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GEOLOGICAL INVESTIGATION OF THE SOCORRO GEOTHERMAL AREA

FINAL REPORT

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Final Report
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EXPLORATION FRAMEWORK OF THE SOCORRO GEOTHERMAL AREA, NEW MEXICO

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

This report summarizes the results of a comprehensive geological and geochemical study of the Socorro geothermal area begun in September 1976 under contract no. ERB-76-201,65-23 from the New Mexico Energy Resources Board. We have integrated our data with the geophysical data of A. R. Sanford in order to present a complete and well-documented report on: 1) why the geothermal activity is there, 2) the main structural and stratigraphic controls of the geothermal system, 3) the geothermal potential of the area, and 4) a model based on the Socorro area which may be useful in geothermal exploration elsewhere in the rift. The report (minus the appendices) will be published in May 1978 in New Mexico Geological Society Special Publication No. 7 entitled "Cauldrons and mining districts of the Datil-Mogollon volcanic field". A copy of the report with a complete set of geologic maps, cross sections, and tables of radiometric dates and chemical analyses is available for inspection in Socorro as Open-File Report No. 88 of the New Mexico Bureau of Mines and Mineral Resources.

Geothermal activity is present in the Socorro area because of a "leaky" transverse shear zone which connects en echelon segments of the Rio Grande rift. The transverse shear developed where the Rio Grande rift broke en echelon

style across the Morenci lineament, a major flaw in the continental plate. The transverse structure has "leaked" magmas at intervals since at least 32 m.y. ago. Seven overlapping and nested cauldrons, ranging in age from 32 to 26 m.y., occur along the transverse shear zone between Socorro and the north end of the Black Range, a distance of about 50 miles. The Socorro geothermal area is located in the north half of the northeasternmost of these cauldrons. Silicic magmatism occurred in the north half of the Socorro cauldron between 12 and 7 m.y. ago; the vents occur to either side of the transverse structure and are approximately bisected by it. Basaltic magmas were erupted about 4 m.y. ago from vents near the transverse structure and approximately in the middle of the area of 12-7 m.y. old silicic volcanism. The present-day sill-like magma body, which extends southward from the Bernardo area, as outlined by Sanford and others using reflections from microearthquakes, ends against the transverse shear zone at a depth of about 18 km. Several shallow, dike-like magma bodies occur along the transverse shear zone above the termination of the deep magma body. The shear zone apparently acts as a barrier to lateral movement of magma at depth but allows magmas to bleed upward along it and fill north-trending fractures. The known shallow magma bodies occur within or near the Socorro cauldron, which may provide additional channelways for rising magma.

The main structural controls of the Socorro geothermal area are the transverse shear zone and the ring fracture zone of the Socorro cauldron. A north-trending rift fault, superimposed across the Socorro cauldron contemporaneously with cauldron collapse, influenced the amount of subsidence and formed the east edge of the resurgent dome. The older Sawmill Canyon cauldron, overlapped and buried by the Socorro cauldron, acted as a buoyant block; cauldron facies tuffs are thinner on this block and moat deposits are absent. Break up of a broad early-rift basin between 7 and 4 m.y. ago superimposed the Chupadera-Socorro-Lemitar uplift and the adjacent La Jencia and Socorro grabens across the Socorro and Sawmill Canyon calderas. Cumulative effects of cauldron subsidence and graben subsidence drop potential reservoir rocks to the greatest depths where grabens overlap the cauldrons.

Potential reservoir rocks are provided by Paleozoic limestones, several ash-flow tuff units, and the basal fanglomerates of the rift fill. The ash-flow tuffs were reservoir rocks in an ancient geothermal system. Chemical analyses show K_2O values of 6 to 11.5% in tuffs which normally contain 4 to 5% K_2O. Experimental studies elsewhere have shown that potassium leached from hotter rocks displaces sodium in cooler rocks in vapor-dominated systems. The chemical data is substantiated by petrographic studies which show that plagioclase feldspars are progressively replaced by potassium feldspar and potassium-rich "clays" as the K_2O content of the rock increases. Permeability within the brittle, densely welded tuffs is provided by cooling joints and by fractures formed during faulting, cauldron collapse, and resurgent doming. Relatively impermeable caprocks are provided by Paleozoic shales, volcaniclastic rocks of the Spears Formation, and by playa claystones in the rift fill.

Potential for discovery and development of commercial geothermal reservoirs in the Socorro area is good because of the presence of: 1) shallow magma bodies (as shallow as 4-5 km), 2) high heat flow (as high as 11.7 HFU), 3) a "leaky" transverse shear zone which has controlled magma injection in the past and seems to be doing so today, 4) a zone of subdued aeromagnetic anomalies along the transverse shear zone which suggests that the Curie point isotherm occurs at relatively shallow depths, 5) several potential reservoir rocks which show evidence of having been reservoir rocks in an ancient geothermal system, 6) down faulting of potential reservoir rocks to depths near the tops of shallow magma bodies because of the cumulative effects of graben subsidence across areas of multiple cauldron subsidence, and 7) relatively impermeable cap rocks.

Recognition of the transverse shear zone and its effect on magma injection, high heat flow, and movement of geothermal fluids suggests that similar conditions may exist where the Rio Grande rift transects other crustal lineaments. Characteristics of these transverse zones are: 1) en echelon offsets of rift basins, 2) changes in direction of rotation and step faulting on opposite sides of a lineament, 3) jutting of transverse horsts into rift basins, 4) persistent uplift of one side of a lineament, 5) recurrent volcanism, and 6) thermal springs and other evidence of high heat flow. Not all of these characteristics may be present.

INTRODUCTION

The Socorro geothermal area is located about 75 miles (120 km) south of Albuquerque, New Mexico, at the town of Socorro (fig. 1). Geothermal activity has been known in the area for a long time. In fact, Socorro owes its existence to two warm springs on the southwest edge of town which have provided a reliable source of potable water since before the Spanish settlement of New Mexico. These springs (plus a third man-made spring) still supply a major portion of the town's water needs. Attention has been focused on the Socorro area in recent years because of studies of microearthquakes and magma bodies by Caravella (1976), Fischer (1977), Rinehart (1976), Sanford (1977a), Sanford and Long (1965), Sanford and others (1973, 1977a, 1977b), Shuleski (1976), Shuleski and others (1977); heatflow by Reiter and others (1975), Reiter and Smith (1977), Sanford (1977b); modern uplift by Reilinger and Oliver (1976); and deep crustal structure by Sanford (1968), Toppozada and Sanford (1976), Oliver and Kaufman (1976), and Brown and others (1977).

In April 1975, the New Mexico Bureau of Mines and Mineral Resources began a detailed geologic study of the Socorro area in anticipation of probable geothermal exploration and development. Since July 1976, the project has been funded by a grant from the New Mexico Energy Resources Board through the Energy Institute at New Mexico State University. The geophysical studies of Sanford have been supported by a series of grants from The New Mexico Energy Resources Board and The National Science Foundation. In 1976, the U.S. Geological Survey designated approximately 140 square miles (362 km^2) in and around Socorro as the Socorro Peak Known Geothermal Resources Area (KGRA). The U.S. Bureau of Land Management designated a much larger area (624,814 acres) as the Socorro Peak Geothermal Leasing Area. The first competitive lease sale was held in November 1977 with nine tracts totaling 17,000 acres being leased within the Socorro Peak KGRA for $275,411.46.

GEOLOGIC SETTING

The Socorro geothermal area is located within the Rio Grande rift (fig. 1), where the rift transects the northeastern portion of the Datil-Mogollon volcanic field of Oligocene to early Miocene age. The north-trending fault block ranges of the rift expose thick sequences of rhyolitic ash-flow tuffs overlain by, and interbedded with, basaltic andesite flows (fig. 3). Beneath the ash-flow tuffs are latitic conglomerates, mud-flow deposits, and sandstones representing the alluvial apron which surrounded the Datil-Mogollon field prior to its ignimbrite climax. The base of the volcanic pile rests unconformably upon rocks ranging from late Eocene to Precambrian in age. Most of the area west of the Rio Grande and south of San Acacia lies on the northeast flank of a major Laramide uplift from which the Mesozoic rocks were stripped by early Tertiary erosion. Basal volcanic rocks

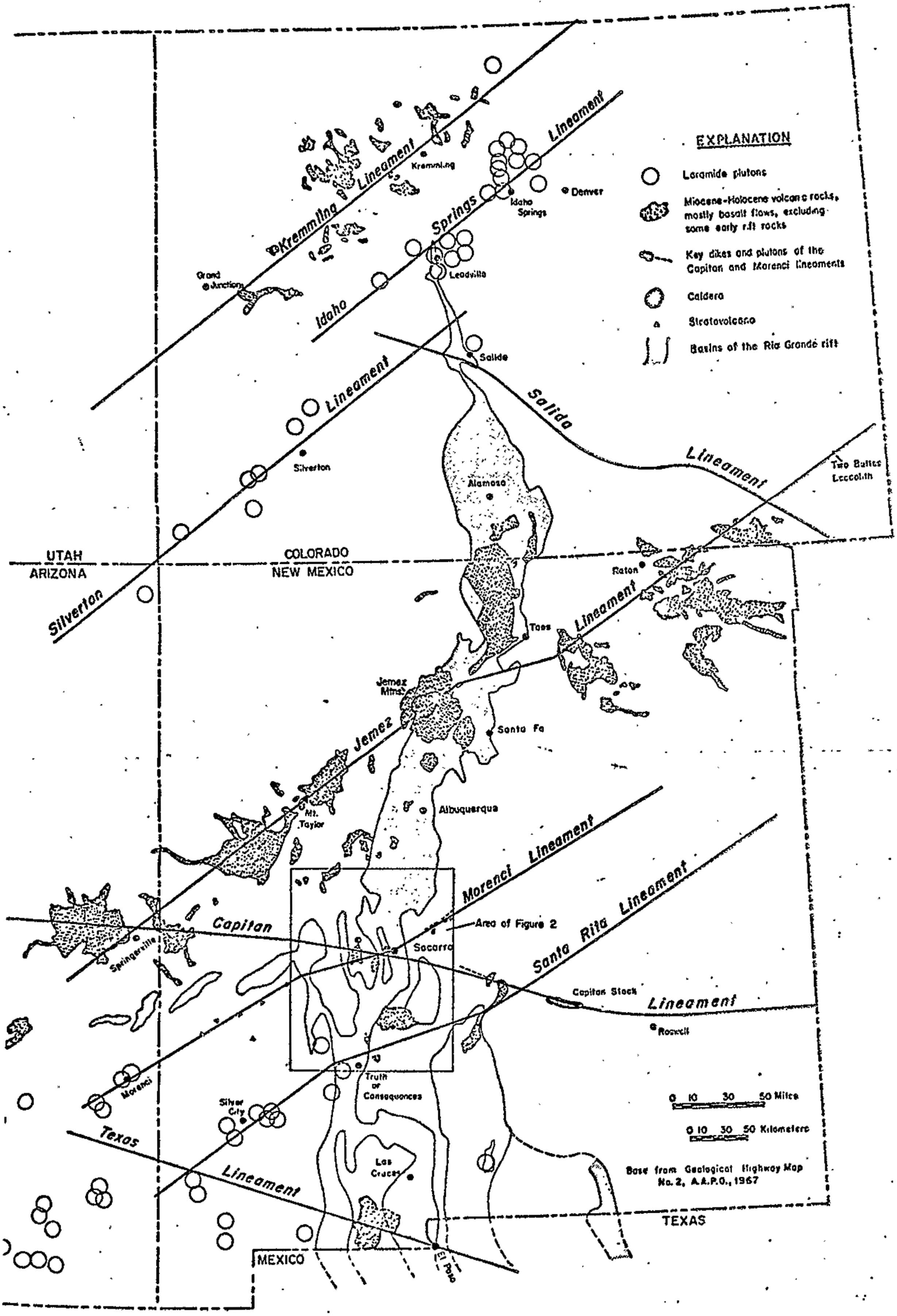


Figure 1. Generalized map of the Rio Grande rift (after Chapin, 1971; Chapin and Seager, 1975) and major crustal lineaments.

resting upon late Paleozoic limestones, quartzites, or shales on the uplift lap off the structure onto Eocene arkosic sediments which overlie Cretaceous sandstones and shales. Precambrian rocks in the Socorro area generally consist of low-grade metasedimentary rocks (especially quartzites and argillites), metavolcanic rocks, and intrusive rocks ranging from large granitic plutons to gabbroic stocks and diabase dikes. The high-potassium Precambrian granites (Condie, 1978) may be the main source of K_2O for the potassium anomaly described in a later section.

Two major crustal lineaments (fig. 1) intersect in the Socorro area. The Morenci lineament is one of a series of northeast-trending shear zones that dominate the structural grain of Precambrian rocks in the southern Rocky Mountains. Documentation for each of the lineaments labeled on Figure 1 will be presented in a later paper. They are included on Figure 1 to illustrate how structures in the Socorro area fit into the regional framework. The three northern lineaments are en echelon segments of the Colorado lineament of Warner (1978). Of these, the Silverton and Idaho Springs lineaments are generally lumped as the well-known Colorado mineral belt (Tweto and Sims, 1963). The Capitan lineament parallels the better known (and highly controversial) Texas lineament (Albritton and Smith, 1956; Wertz, 1970) and may be related to it. The important point is that these lineaments are deeply penetrating flaws in the lithosphere that tend to "leak" magmas and to influence deformation in the brittle near-surface rocks. The Morenci lineament has had a major influence on tectonics and magmatism in the Socorro area for the past 32 m.y. The recognition that a transverse shear zone of the Morenci lineament separates fields of tilted blocks undergoing rotation and step faulting in opposite directions has been one of the most significant discoveries of our geologic research. This shear zone is acting as an incipient transform fault connecting en echelon segments of the Rio Grande rift. Figure 2 and Plate 1 (in pocket) document the shear zone and illustrate its effect on magmatism, both past and present.

