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GEOLOGY OF THE SOUTHERN BEAR MOUNTAINS,

SOCORRO COUNTY, NEW MEXICO

A Thesis

Presented to

the Faculty of the Department of Geology

New Mexico Institute of Mining and Technology

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

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by

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OF 42

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ABSTRACT

Rocks exposed in the southern Bear Mountains were formed during middle and late Cenozoic time. In ascending stratigraphic order the major rock units are: (1) the Spears Formation (37 m.y.), a thick pile of latitic to andesitic conglomerates and sandstones with laharic breccias, ash-flow tuffs and lava flows in its upper third, (2) the Hells Mesa Formation (31-32 m.y.), an alternating sequence of quartz latitic and rhyolitic ash-flow tuffs separated by thin andesite flows, (3) the La Jara Peak Formation (24 m.y.), a thick pile of basaltic-andesite flows with minor volcaniclastic sedimentary rocks, and (4) the fanglomerates of Dry Lake Canyon, a thick wedge of epiclastic sedimentary rocks derived by erosion of the La Jara Peak Andesite during late Cenozoic block faulting.

The Hells Mesa Formation consists of eight members in the southern Bear Mountains; these members, listed in ascending stratigraphic order are: the tuff of Goat Spring, andesite flows 1, the lower tuff of Bear Springs with interbedded tuff of La Jencia Creek, andesite flows 2, the upper tuff of Bear Springs, andesite flows 3, and the tuff of Allen Well. Two distinctly different types of ash flows, a crystal-rich quartz latitic variety and a crystal-poor rhyolitic variety,

occur repeatedly in the section. The two varieties either originated from different levels of a fractionally crystallizing magma chamber or from two different pyroclastic sources active at the same time. Primary laminar flow structures in the tuff of Bear Springs indicate that the source area lay somewhere south or southwest of Magdalena.

At least two major periods of faulting have affected the area since middle Tertiary time. During the late Oligocene, an intense zone of north-trending normal faults cut the Spears and Hells Mesa Formations and localized the emplacement of hypabyssal intrusives of andesitic, monzonitic, and granitic composition. Two of these stocks have been dated at 28 m. y. In Miocene and Pliocene time, the Bear Mountains were uplifted and tilted westward by block faulting related to the Rio Grande rift. At the same time northeast-trending oblique-slip faults *en echelon* with the San Augustin graben dropped the southern Bear Mountains to form a trough between the Magdalena Mountains and the high part of the Bear Mountains.

Surface mineralization within the study area is restricted to epithermal vein deposits marginal to the La Jencia monzonite stock. Replacement-type deposits may be found in the underlying Paleozoic limestones but such deposits would be buried beneath a Tertiary volcanic cover from 2000 to 2500 feet thick near the La Jencia stock. Surface mineralization in this area is very weak and does not offer much encouragement for deep exploration. A possible exploration target may exist just west of the map area. Uplift and tilting of the Hells Mesa Formation and intense hydrothermal alteration along Council Rock Arroyo suggest the possibility of stock intrusion in this area.

INTRODUCTION

Statement of the Problem

The purpose of this investigation is to determine the stratigraphic and structural relationships of the Tertiary volcanic rocks and hypabyssal intrusive rocks in the southern Bear Mountains. The study was undertaken as part of an extensive mapping project of the Magdalena area presently being conducted by the New Mexico Bureau of Mines and Mineral Resources.

A detailed geologic knowledge of the southern Bear Mountains is important for two reasons:

1. The stratigraphic units are strategically located for correlation southward into the Magdalena mining district, eastward to the Rio Grande rift zone, and westward into the heart of the Mogollon Plateau volcanic province.
2. Future exploration of the Magdalena mining district is dependent upon an adequate stratigraphic and structural framework which heretofore has not been available.

Location and Accessibility

The area of investigation is located north of Magdalena, New Mexico. Physiographically, the area includes the south ern end of the Bear Mountains and a group of unnamed hills at the north end of the Magdalena Mountains. The area consists of about 50 square miles within the Silver Hill and Magdalena topographic quadrangles. Boundaries are the Puertecito Quadrangle on the north, La Jencia Creek on the south, Snake Ranch Flats on the east, and the western flanks of the Bear Mountains on the west. The area lies almost entirely within the Cibola National Forest. Geologically, the study area is situated at the northeastern tip of the Mogollon Plateau volcanic province near the boundary between the Basin and Range province and the Colorado Plateau province.

Access to the eastern part of the area is provided by an unpaved road from Magdalena to Riley. The western part of the area can be reached by State Road 52, which has recently been paved. These two main roads are connected by an unimproved dirt road which bisects the area and passes through the vicinity of Bear Springs. In addition, there are a number of trails used by ranchers and woodcutters which provide easy access to almost any point by four-wheel drive vehicle.

Methods of Investigation

Detailed geologic mapping was conducted at a scale of 1:24000. A base map was prepared by enlarging part of the

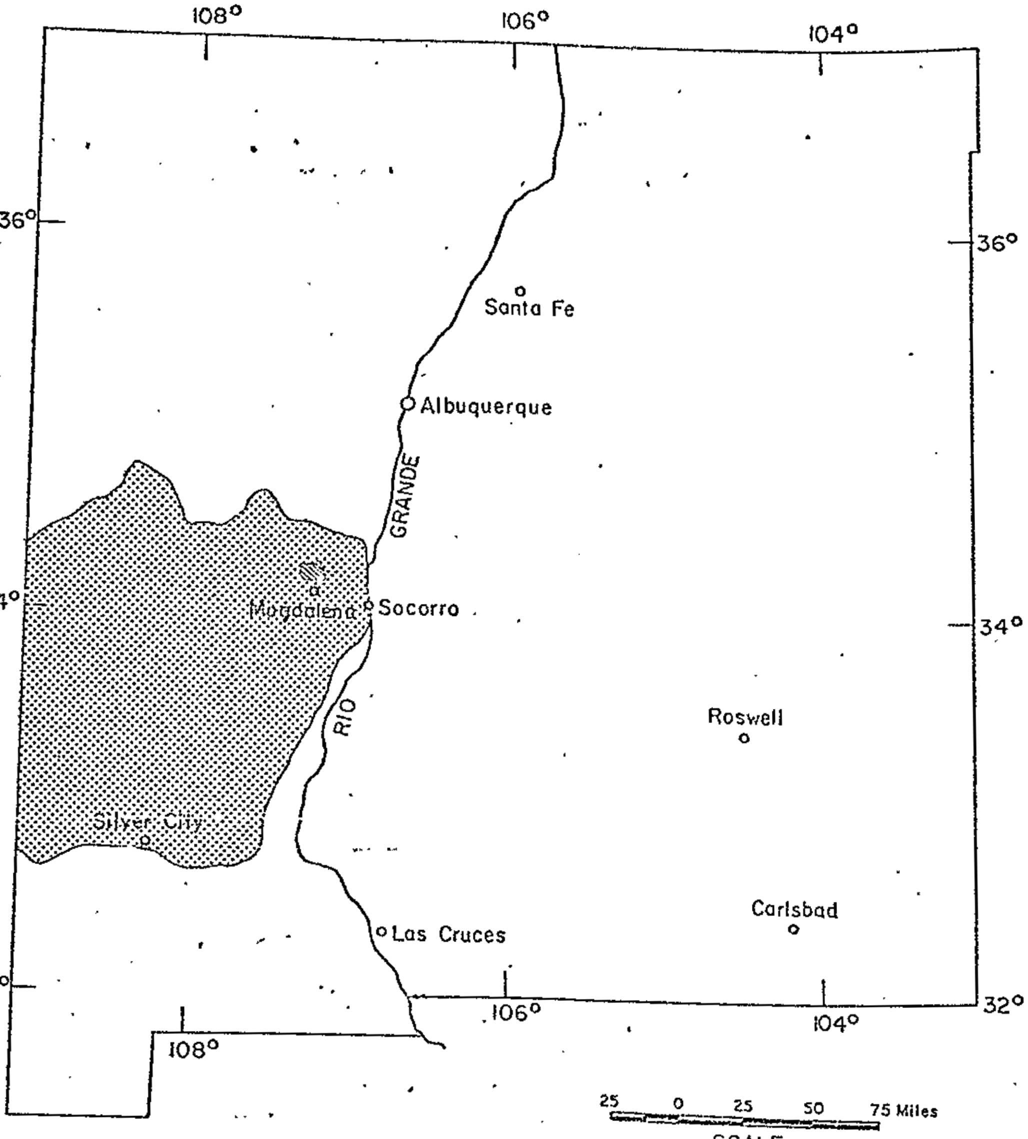
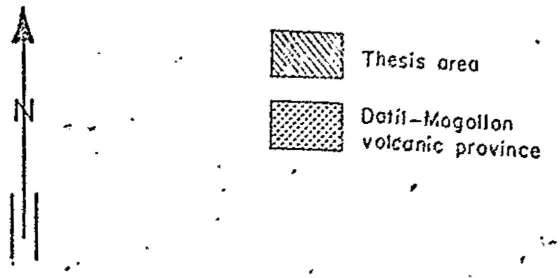


FIGURE I

INDEX MAP OF NEW MEXICO, SHOWING LOCATION OF THESIS AREA



Magdalena 15-minute quadrangle to a 7.5-minute scale and joining it to part of the Silver Hill 7.5-minute quadrangle. U. S. Geological Survey aerial photographs of the GS-VMA (1956) and GS-VARJ (1963) series were used as guides to the location and configuration of outcrops.

