS

Tertiary rocks are widespread throughout the southern and eastern portions of the study area (fig. 26). In this study, five Tertiary units will be briefly described: the volcaniclastic Spears formation, and four varieties of intrusive rocks, the Water Canyon quartz monzonite, monzonite to quartz monzonite dikes, white rhyolite dikes, and dikes of intermediate composition. The intrusive rocks are believed related both structuraly and petrographically to the extensive cauldron activity now being documented in the southern portion of the Magdalena Mountains (Chapin and others,1978).

The Tertiary rocks in the Magdalena Mountains have been intensely studied. In the study area, Tertiary rocks have been mapped and described by Kalish (1954) and Krewedl (1974). Blakestad (1977), and Bowring (in prep.) discuss the North Baldy cauldron whose northern boundary is found in North Fork Canyon. Chamberlin (in prep.) and Osburn (1978) discuss the Socorro Cauldron and tentatively place the cauldron margin in Water Canyon. An overview of the geology of these cauldrons is provided by Chapin and others (1978).

The Spears Formation

The Spears formation serves as a boundary for the study area west of the El Tigre mine (sec.17,20,21,T.3 S.,R.3

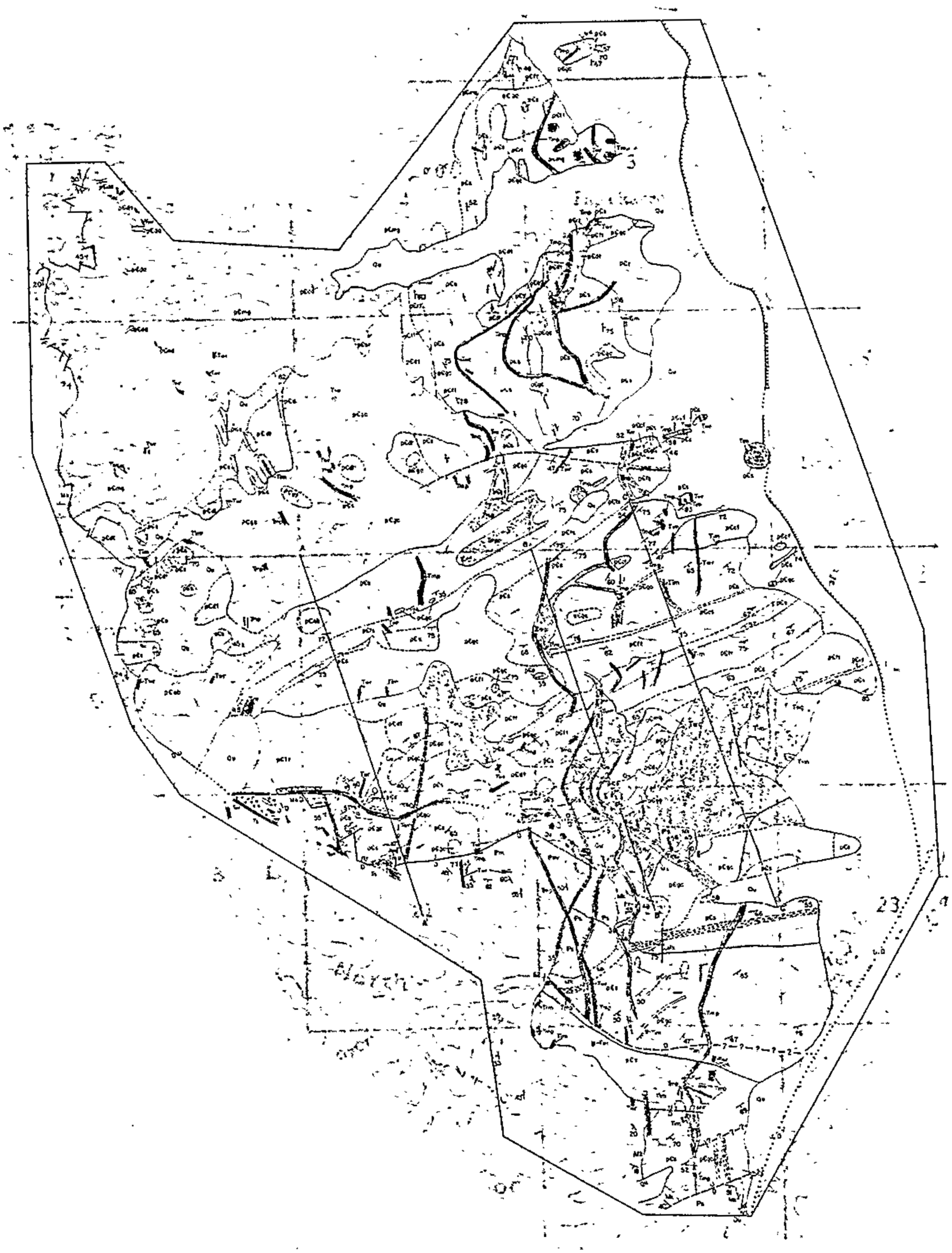

Figure 26: Map of the thesis area with Tertiary rocks colored.

W.). Here, the Spears is in fault contact with Proterozoic rocks along the east trending North Fault Canyon fault zone. The Spears has been dated at 37-33 m.y. (Chapin and others,1978) and is the oldest Tertiary unit found in the study area. The unit has been described in detail by numerous authors including Tonking (1957), Brown (1972), Krewedl (1974) and Wilkinson (1976).

In general, the Spears is a volcaniclastic unit composed of conglomerates, mudflow deposits, sandstones, lavas, and ash-flow tuffs of andesitic to latitic composition (Chapin and others,1978). In the study area, the Spears consists of lavas and conglomerates. Krewedl (1974) measured 3500 feet (1067 m) of Spears in North Fork Canyon; this is approximately twice the thickness reported by Chapin and others (1978) and the unit has most likely been repeated by faulting.

Water Canyon Quartz Monzonite

The Water Canyon quartz monzonite covers approximately 0.25 square miles (0.6 sq km) in sections 15 and 22 (T.3 S.,R.3 W.) and is well-exposed throughout the mapped area. The stock was probably intruded along the North Baldy cauldron margin (North Fork Canyon fault zone) as a post-collapse intrusion. Stocks in a similar position relative to the Magdalena cauldron are reported in the Kelly district by Blakestad (1978). Like the stocks in the Kelly district, the Water Canyon stock is a medium-to coarse-grained quartz monzonite.

Kalish (1953) first described the Water Canyon stock and thought it was a Precambrian granite. Krewedl (1974) described the unit and named it the Water Canyon stock. He also felt that the monzonite and quartz monzonite dikes found in the study area were genetically related to the stock. Krewedl mentioned similarities between the Water Canyon and Nitt and Anchor Canyon stocks found in the Kelly district. Chapin and others (1978) report a date of 30.5+-1.2 m.y. (K/Ar on biotite) for the stock.

The Water Canyon stock is believed to be the oldest Tertiary rock in the study area except for the early Oligocene Spears Formation. Age relationships with the monzonitic dikes, however, are not clear since contacts between the two intrusions are obscured by colluvium. White rhyolite and intermediate dikes intrude the stock.

Contacts between the Water Canyon stock and the surrounding rocks are, in most cases, well exposed and easily located. To the west and north of the stock, a metamorphic aureole of spotted siltstone is formed at the contact with the Proterozoic sedimentary and tuffaceous units. The gabbro of Garcia Canyon cropping out south of the stock shows no contact effects that are related to the Water Canyon stock. The Mississippian Kelly Limestone contains several small skarns along the contact of the stock. To the east, Quaternary deposits of the La Jencia basin cover the intrusive. Krewedl (1974) suggested that movement along the northern Magdalena Mountains range-bounding fault and the Water Canyon fault zone exposed the Water Canyon stock. Outcrops of the stock are generally gray to pinkish gray and rounded, in contrast to the blocky outcrops of the Magdalena granite. A grus often covers outcrops of the stock.

In hand specimen, the rock is porphyritic with conspicuous light to dark potash feldspars as long as 1.5 inches (4.0 cm). Thin-section analysis shows the essential minerals to be sodic plagioclase, potash feldspar, and quartz. Plagioclase and potash feldspar are found in nearly equal proportions. Accessory minerals include magnetite, biotite, and a white mica which is an alteration product of the feldspars. Texturally, the rock is holocrystalline and porphyritic with small areas of graphic intergrowths (feldspar and quartz) and myrmekitic texture.

Field evidence supports the mid-Tertiary age date for the Water Canyon stock. Emplacement of the stock was probably controlled by the North Baldy cauldron margin (North Fork Canyon fault zone), possibly in conjunction with a north-northwest-trending normal fault. Stocks of similar composition were intruded along the margin of the Magdalena cauldron in the Kelly district (Blakestad,1978). Significant mineralization or alteration has not been found associated with the Water Canyon stock. Mineralization at the Hillside mine is spatially associated with the stock but is also found adjacent to monzonitic and rhyolitic dikes and may therefore be related to those dikes.

Monzonite to Quartz Monzonite Dikes

Tertiary monzonite to quartz monzonite dikes and plugs are important in defining structure in the area. The monzonite dikes are located primarily in the eastern portion of the study area and, although discontinuous, can be followed for nearly 4.5 miles (7.2 km). Determination of rock type is often difficult due to the intensity of alteration which is evident from secondary calcite, clays, and micas; most samples were found to be monzonites. The host rocks are occasionally bleached and baked in a narrow zone surrounding the dikes. Good exposures of the monzonite dikes are found in Hillside and North Fork Canyons.

Kalish (1953) was the first to describe the monzonitic dikes in the study area. Krewedl (1974) discussed the dikes in some detail and noticed a spatial association between the dikes and the Water Canyon stock. Park (1976) did not make a distinction between the monzonitic and rhyolitic dikes on his map of the Papa Ranch area.

Field relations in the study area indicate the monzonite dikes are the oldest dikes in the area. In the

Kelly District, Loughlin and Koschmann (1942) found the monzonite dikes to be younger than the intermediate to mafic dikes. Kalish (1953) found age relationships which agree with this report, but Krewedl's (1974) findings are similar to those of Loughlin and Koschmann (1942).