In addition to exposing a good cross section of volcanic and pre-volcanic rocks, the north-trending, tilted, fault-block uplifts, also transect several cauldrons and related vent areas. The area from Socorro southwestward to beyond the San Mateo Range, a distance of about 50 miles (80 km), consists of at least seven overlapping cauldrons (fig. 2). These circular to elliptical subsidence structures formed by collapse of the roofs of large, shallow magma chambers as a consequence of the voluminous ash-flow eruptions which deposited the widespread tuff sheets that cap the Datil-Mogollon volcanic pile. The north margin of one of the youngest of these cauldrons is exposed on Socorro Peak; the ring fracture zone and moat of this cauldron partly control the location and plumbing system of the Socorro geothermal area. The Socorro cauldron formed about 27 m.y. ago during onset of the extensional stress field which pulled apart the earth's

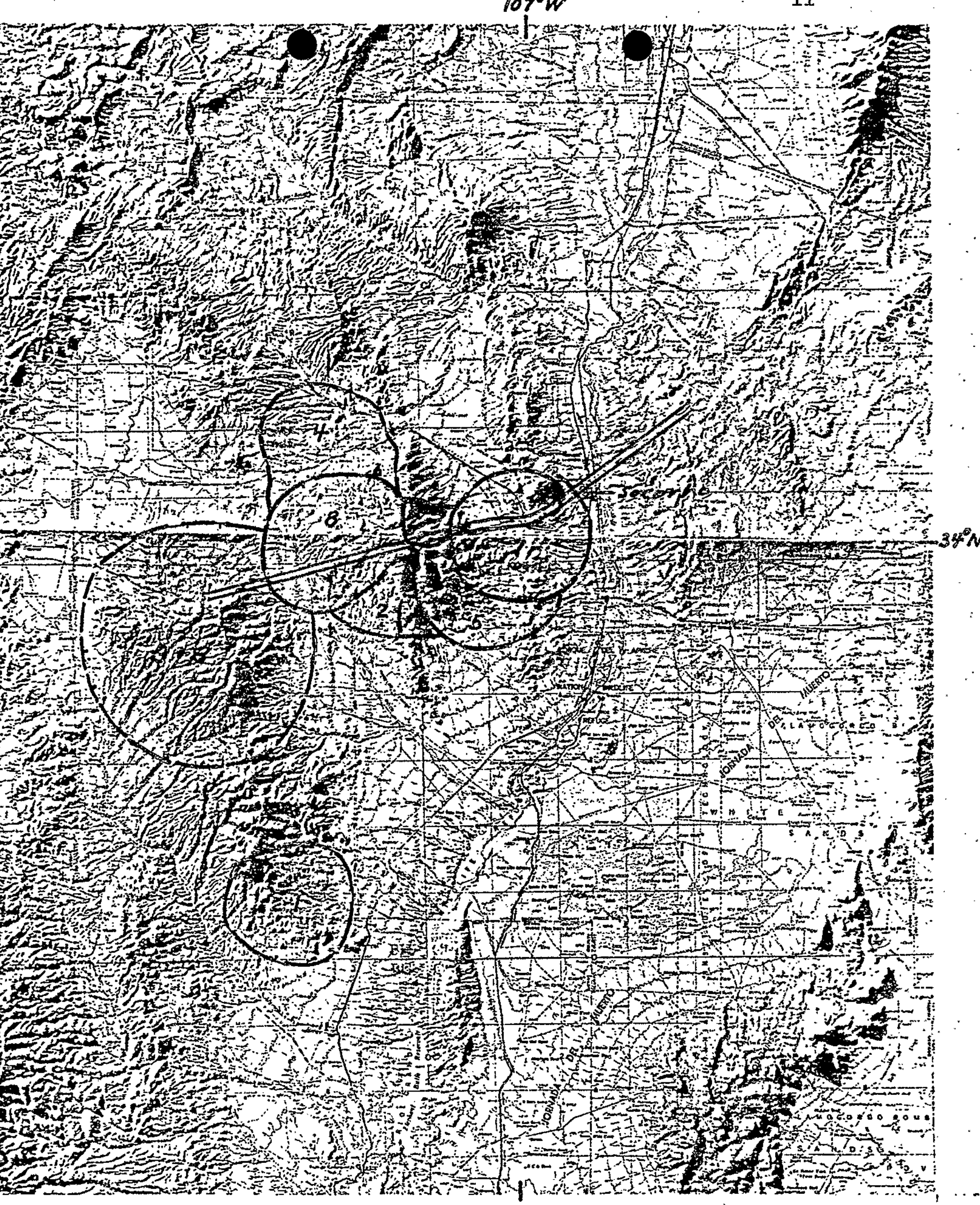


Figure 2. Overlapping and nested cauldrons and a transverse shear zone (double line) in the Socorro-Magdalena area. The cauldrons from oldest to youngest are: 1) Nogal Canyon, 2) North Baldy-32 m.y., 3) & 6) Mt. Withington, 4) Magdalena, 5) Sawmill Canyon, 7) Socorro-27 m.y. and 8) Hop Canyon - 26 m.y.

crust along the Rio Grande rift. As a result, fault patterns within the caldera interrelate in a complex manner with those outside the structure.

After collapse, the floors of many cauldrons are domed upward by renewed magma pressure to form a central resurgent dome separated from the cauldron walls by a trough-like annulus called a moat (Smith and Bailey, 1968). Because the moat is underlain by the deeply penetrating ring fractures of the cauldron, post-collapse magmatism usually fills it with lava flows, lava domes, and local tuffs which are interbedded with sediments washed in from the resurgent dome and from the outer cauldron walls. Volcanism may continue along the moat for many millions of years after cauldron collapse because the underlying ring fractures provide the easiest route of ascent for magmas (Lipman and others, 1976). Likewise, the ring fracture zone often controls geothermal systems by providing magma bodies and highly fractured rock beneath a permeable sequence of moat deposits. This idealized picture is true in a general way for the Socorro cauldron. Cauldron collapse was followed by resurgent doming and accumulation of moat volcanics and sediments. After a long lull in magmatism, during which the cauldron was largely buried by sediments of the Popotosa basin, renewed magmatism occurred during the interval 12 to 7 m.y. ago. After another quiet spell, basaltic lava flows were emplaced at about 4 m.y. ago (Bachman and Mehnert, 1978). Volcanism again became dormant, but the geophysical studies of A. R. Sanford and others indicate that magma bodies are again rising along, and near, the ring fracture zone (pl. 1, map 4).

Another important element in the geologic setting is the formation and disruption of a broad sedimentary basin which spanned the Rio Grande rift in the Socorro area during the interval from about 26 m.y. to 7 m.y. ago. The basin extended from the Gallinas Range on the west to the high mesas east of the Rio Grande and from the Ladron Mountains on the north to the eastern Magdalena and central Chupadera mountains on the south. Within the basin accumulated several thousand feet of alluvial-fan, piedmont-slope, fluvial, and playa deposits now known as the Popotosa Formation (Denny, 1940; Bruning, 1973). The lowest portions of the basin floor persistently occupied a north-trending area along the present site of the Chupadera, Socorro, and Lemitar Mountains. Alluvial fans graded downslope from the bordering uplifts to playa lakes along this depression. At least 800 to as much as 2500 feet (244-762 m) of relatively uniform, gypsiferous clays were deposited from the playas. During the interval 12 m.y. to 7 m.y. ago, rhyolitic magmas rose along the northern moat of the buried Socorro caldera, spread over the thick clay deposits, and lapped onto bedrock highs along the east side of Socorro Peak and in the northern Chupadera Mountains and eastern Magdalena Mountains. Chemical and petrographic data suggest that a very large geothermal system existed at that time.

The Popotosa basin was disrupted sometime after about 7 m.y. and before 4 m.y. by extensional forces which broke the basin into tilted fault-block uplifts and grabens. The reason for this disruption is not known. It coincides in time with a pulse of uplift and faulting throughout the Rio Grande rift, but it may also be related, in part, to intrusion of a large sill-like magma chamber similar to the one now present at a depth of 18 to 20 km (Sanford and others, 1973, 1977a). The area occupied by the playa lakes was uplifted to form the Chupadera-Socorro-Lemitar mountains. Many slopes in the Socorro Peak, Black Mesa, and Strawberry Peak areas are underlain by red Popotosa claystones; slump blocks of the overlying volcanic rocks are riding downslope on the claystones and have masked much of the underlying bedrock (pl. 1, map 1). Drill holes along the canyon bottoms indicate that several hundred feet of claystone is yet to be exposed.

Extensive pediment surfaces were carved across uplifted and tilted Popotosa beds and older rocks on the Chupadera-Socorro-Lemitar horst during the Pliocene and Pleistocene periods. The rock removed was dumped mainly into the Socorro basin on the east. Sometime during the breakup of the Popotosa basin, the regional drainage was integrated to form an ancestral Rio Grande. Extensive deposits of light-colored, well-sorted arkosic sands were laid down by this river and some of its larger tributaries. These sands underlie much of the Rio Grande valley east of the frontal faults of the Chupadera-Socorro-Lemitar uplift and provide an important aquifer for New Mexico Institute of Mining and Technology and the Town of Socorro. Broad, gently sloping piedmont plains graded to the ancestral Rio Grande and on these accumulated gravels, sands, and silts which interfinger with the clean sands and muddy overbank deposits of the trunk stream. Both the piedmont and main-stem fluvial deposits have been named the Sierra Ladrones Formation (Machette, in press). These deposits locally overlie the Popotosa Formation with angular unconformity and are lighter in color, less indurated, and contain a larger portion of clasts derived from prevolcanic rocks. At about 4 m.y. ago, basalt flows were erupted in the Sedillo Hill area, south of Socorro Peak. These lavas flowed eastward down a pediment surface, across truncated Popotosa claystones and silicic domes and flows of the rhyolite of Socorro Peak, and onto fluvial sands of the ancestral Rio Grande.

Capture of the ancestral Rio Grande at El Paso in middle Pleistocene time (between 300,000 and 500,000 years ago; Kottlowski, 1958; Hawley, 1975), and its integration to the sea, lowered its base level and caused it to entrench deeply into its earlier deposits. The highest outcrops of ancestral Rio Grande deposits in the Socorro area are about 600 feet (180 m) above its present floodplain; about half the elevation difference is due to entrenchment and half to uplift along the east flank of the Chupadera-Socorro-Lemitar horst. The present landscape consists of four elements: 1) the mountain ranges, 2) the present floodplain of the Rio Grande, 3) broad piedmont surfaces of Pleistocene to Holocene age, and 4) arroyos which grade to the present Rio Grande and are dissecting the piedmont slopes. The largest of the arroyo systems, such as Socorro Canyon and Nogal Canyon, head in the Magdalena Range and cross the Chupadera-Socorro-Lemitar uplift. This is an anomalous situation which probably occurs because the Chupadera-Lemitar block was uplifted within a broad basin and beveled by a Pliocene pediment. During subsequent uplift streams have been able to maintain their courses across the upthrown block.

The geophysical characteristics of the Socorro area and their spatial relationships to the Socorro cauldron and the transverse shear zone are shown on a series of maps accompanying the generalized geologic map (pl. 1, maps 1-4, in pocket). Map 2 is a residual Bouguer gravity map (Sanford, 1968); Map 3 is an aeromagnetic map prepared by the U.S. Geological Survey. Map 4 shows the extent of a deep magma body at about 18 km depth and several shallow magma bodies inferred by Sanford and others from seismic studies. The distributions of microearthquakes (Sanford and others, 1977a, b) and heat flow measurements (Reiter and Smith, 1977; Sanford, 1977) are also shown on this map. In summary, the magma bodies, seismic activity, high heat flow, geothermal activity, and modern uplift of the Socorro area occur in a geologic setting which has experienced repeated magmatism in the past and is likely to again in the future.

STRUCTURAL CONTROLS

Structural controls of the Socorro geothermal area may be divided into those that: 1) control the ascent of magma bodies, i.e. the location of heat sources; 2) control the location and thickness of permeable reservoir rocks and impermeable cap rocks, hence, the lateral migration and storage of geothermal fluids; 3) control the upward migration of geothermal fluids; and 4) control the fracture trends and fracture spacing in rocks whose reservoir characteristics are dependent upon fracture permeability. These controls are interrelated; their relative importance to discovery and development of a commercial geothermal reservoir in the Socorro area is yet to be tested.

Structural Controls of Magmatism

The major structural controls of the Socorro geothermal area are the Rio Grande rift, a transverse shear zone of the Morenci lineament, and the Socorro cauldron. The ring fracture zone of the Socorro cauldron has influenced the ascent of magmas at intermittent periods since cauldron formation. K-Ar dates on volcanic rocks indicate periods of magmatism at 27-20 m.y., 12-7 m.y. and 4 m.y. Geophysical data indicates that magma bodies are again present in the plumbing system (pl. 1, map 4). Reiter and others (1978) have recently pointed out the association of several heat-flow anomalies along the Rio Grande rift with cauldron margins.

Until very recently, we thought that the Socorro cauldron margin was the most important structural control of magmatism other than the Rio Grande rift. However, when the detailed geologic maps of the eastern Magdalena Mountains (Osburn, 1978) and the Socorro Peak- Lemitar Mountains area (Chamberlin, 1978) were completed, a remarkable pattern began to emerge. To the north of a line extending southwestward from Socorro through the South Baldy area of the Magdalena Mountains, formations are tilted to the west and stepped down to the east by north-trending normal faults (pl. 1, map 1, cross section A-A'). To the south of this line, formations are tilted to the east and stepped down to the west (cross section B-B'). Examination of other geologic maps, both completed and in progress, revealed that this pattern persists southwestward at least as far as Mount Withington in the San Mateo Range and northeastward to the Mesa del Yeso area. The rotation and step faulting of rocks at the surface in opposite directions across this line must be accompanied by shearing in the underlying lithosphere. The sense of the shearing is left lateral, yet the shear zone connects en echelon segments of the Rio Grande rift which have a right-lateral apparent offset (Albuquerque graben to the northeast, Mulligan Gulch and Winston grabens to the southwest). Hence, the shear zone is acting as a transform fault connecting en echelon axes of extension. The rates of shearing and extension, however, are very slow compared to ocean ridges and the transform is in a very early stage of development. Barberi and Varet (1977) have recently described transverse structures, some of which are transform faults, in the Afar depression of east Africa. They note that the transverse structures connecting offsets of spreading centers tend to occur along prerift lines of tectonic weakness in the continental block; that transform faults in the initial stages of development are somewhat obscure and may be represented at the surface by zones of en echelon faults whose trends may diverge by 15° to 30° from the trend of the transform and whose motions are partly shear and partly extensional; that the common occurrence of volcanism along transverse structures suggests a tendency to "leak" magmas; that large central volcanoes tend to occur at the intersections of transverse structures with faults bordering depressions; and that magmas erupted along transverse structures are usually alkalic and contain peridotite xenoliths. All but the last of these characteristics are also true of the transverse shear zone at Socorro. The Socorro structure occurs along the Morenci lineament, a major northeast-trending flaw of probable Precambrian age; its surface expression is marked by a zone of jostled fault blocks a mile (1.5 km) or more in width across which the tilt of beds and sense of extension changes markedly; it has leaked magmas at irregular intervals since late Oligocene time and is leaking them today.

The deep magma body at about 18 km, outlined by Sanford and others (1977a) using reflections from microearthquakes, terminates in an irregular manner against the transverse shear zone. The five shallow magma bodies inferred by Sanford and others (1977b) from changes in Poisson's ratio, screening of S waves, and distribution of microearthquake foci, are distributed along the shear zone and lie within 3 or 4 miles (5-6 km) of either side of it. Thus, the transverse shear zone seems to influence both the lateral and vertical movement of magma. The deep magma body may terminate against the shear zone because of a structural "curtain" of sheared and recrystallized rock, and/or the compositions and physical properties of basement rocks may be different on opposite sides of the shear zone. Note on the aeromagnetic map (pl. 1, map 3) the change in trend of magnetic anomalies across the shear zone. Magmas may "bleed" upward along the shear zone and accumulate in shallow reservoirs. The north-south orientation of the shallow magma bodies (pl. 1, map 4) probably reflects the dominance of north-trending, rift-related fractures in the shallow crust and the favorability of fractures of this orientation for dilation and magma injection. The fact that the shallow magma bodies lie within or close to the Socorro cauldron could be fortuitous, but the well-documented relationship of recurrent magmatism to cauldrons elsewhere suggests that the cauldron ring fractures provide additional vertical permeability to the magma plumbing system. In the last several kilometers of ascent, the combination of north-trending rift fractures and intersecting cauldron ring fractures may tend to draw the magmas towards the cauldron by providing paths of least resistance.

Control of past magmatism by the transverse shear zone is evident from Figure 2 and Map 1 (pl. 1, in pocket). Going back in time, the vent for the 4 m.y. old basalt of Sedillo Hill lies on the shear zone; the two youngest silicic domes (Grefco dome, 7 m.y.; unnamed dome between Black Mesa and Socorro Spring, 8 m.y.) lie on the shear zone, the area of 7-12 m.y. old silicic volcanism is approximately bisected by the shear zone and all known vents for this period of magmatism lie within 3 or 4 miles (5-6 km) of it (pl. 1, map 1); and, finally, the seven overlapping and nested cauldrons of the Socorro-Magdalena area are clustered along the shear zone.