Eighty thin sections were made from samples taken along a stratigraphic section measured jointly with C. E. Chapin of the New Mexico Bureau of Mines. Twenty-five additional thin sections were made of rocks from elsewhere in the area. Petrographic analyses were made using a Zeiss microscope equipped with a Swift automatic point counter. Modal analyses of samples from the measured section were performed by Douglas Cowan and James Bruning and checked by the author. Mineral grains were counted on a rectangular grid 1/3 mm. x 1.0 mm., giving 2000 to 2500 points per thin section for the upper and lower tuff of Bear Springs and 1200 to 1400 points for the tuff of Goat Spring.

Previous Investigations

The earliest work done in the Bear Mountains was that of general reconnaissance. In 1900, C. L. Herrick conducted a reconnaissance survey of western Socorro and Valencia counties. He briefly noted that the Bear, Gallinas, and Datil Mountains are composed of trachyte and rhyolite intrusives. In 1920, D. E. Winchester published the results of an investigation of the geology along Alamosa Creek, now known as the Rio Salado. Winchester named the entire Tertiary sequence of the Datil Formation after the Datil Mountains and described the type section at the north end of the Bear Mountains. In 1928, N. H. Darton published his regional "Red Beds" study, which contained a summary of his reconnaissance in the area, as well as Winchester's previous work.

Loughlin and Koschmann (1942) studied the Magdalena mining district, and noted that some of the Tertiary volcanic rocks extend to the north and northwest outside the district. W. H. Tonking (1957) made the first detailed study of the Datil volcanic rocks north of the Magdalena area. He subdivided the Datil Formation into three members, which are in ascending order: (1) The Spears Member, a thick sequence of latite tuffs and volcanic sediments, (2) The Hells Mesa Member, composed of welded rhyolite ash-flow tuffs, and (3) The La Jara Peak Member, a thick pile of basalt and basaltic andesite flows. Willard (1959) tentatively correlated Tonking's La Jara Peak Member with the Mangas basalt, a post-Datil sequence. Following Willard's suggestion, Weber (1963) excluded the La Jara Peak Member from the Datil Formation. Weber (1971) also suggested raising the Datil Formation to group status in order to accommodate subdivision into formations and members.

Johnson (1955) attempted to correlate the volcanic rocks of the Magdalena mining district with those of Tonking's Puertecito Quadrangle. He produced a crude map of the area from Tonking's southern boundary to the northern boundary of Loughlin and Koschmann. D. E. Park (1971) studied the petrology of the Anchor Canyon monzonite stock, which is located in the Kelly mining district.

An important contribution to the regional geology of the Datil-Mogollon volcanic province has been made by Elston and others (1968, 1970) who are presently studying the volcano-tectonic framework of the Mogollon Plateau area.

A number of K-Ar ages are now available for Datil and post-Datil rocks in the area. Weber and Bassett (1963) dated a welded tuff near the base of the Hells Mesa Member, as well as the Nitt and Anchor Canyon stocks in the Magdalena mining district. Burke and others (1963) dated the Spears Member and two more welded tuffs from the Hells Mesa Member. Kottlowski, Weber, and Willard (1969) published a summary of more than 60 K-Ar dates of Tertiary rock units in New Mexico including many from the Mogollon Plateau and surrounding areas. More recently, Weber (1971) has published a list of K-Ar dates fro Tertiary rocks in central and western New Mexico and Chapin (1971-a) has reported a date on the La

Jara Peak Member.

Acknowledgements

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Appreciation is also extended to the individuals who provided the author with ideas and information about various aspects of the project, including R. H. Weber, Kent Condie, and A. J. Budding. Special thanks are due the thesis advisor, C. E. Chapin, for the original suggestion of the thesis area and for valuable advice in the field and office. Mr. and Mrs. Donald Hudgins and Felix and Jody Sanchez extended hospitality during the course of the field work and Margie Mora assisted in the preparation of the map and manuscript.

STRATIGRAPHY AND PETROLOGY

Pre-Tertiary Rocks

No rocks older than the Tertiary are exposed within the thesis area. To the south, Loughlin and Koschmann's map (1942) shows that on the east side of Granite Mountain the base of the Spears Formation rests unconformably on the Madera Limestone of Pennsylvanian age. To the north, Tonking's map (1957) shows that the base of the Spears rests conformably on the Baca Formation (Eocene). The Baca, in turn, disconformably overlies the Crevasse Canyon Formation of Cretaceous age.

The Magdalena area is situated on the flanks of a Laramide uplift which was subjected to erosion during deposition of the Baca Formation in adjacent basins. Central New Mexico was beveled by an erosion surface of moderately low relief prior to the beginning of Oligocene volcanism (Chapin, 1971-b) so that the base of the volcanic pile rests on progressively older rocks as the Magdalena area is approached and the nature of the contact changes from conformable in the basins where the Baca accumulated to an angular unconformity on the beveled uplift. It is difficult to predict where this transition occurs within the study area since no exposures are available.

Tertiary Volcanic Rocks

The rocks exposed in the study area are predominantly volcanic rocks and interbedded volcani-clastic sedimentary rocks of Tertiary age. These rocks can be divided into two main units separated by an angular unconformity: (1) the Datil Group comprised of the Spears and Hells Mesa Formations, and (2) the La Jara Peak Formation comprised of post-Datil basaltic andesite flows. The combined thickness of these volcanic rocks may be six thousand feet or more (Figure 2).