Relationships of the monzonitic dikes and plugs with the Water Canyon stock are unclear. A contact between the stock and a monzonitic dike is covered by colluvium. Compositionally, they are nearly the same; the stock appears to be somewhat richer in potash feldspar.

Outcrops of the monzonitic dikes are variable in their surface expression. All are light gray to white in color and are rounded; some outcrops form low rubbly exposures while others are prominent. A grus is often formed. In handspecimen, the rock is light tan to light gray, weathers with a rough surface, and is porphyritic. Recognizable minerals include potash feldspar, quartz, hornblende, pyrite, and biotite. The monzonitic dikes are differentiated from the Water Canyon stock by fewer phenocrysts and lesser amounts of potash feldspar. In the dikes, phenocrysts appear to make up from 10 to 40 % of the rock and are primarily feldspars in a matrix of quartz and feldspar (fig. 27). A majority of the samples analyzed in thin section are monzonites; the remaining samples are quartz monzonites. The essential primary minerals are quartz, potash feldspar, and intermediate to sodic

Figure 27: Outcrop of a monzonite dike showing numerous, and often conspicuous, potash feldspar phenocrysts.

plagioclase. Plagioclase occasionally shows well-developed zoning. Accessory minerals include biotite and magnetite. Chlorite and epidote are secondary minerals after hornblende and biotite. Trace minerals include zircon, apatite, sphene, and pyrite. Most samples have a porphyritic texture with phenocrysts of potash feldspar and plagioclase. Phenocryst size is variable to 1.5 inches (4 cm). One sample contained a minor amount of quartz and feldspar micrographically intergrown.

The intensity of alteration in the monzonite dikes is easily seen in thin section. A majority of the rock is now a white mica, clay, and calcite. A zeolite, probably natrolite, is also visible in thin section. This mineral appears to have replaced the groundmass and the zeolite is now largely replaced by calcite and a white mica. Mineral determination was made by relict textures and form (radiating).

Monzonitic to quartz monzonite dikes are important in the study area for the determination of structure. The relation of these dikes to the Water Canyon stock is questionable. The two plugs found west of the stock (secs.15,16) may be higher portions of the stock considering the tilt imposed on the range (30-40 degrees to the west). This could not be substantiated with the methods used and may require a geochemical approach.

Mineralization related to the dikes is limited to small prospect pits; the largest of these pits is found west of the Strozzi Ranch.

White Rhyolite Dikes

White rhyolite dikes (plate 1) are important as they mark faults and fractures and possibly the roof zones of plutons. Rhyolite dikes are found primarily in the southwest portion of the area along the Proterozoic-Phanerozoic contact. These dikes also occur sporadically in the eastern and far northwestern portions of the study area. In most cases, the dikes have been bleached and altered to a quartz-sericite-pyrite assemblage. The best exposures are along the east-trending North Fork Canyon fault zone, west of the El Tigre mine.

Loughlin and Koschmann (1942) were the first to map and discuss white rhyolite dikes in the Magdalena Mountains. Krewedl (1974) describes the rhyolitic dikes in some detail as they are more prolific in his map area. Park's (1976) map of the Papa Ranch area did not distinguish white rhyolite from monzonitic dikes.

White rhyolite dikes in the study area are fault controlled and often occur along the same structures as do monzonite and quartz monzonite dikes (plate 1) The longest observable strike length is nearly one mile (1.6 km) and occurs along the Proterozoic-Phanerozoic contact in the southwestern portion of the study area. The thickest outcrop of white rhyolite is also found in this area (fig. 26).

Age relationships between the white rhyolites and other Tertiary intrusives are unclear as few outcrops showing cross-cutting relationships are seen. In the study area, rhyolitic dikes intrude the Water Canyon stock and a monzonitic dike. The intermediate to mafic dikes are probably younger as they are seen to intrude the white rhyolites. Loughlin and Koschmann (1942) and Krewedl (1974) found the rhyolite dikes to be the youngest intrusions in their respective areas. It is likely that there were several episodes of rhyolitic, monzonitic, and mafic intrusion.

Outcrops of white rhyolite are easily recognized as they are white and often form walls. Some outcrops show conspicuous flow banding (fig. 28). In handspecimen, the rock is observed to contain quartz and pyrite phenocrysts in a creamy-white aphanitic groundmass. Slabbed sections show feldspar phenocrysts well. Most samples have either an iron or manganese stain. In thin section, the essential minerals are quartz, potash feldspar, sodic plagioclase, and sericite as an alteration product of the feldspars. Quartz is the most abundant mineral and comprises approximately 50% of the rock both as a portion of the fine grained matrix and as phenocrysts. Phenocrysts of quartz, potash feldspar, and plagioclase make up 10-30% of the rock and are as large as 3 millimeters. Quartz phenocrysts occasionally have reaction

Figure 28: Prominent flow banding in a white rhyolite dike west of the Strozzi Ranch. Here, the rhyolite intrudes Proterozoic channel-fill deposits.

rims and/or a nearly square inclusion composed of potash feldspar and a white mica (fig. 29). The feldspars are usually altered to sericite and/or clays. Trace amounts of pyrite are often weathered to limonite. All samples have a porphyritic texture.

White rhyolite dikes are found throughout the Magdalena Mountains (Loughlin and Koschmann,1942; Krewedl,1974; Park,1976; Blakestad,1977; Osburn,1978; Petty,1979). Slight variations occur in composition, color, and phenocryst content. Loughlin and Koschmann (1942) found the rhyolites spatially associated with the monzonitic to granitic stocks in the Kelly District. In the study area, white rhyolite dikes are found along both the north-trending and east-trending structures. A majority are found along the North Fork Canyon fault zone and many are found spatially associated with the Water Canyon stock (fig. 26). A genetic relationship with the Water Canyon stock is uncertain.

A slight bleaching of the wall rock is often seen surrounding white rhyolite dikes. In the study area, the El Tigre and Hillside mines and several smaller prospects are found along white rhyolite dikes. This relationship has been noted elsewhere in the district (Loughlin and Koschmann,1942; Krewedl,1974; Blakestad,1978; Petty,1979).. Apparently the fractures filled by the white rhyolite dikes later became conduits for hydrothermal solutions. Mineralization at the El Tigre mine includes barite, sphalerite, and galena.

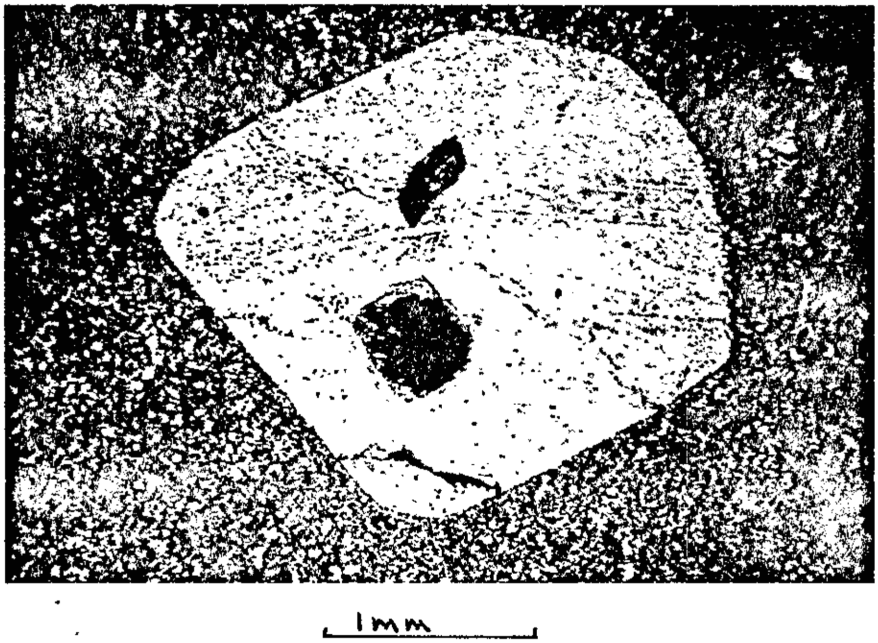

Figure 29: Photomicrograph of a rhyolite dike showing a potash feldspar inclusion in a quartz phenocryst.

Mafic to Intermediate Dikes

Mafic to intermediate dikes are associated with the most prominent and widespread alteration found in the area. Rock types range from gabbro to granodiorite and all are altered. These dikes are found throughout the area but show their greatest concentration north and west of the Kelly Ranch (sec.22,23,27,T.3 S.,R.3 W.) (plate 1). The dikes are best exposed in a road cut north of the Water Canyon campground; they have variable strikes, are usually short, and less than ten feet thick.

Loughlin and Koschmann (1942) found mafic to intermediate dikes (lamprophyre) spatially associated with monzonitic stocks in the Kelly district. Kalish (1953) was the first to describe the dikes in the study area. He called the dikes lamprophyres and recognized two types: 1) a plagioclase-rich, dense, black dike, and 2) a gray-green rock composed of plagioclase, pyroxene, and coarse-grained quartz. Krewedl (1974) found the dikes concentrated west of the Kelly Ranch. In the study area, mafic to intermediate dikes intrude white rhyolite dikes and are believed to represent the youngest igneous event in the area. This age relationship is similar to Kalish´s (1953) stratigraphy but Krewedl believed the mafic dikes to be the oldest set of dikes. North and west of the Kelly Ranch, the attitudes of the individual dikes are quite variable and do not follow the orthogonal system intruded by the more felsic dikes. Dike trends range from N80W to N30E with dips moderate to steep to the northeast and east. Despite the attitude of the dikes, the pattern of greatest concentration is east-trending, parallel to the North Fork Canyon fault zone. Two surveys in the area of greatest dike concentration showed a dike every 30 to 50 feet.

Contacts of the mafic to intermediate dikes with the country rocks are sharp and may be surrounded by a small baked zone. Contact effects are least pronounced in the siltstone intervals. In the metagabbro, effects of later hydrothermal alteration are apparent by the formation of veins and veinlets of quartz, calcite, epidote and magnetite. This alteration is best observed in the metagabbro south of the Water Canyon stock.