On the aeromagnetic map (pl. 1, map 3), the transverse shear zone is marked by a "quiet" zone which separates an area of north-trending magnetic anomalies to the north from an area of northeast-trending magnetic anomalies to the south. The transverse shear zone seems to be following a major discontinuity in the continental crust across which the structural grain of basement rocks changes from northerly to northeasterly. Along a zone about 8 miles (13 km) wide and extending from Socorro southwestward across Socorro Peak and the northern Chupadera Mountains through the Magdalena Range, the aeromagnetic anomalies are muted. In spite of rugged topography and exposure of Precambrian rocks at the surface, Socorro Peak is a relatively featureless area on the aeromagnetic map. The "quiet" zone extends across the highest and most rugged part of the Magdalena

Range with bold aeromagnetic anomalies to the north and south but greatly subdued anomalies within it. The "quiet" zone seems independent of rock types and terrain. The most logical explanation is that high heat flow along the transverse shear zone has raised the Curie temperature isotherm to shallower depths and thus canceled the aeromagnetic signature of the deeper crust. Considering the rather striking control of volcanism exerted by the transverse shear zone in the past, high heat flow along this zone seems a reasonable possibility.

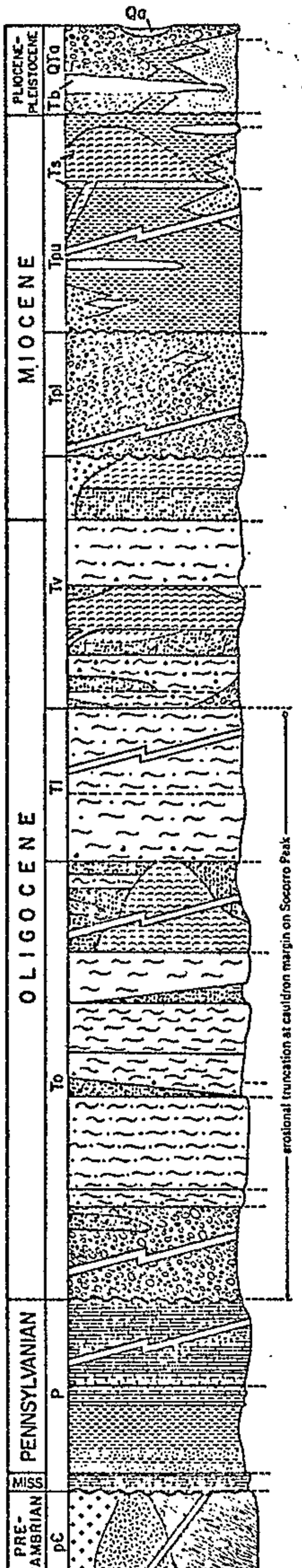
Structural Controls of Reservoir Rocks and Cap Rocks

High heat flow above the shallow magma bodies may lead to development of geothermal reservoirs if: 1) permeable water-bearing reservoir rocks are present, and 2) an impermeable cap exists above the reservoir to prevent loss of fluid and dissipation of heat. Sanford and others (1977b) estimate depths of 4 to 5 km to the tops of the shallow magma bodies. At these depths, the magma bodies are within either Precambrian basement rocks or crystalline rocks of the late Cenozoic batholith of which the Socorro cauldron is a surface manifestation. Rocks at these depths are probably dry, but envelopes of high heat flow above the shallow magma bodies may intersect permeable water-bearing horizons at shallower depths. The depth of rock units with good aquifer characteristics is apt to be greatest within the Socorro cauldron because this subsidence structure has dropped pre-cauldron rocks an undetermined distance below the elevations at which they are normally found. The Socorro and La Jencia grabens (pl. 1, maps 1, 2) were superimposed across the Socorro cauldron during and after its collapse. Where these grabens overlap the cauldron, subsidence effects are additive so that potential reservoir rocks are depressed to the greatest depths. Where these zones of additive subsidence overly shallow magma bodies, temperatures in potential reservoir rocks should be highest.

The Socorro cauldron overlaps and buries the eastern half of the older Sawmill Canyon cauldron (fig. 2). The buried ring fracture zone of this older cauldron is difficult to locate; however, the stratigraphic sequence in a drill hole at the Tower mine (pl. 1, map 1) suggests that it lies east of the drill hole. An unusual feature of the Socorro cauldron is the fact that moat deposits are very thick in the northern Chupadera Mountains, northeast of the Tower mine, and along the east-facing escarpment of Socorro Peak; whereas, from the Tower mine west, moat deposits are thin to absent and the tuff of Lemitar Mountains is only about one-third as thick as it is to the east. It seems possible that during subsidence of the Socorro cauldron the buried Sawmill Canyon cauldron behaved as a rigid, bouyant block which did not subside as much as the rest of the Socorro cauldron. Another possible explanation is that subsidence was much greater east of a major north-trending contemporaneous rift fault. A north-trending rift fault zone is known to control the thickness of the outflow sheet of the tuff of Lemitar Mountains north of the Socorro cauldron (pl. 1, map 1, cross section A-A'). Whatever the cause, or combination of causes, the eastern third of the Socorro cauldron seems to have subsided considerably more than the rest of the cauldron and accumulated as much as 3,000 feet (900 m) of cauldron facies tuff of Lemitar Mountains and as much as 2,000 feet (610 m) of moat deposits. Thus, the depth to pre-caldera rocks may be as much as 5,000 feet (1.5 km) greater east of a line trending north-northwest from a point about 0.6 miles (1 km) east of the Tower mine, to the north edge of the Socorro cauldron. Alternatively, this buried escarpment may bend northwestward towards the mouth of South Canyon to follow the inferred margin of the buried Sawmill Canyon cauldron. However, gravity data (pl. 1, map 2) favors the first alternative.

Structural Controls of the Ascent of Geothermal Fluids

The location of the two warm springs southwest of Socorro seems to be controlled by the intersection of the moat of the Socorro cauldron with the major fault zone bounding Socorro Peak on the east. Downfaulting of the thick claystone interval in the upper Popotosa Formation (fig. 3) may have blocked the eastward migration of heated ground waters, thus forcing them to the surface. Alternatively, these hot waters may be leaking upward along the range-bounding fault from a deep reservoir heated by a shallow magma body.



Post Santa Fe Alluvium: (0-50', 15 m) ALLUVIUM, SLUMP BLOCKS, and COLLUVIUM: Inset deposits of gravel, sand, & mud along the Rio Grande & its tributaries. Fan, piedmont-slope and playa deposits of La Jencia bolson. Extensive slump & colluvial deposits on slopes around Socorro Pk., Strawberry Pk., & Black Mesa mantle mudstones of upper Popotosa Fm.

Sierra Ladrones Formation: (0-1000', 305 m) PIEDMONT-SLOPE, RIVER CHANNEL and FLOOD PLAIN DEPOSITS, and BASALT FLOWS: buff to pale-rd., poorly indur., fangl. w/ mixed clasts of all major rock types shed off present highlands. Fangl. intertongue w/ lt.-gry., friable, well-sorted, fn.-med.-gnd. sands of ancestral Rio Grande. Flood plain deposits are rd. & grn. mudst. & siltst. Basalt of Sedillo Hill (4 m.y.) underlies piedmont-slope facies & overlaps ancestral Rio Grande sands & piedmont facies near Grefco mine.

Rhyolite of Socorro Peak: 7-12 m.y. (0-800', 244 m) SILICIC DOMES, FLOWS, and TUFFS: pale-rd.-gry. to lt.-gry. rhyolite & rd.-brn. to lt.-gry. rhyodacite flow-banded lavas, domes, necks, & tuffs. Tuffs interbedded w/ clayst. of upper Popotosa at Socorro Spring, W. of Blue Canyon, Kelly Ranch (12 m.y.), and N. of Sedillo Hill.

Upper Popotosa Formation: (0-2500', 762 m) CLAYSTONES, MUDSTONES, SILTSTONES, SANDSTONES, CONGLOMERATES, and BASALT FLOWS: Dk.-rd.-maroon gyp. playa clayst. & mudst. w/ thn. bds. of yel.-brn. to grn.-gry. clayst. North of Strawberry Pk., playa deposits intertongue w/ buff, cgl. ss w/ hydro. altered clasts derived from Magdalena area. At Grefco mine, mudst. intertongue w/ pale-rd. cgls. derived from E. of Rio Grande and w/ perlite-rich cgls. shed from Grefco dome. Basalt flows interbedded w/ playa deposits near Pound Ranch, Strawberry Pk., & Hwy. 60.

Lower Popotosa Formation: (0-1500', 457 m) MUDFLOW DEPOSITS, FANGLOMERATES, and minor LACUSTRINE DEPOSITS: rd.-brn., v. well-indur., heterolithic, crs. cgls. w/ abun. clasts of underlying volc. units & locally grading downward into ancient colluvial breccias. Gry. siltst., mudst., & thn. fresh-water ls. intertongue w/ lt.-gry. to prpl.-gry. cgl. ss. in Socorro Pk.-Blue Canyon area. Facies relationships reflect late-stage topography of Socorro caldera.

Lavas of Water Canyon Mesa: 20 m.y. (0-600', 183 m) INTERMEDIATE to SILICIC LAVAS and TUFFS: rd. silicic lavas & tuffs underlain by intermed., dk.-gry. to dk.-rd.-brn., dense lavas; intruded and overlain by flow-banded wht. rhyolite domes & flows.

Tuff of South Canyon: 26 m.y. (0-600', 183 m) ASH-FLOW TUFFS: multiple-flow, simple cooling unit of rhyolite ash-flow tuffs. Lower zone of lt.-gry., poorly to densely welded, xl.-poor tuff w/ "botryoidal" pumice & lithic-rich lenses. Upper zone of med.-gry. to prpl.-gry., mod. to densely welded, mod. xl.-rich tuff w/ chatoyant sanidine & euhedral qtz.

Unit of Luis Lopez: (0-2000', 610 m) ASH-FLOW TUFFS, ANDESITE LAVAS, RHYOLITE DOMES and TUFFS, minor LANDSLIDE DEPOSITS and TUFFACEOUS SANDSTONES. Moat fill of Socorro cauldron. Lt.-gry., pumiceous, lithic-rich, poorly welded, rhyolite ash-flow tuffs intertongue w/ andesite flows, vent agglomerates, & minor andesitic laharic breccias. Pale-rd., orng.-rd., & lt.-gry. flow-banded rhyolite lavas, domes and tuffs cap sequence. Contemporaneous tongue of La Jara Peak Basaltic Andesite (0-800', 244 m) in Lemitar Mts.

Tuff of Lemitar Mountains: 27 m.y. (0-400', 122 m outflow; 700-2900', 213-884 m cauldron) ASH-FLOW TUFFS: multiple-flow, comp. zoned, simple to compound cooling unit of densely welded tuff. Lt.-gry. to pale-rd., xl.-poor lower member 200-800 ft. (61-244 m) thk. in Socorro cauldron but only locally present as thn. lenses on outflow sheet. Md.-rd., xl.-rich, qtz.- & biotite-rich, 2-feld. upper member 0-400 ft (122 m) outflow facies, 350-2900 ft (107-884 m) cauldron facies. Contact sharply gradational & welded. Xl.-rich clots common at top. Lithic-rich zones w/ Precambrian & andesite clasts widespread S. of Tower mine.

Unit of Sixmile Canyon: (0-2000', 610 m) ANDESITE to BASALTIC ANDESITE LAVAS, RHYOLITE LAVAS and DOMES, ASH-FLOW TUFFS, LAHARIC BRECCIAS, and SANDSTONES: post-collapse fill of Sawmill Canyon cauldron. Drk.-gry. mafic lavas intertongue with & surround other rock types. Heterolithic breccias along cauldron walls. Contemporaneous tongue of La Jara Peak Basaltic Andesite (0-500', 152 m) in Lemitar Mts.

A-L Peak Tuff: 32 m.y. (0-700', 213 m outflow; 2000+', 610+ m cauldron) ASH-FLOW TUFFS: composite sheet w/ basal gray-massive, middle flow-banded, & upper pinnacles members. All densely welded, xl.-poor, l-feld., rhyolite, ash-flow tuffs. Sources are Mt. Withington, Magdalena, & Sawmill Canyon cauldrons. Tongue of La Jara Peak Basaltic Andesite (0-200', 61 m) usually separates flow-banded & pinnacles members.

Lava Flows: (0-300', 91 m) ANDESITE to BASALTIC ANDESITE: unnamed tongue of dense prpl.-rd. flows locally present in SW Lemitar Mts.

Hells Mesa Tuff: 32-33 m.y. (0-500', 152 m outflow; 3000+', 915 m cauldron) ASH-FLOW TUFFS: rhyolite, multiple-flow, simple cooling unit, densely welded, xl.-rich, qtz.-rich, 2-feld., mass. tuffs. Pk. to rd.-brn. when fresh, gry. when propyl. altered. Weathers to blocky bldrs. Basal tuffs similar to tuff of Granite Mtn.; abrupt increase in qtz. 10-25 ft above base.

Spears Formation — tuff of Granite Mountain: (0-100', 30 m) ASH-FLOW TUFFS: qtz.-latite, multiple-flow, simple cooling unit, densely welded, xl.-rich, lithic-rich, qtz.-poor, mass. tuffs; rd.-brn. when fresh, dk.-grn.-gry. when propyl. altered.

Spears Formation — volcaniclastic unit; 37-33 m.y. (0-1500', 457 m) CONGLOMERATES, MUDFLOW DEPOSITS, SANDSTONES, LAVAS, and ASH-FLOW TUFFS: volcaniclastic apron of latite to andesite comp., becomes coarser & contains more volc. units up & to south.

Madera Limestone: (500-1500', 152-457m) LIMESTONES: thk., homo. sequence of gry. to blk. micrites w/ a few thn. bds. of med.-crs.-gnd. qtz. ss. Up. 200-300 ft (61-91 m) is rd., grn., & gry. micrites grading up. into arkosic bds. of Abo Fm. Nodular micrites abun. throughout.

Sandia Formation: (550-650', 168-198 m) SHALES, QUARTZITES, and LIMESTONES: gry. to blk., sdy., carb. sh. and siltst. w/ thn. bds. of gry. to brn., med.-crs.-gnd. qtz. ss. (abun. near base) & gry., med.-gnd. micritic ls. (gradational w/ Madera).

Kelly Limestone: (0-90', 27 m) LIMESTONE: lt.-gry., med.-crs.-gnd., thk.-bdd. crinoidal biosparrites.
Caloso Formation: (0-30', 9 m) LIMESTONES and CONGLOMERATES: basal arkosic cgl. overlain by gry., mass., sdy. or pbly. micrites.

Basement: ARGILLITES, QUARTZITES, VOLCANIC and PLUTONIC ROCKS: thk. sequence of low-grade metased. & metavolc. rocks intruded by granitic & gabbroic plutons, & diabase dikes.

Figure 3. Composite stratigraphic column of the Socorro area. Thickness of units not to scale.

The thermal springs lie directly on the transverse shear zone across which the rotation of tilted fault blocks changes from easterly to westerly and the sense of extension changes 180 degrees. These changes must be accompanied at depth by shearing and at shallow depths by a twisting motion. Beds which have a northerly strike but opposing dip directions, to the north and south of the shear zone generally become parallel to the shear zone in crossing it. These changes in tilt, accompanied by breaking of strata in new directions, may provide escape paths for geothermal fluids leaking from reservoir rocks at depth. Whatever the heat source, the purity and relatively low temperature of the waters (Hall, 1963) issuing from the Socorro thermal springs indicates major dilution by ground water. The tritium studies of Holmes (1963) indicates a transit time of about 4.3 years between recharge in the eastern Magdalena Mountains and discharge at the Socorro springs. This relatively rapid flow also suggests that dilution by ground water has a major effect on any geothermal fluids leaking from depth.