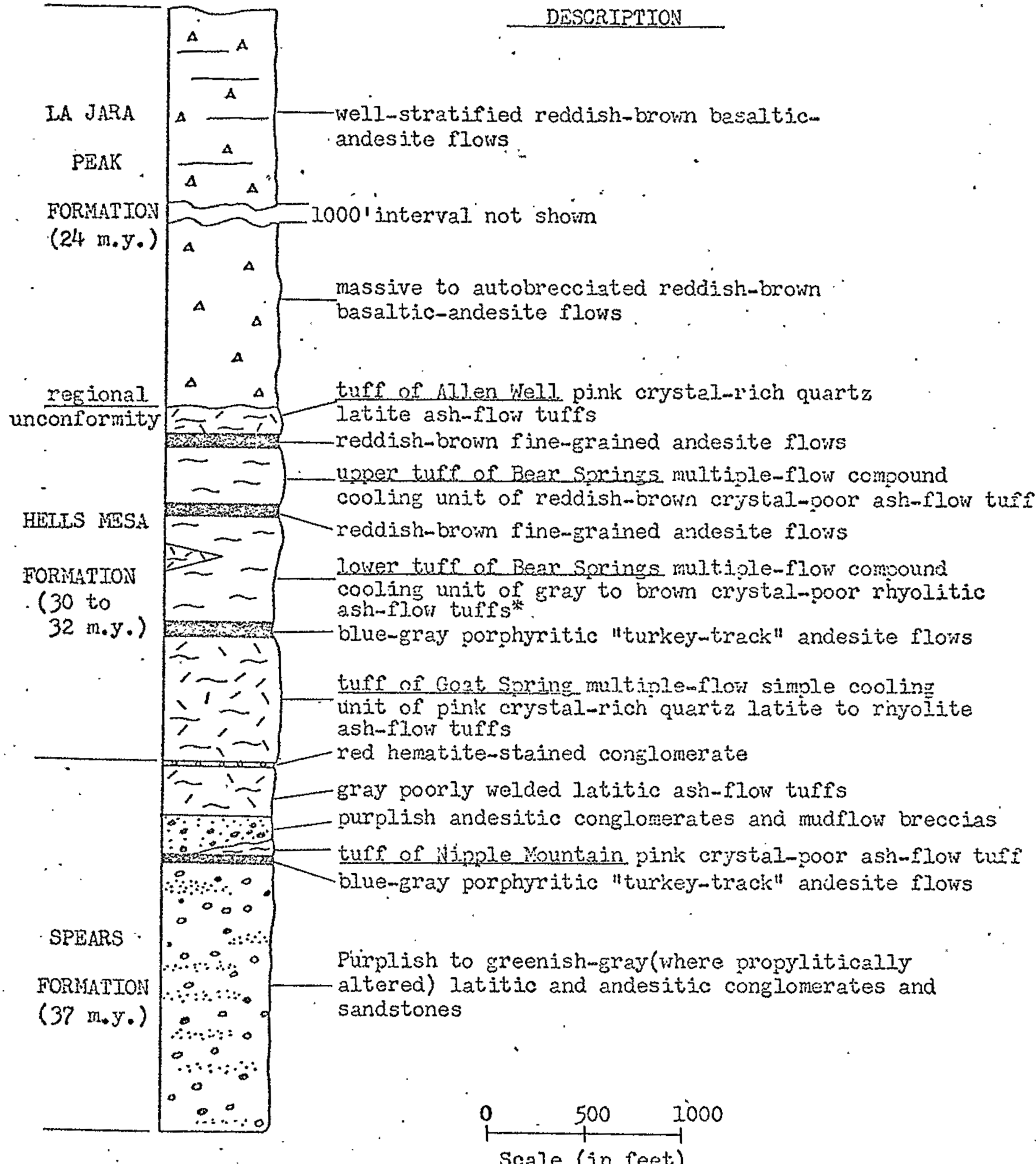
Spears Formation

Volcanism began in the Magdalena area in early Oligocene time with the accumulation of a thick sequence of epiclastic volcanic sediments and interbedded ash-flow tuffs and lava flows named the Spears member of the Datil Formation by Tonking (1957, p. 36-41). The Datil Formation has subsequently been raised to Group status (Weber, 1971) and the Spears to formational status (Chapin, 1971-a). A latite tuff-breccia from the Joyita Hills, approximately 30 miles east of the Bear Mountains, has been correlated with the Spears Formation and dated by the K-Ar method as 37.1 m.y. (Weber, 1963, p. 135; 1971, p. 42).

Marked facies changes occur locally in the Spears. At

Hells Mesa, it consists dominantly of fine-grained fluvial sediments; in the area studied here, it consists mostly of coarse volcanic conglomerates but with some volcanic rocks in the upper part; on Granite Mountain, it consists of a thick section of lava flows and ash-flow tuffs above a relatively thin lower member of volcanic conglomerates; at the south end of the Kelly district, it changes back to a thick section of volcani-clastic sedimentary rocks with minor volcanic rocks near the top (Chapin, 1971, oral communication). The base of the Spears is not exposed anywhere in the thesis area but at the type locality near Hells Mesa, purplish latitic sandstones near the base of the Spears are interbedded with reddish nonvolcanic mudstones and sandstones in the upper part of the Baca Formation (Tonking, 1957; Potter, 1970).

Lower Member. The lower portion of the Spears is best exposed on Nipple Mountain in the southeast corner of the area. A minimum thickness of 1500 feet has been estimated from the map, but this figure is very likely exaggerated by concealed faulting. In the Granite Mountain - Nipple Mountain area, where the Spears is propylitically altered, the color is generally greenish-gray. This color is atypical of the reddish to purplish-brown color of the fresh Spears at Hells Mesa and at the south end of the Kelly district



* The approximate position of the tuff of La Jencia Creek, a series of crystal-rich quartz latite ash-flow tuffs, is shown by the wedge.

Figure 2. Generalized composite section of the Tertiary volcanic rocks and volcaniclastic sedimentary rocks in the southern Bear Mountains.

where Loughlin and Koschmann called it the purple andesite. Outcrops of the lower member consist of a monotonous sequence of propylitized latitic to andesitic conglomerates and sandstones which range in grain size from boulder conglomerates to fine grained sandstones. Stratification is generally crude except for the fine grained sandstone beds, which are usually well-stratified and locally cross-bedded.

In hand specimen, the lower Spears is well-indurated and contains rounded latitic to andesitic clasts ranging in color from grayish-green to purplish-gray or pink. Varying percentages of pale green feldspar, greenish-black hornblende, biotite, and magnetite are visible megascopically.

Petrographically, the clasts are similar to the Spears latites described by Tonking, except that they are pervasively altered in the Nipple Mountain area. The original textures and minerals have been largely obscured by propylitic alteration which uniformly penetrates the entire rock rendering the boundaries between clasts and matrix indistinct. Most of the clasts are porphyritic with abundant trachytically aligned feldspar and hornblende phenocrysts in a cryptocrystalline groundmass which suggests that they are fragments of lava flows.

The latites are mineralogically uniform and consist mainly of plagioclase, sanidine, hornblende, and biotite.

Individual clasts vary considerably, however, in the absolute and relative percentages of these major constituents. Accessory minerals include apatite and quartz. Epidote, chlorite, calcite, magnetite, and hematite are the usual alteration products. The greenish color of the lower Spears is caused by the presence of chlorite and epidote, while the pinkish color of some clasts is probably due to finely divided hematite in the groundmass.

Plagioclase is the most abundant phenocryst and varies from 10 percent to 20 percent. It occurs as subhedral grains from 0.1 to 1.5 mm long and is highly altered to clays and epidote. Sanidine is approximately equal in amount to plagioclase and occurs as subhedral grains from 0.3 to 1.5 mm long. The sanidine is generally less altered than the plagioclase but most grains show varying degrees of argillic alteration. Hornblende is present as euhedral to subhedral pseudomorphs ranging in length up to 1.5 mm. The original hornblende has been replaced by epidote, chlorite, and magnetite. Biotite is usually replaced by chlorite and magnetite.

Upper Member. At the top of Nipple Mountain about 80 feet of volcanic rocks overlie the sedimentary rocks of the lower Spears. The lower 30 feet consists of a blue-gray, amygdaloidal, "turkey-track" andesite flow with 15 percent zoned plagioclase phenocrysts. Above this, the very top of Nipple Mountain is capped by about fifty feet of pink, welded, crystal-poor ash-flow tuff, designated the tuff of Nipple Mountain in this report. The ash flow contains about five percent sanidine phenocrysts and a few percent dark andesitic lithics. These volcanic rocks mark a transition in the Spears from the lower member of volcani-clastic sedimentary rocks to an upper member of andesitic lava flows and latitic ash flows interbedded with laharic breccias and fluvial sediments. The best exposures occur in La Jencia Box southwest of Nipple Mountain, where the section contains more laharic breccias and interbedded andesite flows than it does farther north. In La Jencia Box the upper Spears becomes predominantly mudflow breccias which grade upward imperceptibly into welded lithic-rich ash flows; these crystal-rich ash flows greatly resemble the basal 20 to 40 feet of the tuff of Goat Spring and correlate with the upper latite of Laughlin and Koschmann (1942, p. 25).

North of La Jencia Creek the upper member forms the lower slopes of the tilted fault-block ridges along the eastern margin of the area where it crops out poorly because of mantling by talus from the overlying tuff of Goat Spring. In this area, outcrops occur only where gulleys have trenched into the talus. Most of the flat-floored pediment surfaces along the eastern margin of the Snake Ranch Flats are probably underlain by the upper part of the Spears. A section of the upper member of the Spears was measured about 3/4-mile northwest of Goat Spring along the steep eastern slope of a prominent peak. The measured section (Figure 2) begins in a bluish-gray, prophyritic "turkey-track" andesite flow, similar to the one on Nipple Mountain. Above the andesite flows are about 220 feet of reddish-brown to reddish-purple conglomerates, sandstones, and mudstones. The conglomerates contain rounded clasts ranging in size from one inch to six inches in diameter with occasional boulders up to one foot. The imbrication of the clasts indicates a northerly direction of transport for the sediments. The clasts are predominantly reddish-brown porphyritic latite and "turkey-track" andesites similar to the underlying flows. Interbedded with the conglomerates are thin sandstone layers up to six inches thick.

Above these sediments, approximately 200 feet of latitic ash-flow tuffs were measured. The tuffs are light purplish-gray, poorly welded, and occasionally show a north-south lineation defined by elongated pumice. Chalky white plagioclase, bronzy biotite, and dark-brown porphyritic andesitic lithic fragments characterize the hand specimens. Often the compaction foliation is defined by gray streaky pumice.