Outcrops of the mafic to intermediate dikes weather easily and generally form spheroidal rubble or slight topographic depressions. They are generally gray-green to nearly black in color and are distinguished from the metagabbro by their greater susceptibilty to weathering. In handspecimen, samples of the dikes are generally gray, but may be darker. Upon weathering, they may have a greenish tint. The rocks are porphyritic with phenocrysts of plagioclase, an amphibole, and occasionally quartz. Phenocrysts make up less than 25% of the rock, the remainder is a fine-grained groundmass.

In thin section, the essential minerals in the mafic to intermediate dikes are intermediate to calcic plagioclase and hornblende. These minerals are usually found both as phenocrysts and in the groundmass; they make up 40-60% and 10-40% of the rock, respectively. Accessory minerals include clinopyroxene, magnetite, and quartz. The clinopyroxene is altered to the amphibole; magnetite is usually evenly distributed throughout the sample and may make up 10% of the sample. Quartz phenocrysts are found in only a few slides. All samples were holocrystalline; most were porphyritic and contained a felty groundmass of plagioclase and amphibole laths. Phenocrysts are as large as 3 millimeters and amphibole phenocrysts are mostly euhedral. Alteration within the samples ranges from moderate to extreme. One slide shows intense silicification with nearly 60% quartz and the formation of biotite. Secondary minerals include chlorite after the amphiboles and calcite after the plagioclase.

The large number of diorite dikes and the variablity in their attitudes in the area west of the Kelly Ranch (sec.22,23) is suggestive of a buried stock. The proposed buried stock lies to the east of a stock inferred by Krewedl (1974) in sections 21 and 28. The two areas may represent one stock which was intruded along the North Fork Canyon fault zone.

CONTACT METAMORPHIC ROCKS

The effects of intrusions on the Precambrian supracrustal succession are variable and are generally expressed only in the sandstone-siltstone units. Contact metamorphic effects are not seen around either the intrusion of the gabbro of Garcia Canyon or the rhyolite of North Baldy. The intermediate porphyritic rock southwest of the Papa Ranch (sec.4,T.3 S.,R.3 W.) has a small alteration halo in which the siltstone is spotted. The Magdalena granite has a fine-grained border phase where it intrudes the siltstones.

Tertiary intrusives similarly have a wide range of contact effects. The Water Canyon stock has a metamorphic halo in which spotted hornfels are formed; monzonite and white rhyolite dikes appear to bleach the siltstones; intermediate dikes show little effect on the siltstones. Around the valley-fill sequence (see section below) south of the Papa Ranch, the siltstones are silicified, perhaps as a result of a buried Tertiary intrusion.

Spotted Hornfels

Contact metamorphic effects as seen by the formation of spotted hornfels are found in siltstones and sandstones partially surrounding two igneous rocks in the study area. The hornfels is found near the dacitic rock southwest of the Papa Ranch (sec. 4, T.3 S., R.3 W.) and west and north of the Water Canyon stock (sec. 15,22,T.3 S.,R.3 W.). The hornfels is best exposed on a ridge south of Shakespeare Canyon (fig. 30).

Outcrops of the hornfels are similar to the siltstones in structure and shape. The spotted green and white color is noticeable at a distance. In some outcrops the porphyroblasts are aligned (impingment texture). This alignment approximately parallels bedding, however individual grains of mica within the spots appear to have random orientations. In handspecimen, the porphyroblasts make up from 10-50% of the rock and may range in size from 1-3 millimeters. The porphyroblasts are generally a round to ovoid white area surrounding ragged, green ovoid forms. Contacts between the outer portion, the white portion, and the green inner portion are gradational. The white portion does not always completely surround the green portion and white and green features are not always aligned.

Thin section analysis of the spots shows the color differences are due to different micas. The white outer portion of the spot is made up primarily of quartz and a white mica. This white portion lacks biotite found in the original rock, and, biotite and chlorite are found in the inner portion of the spot (fig. 31). Biotite is predominant in the unmetamorphosed rock. Darker patches of chlorite are occasionally found surrounding or within the lighter portions of the spots.

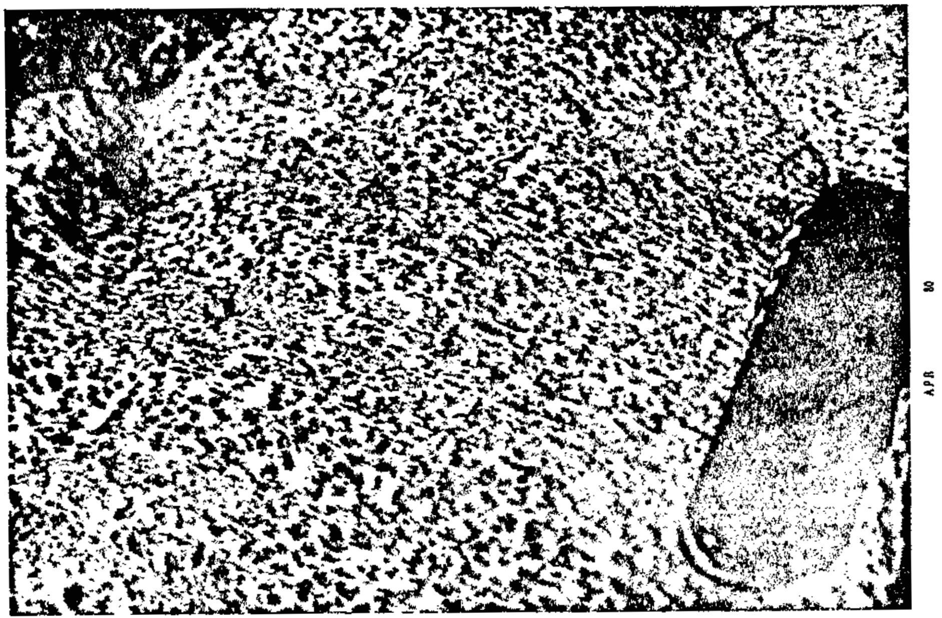

Figure 30: Spotted hornfels develpoed in siltstone west of the Tertiary Water Canyon stock.

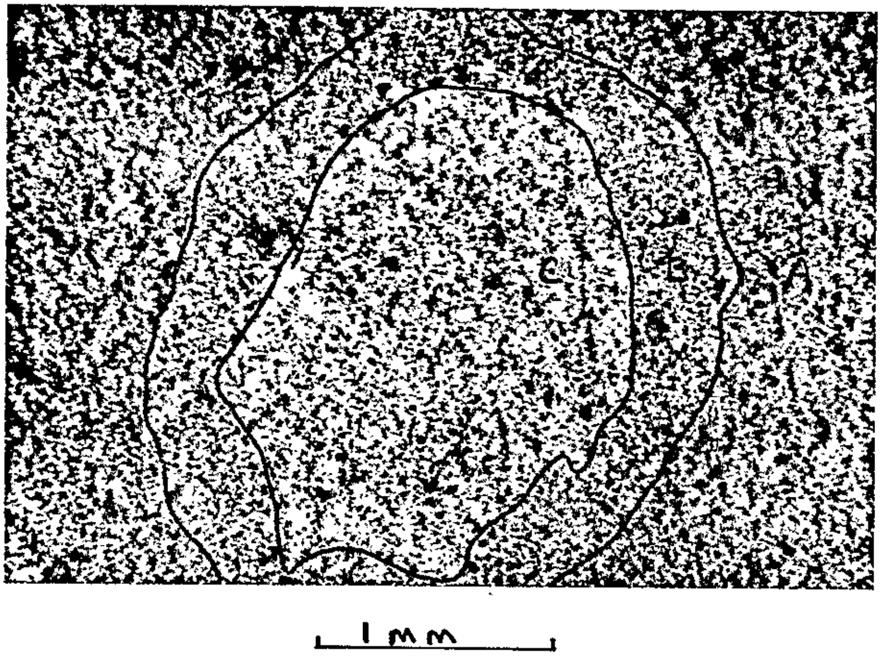

Figure 31: A photomicrograph of a spot in the spotted hornfels found west of the Water Canyon stock. A-original rock, B-white outer portion, C-green inner portion.

The spotted hornfels were not broken out on the map. Metamorphism in the study area is discussed later.

Quaternary Deposits

Alluvial-fan and piedmont-slope deposits, stream terraces, colluvium, talus, and stream sediments were mapped as Quaternary undifferentiated. The largest area of Quaternary deposits is on the eastern border of the study area along the edge of the La Jencia Basin (plate 1). Here, an extensive piedmont slope has been formed by coallescing alluvial fans. Large areas of talus and colluvium cover slopes near the crest of the range. In general, Quaternary units were mapped only where important geologic contacts were obscured.