Structural Controls of Fracture Permeability

All rocks in the Socorro geothermal area have abundant fractures and joints, except for the claystone interval of the Popotosa Formation and the younger, less-indurated sedimentary deposits. Primary cooling joints in lava flows and ash-flow tuffs provide excellent permeability at right angles to bedding. The interconnection of these joints provides good permeability parallel to bedding. The long history of faulting has superimposed abundant tectonic fractures on the primary joint patterns. Thus, fracture permeability should be good in all of the brittle volcanic rocks and well-indurated sedimentary rocks. Fracture permeability is probably highest in the brittle, densely welded tuffs, such as the A-L Peak Tuff and the tuff of Lemitar Mountains. The distribution of potassium enrichment in reservoir rocks of an ancient geothermal system indicates that the well-jointed and fractured ash-flow tuffs did have the greatest permeability in that system.

STRATIGRAPHIC CONTROLS

Possible stratigraphic controls of the Socorro geothermal area are the sequence, thickness, facies changes, and lateral and vertical permeability of geologic formations which comprise the rock column in the area. For purposes of discussion, the stratigraphic units may be divided into: 1) Paleozoic rocks, 2) volcanic and volcaniclastic rocks older than the Socorro cauldron, 3) rocks of the Socorro cauldron and its moat, 4) volcanic rocks younger than the moat deposits, 5) sedimentary rocks of the Santa Fe Group (alluvial fill of the Rio Grande rift).

Paleozoic Rocks

Paleozoic rocks (fig. 3) consist of the Caloso Formation and Kelly Limestone of Mississippian age (Armstrong, 1962) and the Sandia Formation and Madera Limestone of Pennsylvanian age (Kottlowski, 1960; Siemers, 1978). These rocks vary from 1050 to 2270 feet (320-690 m) in thickness in the Socorro area because of varying degrees of removal during Eocene erosion of the Laramide uplift and, to a minor degree, because of differences in the thicknesses deposited. The Kelly and Madera limestones are well-jointed, relatively brittle rocks which have good fracture permeability at shallow depths. The new municipal well for the town of Magdalena produces 100 gallons/minute from fractured Paleozoic limestones along a major fault about 1.5 miles (2.4 km) northeast of Magdalena. The Kelly Limestone was highly permeable to hydrothermal fluids during stock intrusion and ore deposition in the Kelly mining district. The Sandia Formation, however, is largely shale and formed a very effective impermeable cap above the Kelly Limestone during circulation of hydrothermal fluids. Both the Kelly and Madera limestones could provide deep reservoir rocks within the Socorro geothermal system. The Sandia shales would provide an impermeable cap above the Kelly and the volcaniclastic rocks of the Spears Formation would provide a relatively impermeable cap above the Madera Limestone.

The Paleozoic rocks have been downfaulted to depths of 4,000 to 12,000 feet (1220-3660 m) within the Socorro cauldron and possibly to depths as great as 17,000 feet (5180 m) where the Socorro graben overlaps the eastern edge of the Socorro cauldron. The reservoir characteristics of the Kelly and Madera limestones at these depths and temperatures are unknown. However, they provide potential reservoir rocks relatively close to the tops of the shallow magma bodies delineated by Sanford and others (pl. 1, map 4) and may be worth testing if shallower reservoirs prove inadequate.

Pre-cauldron Volcanic and Volcaniclastic Rocks

Volcanic and volcaniclastic rocks older than the Socorro cauldron are, in ascending order, the Spears Formation, Hells Mesa Tuff, A-L Peak Tuff, and unit of Sixmile Canyon (fig. 3). The Spears Formation consists mainly of volcanic conglomerates with thin interbeds of volcaniclastic sandstones. Mudflow deposits become increasingly abundant upward in the Spears; ash-flow tuffs and basaltic andesite flows are common near the top. The muddy matrix and high degree of induration of the sedimentary rocks makes them relatively impermeable. The poor permeability and great thickness (0 to 1500 ft, 0-457 m) of the Spears Formation makes it a possible cap rock for the underlying Madera Formation.

Outflow facies Hells Mesa Tuff consists of 0 to 500 feet (0-152 m) of densely welded, massive rhyolitic ash-flow tuffs; the cauldron facies is as much as 3,000 feet (915 m) thick. The brittle character and good jointing of these rocks, together with their lateral continuity and substantial thickness suggests good potential as a reservoir. The Hells Mesa is often separated from the overlying A-L Peak Tuff by

0 to 300 feet (0-90 m) of basaltic andesite flow rocks. These flows are probably too thin and permeable to provide an effective cap. The overlying A-L Peak Tuff consists of 0 to 700 feet (0-213 m) of moderately to densely welded, rhyolitic ash-flow tuffs. A thin tongue of basaltic andesite flows of the La Jara Peak Formation generally separates the A-L Peak into an upper and lower cooling unit. The tuffs are generally well-jointed and brittle and should have good fracture permeability. Anomalously high K_2O values in the flow-banded and pinnacles members of the A-L Peak in the Lemitar Mountains (table 1) indicate that these units provided reservoir rocks for an ancient geothermal system.

The A-L Peak Tuff interfingers to the northwest with basaltic andesite lavas of the La Jara Peak Formation. In the Lemitar Mountains, the A-L Peak is overlain by 0 to 500 feet (0-152 m) of basaltic andesite flows. These lavas accumulated on downthrown blocks during early rift faulting; on upthrown blocks they are generally thinner and may be missing entirely so that the tuff of Lemitar Mountains rests directly on A-L Peak Tuff. In the Magdalena Mountains, mafic lavas vary from 0 to 600 feet (0-183 m) on the outflow sheet and to as much as 2,000 feet (610 m) within the Sawmill Canyon cauldron. The basaltic andesite flows are well jointed but not as brittle as the densely welded tuffs. Their lateral and vertical permeability is probably too good to be an effective cap rock but relatively poor for a reservoir rock. However, these mafic flows are receptive to deposition of calcium carbonate and silica and they may provide a cap rock in areas of secondary cementation.

The Socorro cauldron overlapped and buried the eastern half of the Sawmill Canyon cauldron from which the pinnacles member of the A-L Peak Tuff was erupted. At least 2,000 feet (610 m) of densely welded A-L Peak Tuff accumulated within the Sawmill Canyon cauldron. Where exposed in the Magdalena Range, this tuff is pervasively jointed with closely spaced (5 to 15 cm) sheet joints that are approximately perpendicular to the foliation. This thick puddle of A-L Peak Tuff may provide one of the best reservoir rocks in the area. A drill hole near the Tower Mine in the northern Chupadera Range penetrated about 300 feet (92 m) of hydrothermally altered and pervasively sheared A-L Peak Tuff and was bottomed in it.

Overlying the A-L Peak Tuff in the Sawmill Canyon cauldron is a thick series of cauldron-fill or moat deposits consisting of andesitic flows, talus breccias, sedimentary rocks, rhyolitic domes and flows, and local ash-flow tuffs. These deposits have been termed the unit of Sixmile Canyon (Osburn, 1978) for good exposures in the ampitheater at the head of this canyon. The unit of Sixmile Canyon ranges from 0 to 2000 feet (0-610 m) in thickness with andesitic lavas consisting of about two-thirds of the thickness at the type locality. A drill hole near the Tower Mine in the northern Chupadera

Mountains intercepted a 213-foot (65 m) interval of rhyolitic to andesitic sandstones and conglomerates above the A-L Peak and below the tuff of Lemitar Mountains. Both the stratigraphic position and the rock types present in this interval are similar to the unit of Sixmile Canyon. If this correlation is valid, then the eastern edge of the Sawmill Canyon cauldron may extend as far east as the Tower mine. The area of overlap of the Sawmill Canyon and Socorro cauldrons seems to have acted as a bouyant, resurgent block following collapse of the Sawmill Canyon cauldron and during collapse of the Socorro cauldron. Both the moat deposits of the Sawmill Canyon cauldron (unit of Sixmile Canyon) and the caldera-facies tuff of Lemitar Mountains of the Socorro cauldron are anomalously thin on this block. Structural and stratigraphic traps may be present in tilted formations along the eastern and northern boundaries of the resurgent block; structural closure may exist on the resurgent block for reservoir rocks from the tuff of Lemitar Mountains through Paleozoic rocks.

Rocks of the Socorro cauldron and its Moat

Collapse of the Socorro cauldron occurred during, and as a result of, eruption of the tuff of Lemitar Mountains. The lower crystal-poor member of the tuff of Lemitar Mountains accumulated to thicknesses in excess of 800 feet (244 m) within the cauldron (the base of the lower member is rarely exposed with the cauldron so the maximum thickness may be much greater). Outside the cauldron, the lower tuff of Lemitar Mountains is discontinuous and thin (0 to 100 feet, 0-30 m). The upper, crystal-rich member is also thicker within the caldera (350 to 3,000 feet, 107-884 m), but its outflow facies is relatively thick (0 to 400 feet, 0-122 m) and arealy extensive. Anomalously high K_2O values and altered plagioclase feldspar within both the upper and lower members, both inside and outside the cauldron, indicate that the tuff of Lemitar Mountains may have been an important reservoir rock during the ancient system. Both members are densely welded and brittle with well-developed jointing and good fracture permeability.

During and after eruption of the tuff of Lemitar Mountains, a north-trending zone of differential subsidence existed in what is now the northern Chupadera Range. At the Tower Mine in the western Chupadera Mountains, 690 feet (210 m) of the tuff of Lemitar Mountains have been intercepted in a drill hole; whereas, about 0.6 mile (1 km) to the southeast, a minimum of 2900 feet (884 m) of the upper member of the tuff of Lemitar Mountains is exposed in continuous section on the resurgent dome. Elevation of the resurgent dome formed a structural moat between its northern and eastern sides and the outer, topographic wall of the Socorro cauldron. Within this moat accumulated as much as 2,000 feet (610 m) of landslide deposits, local lithic-rich ash-flow tuffs, and andesite flows capped by rhyolite domes and tuffs. Collectively, these moat deposits have been termed the unit of Luis Lopez (Chamberlin, 1978). Their reservoir characteristics are quite varied but, in general, they form a relatively permeable unit with abundant joints, fractures and unconformities. The occurrence of the Socorro thermal springs where the frontal fault of the Socorro Range cuts the moat deposits may be partly related to this permeability.

Volcanic Rocks Younger than Moat Deposits

The outflow sheet of another major ash-flow tuff unit was emplaced across the Socorro cauldron and surrounding areas about 26 m.y. ago, shortly after the cauldron had filled. This tuff, informally termed the tuff of South Canyon (Osburn, 1978), is a multiple-flow simple cooling unit generally ranging from 0 to 600 feet (0-183 m) in thickness. The tuff of South Canyon is so high in the stratigraphic column that it probably has no chance of being a reservoir rock except where downfaulted beneath the Socorro or La Jencia grabens. In these basins, it may occur at depths of 1,000 to 5,000 feet (305-1524 m) and, because of the high thermal gradient, could have reservoir potential. The lower, poorly welded zone and the overlying lithophysal zone are moderately porous and total about 180 feet (55 m) in thickness at the type locality. The upper 440 feet (134 m) of the tuff at the type locality is moderately to densely welded and brittle, with well-developed jointing and good fracture permeability. The tuff of South Canyon was a reservoir rock in an ancient geothermal system as evidenced by anomalous K_2O values and highly altered plagioclase phenocrysts.

The tuff of South Canyon is generally separated from the underlying Lemitar Tuff by basaltic andesite flows which range in thickness from about 100 feet (30 m) in the Socorro cauldron to as much as 1,100 feet (244 m) in the Lemitar Mountains. This basaltic andesite interval is probably a tongue of La Jara Peak Basaltic Andesite; the flows are also very similar to basaltic andesites interbedded in the A-L Peak Tuff and between the A-L Peak and the tuff of Lemitar Mountains. A typical basaltic andesite flow is about 15 feet thick with autobrecciated zones above and below a thin, massive core. Thin andesitic sandstones and conglomerates are occasionally interbedded between flows. The entire basaltic andesite interval initially had high lateral and vertical permeability but much of the primary permeability has been lost by deposition of calcite and silica in void spaces. The basaltic andesites are not as brittle as the densely welded tuffs and are probably now a relatively poor reservoir rock.

The basal fanglomerates and mud-flow deposits of the rift-fill sediments (lower Popotosa Formation) rest directly on the tuff of South Canyon in the Lemitar Mountains on Socorro Peak, and in the northern Chupadera Mountains. In the Water Canyon Mesa area of the eastern Magdalena Range, rhyolitic domes and flows, local rhyolitic tuffs, and a few intermediate lavas separate the tuff of South Canyon from the overlying Popotosa Formation. However, this seems to be a local occurrence.

The most extensive volcanic rocks younger than the moat deposits of the Socorro cauldron are the silicic flows and domes of Socorro Peak, Strawberry Peak, and Pound Ranch. These rocks were erupted between 12 and 7 m.y. ago and locally rest on top of all but the very youngest Popotosa Formation; however, they also lap unconformably onto the lower Popotosa Formation and tuff of South Canyon in the Blue Canyon, Tower Mine, and Pound Ranch areas. They are as much as 800 feet (244 m) thick but are so high in the stratigraphic column that they have virtually no chance of being reservoir rocks. They were not reservoir rocks in the ancient geothermal system as evidenced by their normal K_2O values and relatively fresh plagioclase. They overlie the thick playa claystone section of the Popotosa Formation which may have provided an impermeable cap for the ancient geothermal system. These claystones would locally provide a similar cap to a modern geothermal system so that, even where downfaulted beneath the Socorro and La Jencia grabens, the late Miocene silicic domes and flows would probably be above the geothermal system.

Sedimentary Rocks of the Santa Fe Group

Following eruption of the tuff of South Canyon, the Socorro area subsided as part of a broad, early-rift basin in which as much as 5,000 feet (1524 m) of sediments of the Popotosa Formation accumulated. The sediments were deposited as coalescing alluvial fans which graded down broad piedmont slopes to playa lakes on the floor of the basin. The present site of the Lemitar-Socorro-Chupadera uplift was a persistent north-trending low on the basin floor. At least 800 feet (244 m) of red, gypsiferous clays accumulated along this axis. When volcanism again became active in the Socorro area about 12 m.y. ago, the silicic magmas intruded through the basin-fill alluvium and spilled out onto the playa deposits. The silicic lavas also lapped onto older bedrock, along the southern margin of the basin in the Pound Ranch-Tower mine area. An unconformity which locally separates the lower and upper members of the Popotosa Formation is a reflection of this basin margin. Sedimentation continued during the silicic volcanism; consequently stratigraphic relationships are complex between contemporaneous volcanic and sedimentary rocks in the uppermost Popotosa Formation. An ancient geothermal system may have been established during this interval with the playa claystones locally forming an impermeable cap.

The coarser sediments of the lower Popotosa Formation (mud-flow deposits, fanglomerates and sandstones) may have been cemented and partially oxidized during the ancient geothermal activity. They are for the most part anomalously well-indurated and red for rift sediments. East of Socorro Peak and in the central Lemitar Mountains, the red, well-indurated facies intertongues and grades abruptly to light-gray, moderately indurated conglomeratic sandstones with opposing paleocurrent directions. How these primary facies relationships control the apparent secondary coloration and cementation is as yet unknown. The red facies of the lower Popotosa is now hard and brittle with little primary permeability left. However, these rocks are moderately well-jointed and brittle enough to develop good fracture permeability in fault zones, as evidenced by the fact that Socorro Spring, Sedillo Spring, and an unnamed cold spring northeast of Strawberry Peak issue from this unit.