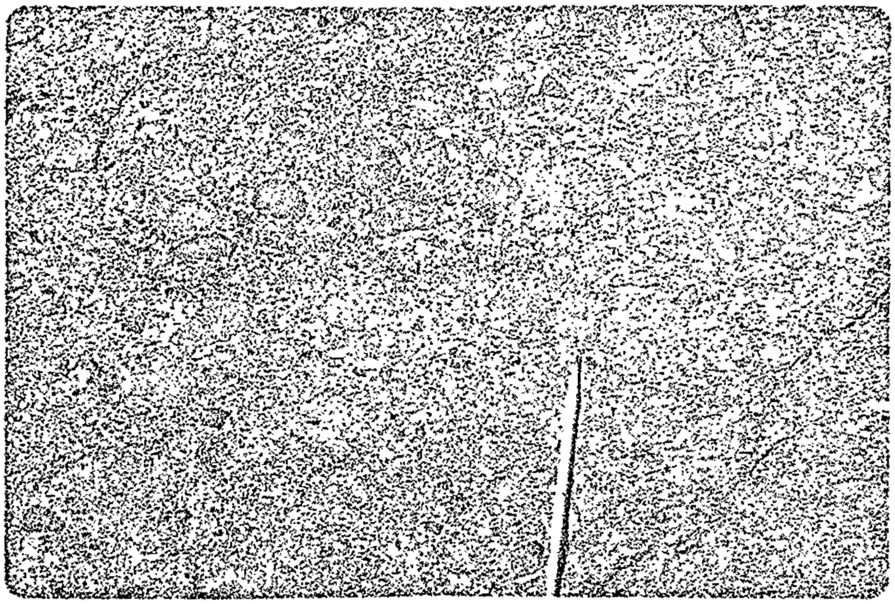


Figure 3. Latitic mudflow breccia in the upper Spears Formation showing angular to subrounded andesite and latite clasts "floating" in a crystal-rich matrix. The white specks in the matrix are altered plagioclase crystals. Note the lack of sorting and stratification.

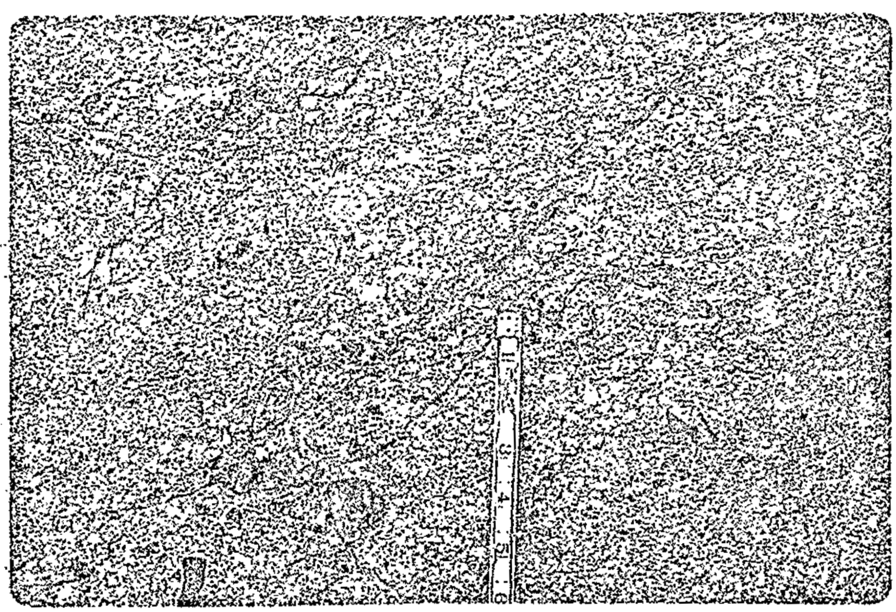


Figure 4. Poorly welded latitic ash-flow tuff in the upper Spears Formation. Close-up of surface shows white poorly welded pumice, dark andesite lithic fragments, and abundant chalky-white feldspar crystals.

In places it is difficult to distinguish the Spears ash flows from the overlying quartz-poor base of the tuff of Goat Spring.

The top of the Spears is marked by a distinctive hematite-stained conglomerate. The conglomerate is zero to forty feet thick and contains hydrothermally altered clasts coated with reddish-brown hematite. Many of the clasts are so altered and silicified as to resemble chert, but close inspection usually reveals relict phenocrysts. Several small prospect pits have been dug at this horizon along the east edge of the study area. The hematite-stained clasts are easily recognized in the float; thus this conglomerate provides a useful marker bed at the top of the Spears.

Because of their soft, porous nature, the ash-flow tuffs in the Spears at the measured section are highly altered and little can be learned about them petrographically. Their texture is porphyritic and seriate, with abundant feldspar phenocrysts grading in size from laths 1.0 mm long down to grains barely discernible from the groundmass. The individual feldspar grains are often broken and show a crude alignment parallel to the compaction foliation. Only a faint eutaxitic structure is visible because of the low degree of welding and the high degree of alteration.

Mineralogically, the ash flows seem to resemble the latite clasts in the lower Spears, except that hornblende is absent. The thin sections contain from 20 percent to 40 percent feldspar phenocrysts; plagioclase and sanidine are both present, but alteration makes it difficult to estimate their relative proportions. Plagioclase appears to be more abundant, and occurs as subhedral, often broken, grains from 0.1 mm to 1.5 mm long. The phenocrysts are highly altered to clays and calcite. Sanidine ranges from 0.1 mm to 1.0 mm in length, and shows varying degrees of argillic alteration, from incipient to complete replacement. A few percent biotite occurs as small opaque grains replaced by iron oxide. Traces of clinopyroxene, quartz, apatite, and muscovite are also present. The groundmass is aphanitic and has been replaced by a fine-grained aggregate of clay minerals and calcite.

Hells Mesa Formation

The Hells Mesa Formation is a thick series of welded quartz latite to rhyolite ash-flow tuffs and interbedded andesite flows. Tonking (1957, p. 24-30, 56) named the unit for Hells Mesa at the eastern edge of the Bear Mountains and measured a type section at this locality (Sec. 31, T. 2N. R. 4 W.; Puertecito Quadrangle). He gave the unit member status in the Datil Formation, but the Datil has since been raised to group status and the Hells Mesa is considered here as a formation. Tonking measured only 289 feet of the Hells Mesa at his type section which represents only the thin edge of the formation. In the southern Bear Mountains the Hells Mesa attains a thickness of about 1700 feet and has been subdivided in this report into seven members, as described in the following paragraphs.

Tuff of Goat Spring. The tuff of Goat Spring is the informal name proposed here for the basal member of the Hells Mesa Formation. It is a distinctive unit in the Bear, Gallinas, San Mateo, Lemitar, and Magdalena Mountains and will undoubtedly be considered a separate formation when more regional work is done. This unit was mistakenly identified as a rhyolite porphyry sill, first by Loughlin and Koschmann (1942) and later by Johnson (1955). It is actually a multiple-flow, simple cooling unit of welded quartz latite to rhyolite ash-flow tuffs. A sample from the base of the unit was dated by the K-Ar method as 30.6 $\pm$ 2.8 m. y. (Weber and Bassett, 1963).

The tuff of Goat Spring covers about five square miles of the study area. Its main area of outcrop extends in a northerly manner from Granite Mountain on the south

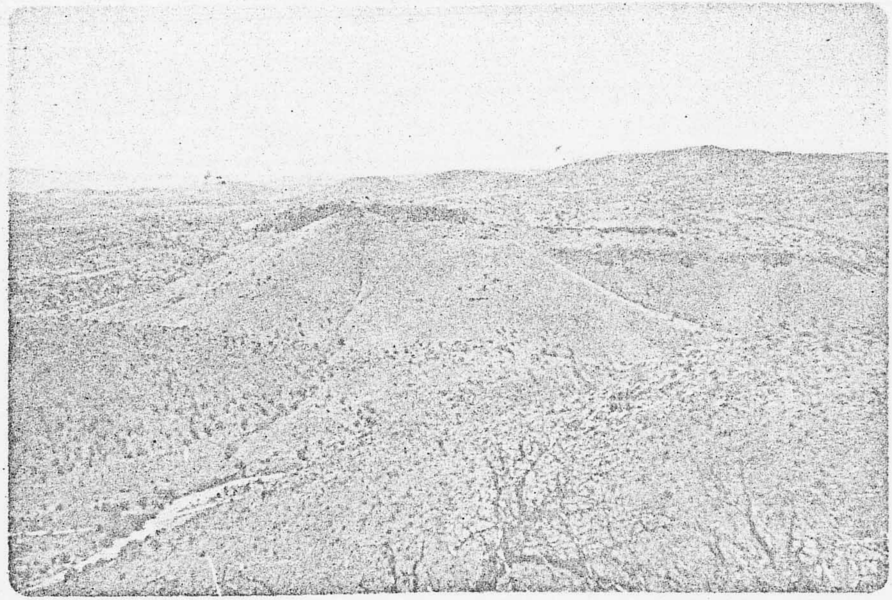


Figure 5. Stratified outcrops of the Hells Mesa Formation near Bear Springs draw. Double ledge at the top of the hill is formed by the contorted and pumiceous ash-flow units which cap the lower cooling unit in the tuff of Bear Springs. Middle slope-forming part is underlain by the gray massive unit of the tuff of Bear Springs. Dark ledge-forming outcrops at the base and in the foreground are the tuff of Goat Spring. View is looking southwest; Tres Montosas are the high peak just visible to the right of center.

along the eastern margin of the area to Hells Mesa on the north. At Hells Mesa it forms the basal 175 feet of Tonking's measured section.[1] Its maximum thickness has been measured as about 640 feet near Goat Spring (NW ¼, Sec. 26, T. 1 S., R. 4 W.) and it thins rapidly northward into the Puertecito Quadrangle.