STRUCTURE

The study area lies near the intersection of three structural zones: 1) the west-northwest-trending Capitan lineament, 2) the northeast-trending Morenci lineament, and 3) the north-trending Rio Grande rift (fig. 32). Effects from all three zones may be present in the area. Major events which can be documented within the area are: 1) a Proterozoic cauldron and the associated volcanism, 2) intrusion of a gabbro and the formation of roof pendants of the Proterozoic section, 3) emplacement during the roterozoic of a large granitic stock and diabase dikes, 4) movement along an east-trending fault of possible Proterozoic age, 5) collapse of an Oligocene caldera and the subsequent intrusion of stocks and dikes along the caldera margin, and 6) beginning in the Oligocene, block faulting associated with the Rio Grande rift. The study area does not contain evidence for uplift during the Laramide orogeny. This topic is discussed by Loughlin and Koschmann (1942) and Blakestad (1978) in their structural interpretations of the Kelly district. The area does not contain complete evidence for much of the Tertiary tectonism, and readers are referred to Loughlin and Koschmann (1942) and Blakestad (1978) for discussions of structure in the northern Magdalena Mountains and to Osburn (1978), Petty (1979), Allen (1979), and Bowring (in prep.) for structure in the southern portion of the

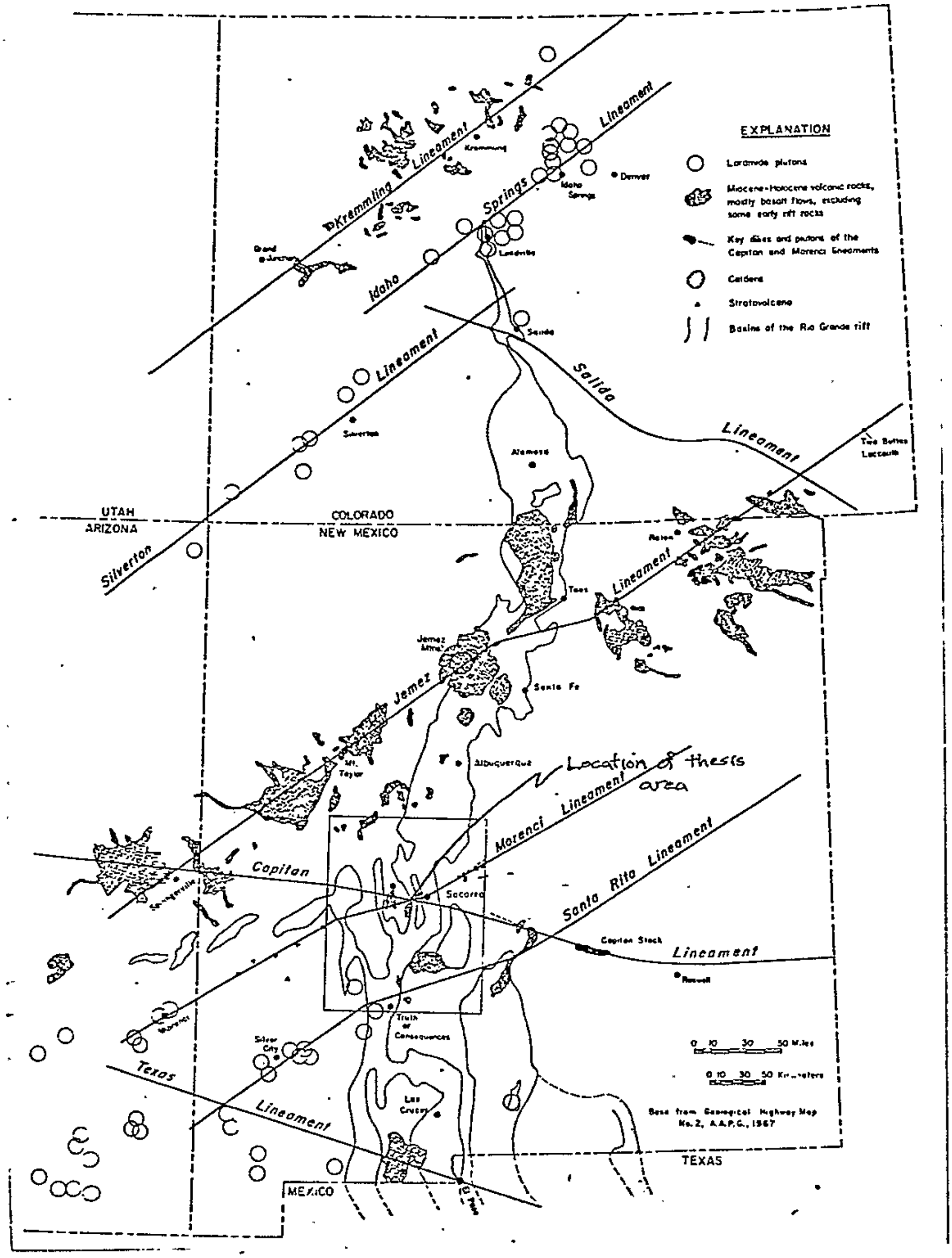

Figure 32: Generalized map of the Rio Grande rift and major crustal lineaments (Chapin and others, 1978).

range. Chapin and others (1978) provide an overview for the entire range and Chamberlin (1978) discusses the style of faulting associated with rifting in the Socorro area.

Proterozoic Structure

Interpretation of regional Proterozoic structure is difficult as outcrops of Proterozoic rocks are widely spaced in central New Mexico. Within the Magdalena Mountains, several structural features deserve attention. These include: 1) a north-trending fault and an adjacent thick interval of rhyolitic tuff, probably a portion of a caldera, 2) the intrusion of the gabbro of Garcia Canyon and the formation of roof pendants of Proterozoic supracrustal rocks, and 3) movement along the North Fork Canyon fault zone of possible Proterozoic age.

Proterozoic Caldera Structure

A north-northwest-trending Proterozoic fault is inferred in section 16. Evidence for the fault includes; 1)an offset of the interbedded tuff-siltstone unit, 2) a peculiar thinning of the gabbro in section 16, 3) strikingly different Proterozoic sections on either side of the inferred fault (compare x-section AA´ with BB´ or CC´), and 4) the intrusion of Tertiary rhyolitic and monzonitic dikes along the inferred structure. Tertiary faulting in the study area, associated with the Rio Grande rift, has a similar attitude as does the fault defining the inferred cauldron or graben margin. This faulting is assigned to the Proterozoic due to the difference in Proterozoic sections from one side of the fault to the other. This fault probably represents the margin of a cauldron or graben. This interpretation is somewhat tenuous as the North Fork Canyon area is structurally complex and outcrops are lacking in key areas. Despite these problems, certain features support this interpretation. The fault zone is approximately perpendicular to the attitude of the volcaniclastic and sedimentary rocks which would allow for a steeply dipping fault when the beds are rotated to the horizontal. Upon rotation, the fault appears to dip towards the inferred downthrown side of the fault. Steeply dipping normal faults are common in calderas. The margin of the Oligocene North Baldy cauldron exposed in North Fork Canyon, for example, dips 77 degrees towards the downthrown (south) block.

The west side (SW,sec.16;SE,sec.17) of the fault is interpreted to be the downthrown side. This interpretation is based primarily on the extraordinary thickness of tuff on the west side (1450 ft,442 m) in comparison with thicknesses of other tuffs in the map area (10 to 775 ft,3 to 236 m). The anomalously thick tuff may be thicker than measured as the top of the unit has been cut off by Proterozoic (?) and Tertiary faulting and the bottom has been intruded by the gabbro of Garcia Canyon. Attitudes on either side of the fault do not vary greatly, indicating a simple downdropping of the block and further suggestive of a cauldron structure.

Lineations on pumice in the tuffs (plate 1) may provide evidence for volcanism in the area of the inferred caldera. Measurements made along the eastern margin of the map area show a reconstructed axis of transport of approximately N60-70W and S60-70E. This direction is permissible with a volcanic source area near the inferred caldera structure in section 16.

Further evidence for a volcanic center in the area is provided by the rhyolite of North Baldy. This rhyolite shows a strong pyroclastic texture, a foliation approximately perpendicular to bedding, a heterogeneous xenolith population, and an intrusive outcrop pattern. The above features suggest that the rhyolite of North Baldy is a vent for the tuffs mapped in the study area.

Intrusion of the gabbro of Garcia Canyon

The intrusion of the gabbro of Garcia Canyon resulted in the overlying supracrustal rocks becoming roof pendants. This interpetation is supported by the pervasive outcrop pattern of the gabbro (plate 1), in many cases surrounding large outcrops of Proterozic supracrustal rocks. This event has been dated by White (1977,Rb-Sr, whole-rock) at 1517+-239 m.y. At least five large roof pendants, each with different but internally consistent attitudes, are preserved in the Proterozoic section of the Magdalena Mountains (fig. 3). The largest of these blocks covers approximately four square miles (10.4 km sq) in the southeast portion of the study area. The smallest pendants are less than 500 feet (152 m) on a side. No alteration or metamorphism of the supracrustal rocks is observed as a result of this intrusion.

East-trending Normal Fault

An east-trending fault of possible Proterozoic age is found adjacent to the east-trending Phanerozoic-Proterozoic fault in North Fork Canyon. Evidence for this fault consists of a wide zone of brecciation along the white rhyolite dike, west of the El Tigre mine (sec.16). The breccia zone may be as much as 120 feet (37 m) wide and can be followed along strike for approximately 0.75 miles (1.2 km). The breccia consists of fragments of Proterozic rocks as much as 3 inches (7.5 cm) long. Fragments of the breccia are made up entirely of Proterozic siltstones, volcaniclastic rocks, and gabbroic rocks (fig. 33). The exclusion of Phanerozoic fragments within this breccia is suggestive of a Proterozoic age for the fault. It is, however, possible that the level of erosion of the fault in this area may be such that only Proterozoic rocks were involved and that movement occurred in the Phanerozoic. The fault was active in the Phanerozoic as shown by the

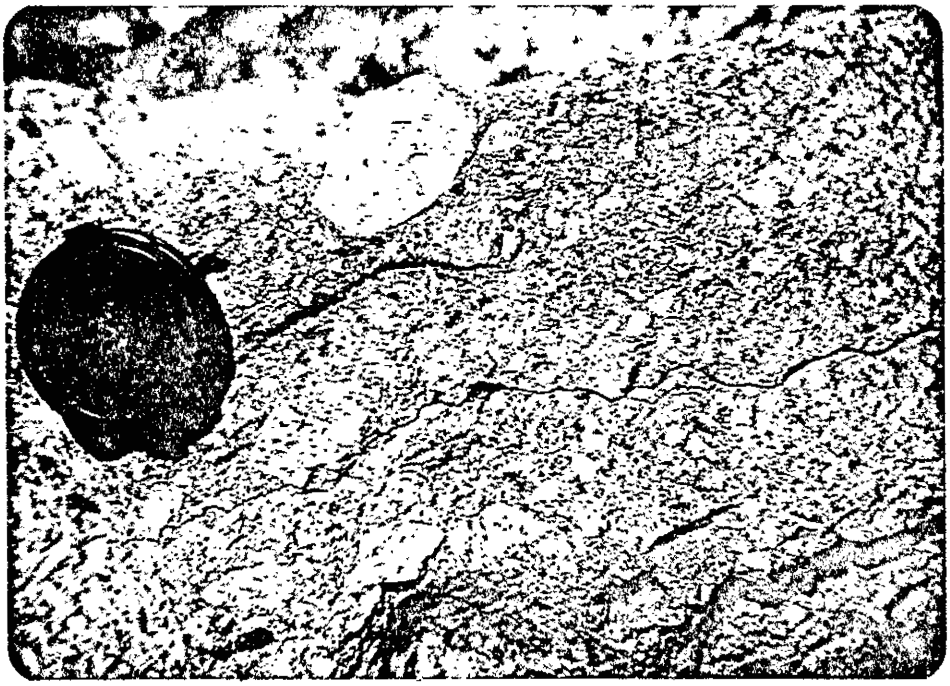

Figure 33: Typical breccia along the Phanerozoic-Proterozoic contact east of North Baldy. Fragments in the breccia are entirely Proterozoic in age.

juxtoposition of the Tertiary Spears Formation with the Proterozoic section. A large limestone block (+50 ft, 15 m) found within the breccia is probably a landslide block. This is indicated by a large discrepancy in sizes between the fragments and this block.