Sometime after emplacement of the 7 to 12 m.y. old silicic domes and flows, the Popotosa basin was disrupted by uplift of tilted fault blocks to form the Lemitar-Socorro-Chupadera mountain chain. The Popotosa sedimentary rocks were tilted and beveled by pediment surfaces on top of which a new cycle of rift sedimentation began. The younger sediments were derived from the uplifted blocks and contain significant quantities of clasts of Paleozoic and Precambrian rocks. These upper Santa Fe sedimentary rocks are generally lighter in color, less indurated, and less deformed than rocks of the underlying Popotosa Formation. These younger rift sediments have been termed the Sierra Ladrones Formation by Machette (in press). Beginning sometime prior to eruption of the 4 m.y. old basalt of Sedillo Hill, the drainage was integrated to form an ancestral Rio Grande. The extensive fluvial sands deposited by this trunk stream interfinger with piedmont-slope deposits of the Sierra Ladrones Formation and were included by Machette as a fluvial facies of that formation. The ancestral Rio Grande sands form the major fresh-water aquifer of the Rio Grande Valley in the Socorro area.

AN ANCIENT GEOTHERMAL SYSTEM

Preliminary chemical analysis and microscopic examination of thin sections of volcanic rocks in the Socorro area has revealed a pervasive addition of potassium to several of the major ash-flow tuff sheets. Tuffs which normally contain 4 to 5% K_2O were found to contain 6 to 11.5% K_2O. Sodium was found to be depleted in rocks enriched in potassium, thus suggesting an alkali exchange phenomenon. Rocks with moderately elevated K_2O values were found in thin section to have plagioclase feldspar partly replaced by potassium feldspar. In rocks with higher K_2O values, the plagioclase feldspar has been completely altered to a white, fine-grained aggregate of potassium-rich, "clay-like" material which has not yet been identified. Upon staining with sodium cobaltinitrite, everything in the thin sections, except for quartz phenocrysts, gave a yellow stain indicative of the presence of potassium. The pervasive potassium stain and the very high K_2O values indicate that, in addition to replacement of sodium by potassium, there is a net addition of potassium to some of these rocks. There also appears to be significant addition of iron to the rocks and subtle reddening of their color, which probably indicates an increase in the ferric-ferrous ratio. Table 1 compares relatively fresh and altered samples of the A-L Peak Tuff and the tuff of Lemitar Mountains. The tuff of Lemitar

Mountains samples are all altered to some extent, but sample LM-6-3 and PR-1-77L are comparatively fresh. Note the dramatic increase in the K_2O/Na_2O ratio, increase in total alkalies, and increase in total iron in the altered samples. Yet none of these rocks appear altered in outcrop; the potassium metasomatism is a subtle, easily overlooked alteration.

In addition to the above chemical and mineralogical changes in some of the ash-flow tuff sheets, the sedimentary rocks of the Popotosa Formation are anomalously red and very well-indurated in the Socorro area. Reconnaissance of other graben-fill sedimentary rocks along the Rio Grande rift indicates that the normal color is buff to gray or cream and that the rocks are normally only slightly to moderately indurated. Only one other locality along the rift was found to have such red and highly indurated early-rift sedimentary rocks - the San Diego Mountain-Rincon areas near Hatch, New Mexico. Detailed chemical studies have not been done in this area, but a chemical analysis of a rhyolite sill in the Robledo Mountains (Seager and Clemons, 1975, p. 11) gave 7.04% K_2O and only 0.68% NA_2O - values similar to those of potassium metasomatized rocks in the Socorro area.

The potassium anomaly in the Socorro area is very extensive both laterally and vertically. Our chemical coverage of the anomaly is still very incomplete, but thin-section examination of samples for plagioclase alteration

Table 1 - Comparison of preliminary chemical analyses of fresh and potassium metasomatized samples of the A-L Peak Tuff and tuff of Lemitar Mountains.

Sample #	Location	Total Fe_2O_3	Na_2O	K_2O	K_2O/Na_2O	Total Alkalies
A-L Peak Tuff						
Flow-banded Member		Altered				
76-6-7	Lemitar Mts.	2.03	3.39	6.61	1.95	10.00
Pinnacles Member						
76-1-11	Lemitar Mts.	2.46	1.46	9.48	6.49	10.94
Basal vitrophyre		Fresh				
72-12	San Mateo Mts.	1.28	4.64	3.95	0.85	8.59
72-2	San Mateo Mts.	1.26	3.85	4.68	1.22	8.53
Tuff of Lemitar Mountains						
Lower Member		Altered				
LM-6-2	Lemitar Mts.	2.02	1.98	7.94	4.01	9.92
LM-6-2b	Lemitar Mts.	1.01	2.22	8.12	3.66	10.34
		Relatively Fresh				
LM-6-3	Lemitar Mts.	2.42	2.63	5.80	2.21	8.43
Upper Member		Altered				
LM-6-5	Lemitar Mts.	3.11	2.75	10.63	3.87	13.38
LM-6-6b	Lemitar Mts.	2.78	1.79	9.55	5.34	11.34
LM-6-8	Lemitar Mts.	2.26	1.54	8.67	5.63	10.21
LM-6-8b	Lemitar Mts.	2.71	1.97	9.46	4.80	11.43
76-1-10	Lemitar Mts.	2.87	1.97	8.37	4.25	10.34
LM-6-8a	Lemitar Mts.	3.88	1.57	11.57	7.37	13.14
PR-1-77d	East Magdalena Mts.	2.70	3.65	8.45	2.32	12.10
		Relatively Fresh				
PR-1-77L	East Magdalena Mts.	1.88	3.63	5.97	1.64	9.60

and staining with sodium cobaltinitrite has helped to establish the general extent of the anomaly. It appears that the more permeable volcanic and sedimentary rock units older than, or interbedded with, the Popotosa claystones have been affected from South Baldy in the central Magdalena Range on the southwest to the Ladron Mountains on the north. Using Socorro Peak as a center, these two lines form radii of about 14 and 20 miles (22.5 and 32.2 km), respectively. The extent of the anomaly to the south is not known. In vertical section, ash-flow tuff units aggregating 1,300 to 3,000 feet (396-914 m) in thickness are known to be affected; a minimum of 800 feet (244 m) of Popotosa fanglomerates are inferred to have been involved because of their anomalously red color and high degree of induration.

If we assume a rectangular block of altered rock 15 miles wide by 25 miles long x 1 mile thick (24.1 x 40.2 x 1.6 km), an average increase in K_2O content of 3 percent, and an average density of 2.7, the net addition of K_2O is approximately 11 x 109 tons. The only reasonable mechanism for deriving such a large quantity of K_2O seems to be the leaching of potassium from granitic rocks in the Precambrian basement. Orville (1963) demonstrated experimentally that if a temperature gradient and a pervasive vapor phase exists in a two-feldspar rock, alkali ions will diffuse through the vapor in a reciprocal transfer process that depletes the hotter rock in potassium and enriches the cooler rock. He pointed out that hot spring waters are generally depleted in K relative to Na and cited evidence by White (1955) and Fenner (1936) that potassium is replacing sodium in plagioclase in rocks of the Wairakei, New Zealand, and Yellowstone geothermal systems. Battey (1955) demonstrated that alkali-rich volcanic rocks (called keratophyres) in New Zealand were normal rhyolite flows originally, but during deep burial they were held for a long time at moderately elevated temperatures during which alkali exchange took place by diffusion in pore fluids. In these rocks, the total alkali content remained constant but some rocks became enriched in potassium while others nearby were enriched in sodium.

Orville (1963) also demonstrated that an increase of calcium in plagioclase of the two-feldspar-plus-vapor assemblage affects the vapor-feldspar equilibrium by increasing the K/Na ratio in the vapor. He postulated that original inhomogeneities in the calcium content of rocks will result in compositional gradients with respect to alkalies in the vapor phase and hence to alkali transfer. Rocks originally rich in calcium will tend to be depleted in potassium while those originally poor in calcium will tend to be enriched. Preliminary data indicates that mafic flows interbedded with potassium-enriched ash-flow sheets in the Socorro area are enriched in sodium relative to potassium. The data is as yet too sketchy to present; however, sodium enrichment of these mafic flows would fit Orville's experimental results and would explain where some of the sodium goes after it is replaced by potassium in the tuffs. This would also fit Battey's observations that adjacent rock masses in the New Zealand keratophyres are enriched either in potassium or in sodium.

Ratté and Steven (1967) discovered a similar potassium anomaly in the Bachelor Mountain cauldron of the San Juan Mountains (see also Steven and Lipman, 1976, p. 20). The potassium-enriched Bachelor Mountain Rhyolite contains 6 to 11.4% K_2O compared to about 4.7% K_2O in the unaltered rock. As the K_2O content of these samples increases, the Na_2O content decreases. Ratté (personal commun., 1977) was able to partially outline the potassium anomaly by contouring the K_2O values of about 30 samples. The exposed portion of the anomaly is about 6 miles wide by 10 miles long (9.7 x 16.1 km). Much of the anomaly, however, has been downfaulted beneath the younger Creede cauldron. We are especially grateful to Jim Ratté for helping us to interpret the Socorro anomaly.

The potassium anomaly in the Socorro area is a very interesting discovery which may be quite useful in evaluating the present geothermal system. It indicates, first of all, that a very large geothermal system existed in the Socorro area in the past; probably in late Miocene time (about 7 to 12 m.y. ago) during intrusion of rhyolitic magmas along the northern margin of the Socorro cauldron, but possibly also in early Miocene time during moat volcanism. Geophysical data indicates that magmas are again being intruded in this area and that the heat flow is very high. An ion exchange process is currently taking place in waters emerging from the Socorro thermal springs; waters in the recharge area are calcium bicarbonate types whereas those discharging at the springs are sodium bicarbonate types (Hall, 1963). Secondly, the distribution of potassium metasomatized rocks in the stratigraphic column can be used to determine which formations were the reservoir rocks of the ancient geothermal system and, by analogy, which formations may be the best reservoir rocks in the present system. And, finally, the lack of potassium enrichment in rocks above the Popotosa claystone horizone suggests that the claystones probably provided an impermeable caprock for a late Miocene geothermal system and are likely to do so again.

MODERN MAGMA BODIES

Two types of magma bodies have been detected in the vicinity of Socorro. The first is an extensive body, shown in red on Map 4 (pl. 1), which covers a minimum area of 1700 km^2. Depths to this body range from 18 km to 22 km and the evidence to date suggests it has a thin, sill-like shape.

The second type of magma body is small intrusives located in the regions shown in yellow on Map 4 (pl. 1). These anomolous crustal segments appear to extend from the deep magma layer to within about 4 km of the surface.

Extensive Mid-Crustal Magma Body

The initial evidence for an extensive magma body at mid-crustal depths came from an analysis of the arrival times and amplitudes of two reflection phases on microearthquake seismograms (Sanford and Long, 1965; Sanford, Alptekin and Toppozada, 1973). These two reflections, S to P and S to S, are impulsive and have the same general frequency content as the direct S-phase. Recordings by instruments with a broad frequency response show that the S to S phase contains a wide range of frequencies -- from 3 to 15 Hz (Rinehart, 1976). This observation indicates that the reflecting discontinuity is sharp and singular. In addition, the absolute strength of the reflections as well as the ratio of their amplitudes indicates that the discontinuity producing the reflections is underlain by magma (Sanford, Alptekin, and Toppozada, 1973; Sanford, 1977a).

The geographical extent of the magma body is being determined from the presence and absence of reflections on the microearthquake seismograms (Sanford et al., 1977a; Sanford, 1977a). Beyond the boundaries of the magma body no S to S reflections have been observed to date although the instruments have been positioned to record such reflections. Northward, beyond the limits of Map 4 (pl. 1), the boundaries are not closely defined by the S-phase reflection data. However, good control on the extent of the magma body in this region has been obtained from high-resolution seismic reflection profiles (Oliver and Kaufman, 1976; Brown and others, 1977). These crustal profiles show very strong P-wave reflections from approximately the same depth as the S wave reflections. In addition, the P-wave reflections have a northward dip of about 6 degrees which is in agreement with the S-wave reflection data from the top of the magma layer.

The available observational data indicate that the magma body is very thin relative to its extent. P-wave residuals for teleseisms (Fischer, 1977) do not support the existence of a thick magma layer even after station corrections are applied. Analysis of the Gasbuggy refraction data (Toppozada and Sanford, 1976) indicates that time delays for P_n arrivals passing through the magma layer cannot be much greater than 0.1 second. A layer of magma (full-melt) 0.6 km thick would be sufficient to produce a 0.1 second time delay. Finally, no clearly defined reflection phases from the bottom of the magma layer have been identified on microearthquake seismograms. If such reflections exist, they must occur so closely in time to the reflections from the top of the magma body that they cannot be easily identified.

Small Shallow Magma Bodies

Three types of observations suggest the existence of small magma bodies above the southern end of the mid-crustal magma layer: (1) the screening of SV waves, (2) the spatial distribution of Poisson's ratio, and (3) the spatial distribution of microearthquake hypocenters.

Screening of SV Waves. For many microearthquakes in the vicinity of Socorro, SV waves are absent or extremely weak on seismograms for one or more stations in the array (Shuleski, 1976; Sanford and others, 1977a). About 40 percent of these observations can be explained by the fault mechanism of the microearthquakes; the remaining 60 percent apparently result from SV screening by molten or partially molten rock bodies (Kubota and Berg, 1968; Matumoto, 1971). Magma bodies located within the regions shown in yellow on Map 4 (pl. 1) can explain the observed SV screening in the Socorro area.

Spatial Distribution of Poisson's Ratio. From an analysis of S-P times and P travel times for microearthquakes, the spatial distribution of Poisson's ratio in the upper crust has been determined (Caravella, 1976). Several segments of the crust with average Poisson's ratios greater than 0.29 have been mapped in the Socorro region. These anomalously high values of Poisson's ratio can be explained by the same distribution of shallow magma bodies that is used to account for the SV screening.

Spatial Distribution of Microearthquake Hypocenters. A detailed three-dimensional analysis of the spatial distribution of microearthquake foci shows activity surrounding, but not within, the anomalous crustal segments mapped in yellow on Map 4 (Shuleski and others, 1977; Sanford and others, 1977a). Above these regions, microearthquake hypocenters are never deeper than about 2-1/2 km, whereas adjacent to those regions, activity occurs to depths of 8 km or greater. Earthquake activity is not expected in segments of the crust containing magma inasmuch as high temperatures prevent accumulation of elastic strain energy.

Configuration and Distribution of Shallow Magma Bodies. The techniques employed in detecting shallow magma bodies do not permit precise determination of the shape or volume of magma injected into the crust. However, an acceptable model at this time is injection of thin, discontinuous dikes of magma such that the fractional volume of molten material in the yellow regions of Map 4 is quite small.

To date we have only looked for shallow magma bodies above the southern end of the extensive magma body. Thus we cannot be certain this is the only region where magma leaks upward through the crust from the deeper magma body.

Other Geophysical Evidence for Magma Bodies

An independent geophysical observation suggesting magma bodies at shallow depths in the Socorro area is the high temperature gradients (maximum, 241°C/km) and heat-flows (maximum, 11.7 HFU) measured in boreholes within the Socorro Mountain block (Reiter and Smith, 1977; Sanford, 1977b). Values of measured temperature gradients and heat-flow are shown on Map 4. The low temperature gradients for stations in the Rio Grande Valley are most likely the result of southward flow of groundwater within the basin (Bushman, 1963).