The tuff of Goat Spring outcrops as prominent cliffs and hogback ridges. It weathers distinctively into large rounded blocks bounded by joints. Many outcrops have elongated cavities up to four inches long where pumice has been removed by weathering.

Fresh hand specimens range in color from pinkish-gray to purplish gray and weather to buff or gray. Most specimens are densely welded and crystal-rich with phenoclasts accounting for 40 to 50 percent of the rock. Phenoclasts include sanidine, smoky quartz, and coppery biotite. Locally, aphanitic purplish-brown lithic fragments and gray flattened pumice are abundant.

In thin section, samples are distinctively porphyritic and contain from 40 to 50 percent broken and partially resorbed crystal fragments. Comminution of the crystals during emplacement has produced a seriate texture character-

[1] Tonking's section, p. 56, is upside down.

ized by a complete gradation from large crystals 3 mm in diameter down to fragments 0.01 mm or less in diameter.

Sanidine is the most abundant phenoclast and varies from 10 to 30 percent of the rock. It occurs as subhedral to euhedral grains from 0.1 mm to 4 mm in length with an average length of about 1.5 mm. Most grains are partially resorbed and show incipient alteration to clays and hematite along cleavages which gives the sanidine its pinkish cast in hand specimen.

Plagioclase varies from 10 to 20 percent of the rock and averages about 12 percent. The grains are subhedral to euhedral and usually have corroded and embayed borders. The plagioclase is generally smaller than the sanidine and ranges from 0.1 mm to 1.5 mm in length. Various degrees of alteration to clays and calcite are present, ranging from incipient alteration along cleavages to complete replacement. The compositions of the plagioclase phenoclasts in a number of samples were determined using the Fouqué method. The average composition was determined as sodic andesine and there appears to be a systematic variation in the plagioclase composition from about An_{31} near the base of the unit to about An_{36} near the top.

Quartz occurs as large rounded grains from 1 mm to 3 mm in diameter. It is absent or very scarce in the lower

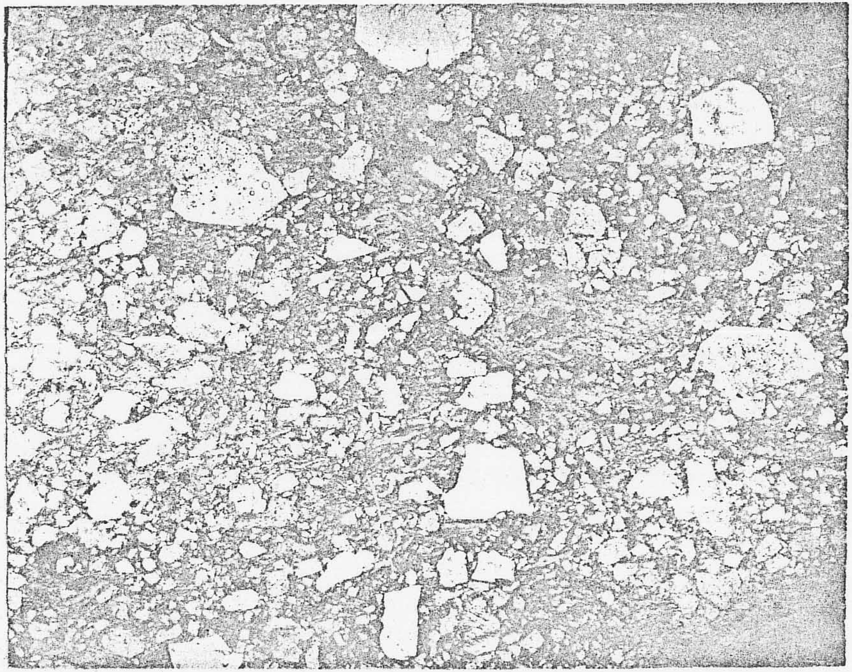


Figure 6. Tuff of Goat Spring. Low magnification (4X) shows the abundance and range in size of crystal fragments. Altered feldspars are light gray, quartz is white, biotite and opaques are black.

10 to 20 feet of the unit, then increases abruptly to about 5 percent of the rock and continues to increase to about 15 percent near the top. Most grains have embayed borders and holes filled with groundmass glass.

From 1 to 4 percent biotite occurs as yellowish-brown pleochroic grains partially to completely altered to iron oxide. Minor amounts of pyroxene may have been present as suggested by pale brown pseudomorphs with euhedral outlines. The pseudomorphs are composed of calcite and have magnetite borders. The original cleavage traces have been preserved by magnetite replacement in some grains.

The groundmass of these crystal-rich ash-flow tuffs is pale brown and is usually devitrified to radiating aggregates of feldspar and cristobalite. Under high magnification, small patches of glass, broken phenocryst fragments, and finely divided hematite can be seen.

Lithic fragments are common in the tuff of Goat Spring, especially in the upper and lower parts of the unit where they constitute as much as 15 percent of the rock. Most of the fragments are angular and range from 2 mm to 8 cm in diameter. The most common type of lithic is reddish-brown, porphyritic andesite with argillized plagioclase phenocrysts and magnetite pseudomorphs after biotite in an opaque, hematized groundmass. Near the base of the unit, a few porphyritic "Spears-type" latite fragments are present.

A stratigraphic thickness of 640 feet was measured northwest of Goat Spring (Sec. 26, T. 1 S., R. 4 W.). The modal variations and sample locations are shown diagrammatically in Figure 7. Phenocryst modes were point counted from thin sections by Douglas Cowan; modal data for pumice and lithics were estimated visually in the field and in hand specimen by the author. The tuff of Goat Spring is relatively homogeneous throughout its thickness, both in mineralogy and degree of welding. The total amount of crystals increases abruptly in the basal 30 feet to an average of about 47 percent for the unit; a more crystal-rich zone is evident between 150 and 250 feet above the base. Quartz increases upward in a somewhat erratic manner to achieve a maximum of 15 percent in the upper 130 feet of the unit; it is scarce to absent in the basal 30 feet. The plagioclase/sanidine ratio averages about 0.5 and shows little variation vertically within the unit except near the base, where plagioclase and sanidine occur in nearly equal proportions. Sanidine, plagioclase, and mafic minerals are all nearly constant above the basal 30 feet.

The tuff of Goat Spring displays no obvious variations typical of zoned ash-flow cooling units described in the

Table I. Modes in volume percent from the tuff of Goat Spring

	Sample Number	Total pheno-crysts	Phenocryst Proportions: Sani-dine	Plagio-clase	Quartz	Biotite and opaques	Total points counted
Top of unit							
1	M-24-37	46.1	22.5	7.3	14.4	1.9	1389
2	M-24-36	46.6	21.2	10.0	13.6	1.8	1384
3	M-24-34	50.9	22.9	11.1	15.6	1.3	1323
4	M-24-33	49.9	24.2	9.1	15.0	1.6	1277
5	M-24-31	49.0	24.5	12.8	8.9	2.8	1389
6	M-24-30	49.8	28.2	10.7	6.1	4.8	1334
7	M-24-29	43.3	23.4	7.8	9.8	2.3	1318
8	M-24-28	48.7	24.8	12.5	7.8	3.6	1339
9	M-24-27	47.9	27.1	11.9	3.8	5.1	1441
10	M-24-26	55.7	27.2	17.6	5.6	5.3	1303
11	M-24-25	59.1	27.4	15.9	10.9	4.9	1385
12	M-24-24	55.3	29.2	13.7	7.3	5.1	1389
13	M-24-23	49.6	28.4	10.4	6.1	4.7	1292
14	M-24-22	49.0	26.8	13.0	4.8	4.4	1318
15	M-24-21	47.1	23.6	13.9	3.8	5.8	1320
16	M-24-20	36.7	20.4	10.0	0.6	5.7	1444
17	M-24-19	40.3	15.0	19.5	0.4	5.4	1378
18	M-24-18	28.4	14.1	10.2	0.9	3.2	1205
Base of unit							