Laramide Structure

Evidence for Laramide structure is not exposed in the area. The study area was part of one or several uplifts which shed sediments to both the southeast and to the northwest forming the Baca Formation (Chapin, Blakestad, and Loring, 1974). Uplift during the Laramide is responsible for the erosion of Mesozoic and Permian rocks in the Magdalena Mountains such that the early Oligocene Spears Formation rests unconformably on the Permian Abo Formation (Chapin and others, 1975).

Tertiary Structure

Tertiary structure in the study area was controlled by two processes: 1) collapse of the North Baldy cauldron and 2) extensional faulting associated with the Rio Grande rift. The North Fork Canyon fault zone was probably formed by the collapse of the North Baldy caldera which errupted the Hells Mesa Tuff at 33-32 m.y. ago (Chapin and others, 1978). Rifting is probably responsible for north-trending faults in the area which have been intruded by rhyolitic, monzonitic, and dioritic magmas.

North Baldy Cauldron

The North Fork Canyon fault zone probably represents the structural margin of the North Baldy caldera. This fault zone extends from just south of North Baldy eastward to the Water Canyon stock, a distance of 2.5 miles (4 km). The zone is expressed by two large east-trending faults that dip steeply to the south, numerous fault blocks of Paleozoic sedimentary rocks, an area of jumbled Madera Limestone, the Water Canyon stock, smaller blocks of Paleozoic rocks interpreted to be landslide blocks, and a large brecciated zone which may be Proterozoic in age.

The North Fork Canyon fault zone is probably the margin of the North Baldy cauldron because: 1) the Hells Mesa Tuff is anomalously thick in the Water Canyon area (as much as 3850 ft, 1173 m, Krewedl, 1974), 2) major down-to-the-south normal faults of approximately 1400 feet (427 m) displacement have faulted the Oligocene Spears Formation against the Proterozoic rocks, 3) the zone represents the continuation of the North Baldy cauldron margin found west of North Baldy by Blakestad (1978), 4) the Water Canyon stock is found within this zone, and 5) the presence of landslide blocks along the zone. These blocks are found just west of the Water Canyon stock, south of the El Tigre mine with blocks of the Spears Formation, and in the breccia west of the El Tigre mine.

The North Fork Canyon fault zone appears aligned with, and may be an expression of, the Capitan lineament (fig. 32). Evidence presented above suggests that this zone was created prior to Tertiary caldera activity. Evidence that this zone is not limited to North Fork Canyon is provided by Wilkinson (1976) in the Tres Montosas-Cat Mountain area, and by Lopez (1975) and Bornhorst (1976) on the west side of the San Augustin Plains. All found major down-to-the-south faults along strike of the North Fork Canyon fault zone.

Block Faulting

A nearly orthogonal grid of north-northwest-trending and east-trending faults is found in the study area (fig. 34). Most faults are seen in the southern and eastern portions of the area and have been intruded by Tertiary magmas to form dikes. Some movement on both sets of faults probably began in the Oligocene (Chapin and others, 1975) and the youngest movement is probably late Pleistocene (M. Machette,1979, oral commun.).

Down-to-the-East Normal Faults

The north-trending normal faults in the study area are probably related to extensional tectonics associated with the Rio Grande rift. Throughout much of the area, outcrop is

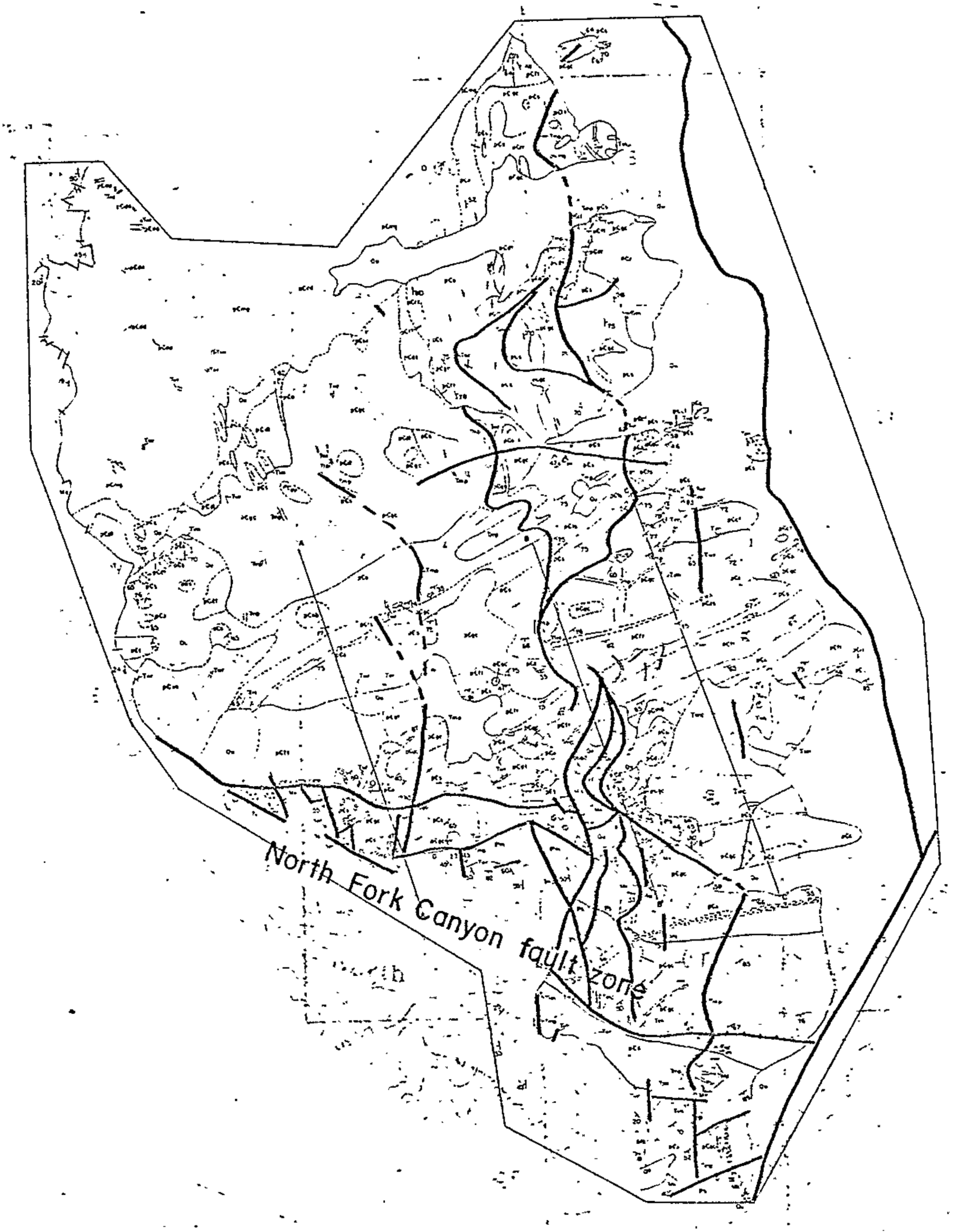

Figure 34: Map of the thesis area with faults highlighted.

not sufficient for good stratigraphic control and only in a few places (around the Hillside Canyon) are the faults demonstrably normal and down-to-the-east. The reader is referred to Osburn (1978) and Chamberlin (in prep.) who described rift-related faulting in the eastern Magdalena Mountains and Lemitar Mountains, respectively.

Down-to-the-east normal faults can be traced over the entire length of the study area, a distance of approximately 4.75 miles (7.6 km). Outcrops of the Tertiary dikes intruded into the faults suggest that the faults bifurcate and pinch out along strike. This style is well-developed between North Fork and Shakespeare Canyons. Strikes on the faults range from N20E to N50W; however, most strike north-northwest. Dips vary from 20-30 degrees to the east to nearly vertical. The wide range in dips of these faults may indicate listric faults (curved faults whose dips shallow with depth) or faults of different ages which have been differentially tilted. No independent evidence for listric faults can be observed in the study area. The ridge between Jordan and Garcia Canyons, south of the Papa Ranch, may contain evidence for "domino style" faulting (Chamberlin, 1978) and several periods of tilting. In this area, faults with 20-30 degrees of dip, 50-70 degrees of dip, and near vertical dip, are mapped. It is believed that the two sets of lower angle faults were originally high angle and have subsequently been tilted.

East-Trending Faults

East-trending faults, excluding the North Fork Canyon fault zone are generally short (less than 0.25 mi,0.4 km) and difficult to trace. These faults are found exclusively in the eastern portion of the study area from Copper Canyon to Garcia Canyon. East-trending faults are usually cut off by north-trending normal faults, but may themselves cut off north-trending faults. Strikes are somewhat variable and range from N10E to N60W. Poor outcrops make determination of dips difficult. In North Fork Canyon, a near vertical dike along one of the faults indicates that the faults may dip steeply. East-trending faults in the study area are probably related to the collapse of the North Baldy caldera or to adjustments transverse to the north-trending structural grain.