Two observations suggest that magma may have been injected into the crust in very recent times. The first is the discovery by Reilinger and Oliver (1976) of historical uplift in the Socorro area roughly coincident with the spatial extent of the extensive mid-crustal magma body. The second is the pattern of seismic activity in space and time (Sanford and others, 1977a). The microearthquake activity is diffusely distributed over an area of 2000 km^2 that is roughly centered on the extensive magma layer as presently mapped. Most earthquakes in the Socorro area have occurred in swarms, which is the characteristic seismic behavior for volcanic regions. One of the Socorro earthquake swarms (from 1906-1907) appears to have been comparable to the Matsushiro swarm (from 1965-1967) which Stuart and Johnston (1975) believe was caused by magmatic intrusion.

GEOTHERMAL POTENTIAL OF THE SOCORRO AREA

High heat flow, the presence of shallow magma bodies, the existence of both reservoir rocks and cap rocks in the rock column, and the downfaulting of potential reservoir rocks to considerable depths makes the Socorro area an attractive target for geothermal exploration. Recognition of the transverse shear zone, its long history of "leaking" magmas, and the probable upwarp of the Curie temperature isotherm along it reinforces this conclusion. Exploration, however, must take into account the rapid flow of ground water from recharge areas in the Magdalena Mountains towards the Rio Grande. The travel path for most of this water is beneath the thick Popotosa claystone section; hence, temperature measurements made in shallow holes will not be an effective guide to temperatures at depth.

THE SOCORRO SHEAR ZONE--A POSSIBLE MODEL FOR GEOTHERMAL EXPLORATION ELSEWHERE ALONG THE RIO GRANDE RIFT

Recognition of the Socorro transverse shear zone and its role in controlling magmatism and geothermal activity in the Socorro area provides a possible model for exploration elsewhere along the Rio Grande rift. Several major northeast-trending, subparallel lineaments transect the rift (fig. 1); however, different lineaments have "leaked" magmas at different times. The Jemez lineament has been the most active lineament magmatically during the past 5 million years. The Kremmling lineament was active between 24 and 20 m.y. ago and 14 to 8 m.y. ago, with minor activity of Pleistocene and Holocene age (Larson and others, 1975). The Idaho Springs and Silverton lineaments were the most active of the northeast-trending lineaments during the Laramide orogeny (75-50 m.y. ago). The reasons for this behavior are as yet unknown. In fact, the subject of lineament tectonics and magmatism has been shrouded in mystery and controversy for decades and remains so today (see Gilluly, 1976, 1977; Walker, 1977; Warner, 1978). Apparently, when a regional stress field is applied to a flawed plate, the stress is relieved along different flaws at different times. Why the flaws leak magmas is another, largely unresolved, question.

Basins of the Rio Grande rift are often hinged in opposite directions on opposite sides of transverse lineaments. For example, the upper Arkansas basin is hinged down from the east side with the deepest fill on the west; the San Luis basin is hinged down from the west with the deepest fill on the east. The transition between opposing structural styles occurs where the Salida lineament transects the rift. The Salida area is also the site of several major hot springs. A similar twist in basin geometry occurs across the Jemez lineament. To the north, the southern extension of the San Luis basin is hinged down from the west with the deepest fill to the east; to the south, the Espanola basin is hinged down from the east with the deepest fill to the west. The transition occurs across the Jemez lineament which is marked in this area by the Jemez volcanic field and present day geothermal activity.

Transverse horsts often jut into basins where lineaments cross the Rio Grande rift. Examples are the Browns Canyon horst and the northern tip of the Sangre de Cristo Range in the Salida area, the Picuris Range in the Taos area, and the Mud Springs Mountains near Truth or Consequences. Hot Springs are often present near these horsts. It is also common for one side of a lineament to be elevated relative to the other. In the Socorro area, the La Jencia and Mulligan Gulch grabens shallow southward across the Morenci lineament. Recurring uplift of the south side is reflected in unconformities and facies changes in the basin-fill sediments and in the geomorphology. However, the north side is now being uplifted (Reilinger and Oliver, 1976) because of inflation and thermal expansion related to intrusion of a sill-like magma body at 18 to 20 km depth. In the Espanola basin, the north side of the Jemez lineament seems to have been persistently high. In the upper Arkansas basin, the south side of the Salida lineament has been recurrently high.

Where lineaments cross the Rio Grande rift, deeply penetrating flaws in the continental plate produce a characteristic suite of structural features which are often reflected in the stratigraphy and geomorphology. The direction of tilt of beds and the direction of downthrow across faults may change 180 degrees. Basins may be hinged on the east or on the west on opposite sides of the lineament. Transverse horsts may jut into the basins and one side or the other of the lineament may be persistently up or down relative to the other. Magma injection, volcanism, high heat flow, and geothermal activity are often associated with these areas of transverse tectonics. Recognition of these features may help narrow the search for geothermal exploration targets along the rift. Comparison of geologic and topographic maps with aeromagnetic maps may locate other "quiet" zones where the Curie temperature is at anomalously shallow depths.

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A P P E N D I X I

CHEMICAL DATA FOR SOCORRO-MAGDALENA PROJECT

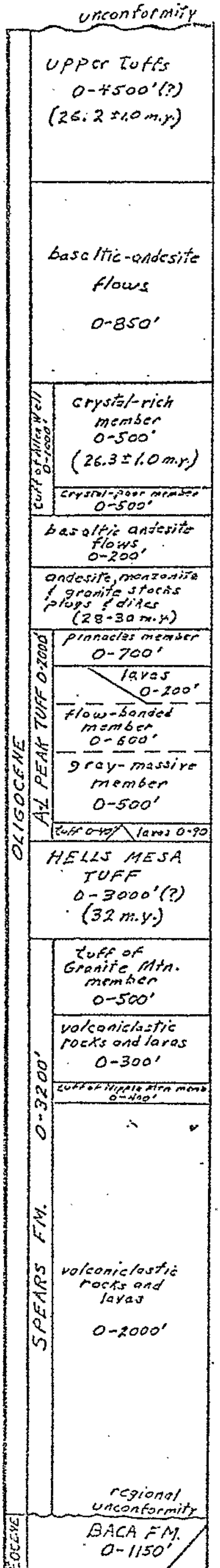
Formation	Sample	K-Ar Age (m.y.)	Sr^{87}/Sr^{86}	SiO_2	Al_2O_3	Fe_2O_3 (total)	MgO	CaO	Na_2O	K_2O	TiO_2	TOTAL
Spears	KA-JH-1	34.5		59.76	17.33	5.74	2.51	5.67	4.04	4.34	0.73	100.12
	KA-JH-1	34.5		59.76	17.33	5.74	2.51	5.67	4.04	4.34	0.73	100.12
	76-1-12		.7062	55.10	16.17	6.84	5.78	5.32	4.33	3.79	1.24	98.57
	76-1-4			73.08	13.15	2.72	0.54	1.42	3.13	5.59	0.14	[illegible]
	76-1-7			54.35	14.20	8.27	8.20	6.89	4.29	2.61	1.37	100.18
	76-1-5			53.30	17.03	10.32	5.26	7.56	4.53	1.72	1.71	99.71
	76-6-10		.7059	54.71	15.48	6.64	3.50	7.12	4.10	3.70	5.01	100.26
	71-49			63.60	16.00	6.09	1.95	4.08	3.88	4.30	0.82	100.72
Hells Mesa	76-1-13		.7076	70.37	15.90	2.98	0.86	2.03	4.67	4.92	0.43	102.16
	M-24-23			70.61	15.34	3.14	0.83	0.53	3.98	5.06	0.45	99.94
	M-24-33			76.72	13.35	1.48	0.58	0.28	1.85	5.42	0.25	99.93
Mafic Flow	76-1-14		.7059	51.18	14.01	8.59	9.99	7.62	3.87	1.59	1.15	[illegible]
A-L Peak	76-6-7	27.4		73.21	14.32	2.03	<0.01	0.22	3.39	6.61	0.34	100.12
	76-1-11		.7198	75.03	14.05	2.46	<0.01	0.63	1.46	9.48	0.35	103.46
	72-12			76.10	12.98	1.28	0.14	0.69	4.64	3.95	0.15	99.93
	72-2			75.83	13.50	1.26	0.21	0.49	3.85	4.68	0.13	99.95
Potato Canyon	71-66			74.89	13.25	1.81	0.23	0.41	3.90	5.13	0.31	99.93
	71-66			74.93	13.25	1.79	0.24	0.38	3.71	5.28	0.32	99.90

Formation	Sample	K-Ar Age (m.y.)	Sr^{87}/Sr^{86}	SiO_2	Al_2O_3	Fe_2O_3 (total)	MgO	CaO	Na_2O	K_2O	TiO_2	TOTAL
Potato Canyon	70-109			76.25	11.74	1.83	0.54	0.74	3.92	4.59	0.22	99.83
	71-131			76.59	12.43	1.57	0.44	0.62	3.45	4.53	0.25	99.88
	71-132			70.86	14.75	2.28	0.43	0.86	4.36	5.79	0.52	99.85
	71-132			71.12	14.75	2.24	0.46	0.92	4.30	5.59	0.47	99.85
Lemitar Tuff	LM-6-2			77.13	13.34	2.02	0.08	0.73	1.98	7.94	0.25	103.47
	LM-6-2b			74.02	14.54	1.01	0.71	0.57	2.22	8.12	0.29	101.48
	LM-6-3			74.73	14.86	2.42	0.63	0.58	2.63	5.80	0.35	102.00
	LM-6-5			64.47	17.89	3.11	0.38	0.81	2.75	10.63	0.61	100.65
	LM-6-6b			65.85	15.47	2.78	0.71	1.73	1.79	9.55	0.57	98.45
	LM-6-8			70.88	16.15	2.26	1.16	0.72	1.54	8.67	0.50	101.88
	LM-6-8b			70.13	15.75	2.71	0.78	0.56	1.97	9.46	0.57	101.93
	76-1-10	26.3	.7130	69.69	15.37	2.87	0.93	0.44	1.97	8.37	0.53	100.17
	LM-6-8a			63.16	18.28	3.88	0.70	1.06	1.57	11.57	0.70	100.92
	PR-1-77b			76.51	12.75	1.88	<0.01	0.53	3.63	5.97	0.32	101.[illegible]
	PR-1-77d			66.73	18.10	2.70	0.50	0.84	3.65	8.45	0.94	101.91
Mafic Flow	77-2-2			51.65	14.15	10.38	8.18	8.66	6.85	1.88	1.24	102.96
	76-1-3		.7070	53.63	14.43	8.44	7.00	7.63	6.27	2.06	1.34	100.80
	76-6-8			49.68	13.79	10.20	11.70	8.50	6.59	1.67	1.29	103.42
Tuff of South Canyon	76-4-2	26.2		77.86	12.00	1.81	0.29	0.58	3.42	4.75	0.19	100.90
	PR-2-77			49.46	17.62	11.01	7.02	9.56	4.62	0.86	1.76	101.91

Formation	Sample	K-Ar Age (m.y)	Sr^{87}/Sr^{86}	SiO_2	Al_2O_3	Fe_2O_3 (total)	MgO	CaO	Na_2O	K_2O	TiO_2	TOTAL
La Jara Peak	SC-PO-2	26.6		57.01	13.80	6.71	5.66	5.02	2.93	4.89	0.81	96.83
	M-46-1	23.8		56.62	13.75	7.65	4.92	7.60	3.20	4.45	1.58	100.88
Hwy 60 rhyolite	77-5-2	28.6		77.80	12.45	0.92	<.01	0.46	2.99	6.39	0.31	101.33
Council RK basalt	76-6-6	17.5	.7061	53.60	16.63	8.13	5.20	8.16	5.50	2.02	1.45	100.69
Kelly Ranch basalt	76-1-9		.7051	53.61	15.79	8.75	8.51	7.40	3.41	2.16	0.35	99.98
Magdalena peak dome	76-2-5	13.1	.7068	72.06	13.43	2.98	1.72	2.07	3.87	3.33	0.41	99.87
Strawberry peak dome	76-6-1a	11.8	.7050	68.50	14.38	3.17	1.14	2.66	1.98	3.55	0.14	95.63
Socorro peak dome	76-4-16	12	.7048	68.28	15.84	3.48	1.91	2.93	2.20	3.57	0.47	98.68
Pound Ranch lava	77-3-1	11.8	.7070	73.00	14.62	1.96	0.51	1.38	3.65	4.79	0.26	100.07
	77-3-2	10.5		72.31	12.34	2.94	3.41	2.01	1.93	4.60	0.39	99.93
Signal Flag dome	76-6-2a	10.5		75.06	13.90	2.15	0.34	2.00	2.11	3.61	0.15	99.32
	76-6-2b		.7135	73.33	12.72	1.14	0.63	1.90	2.97	3.11	0.07	95.87
RR Quarry dome	76-6-3	9.0	.7065	69.79	14.83	2.97	1.12	2.01	3.39	4.40	0.38	98.89
Grefco dome	77-5-4			73.86	13.17	0.20	<0.01	0.57	2.86	4.86	0.06	95.59
	77-5-1	6.0		60.16	15.03	3.95	6.66	4.58	3.70	1.79	0.73	96.60
	76-6-11	4.0	.7044	50.15	12.21	10.79	8.41	8.49	3.06	1.70	1.28	96.09

Formation	Sample	K-Ar Age (m.y.)	Sr^{87}/Sr^{86}	SiO_2	Al_2O_3	Fe_2O_3 (total)	MgO	CaO	Na_2O	K_2O	TiO_2	TOTAL
Blue Canyon	77-7-7			54.79	15.32	5.69	6.28	4.57	4.17	3.45	0.92	95.19
	77-5-6			77.81	13.26	1.14	<0.01	0.07	1.03	8.27	0.31	101.90
	77-5-3			47.43	16.30	10.65	7.63	7.50	5.16	1.24	1.82	97.73