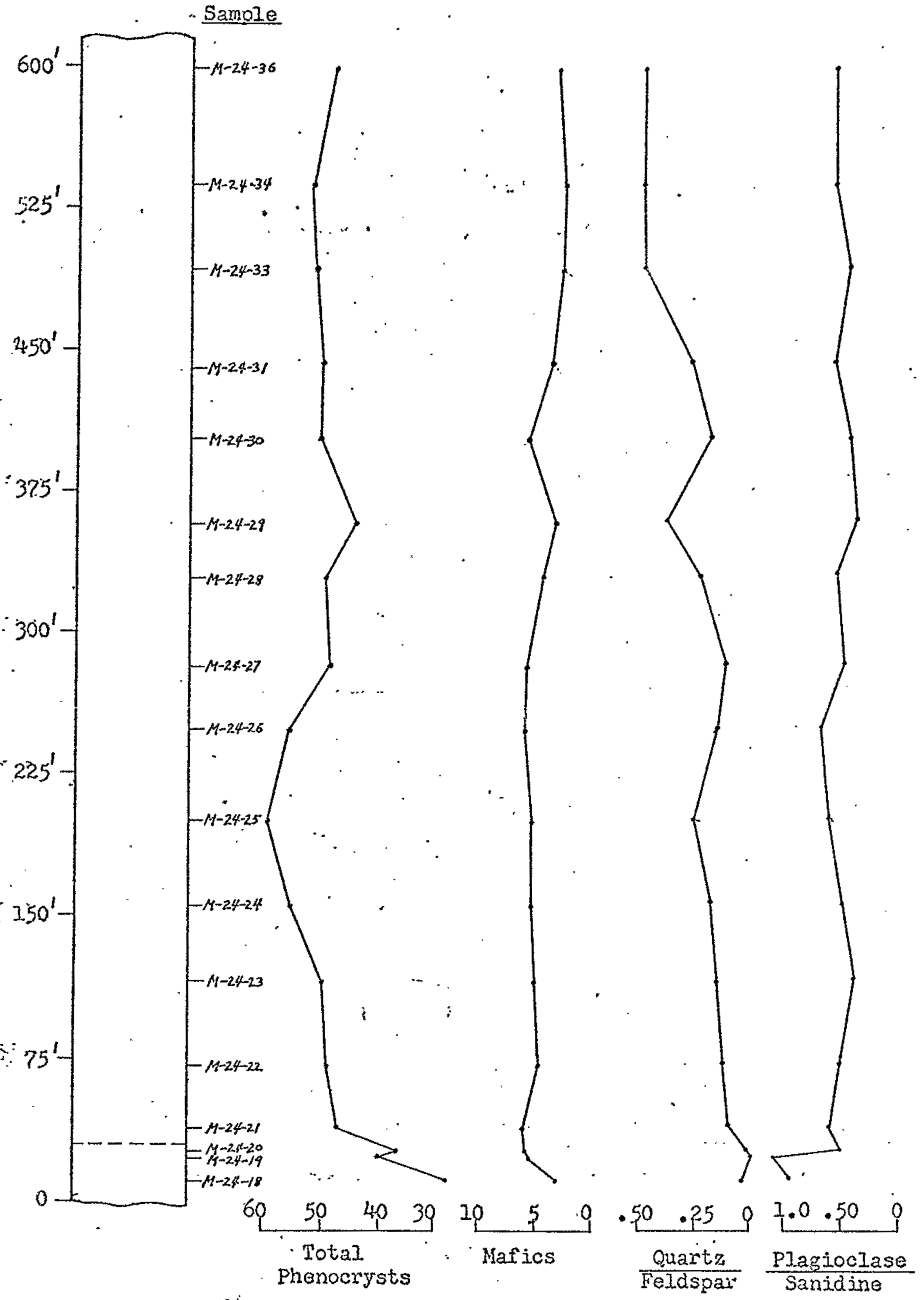


Figure 3. Measured section of the tuff of Goat Spring showing mineralogical variations. Dashed line near the base indicates the upper limit of quartz-poor latitic ash flows. (modal data are in volume percent, taken from Table I).

literature (Ratté and Steven, 1964; Smith and Bailey, 1966; Lipman and others, 1966; Giles, 1967). In a typical zoned sheet total crystals, plagioclase, and mafic minerals all increase upward in the section. The youngest ash-flow tuffs usually contain more calcic plagioclase and less quartz. The plagioclase does become slightly more anorthitic upward in the tuff of Goat Spring but other systematic variations appear to be absent. Some of the larger and more consistent breaks in the profiles of Figure 7 may represent slight differences in modal composition between individual ash flows (Ratté and Steven, 1967, p. 30-33). The most noticeable break is the abrupt change in modal composition near the base of the section. This change may represent a transitional zone between two different types of ash flows: (1) quartz-poor latitic ash flows at the base, possibly derived from the same magma chamber as the crystal-rich ash flows in the upper Spears Formation, and (2) quartz-rich rhyolitic to quartz latitic ash flows from another magma.

In Figure 8 the modal data have been plotted on a sanidine-plagioclase-quartz diagram which shows that the samples vary from latite to quartz latite to rhyolite in mineralogical composition with a marked linear distribution parallel to the rhyolite-quartz latite boundary. In general, the samples plot progressively closer to the

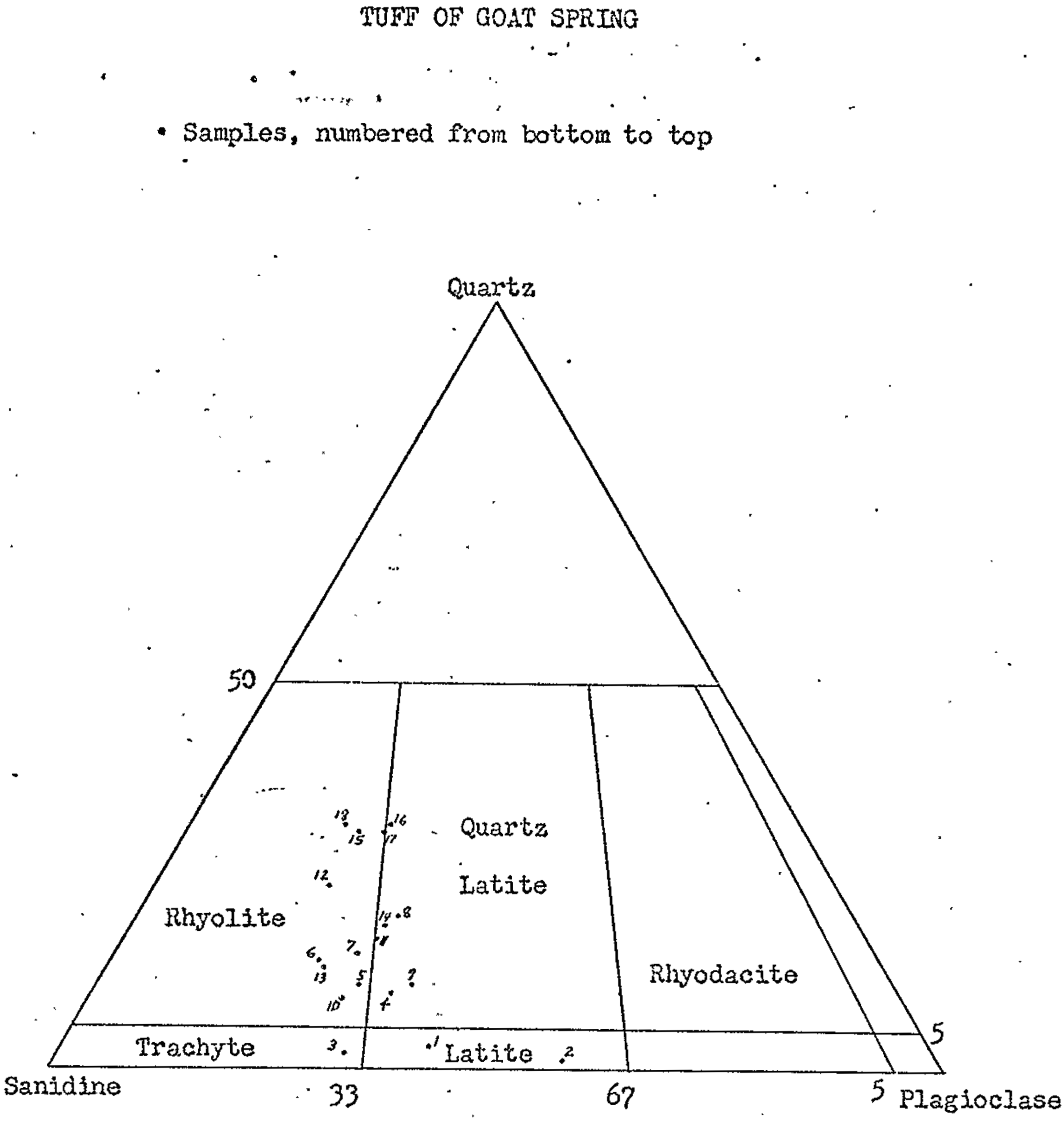


Figure 8. Modal data for the tuff of Goat Spring plotted on a three component diagram (diagram modified from Bateman and others, 1963, p. 13).

quartz corner of the diagram as the samples approach the top of the section. This trend suggests that the magma was undergoing differentiation along a crystallization path which formed more quartz but essentially a constant proportion of feldspars with time. Another explanation for the trend is that the magma became increasingly contaminated with quartz as the eruptions proceeded. The anomalously large quartz crystals may actually be xenocrysts accidentally incorporated during eruption of the tuffs. However, the large volume of quartz required and its systematic increase argue against this origin.