Joints

Since the intrusion of the gabbro of Garcia Canyon at least six different intrusions have been emplaced in the study area: two during the Proterozoic and four during the Tertiary. This has left a confusing pattern of joint surfaces on the rocks. Interpretation is difficult due to the number of intrusions and the effects of mid- to late-Tertiary rifting. In general, dips on the joint surfaces are steep, the majority being greater than 60 degrees. Strikes of joint surfaces trend west-northwest, east-northeast, and north-northwest (least abundant). A direction of principal and intermediate stress may be qualitatively arrived at by using the two most abundant attitudes. These indicate that the principal stress was nearly east-west and the intermediate stress was in a vertical direction. The cause of these joint surfaces is conjectural but may be related to rifting and the intrusion of numerous stocks.

Landslide Blocks

Blocks of Proterozoic clastic sedimentary and volcanic rocks of varying attitudes are found off the crest of the range immediately north of North Baldy. The extreme topography and the variety of attitudes of the beds is suggestive of landslide blocks.

METAMORPHISM

All Proterozoic rocks in the Magdalena Mountains show evidence of regional metamorphism except the Magdalena granite and the diabase dikes. Metamorphism is not always easily noticed due to the nature of the rocks. Portions of the siltstones contain biotite and garnet and it is believed the area underwent upper greenschist facies metamorphism. Contact metamorphic effects, seen by the formation of a spotted hornfels, are found partially surrounding the Tertiary Water Canyon stock and a Proterozoic intermediate porphyritic rock southwest of the Papa Ranch.

Regional Metamorphism

The most abundant metasedimentary rock in the Magdalena Mountains is a metasiltstone. Within the stratigraphic section, siltstones contain the most diagnostic mineral assemblages for the determination of metamorphic grade. Two assemblages are found in the siltstones; 1) feldspar-quartz-muscovite, the most common, and 2) feldspar-quartz-muscovite-biotite-garnet. A pattern for the distribution of the two assembalges cannot be recognized and the two assemblages may be found along strike a few hundred feet apart. This relationship was noticed west of the Strozzi Ranch (sec. 10). In the second assemblage, garnet porphyroblasts comprise less than 3% of the rock and are usually no larger than 0.4 mm. Biotite is aligned parallel to foliation and may make up as much as 10% of the rock.

Mafic igneous rocks are more pervasively metamorphosed and reflect this metamorphism by two assemblages: 1) hornblende-clinopyroxene-chlorite-calcium plagioclase, and 2) hornblende-chlorite-calcium plagioclase. The first assemblage probably reflects the failure of the system to reach equilibrium. The second assemblage is by far the most common. Tremolite was seen in one thin section of the gabbro and probably reflects alteration of the gabbro by hydrothermal fluids.

Foliation throughout the area is weakly developed. The most prominant foliation is visible in the metagabbro. In the gabbro, foliation is caused by the alignment of hornblende and chlorite and is observed near faults and near some contacts. The hornblende-chlorite schist (metagabbro) contains the strongest foliation.

Foliation parallels bedding in the metasedimentary rocks and is expressed by an alignment of biotite. Foliation in the metavolcanic units is probably primary and is defined by compaction and flow features and an alignment of relict pumice fragments.

Mineral assemblages of sedimentary and mafic igneous rocks indicate middle to upper greenschist facies metamorphism (Hyndman,1972) was reached in the Proterozoic terrane of the Magdalena Mountains. This grade of metamorphism is compatible with assemblages found in other Precambrian outcrops in central New Mexico (Condie and Budding,1979). The presence of biotite and garnet and, the absence of staurolite and andalusite requires a P H20 between 3 and 8 KB and a temperature between 400 and 550 degrees C. This implies a slightly elevated geothermal gradient (fig. 35). Effects of retrograde metamorphism are seen primarily in the mafic units by the formation of chlorite from hornblende.

Contact Metamorphism

Contact metamorphic aureoles expressed by the formation of spotted hornfels are present in the study area partially surrounding the Water Canyon stock and the intermediate porphyritic rock southwest of the Papa Ranch. These hornfels are best developed in siltstones but are also developed to a minor extent in tuffs. Surrounding the Water Canyon stock, where the hornfels is best developed, spotted siltstones are found approximately 500 feet (152 m) from the intrusion.

Three mineral assemblages are associated with the spotted hornfels where it is developed in siltstones. These include: 1) feldspar-muscovite-quartz-biotite, the regionally metamorphosed rock, 2) feldspar-muscovite-quartz, in the outer portion of the spot, and 3) feldspar-chlorite-quartz, in the inner portion of the spot.

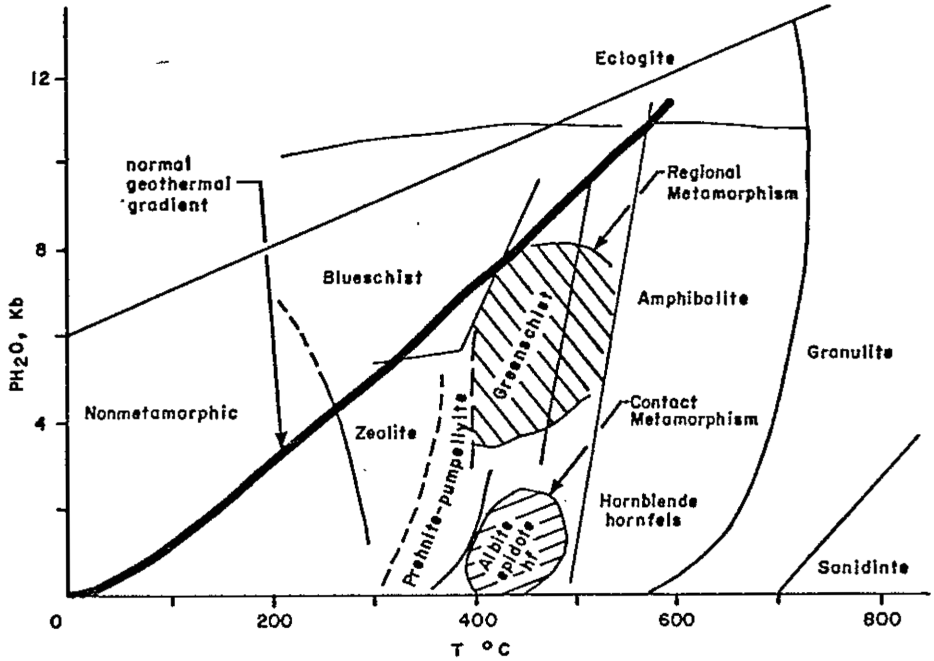

Figure 35: Metamorphic facies boundaries from Hyndman, 1975. Regional and contact metamorphic facies for the Magdalena Mountains are labeled. Normal geothermal gradient from Winkler, 1976.

Williams, Turner, and Gilbert (1954) mention the possibility of forming scattered ovoid knots of coarser micas in a hornfels but do not discuss the chemical differences seen here (movement of iron). The white zones surrounding the green spots were probably a source for the chemical constituents found within the green spots.

The facies developed in these aureoles is best described by the albite-epidote hornfels facies (400-500 degrees C., 2 kb P H2O, Hyndman,1972). The absence of cordierite probably indicates that the system did not reach equilbrium. The destruction of biotite, formed by regional metamorphism, and the spatial association of the hornfels with a Tertiary intrusion suggests that the hornfels formed as a result of a separate and later event.

MINERALIZATION

The study area contains several shafts and adits and numerous smaller workings but has never recorded major production. Waste dumps from the largest workings suggest that base metals and possibly barite were sought. It is believed that the smaller workings were dug in search of gold.

In the past, economic mineralization has been limited to the southern portion of the study area in what Lasky (1932) called the Water Canyon or Silver Mountain district. This district contains the North Fork Canyon fault zone, a principal control of intrusions and mineralization in the area. Workings outside of the Water Canyon district are, in general, small and found along faults and Tertiary dikes.

Previous literature on the mineralization in the study area is nearly complete as there has been no recent production in the area. Lasky (1932) named the district and reviewed the production and history for the Buckeye mine, the Hall-Lyton property, the Nutter lease (El Tigre mine ?), and the Maggie Merchant (Hillside mine ?). Loughlin and Koschmann (1942), Blakestad (1978), and Iovenitti (1977) describe mineralization in the Paleozoic sedimentary rocks along the crest of the Magdalena Range. Mineralization along the crest of the range will not be discussed in this report and the reader is referred to those authors. Kalish (1953) briefly described the Buckeye mine. Krewedl's (1974) description of mineralization in the Water Canyon area is more generalized than is Lasky's (1932). Krewedl discusses ore control and makes comparisons between the Water Canyon and Kelly mining districts. Krewedl also believed the mineralization was mid-Tertiary in age.

Water Canyon District

The Water Canyon district follows the Phanerozoic-Proterozoic contact in Copper, North Fork, and Hillside Canyons. The depositional contact of the Kelly Limestone with the Proterozoic rocks, and portions of the Kelly itself, have long been recognized as favorable ore horizons for base metal mineralization (Lasky,1932; Loughlin and Koschmann,1942; Krewedl,1974). This contact controls the ore for the major producers in the district. In the Water Canyon district, the ore in the Kelly Limestone is primarily associated with silicification and, to a minor extent, with the development of skarn mineralogy. The Kelly Limestone is intersected by the North Fork Canyon fault zone in Hillside Canyon providing a well-developed plumbing system and favorable host rocks. The Hillside mine is found here and ore grade mineralization is seen in the face of the adit.

Small workings usually associated with monzonitic and/or rhyolitic dikes are found along the Phanerozoic-Proterozoic fault contact in North Fork Canyon.

The strongest mineralization observed along this fault is near the El Tigre mine (sec.21) where quartz, sphalerite, galena, and barite are found in the dumps of several prospects and in outcrop (fig. 36).

Within the area of this investigation, the North Fork Canyon area and the associated North Fork Canyon fault zone appear to be the most promising for further exploration. The reasons for this are: 1) the presence of known mineralization in this zone, 2) good ground preparation as seen by the numerous dikes and the rotated blocks of Madera Limestone mapped east of the El Tigre mine, 3) the presence of favorable host rocks, incuding a thick section (1310 ft,399 m, Siemers,1973) of Paleozoic rocks, 4) the presence of known and inferred stocks, and 5) the favorable comparison of this area with the Magdalena district and other cauldron associated districts.