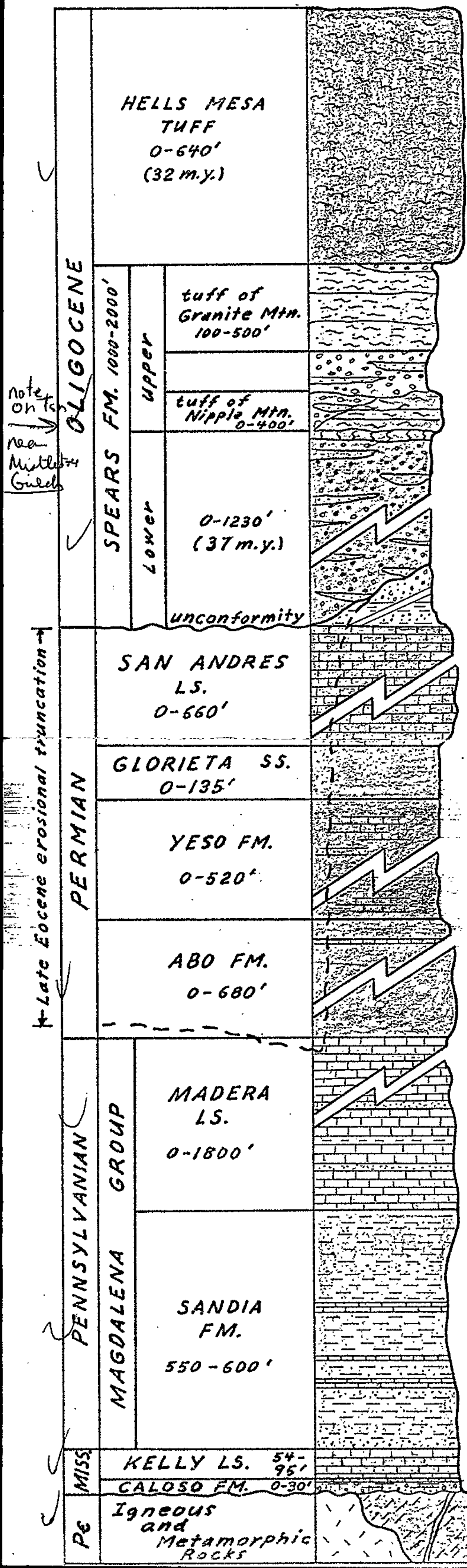
APPENDIX II



K-Ar Age (m.y.)	$^{87}Sr/^{86}Sr$	SiO_2	Al_2O_3	Fe_2O_3 (total)	MgO	CaO	Na_2O	K_2O	TiO_2
23.9		77.8	12.8	1.8	0.2	0.5	3.4	4.7	0.1
	0.7070	51.6	14.1	9.6	10.1	8.2	6.5	1.8	1.2
26.3	0.7130	70.2	15.6	2.4	0.5	0.7	2.3	5.8	0.4
		49.6	13.5	8.3	8.4	8.3	4.7	2.4	0.9
		48.7	13.1	8.6	8.7	11.6	3.8	0.8	1.4
		47.6	14.8	10.6	9.5	8.9	3.2	0.5	1.5
		52.6	15.1	5.9	4.9	8.4	4.1	2.3	0.4
		55.1	17.2	4.5	6.8	6.6	7.0	1.7	0.2
		59.5	21.1	4.2	1.0	4.3	7.7	2.8	0.2
		65.2	15.9	3.6	2.0	0.4	5.1	3.9	0.5
		71.9	14.4	2.4	0.2	0.4	6.2	5.3	0.3
	0.7198	75.0	13.7	1.7	0.1	0.5	3.3	6.1	0.2
	0.7059	51.1	14.0	8.5	9.9	7.6	3.8	1.5	1.1
	0.7076	72.5	14.8	2.5	0.7	0.9	3.5	5.1	0.3
	0.7061	59.1	15.6	6.6	3.9	5.3	4.0	3.7	1.4

Epoch	Group / Formation	Unit	K-Ar Age (m.y.)	$^{87}Sr/^{86}Sr$	SiO_2	Al_2O_3	Fe_2O_3 (total)	MgO	CaO	Na_2O	K_2O	TiO_2
PLEISTOCENE	POST SANTA FE	valley and bolson fill 0-50'(?)										
? ? PLIOCENE	UPPER SANTA FE GROUP 0-500'(?)	piedmont-slope deposits										
		basalt of Sedillo Hill		0.7044	50.1	12.2	10.7	0.4	8.4	3.0	1.7	1.2
		sandstone of ancestral Rio Grande										
	POPOTOSA FM. 0-5000' (Lower Santa Fe Group)	fanglomerate of Ladron Pk.	6.0		60.1	15.0	3.9	6.6	4.5	3.7	1.7	1.2
		domes and flows of Socorro Pk. (11 m.y.)	9.0	0.7065	69.7	14.8	2.9	1.1	2.0	3.3	4.4	0.3
			10.5									
			11.8	0.7135	74.1	13.3	2.1	0.4	1.9	2.5	3.3	0.1
MIOCENE		rhyolite of Magdalena Pk. (14 m.y.)		0.7048	68.2	15.8	3.4	1.9	2.9	2.2	3.5	0.4
				0.7050	68.5	14.3	3.1	1.1	2.6	1.9	3.6	0.1
		sandstone of Kelly Ranch	13.1	0.7068	72.6	13.4	2,9	1.7	2.0	3.9	3.3	0.4
				0.7070	72.6	13.4	2.4	1.9	1.6	2.8	4.6	0.3
		basalts of Council Rock and Socorro area		0.7051	53.6	15.7	8.7	8.5	7.4	3.4	2.1	0.3
			17.5	0.7061	53.6	16.6	8.1	5.2	8.1	5.5	2.0	1.4
		fanglomerate of Dry Lake Canyon										
		perlite dome of Grefco mine (24 m.y.?)			73.8	13.1	0.2	n.d.	0.5	2.8	4.8	0.1
					66.3	14.2	3.4	3.1	2.2	2.5	5.8	0.4
			22.8		77.8	12.4	1.0	0.2	0.4	2.8	6.3	0.3
	LA JARA PK. BASALTIC ANDESITE	upper member 0-600' (24-26 m.y.)										
		lower member 0-600'		0.7076	54.7	13.7	8.2	5.2	6.7	2.7	3.8	1.3
		unit of Montosa Arroyo 0-700' (25 m.y.)										
		unconformity										

COMPOSITE STRATIGRAPHIC COLUMN of the MAGDALENA AREA



ASH-FLOW TUFFS: qtz. latite (chem. rhyolite), multiple-flow, simple cooling unit of densely welded, crystal-rich, qtz.-rich, massive tuffs; pk. to rd.-brn. when fresh, gry. when propylitically altered; forms cliffs and talus-covered slopes; weathers to blky. bldrs. rather than to grus; abrupt change from latite to qtz. latite 10-25 ft. above base; basal tuffs strongly resemble underlying tuffs in Spears Fm.; formation boundary placed at abrupt increase in qtz. when cgl. is absent; mapped as rhyolite porphyry sill by Loughlin and Koschmann.

ASH-FLOW TUFFS: latite (chem. qtz. latite), multiple-flow, simple cooling unit of densely welded, crystal-rich, lithic-rich, massive tuffs; rd.-brn. when fresh, dk. grn. gry. when propylitically altered; mapped as upper latite tuff by Loughlin and Koschmann; overlain by distinctive hem.-stnd. cgl. N. of Magdalena; grades into mud-flow breccias at base.

VOLCANICLASTIC and VOLCANIC ROCKS: latitic to andesitic conglomerates, sandstones, mud-flow breccias, and lava flows.

ASH-FLOW TUFFS: latite, multiple-flow, compound cooling unit of moderately to densely welded, crystal-poor, pumiceous tuff; pk. when fresh, buff to wht. when altered; distinctive "turkey track" andesite at base; interbedded andesite flow near Tres Montosas; mapped as white felsite tuff by Loughlin and Koschmann.

CONGLOMERATES and SANDSTONES: volcaniclastic apron of early latitic phase of Datil-Mogollon field; fluvial deposits of latitic to andesitic debris; crs. sandstones to pbl. and bldr. conglomerates; purp.-brn. when fresh, grn.-gry. when propylitically altered.

BACA FM (Eocene) and MESOZOIC ROCKS: Present in Baca basin north of Magdalena area; position of basin margin uncertain due to burial by Tertiary volcanic rocks.

LIMESTONES: blk., fetid, v.-thk.-bdd., homogeneous, sparsely fossil., dolomicrites; weathers to rough, hackly sruface; mapped as Madera Limestone by Loughlin and Koschmann.

SANDSTONES: lt. to med.-gry., v. thk. bdd., med.-gnd. v. well srt. calc., qtz. arenites and minor limestones; mapped as upper quartzite member of Sandia by Loughlin and Koschmann.

LIMESTONES, SANDSTONES, and SHALES: faulted, incomplete, poorly exposed section near Magdalena; dk.-gry., unfossil., dol. micrites only exposed lithology; mapped as upper limestone member of Sandia Fm. by Loughlin and Koschmann.

SANDSTONES, SILTSTONES, and SHALES: rd.-brn., fn.-gnd., thn.-bdd., qtz. arenites and siltstones; abun. thn. lam. and ripple xlam.; bleached to lt.-rd.-brn. and grn.-gry. near Magdalena and Tres Montosas plutons; mapped as Sandia shales by Loughlin and Koschmann (1942).

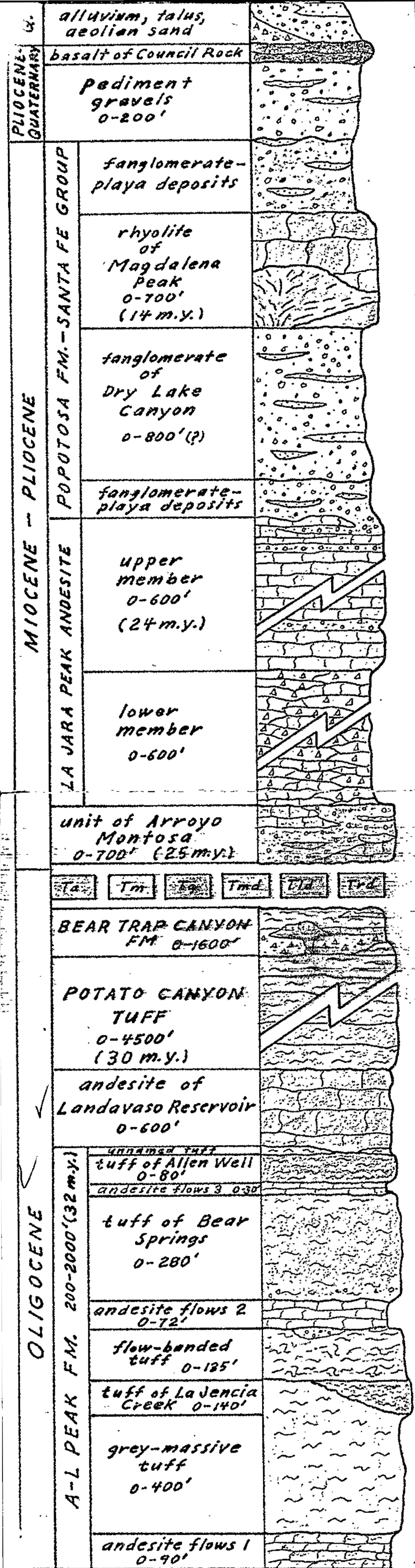
LIMESTONES: Thick, homogeneous sequence of lime muds (micrites) with a few thn. bds. of grn.-gry. to gry., med. to crs.-gnd. quartzite; upper 200-300 ft. consists of rd., grn., and gry. micrites grading upward into arkosic strata of Abo Fm.; nodular micrites common throughout; micrites generally gry. to blk. with strata becoming darker and more fossilferous towards base.

SHALES, QUARTZITES, and LIMESTONES: gry. to blk., sdy., carb., shales and siltstones with thn. bds. of gry., med.-gnd., crinoidal limestones and grn.-gry. to brn., med.-crs.-gnd. quartzites. Loughlin and Koschmann (1942) divided the Sandia into six members but lenticular bedding and rapid facies changes make this subdivision of limited value.

LIMESTONES: lt. gry., med.-crs. gnd., thk.-bdd., crinoidal sparrites; thn. bd. of dol. micrite near middle (Silver Pipe).

LIMESTONES and CONGLOMERATES: gry., pbly., sdy., mas., qtz. micrites and basal ark. cgls.

ARGILLITES, QUARTZITES, and GRANITES: thick sequence of metasedimentary rocks intruded by granites, gabbros, felsites, and diabase dikes.



ALLUVIUM, TALUS, and AEOLIAN SAND: sand extensive N. of Hwy. 60 and N. of La Jencia Creek.

BASALT FLOWS and DIKES: thin flows of dk. gry., dense to vesicular basalt; dikes near Council Rock apparent source; widely scattered remnants west of Magdalena.

PEDIMENT GRAVELS: coarse, heterogeneous gravels and thin sands grading laterally into alluvial fans; caliche deposits and aeolian sand at top; dissected as deep as 200 ft. by arroyos.

FANGLOMERATE - PLAYA DEPOSITS: similar to below but with increasing amounts of detritus from units lower in section; overlain with angular unconf. by buff, poorly indur., deposits of upper Santa Fe Group containing abun. detritus from Paleoz. & Precambrian rocks and by pediment gravels.

RHYOLITE FLOWS and DOMES: pk., dense slightly porphyritic flow-banded rhyolite; vitrophyric and perlitic zones present locally; thin interbedded tuffs; Magdalena Peak dome main eruptive center.

FANGLOMERATES: buff to gry., well-indurated andesitic cgls., thin ss., and mud-flow deposits derived from erosion of La Jara Peak Andesite; other detritus absent to sparse; forms clastic wedge along west side of Bear Mtns.; locally interbedded with uppermost La Jara Peak Andesite; unique facies of Popotosa Fm.

FANGLOMERATE - PLAYA DEPOSITS: rd.-brn. to gry., well-indurated, volc. cgls., thin ss., and mud-flow deposits derived from erosion of volcanic pile during block faulting; A-L Peak, Potato Canyon, and La Jara Peak detritus especially abun.; fangls. grade laterally into rd., poorly indur., siltstones and mudstones of playas.

ANDESITE FLOWS: gry., locally rd., dense, basaltic andesite characterized by abun. small, rd. hematized pyroxene and/or olivine phenocrysts and lack of plagioclase phenocrysts; lower member mostly thin autobrecciated flows that weather to slopes and rounded hills; upper member consists of cliff-forming vesicular flows with fresh pyroxene phenocrysts; amygdules of silica and/or calcite abun. in lower member; upper member interbedded with Popotosa Fm.

DACITE FLOWS and FANGLOMERATES: dk. gry. to rd. flows with unusual phenocryst assemblage of plag. (up to 4 cm), qtz. (up to 1 cm), and sanidine; interbedded cgls. are highly indurated and rd.-brn. like Popotosa but lack La Jara Peak detritus.

STOCKS, PLUGS, and DIKES: major period of intrusive activity at 28-30 m.y.; andesitic, monzonitic and granitic stocks; mafic, latite, and rhyolite dike swarms.

TUFFS, DOMES, FLOWS, and VOLCANICLASTIC ROCKS: Complex sequence of rhyolite pyroclastic rocks, domes, flows, breccias, and sedimentary rocks filling moat of Mt. Withington cauldron (Deal and Rhodes, in press).

ASH-FLOW TUFFS: rhyolite, multiple-flow sequence of slightly to densely welded, moderately crystal-rich to crystal-poor, rd.-brn. to pk. or lt. gry. tuffs; crystal content intermediate between that of crystal-rich and crystal-poor tuffs; perthitic "moonstone" potash feldspar.

ANDESITE: thin flows of rd. to gry. porphyritic andesite with phenocrysts of plagioclase, pyroxene, and biotite; flows highly variable but generally platy with abun. hematite stained bands.

ASH-FLOW TUFFS and ANDESITE FLOWS: Composite sheet of rhyolite crystal-poor tuffs with interbedded quartz latite (chem. rhyolite) crystal-rich tuffs and andesite flows. Relatively homogeneous 2000-foot-thick "puddle" of crystal-poor tuffs in Mt. Withington cauldron (Deal and Rhodes, in press) grades laterally into complex unit shown at left. Crystal poor, rhyolite tuffs are gry., pk., and rd.-brn., moderately to densely welded, platy tuffs that weather to grus of small platy fragments. The flow-banded member is very platy and shows abundant laminar flow structures, such as lineated pumice, flow folds etc. All crystal-poor tuffs are characterized by 6-8% small, euhedral sanidine phenocrysts and 1-2% small, rounded qtz. grains. Crystal-rich, qtz.-rich, qtz. latite tuffs strongly resemble the Hells Mesa tuffs except that they contain more glassy matrix and more biotite. Andesite flows 2 and 3 are thn., dk. gry. to rd.-brn., fn.-gnd. flows similar to the La Jara Peak Andesite in lack of feldspar phenocrysts and abundance of small red, hematized pyroxene and/or olivine phenocrysts. Andesite flows 1 are thn., bl.-gry., porphyritic, vesicular flows with abun. plagioclase phenocrysts. Distribution of the tuff of La Jencia Creek was controlled by NE-trending paleo-valleys. Small channels containing tuffaceous sedimentary rocks are common above flow-banded member.