In addition to the changes in primary mineralogy there are some subtle changes in the texture and alteration within the tuff of Goat Spring. Biotite is more oxidized toward the top of the cooling unit where deuteric alteration was localized by the upward escape of volatiles during welding. Sanidine is more altered and secondary minerals more abundant in the less densely welded zones, which were more porous and underwent more intense vapor-phase crystallization. Although resorption occurs in all parts of the cooling unit, it is best developed in the upper, less densely welded part.

Tuff of Bear Springs. The tuff of Bear Springs is the informal name proposed for the sequence of ash flows, lava flows, and volcaniclastic sedimentary rocks in the upper part of the Hells Mesa Formation. In this report, it has been subdivided into two mappable units separated by a cooling break and interbedded andesite flows.

Lower Cooling Unit

The lower tuff of Bear Springs is a multiple-flow, compound cooling unit of welded rhyolitic ash-flow tuffs which outcrop over an area of about five square miles in the thesis area. The base of the unit is exposed along an approximate north-south line extending from the north end of the La Jencia monzonite stock to the east side of Bear Peak. To the south, it includes Loughlin and Koschmann's Banded Rhyolite and to the north it correlates with Tonking's middle 65 feet of the Hells Mesa.

The lower tuff of Bear Springs includes several ash flows, and varies considerably in its outcrop characteristics. Occasionally it forms rounded hills with a series of alternating ledges and slopes but it typically outcrops as weathered, platy slabs which form the dip slopes of hogback ridges.

In hand specimen, the color of the groundmass varies with the degree of welding from light gray to pinkish-gray or reddish-brown. Weathered surfaces are usually stained buff to reddish-brown. The ash flows are fine grained and contain only 10 to 15 percent phenocrysts of sanidine, coppery biotite, and smoky quartz. The sanidine is euhedral and varies from clear, with a silky-white chatoyancy, to pink and chalky where altered. Samples from the upper part are characterized by as much as 25 percent gray silicified pumice which shows varying degrees of compaction. Two types of lithic fragments are common; one consists of dark brown, aphanitic andesite and the other is a porphyritic biotite-bearing rhyolite.

Petrographically, the ash flows are very similar and consist of broken, partly resorbed phenocrysts of sanidine, quartz, biotite, and plagioclase in an aphanitic, partly devitrified groundmass. The welded portions have a eutaxitic structure defined by compressed and distorted glass shards and pumice. The groundmass is partly devitrified to fine-grained (0.01 mm to 0.1 mm) cristobalite and feldspar sometimes in spherulites or axiolites. In the less welded and less altered samples the groundmass consists of brown, cuspate and Y-shaped glass shards separated by extremely fine dust. Magnetite grains are finely dispersed throughout the groundmass in most samples.

Sanidine is the only major constituent and varies from six to eleven percent by volume. It occurs as unusually well-formed partially resorbed grains from 0.2 to 2.0 mm in length. Carlsbad twins and strained, broken crystals with undulatory extinction are common. The sanidine shows varying degrees of unmixing to perthite which is often intergrown with clear sanidine in irregular patches controlled by the sanidine cleavages. The original sanidine appears to have suffered an unusual degree of perthitic exsolution during dueteric alteration of the cooling ash flows; the perthitic grains were counted as sanidine in the modes.

Quartz is a minor constituent, and occurs as small, anhedral to subhedral, resorbed grains usually less than 1.0 mm in diameter. Occasional shreds of biotite, partially replaced by hematite and other iron oxides, make up the remainder of the phenocrysts. Usually, only a few small plagioclase grains can be found in a thin section.

A stratigraphic thickness of 507 feet was measured approximately one mile southeast of Bear Springs (T. 1 S., R. 4 W., Sec. 22). Figure 9 is a diagrammatic column

Table II. Modes in volume percent from the lower tuff of Bear Springs

Sample Number		Total pheno-crysts	Phenocryst Proportions					
			Sani-dine	Plagio-clase	Quartz	Mafics and opaques	Pumice	Total points counted
Top of unit								
1	M-24-69	2.4	2.0	0.0	0.1	0.3	11.4	1793
2	M-24-68*	1.9	1.1	0.1	0.3	0.4	14.0	1792
3	M-24-66	3.6	2.3	0.1	0.2	1.0	8.6	1990
4	M-24-65	3.8	3.2	0.1	0.2	0.3	7.1	2027
5	M-24-63	3.6	3.0	0.0	0.2	0.4	27.1	1917
6	M-24-62	4.0	3.1	0.0	0.1	0.8	17.8	2076
7	M-24-61	5.3	4.5	0.0	0.1	0.7	8.8	2123
8	M-24-60	3.3	2.7	0.0	0.1	0.5	16.0	1796
9	M-24-59	7.0	6.2	tr.	0.4	0.4	13.3	2395
10	M-24-58	5.2	4.8	0.0	0.1	0.3	15.5	2151
11	M-24-57	4.4	4.0	0.0	0.2	0.2	6.4	1783
12	M-24-56	7.1	6.1	0.0	0.6	0.4	1.2	1923
13	M-24-55	6.6	6.3	0.0	0.1	0.2	5.8	2120
14	M-24-54	5.0	4.5	0.0	0.3	0.2	0.2	2139
15	M-24-53	6.3	5.9	0.0	0.3	0.1	0.0	1751
16	M-24-52	6.5	5.8	tr.	0.6	0.1	2.1	2097
17	M-24-51	6.1	5.0	0.0	1.0	0.1	0.0	2400
18	M-24-50	7.0	5.9	0.1	0.7	0.3	0.1	1958
19	M-24-48	5.8	5.0	0.3	0.1	0.4	0.2	2131
20	M-24-47	5.6	4.5	0.0	0.5	0.6	2.4	2038
21	M-24-46	6.8	5.3	0.3	0.8	0.4	0.0	2223
22	M-24-45	7.8	6.8	0.0	0.6	0.4	0.0	1436
23	M-24-43	5.0	4.3	tr.	0.5	0.2	0.5	2329
Base of unit								