Smaller Workings Elsewhere in the Study Area

Smaller workings elsewhere in the study area are generally observed associated with faults and/or Tertiary dikes. Mineralogy is either quartz, pyrite, limonite with manganese staining or, in prospects near diorite dikes, quartz, epidote, calcite, and magnetite. The largest prospect showing quartz-pyrite mineralization is the Rich Hill "breccia pipe" which forms a small knob west of the Strozzi Ranch. This breccia (plate 1) is found near the

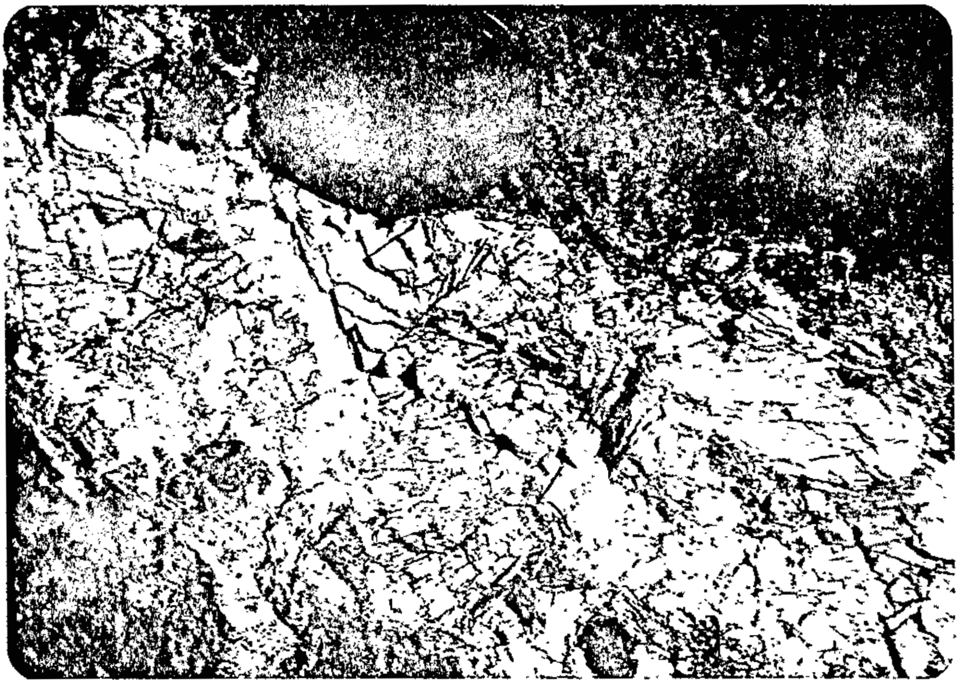

Figure 36: A mineralized vein found along the Proterozoic-Phanerozoic fault contact in North Fork Canyon containing barite, galena, and sphalerite. This outcrop is about 0.25 miles (0.39 km) west of the El Tigre mine.

intersection of the Northern Magdalena Range bounding fault and an east-trending fault. Tertiary dioritic magmas have also been intruded along this structural intersection.

Veins showing propylitic alteration (epidote, calcite, chlorite) plus quartz and magnetite are generally restricted to the southeastern portion of the study area. The largest working on this type of mineralization is found north of Shakespeare Canyon and shows no base metal mineralizaton. Several small quartz-specular hematite veins are also found in this area.

Development of economic mineralization north of North Fork Canyon is hindered by a lack of suitable host rocks. Ground preparation in this case becomes most important and the intersection of faults appears to be the most favorable locations for mineralization.

Uranium and Volcanogenic Massive Sulfide Possibilities

A partial scintillometer survey was made in the study area using a Scintrex model BGS-1SL. The Magdalena granite had the highest readings (230 counts per second) and other intrusives ranged between 150 and 200 cps. No evidence was found to indicate that the Proterozoic rocks of the Magdalena Mountains are favorable for the discovery of commerical uranium deposits. The intrusives have moderate to low radioactivity, the metasedimentary rocks lack organic matter to provide a reductant, and no significant uranium occurrences were found.

The presence of felsic tuffaceous units and rhyolitic intrusions in the Proterozoic section are noteworthy in the search for volcanogenic massive sulfide deposits. Several massive sulfides have been found in the Proterozoic of the southwestern United States (Vuich,1974; Reismeyer,1979). It is probable, however, that the Proterozoic section in the Magdalena Mountains is unfavorable for massive sulfides due to the lack of: 1) a calc-alkaline trend in the volcanics, 2) paleo-submarine features, and 3) proximal facies (cherty iron formations, volcanic breccias).

ALTERATION

Four types of alteration are observed in the study area. These include; 1) propylitic alteration, 2) alteration of the feldspars, 3) silicification, and 4) bleaching of the Proterozoic sediments. Some of this alteration is important as it probably indicates a buried intrusion.

Propylitic alteration is best exposed in the metagabbro south of the Water Canyon stock. This alteration is limited to sections 14,15,22,and 23. Veins of calcite, quartz, epidote, chlorite, and magnetite are spatially associated with diorite dikes and the inferred buried intrusion.

Alteration of the feldspars to white micas and clays is pervasive and is probably a supergene effect. Feldspars in the Magdalena granite are not as affected; this lack of alteration in the granite may be due to fewer joint sets observed in the granite when compared with other Proterozoic rocks.

Silicification, other than that found along faults was recognized in siltstones southwest of the Papa Ranch (sec. 3,10). The silica was probably introduced into the siltstones by Tertiary rhyolite dikes found nearby, or possibly by an inferred intrusion located in the Strozzi Ranch area. No mineralization is associated with the silicification.

A small area west of the Strozzi ranch and north of Shakespeare Canyon (sec. 15) contains bleached siltstones which have moderate to strong limonite staining along joint surfaces. The area lies adjacent to a north-trending white rhyolite and quartz monzonite dike and to an east-trending fault. The alteration may be the result of the intrusion of the dikes. Several small prospects are found nearby.

Alteration in the study area is variable and spotty except for the propylitic alteration around the Kelly Ranch. The lack of developement of alteration in the study area may in part be due to the unreactive nature of the rocks.

CONCLUSIONS

This study has made several contributions which may help in the understanding of the Proterozoic of central New Mexico and the Tertiary of the Socorro-Magdalena area. Evidence found in the Proterozoic supracrustal succession supports a fluvial-deltaic environment of deposition in a volcanically active area. Contributions to Tertiary geology primarily concern structure, especially in relation to mid-Tertiary caldera activity and faulting associated with the Rio Grande rift.

Numerous lines of evidence support a fluvial-deltaic environment of deposition in the Proterozoic terrane of the Magdalena Mountains. These include a thick, fine-grained clastic section, a variety of fluvial sedimentary structures, and the presence of debris-flow and channel-fill deposits(Long,1978; Reineck & Singh,1975). Preserved structures include large-scale cross bedding, ripple cross laminations, soft-sediment deformation, planar laminations, crude graded bedding, scour-and-fill cross bedding, and rip-up structures. The presence of debris-flow deposits, both in channels and interbedded with fine-grained clastic sedimentary rocks, further indicates a fluvial environment. A deltaic or distal fluvial environment is suggested by the fine grain size of the sedimentary rocks and by the lack of conglomerates.

Intermediate to felsic tuffaceous volcanic rocks found in the section tend to support this interpretation. Evidence indicates a volcanic source area in the western portion of the study area. This evidence includes an intrusive rhyolite with vent facies characteristics, an anomalously thick section of tuff, an inferred fault which suggests a graben or caldera, and transport directions which support a source in this area.

The Magdalena Mountain Proterozoic section may represent coalescing alluvial fans or possibly a distal deltaic sequence. The sedimentary detritus appeears to have been mainly fine-grained clastic rocks. Felsic to intermediate volcanism was intermittent and added tuffs, reworked tuffaceous material, and debris-flow deposits to the section.

A possible modern analog to the Proterozoic section of the Magdalena Mountains is the Oligocene Tascotal Formation in Texas (Walton,1979). The Tascotal is a sediment apron formed around felsic eruptive centers and is composed primarily of sand-sized clastic sedimentary rocks interbedded with tuffs and epiclastic sedimentary rocks. Like the Magdalena Mountains Proterozoic section, the Tascotal Formation lacks a coarse grained component expected in alluvial fan deposits. Walton (1979) believes the lack of a coarse fraction in the Tascotal is due to the availability of easily eroded, fine-grained volcanic rocks in the source area for the Tascotal. Such a model may explain the large amount of fine-grained material found in the Proterozoic of the Magdalena Mountains.

Assessment of this area with respect to a regional tectonic setting is difficult. A comparison of the Proterozoic rocks from the Magdalena Mountains with rock associations compiled by Condie and Budding(1979) for eugeoclinal, miogeoclinal, and continental rift settings suggest that the study area rocks were not deposited in any of the above settings (fig. 37). The continental rift association is perhaps a "best fit" but the Magdalena Proterozoic section lacks mafic volcanic rocks and shales and contains intermediate volcanic rocks. This rock association deviates from Condie and Budding's (1979) "most striking signature of continental rift systems", that is "the association of immature arkosic sediments and shales with bimodal (dominantly mafic) volcanism". This does not, however, preclude the possibility that the area is part of a complex (multiple) continental rift system. The study area may be too small to contain conclusive evidence for determination of a regional tectonic setting.