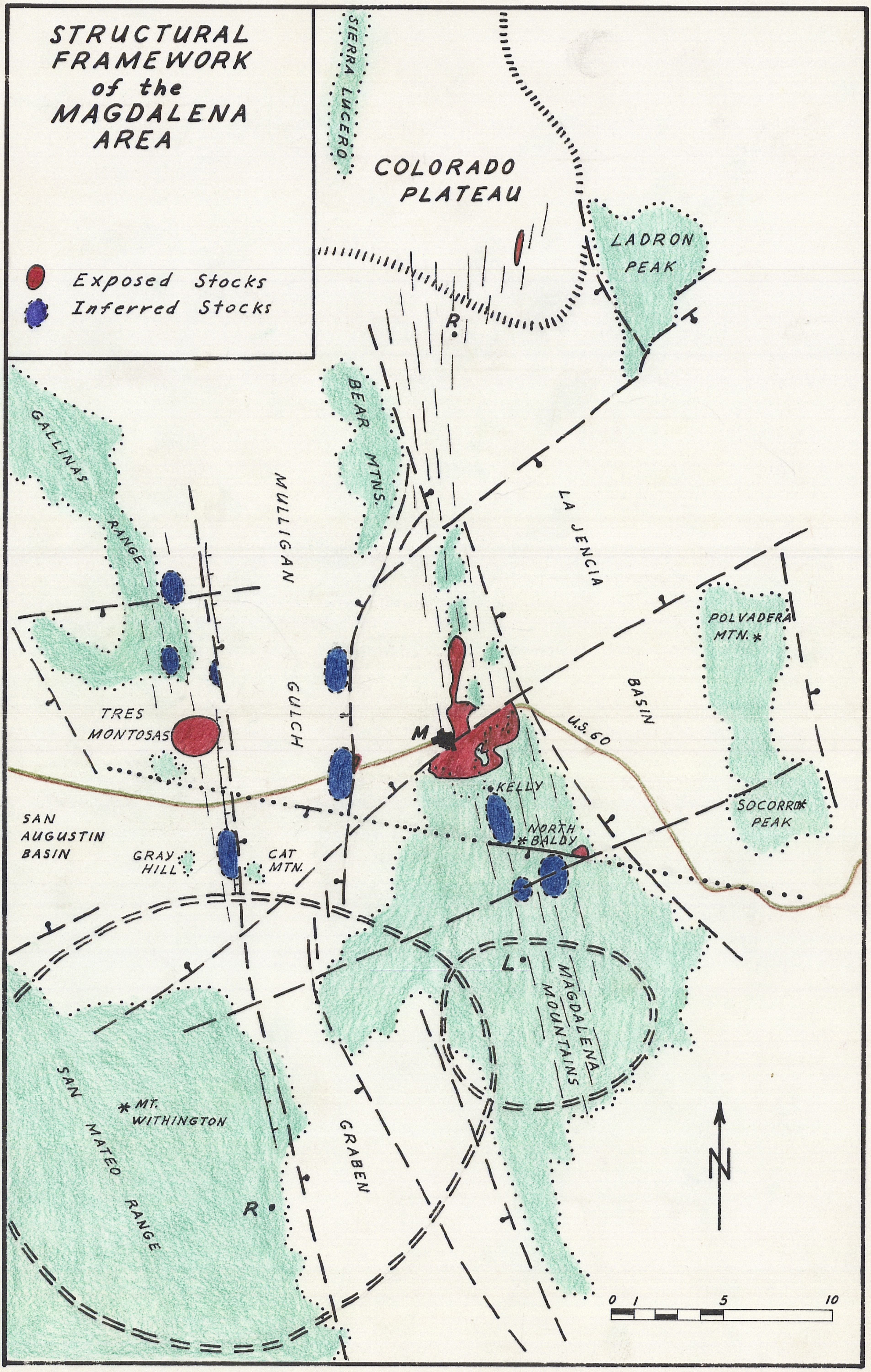

STRUCTURAL FRAMEWORK of the MAGDALENA AREA
Exposed Stocks
Inferred Stocks
SIERRA LUCERO
COLORADO PLATEAU
LADRON PEAK
R.
BEAR MTNS.
GALLINAS RANGE
MULLIGAN
GULCH
GRABEN
LA JENCIA
BASIN
POLVADERA MTN.
SOCORRO PEAK
U.S. 60
TRES MONTOSAS
M
KELLY
NORTH BALDY
SAN AUGUSTIN BASIN
GRAY HILL
CAT MTN.
L.
MAGDALENA MOUNTAINS
SAN MATEO RANGE
MT. WITHINGTON
R.
N
0 1 5 10

PLATE 1

GEOLOGIC MAP AND SECTIONS OF THE EASTERN MAGDALENA MOUNTAINS
WATER CANYON TO POUND RANCH
SOCORRO COUNTY, NEW MEXICO

by

GLENN R. OSBURN

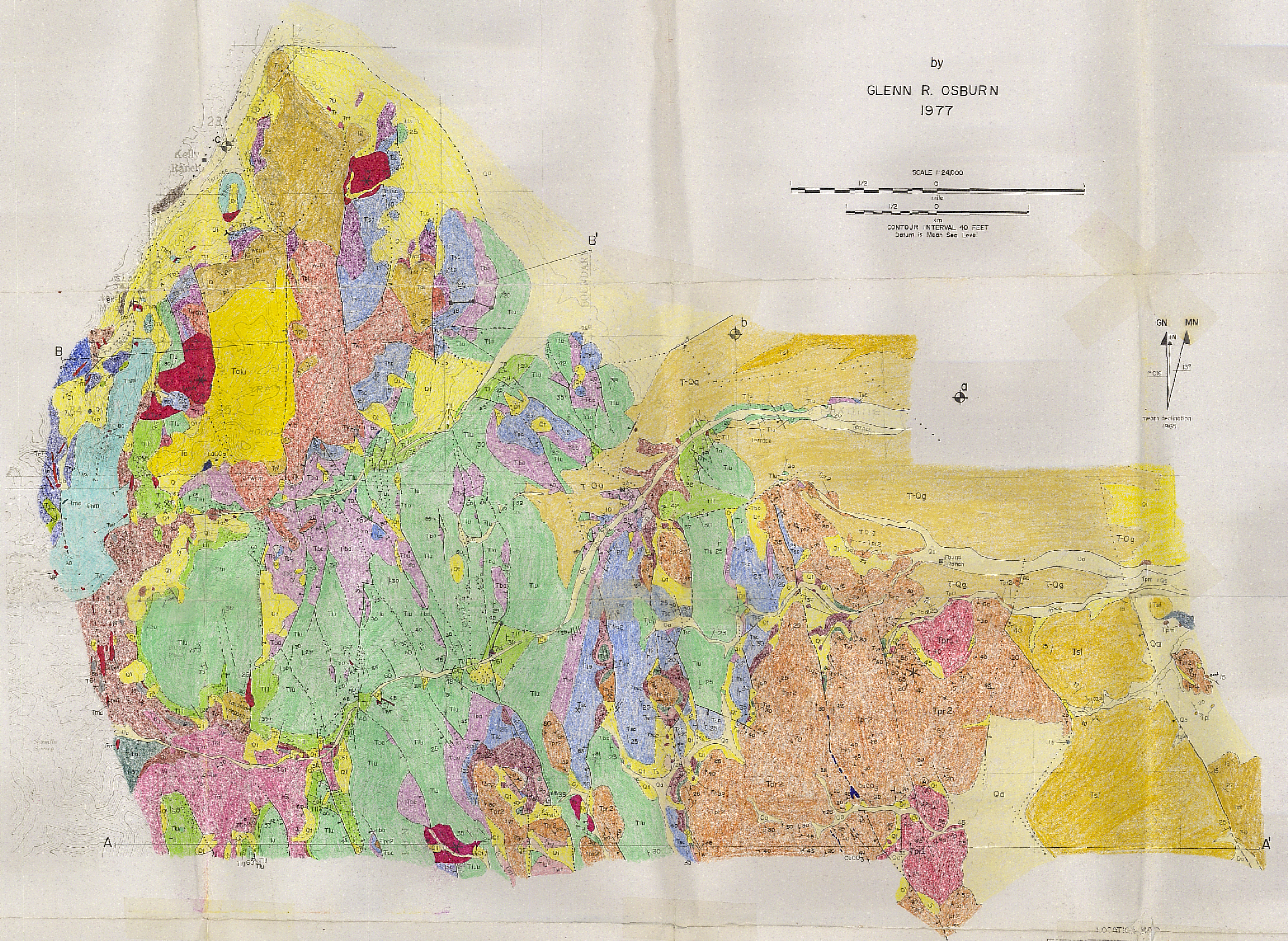
1977

SCALE 1:24,000

1 1/2 0 1 mile

1 1/2 0 1 km.

CONTOUR INTERVAL 40 FEET
Datum is Mean Sea Level



EXPLANATION

QUATERNARY

Qa — alluvium

Qt — talus/Colluvium

Pliocene

T-Qg — piedmont gravels overlying Tsl, undivided

Talu — alluvial deposits of uncertain age

Tsl — Sierra Ladrones Formation: conglomerates, sands, and mudstones

Tb — basaltic lavas

SANTA FE GROUP

Tpm — Popotosa Formation: mudstones

Miocene

Tpr2 / Tvt — upper Pound Ranch lavas (Tpr2) and underlying vitric tuffs, qtz. latite, 10.5 my.

Tpr1 / Twt — lower Pound Ranch lavas and associated (?) tuffs, rhyolite, 11.8my.

Ts — laharic breccias, conglomerates, and sandstone

Tpl — Popotosa Formation, laharic breccias

Tba2 — basalt to basaltic andesite lavas

Twr — white rhyolite domes

Trt — rhyolitic tuffs

Twr — white rhyolite dikes

Twcm / Tlc — Water Canyon Mesa lava, qtz. latite, landslide & colluvium deposits (Tlc)

Til — intermediate lavas

Oligocene

Tsc — tuff of South Canyon: rhyolite ash-flow tuff, 26.2 m.y.

Tba — basaltic andesite lavas

Tr — rhyolite intrusives

Tlu / Tll — Lemitar Tuff: upper crystal-rich, qtz. latitic and lower mod. crystal poor rhyolitic members, 26.3m.y.

Twr — white rhyolite dikes

T6l — unit of Sixmile Canyon: mafic lavas & laharic breccias (Ta), laminated sandstone (Tss), ash-flow tuffs (T6t), rhyolitic lavas (T6l).

Tmd — mafic dikes

Tal — A-L Peak Tuff (?): crystal-poor, rhyolitic tuffs

Tl-m — latite to monzonite dikes

Thm — Hells Mesa Tuff: crystal-rich, qtz.-rich, ash-flow tuff.

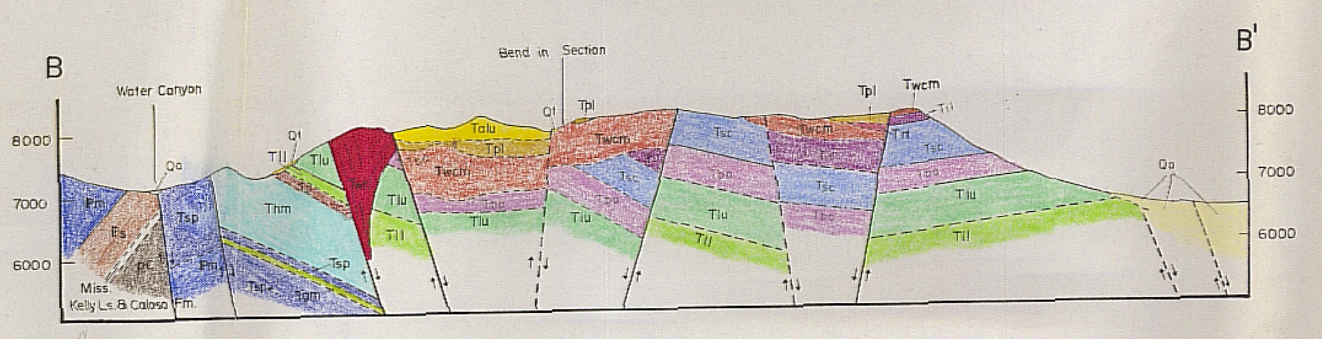
Tsp / Tgm — Spears Formation: mafic lavas and volcaniclastic sedimentary rocks (Tsp), tuff of Granite Mountain (Tgm)

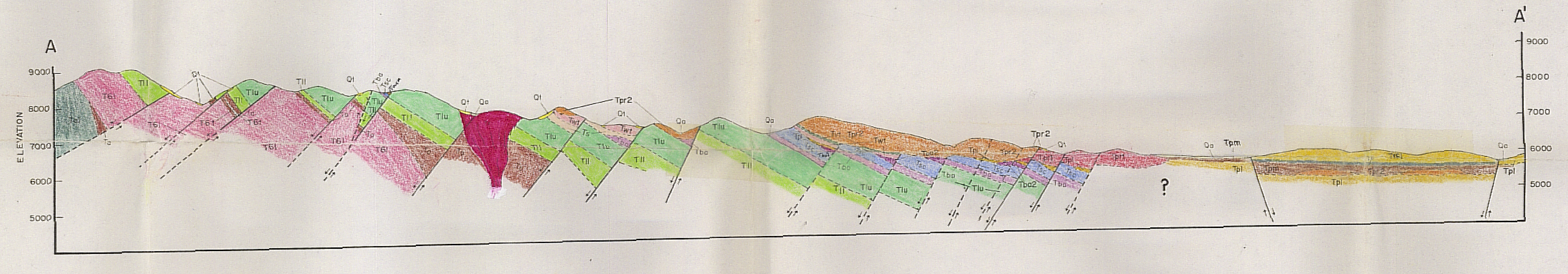
PENNSYLVANIAN

Pm — Madera Limestone

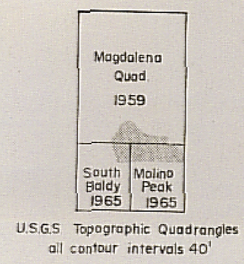
Ps — Sandia Formation

P€ — Precambrian





BASE MAP KEY



U.S.G.S. Topographic Quadrangles
all contour intervals 40'

Socorro County, New Mexico

SYMBOLS

Contact
Dashed where approximately located

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

Strike and dip of bedding

Strike and dip of flow foliation in lavas (Vertical Foliation)

Trend of lineation

Transport direction
in sediments from cross bedding or pebble imbrication

Volcanic vent

Shear zone
no proven displacement

Prospect pit

Adit

Shaft

Open cut

Mine dump

Silicification

Breccia zone

Sample location for K/Ar date

Measured Section

Drill hole data

a) C., Sec.34, 3S, 2W; all upper Santa Fe; 0-20' gravels, 20-40' red clay, 40-110' gravel, 110-380' sandy to gravelly mudstones

b) NW corner, Sec. 33, 3S, 2W, 0-70' gravels (prob. Qa), 70-300' gravelly mudstones (upper Santa Fe)

c) NW/4, SE/4, Sec. 23, 3S, 3W; 0-85' gravels, 85-120' gray to purple andesite (prob. Turkey track andesite of the Spears Fm).