Tertiary structure related to volcanic activity in the Socorro-Magdalena area and along the Rio Grande rift is apparent. The topographic margin of the North Baldy caldera is developed along a zone of weakness, possibly of Proterozoic age. This topographic margin is expressed by two

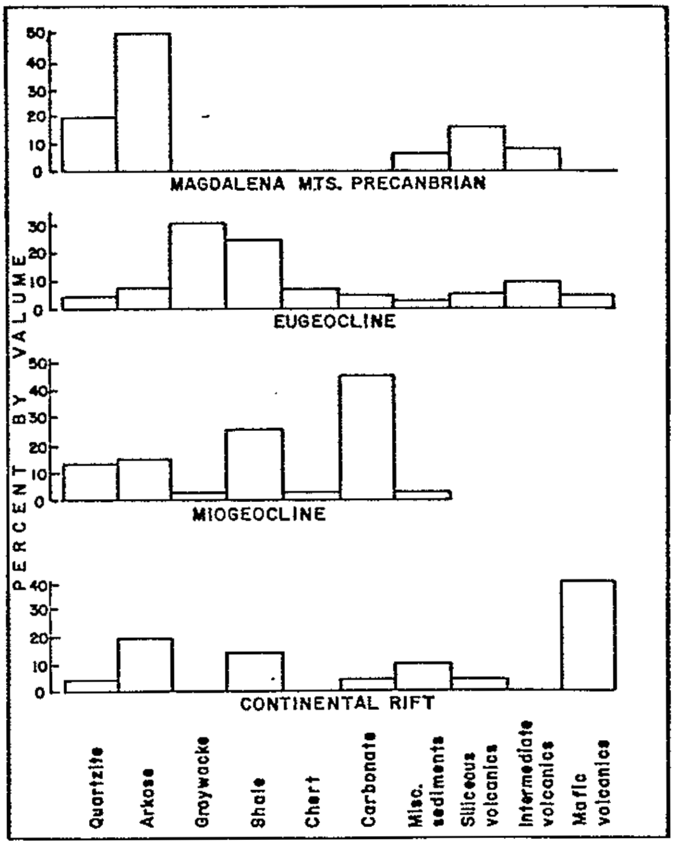

Figure 37: Rock type distribution of the Precambrian in the Magdalena Mountains compared to rock type distributions in Phanerozoic assemblages(compiled by Condie and Budding,1979).

large down-to-the-south faults, an intrusion, jumbled blocks of Paleozoic rocks, and an exceptional thickness of the Hells Mesa Tuff.

Monzonite, quartz monzonite, and white rhyolite dikes intrude north-trending down-to-the-east normal faults associated with the Rio Grande rift. Between Jordan and Garcia Canyons these dikes are found dipping at varying degrees to the east and may represent "domino style" faulting (Chamberlin,1978). Faulting associated with rifting has continued into the Holocene with movement along the eastern range-bounding fault of the northern Magdalena Mountains.

Mineralization in the study area excluding the North Fork Canyon area is small and sporadic. The largest prospects are developed on structural intersections. The Proterozoic-Paleozoic contact is the most important feature for the localization of ore.

Two areas were delineated which may contain buried intrusions. Numerous dikes and limited alteration suggest a buried intrusion west of the Strozzi Ranch. Diorite dikes and associated propyllitic alteration are indicative of a buried intrusion northwest of the Kelly Ranch. Several prospects found west of the Strozzi Ranch may indicate mineralization at depth.

APPENDIX 1

Glossary of some terms used in the text

channel-fill deposits - deposits of various kinds with a channel geometry due to the abandonment of the channel by the stream.

debris flow - a mass movement involving rapid flowage of debris of various kinds under various conditions. (AGI Glossary)

flysch - thick sequences of interbedded sandstone and shales. The sandstones generally have erosional bases and are generally graded. Shales contain a marine fauna. (Selley,1970)

siltstone - an indurated or somewhat indurated silt having the texture and composition but lacking the fine laminations or fissility of shale. (AGI Glossary)

tuff - a compacted pyroclastic deposit of volcanic ash and dust that may or may not contain up to 50% sediments such as sand or clay. (AGI Glossary)

Water-laid tuff - an epiclastic sediment with a recognizable tuff component deposited in or by water.

thickly bedded - bedding equal to or greater than 1 meter.

thinly bedded - bedding equal to or less than 10 centimeters.

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

Clay T. Smith

Date 3/24/80

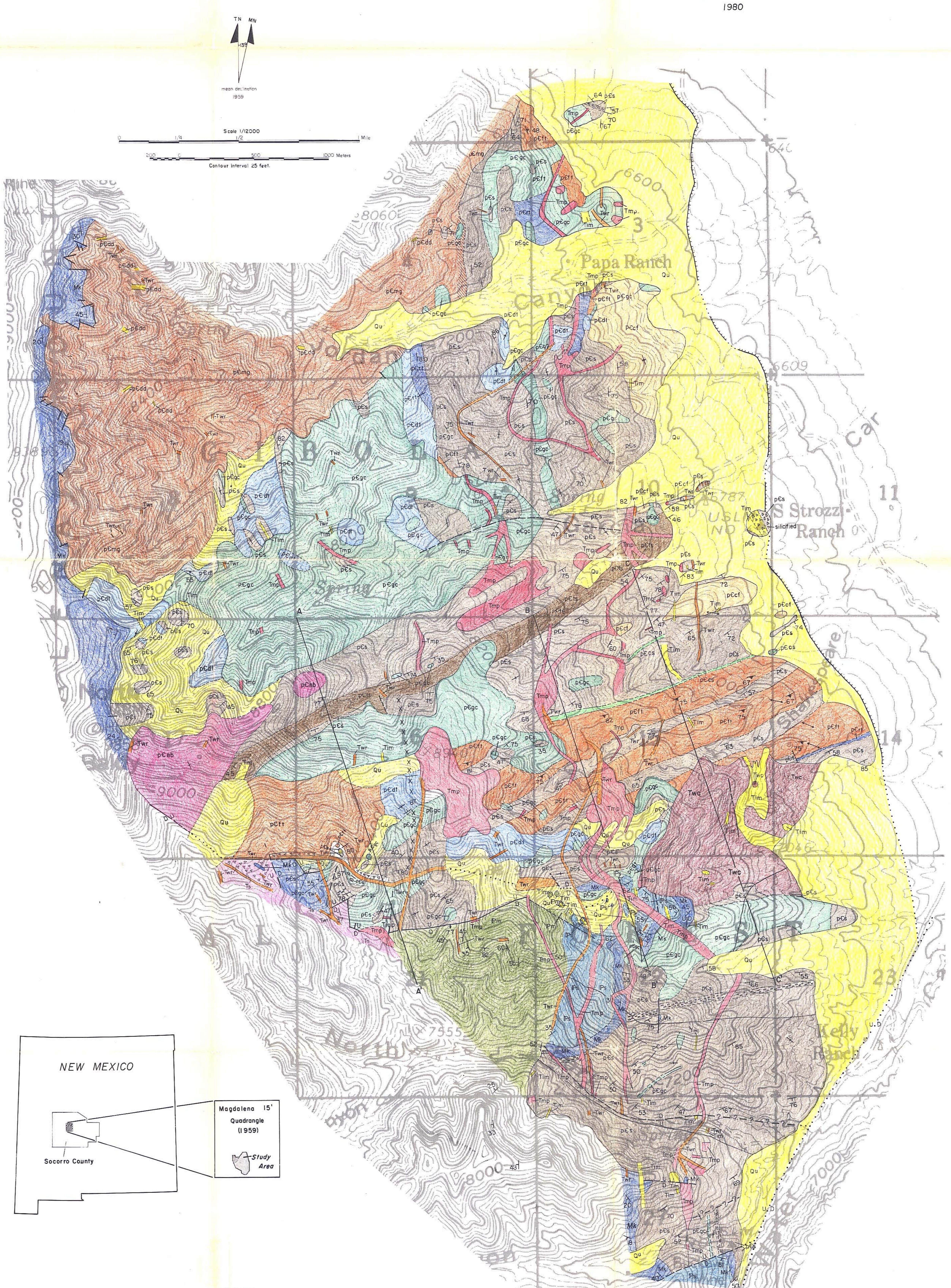
PLATE I

GEOLOGIC MAP AND SECTIONS OF THE WATER CANYON-JORDAN CANYON AREA, MAGDALENA MOUNTAINS,

SOCORRO COUNTY, NEW MEXICO

by

WARD SUMNER
1980



LEGEND

Sedimentary and Volcanic Rocks

CENOZOIC

- **Qu** Quaternary deposits undifferenticted – talus, alluvial fcns, stream deposits, stream terraces
- **Ts** Spears Formation – andesite conglomerates and flows 37-33 my

PALEOZOIC

- **IPm** Madera Limestone (*Pennsylvanian*)
- **IPs** Sandia Shale (*Pennsylvanian*)
- **Mk** Kelly Limestone (*Mississippian*)

PRECAMBRIAN

- **p€s** clastic sediments – argillite, shales, siltstones, sandstones
- **p€rt** reworked tuff – siltstone and sandstone with minor amounts of detrital tuffaceous material
- **p€ts** interbedded tuffs, mudflows, and fine-grained clastic sediments
- **p€cf** volcaniclastic and fine-grained clastic channel fill – mudflows, sandstones, shales
- **p€dt** dacitic tuff – pyroclastic texture with moderately developed foliation
- **p€ft** felsic tuffs – rhyolite to quartz latite, well developed pyroclastic texture and foliation

Intrusive Rocks

- **Tim** intermediate to mafic dikes – andesite, quartz andesite
- **Twr** white rhyolite dikes – rhyolite to quartz latite
- **Tmp** monzonite dikes and plugs – monzonite to quartz monzonite
- **Twc** Water Canyon Stock – quartz monzonite 30.5 ± 1.2 m.y.
- **p€dd** diabase dikes
- **p€mg** Magdalena granite — granite and granite porphyry with fine-grained border phase (*hatchered*)
- **p€cs** hornblende chlorite schist
- **p€gc** Metagabbro of Garcia Canyon
- **p€nb** Rhyolite of North Baldy

SYMBOLS

contact – *dashed where approximately located*

U D fault – *dashed where approximately located, queried where uncertain, dotted where covered, arrow indicates dip direction and angle, labels (U&D) designate up and down sides*

Quaternary fault scarp – *hachured on down side*

breccia zone – *brecciated Proterozoic rocks of varying lithologies except where noted*

mudflow deposits

strike and dip of bedding

strike and dip of foliation

lineation rotated to horizontal

area of intense mafic to intermediate dike injection

X Location of inferred p€ Fault

CROSS SECTIONS