* Badly altered, with numerous phenocryst holes

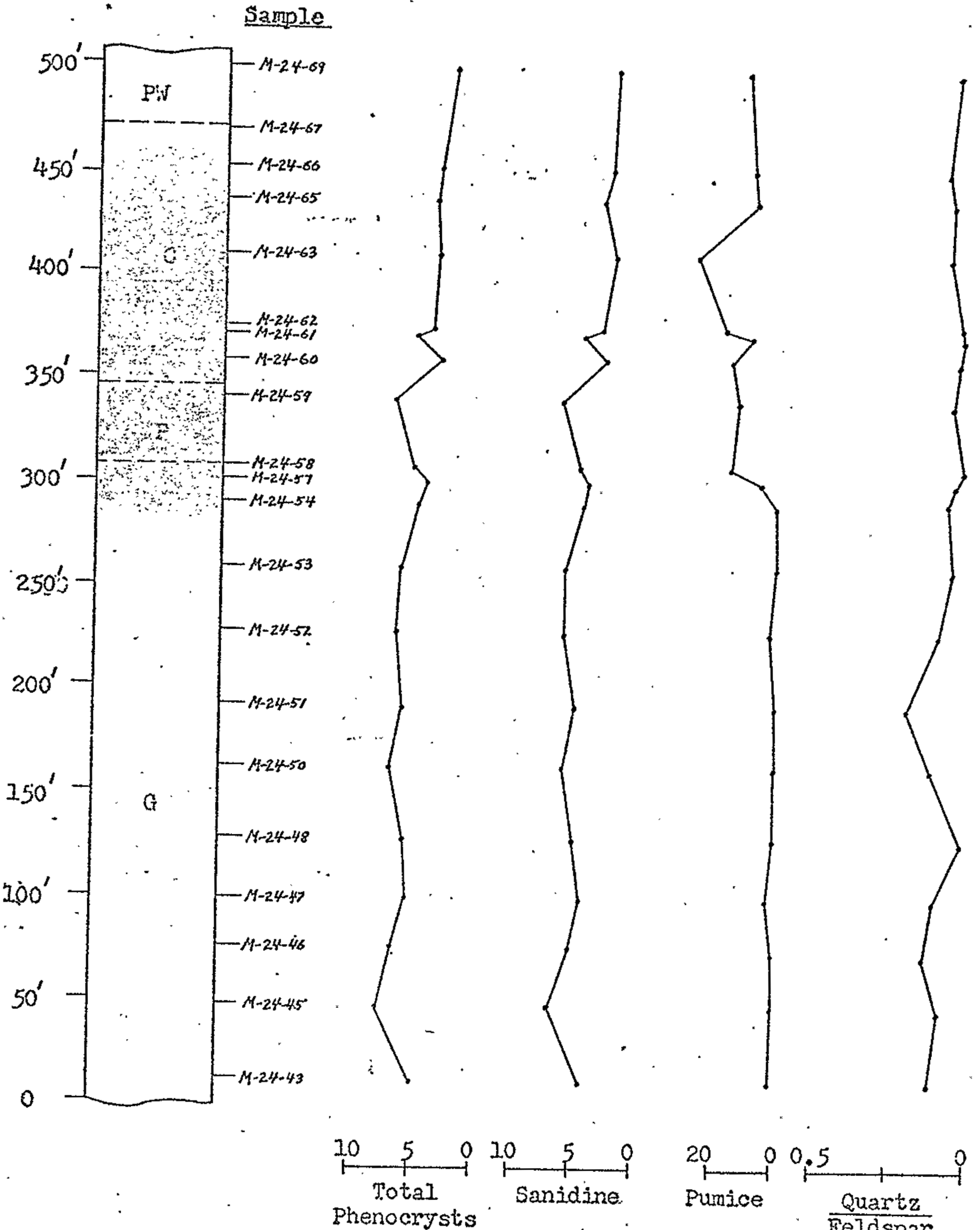


Figure 9. Measured section of the lower cooling unit in the tuff of Bear Springs showing mineralogical variations. Shading indicates degree of welding: dark gray-densely welded; light gray-moderately welded; white-poorly welded. (modal data are in volume percent, taken from Table II)

TUFF OF BEAR SPRINGS

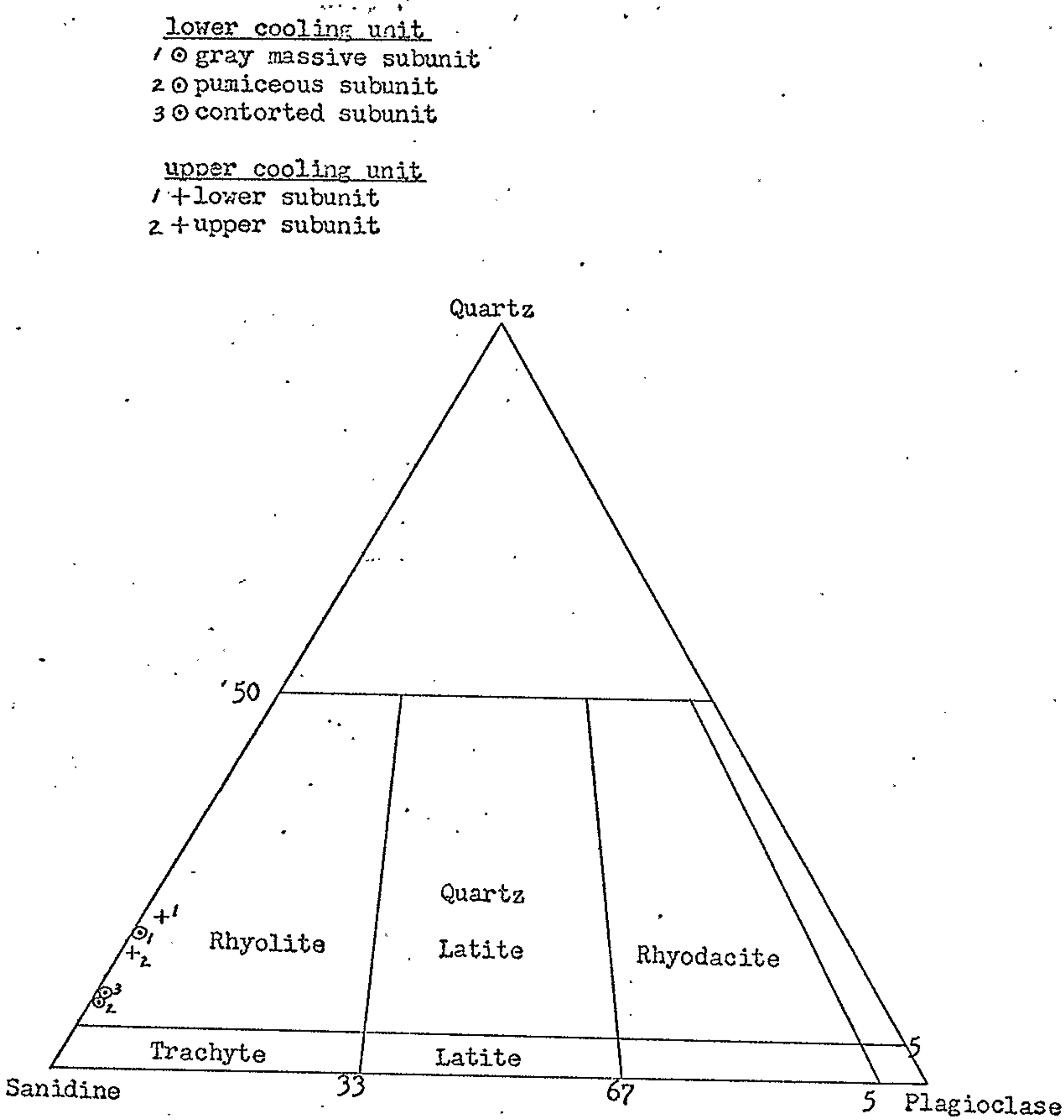


Figure 10. Modal data for the tuff of Bear Springs plotted on a three component diagram (diagram modified from Bateman and others, 1963, p. 13).

showing the individual subunits within the section, each one labelled according to its color or characteristic lithology. The presence of a thick densely welded zone in the upper part indicates that the section is a compound cooling unit. Modal data and sample locations are shown to the side. A distinct break in the modal profiles is evident near the middle of the cooling unit; this break corresponds to the contact between massive, featureless tuffs in the lower half and pumiceous tuffs with well-developed compaction textures in the upper half. The pumiceous tuffs contain slightly fewer total crystals, considerably more pumice, and slightly less quartz relative to sanidine than their more massive counterparts in the lower half.

The gray massive unit (G) is approximately 300 feet thick. The basal unwelded zone is pink in color and contains numerous brown andesite lithics and yellowish-white pumice lentils. The interior of the ash flow is light purplish-gray, moderately to poorly welded, and very fine-grained. Pumice is generally absent except in the upper and lower few feet. The white, poorly-welded top of the unit becomes increasingly reddened and welded upward through the contact with the overlying pumiceous unit.

The pumiceous ash flows (P) are about forty feet thick and are welded to the gray massive unit, with a gradational contact over a vertical thickness of about ten feet. Its color varies from purplish-gray to pinkish-gray. The name is derived from a striking eutaxitic structure defined by numerous flattened, elongated pumice, rotated lithic fragments, and subparallel imbricated sanidine phenocrysts. Petrographically, the groundmass is densely welded and the mineralogy is almost identical with the underlying massive ash flow. Pumice ranges in size from small, almost indistinguishable "ghosts" in the groundmass to large ellipsoidal fragments 3 cm in length. The pumice rims have been devitrified to quartz and fine-grained spherulitic aggregates and the centers often contain coxscomb aggregates of inward-pointing euhedral alkali feldspar crystals surrounded by larger anhedral quartz grains. The pumice commonly has frayed ends and contains phenocrysts of quartz and sanidine.

The contorted unit (C) contains a streaky compaction and/or laminar flow structure which resembles flow banding; this led Laughlin and Koschmann to give the name "Banded Rhyolite" to the equivalent of this unit in the Kelly mining district. The unit is about 120 feet thick and has a sharp but gradational contact with the pumiceous ash flow. It has a dark reddish-brown color on fresh surfaces and is characterized by gray, highly compressed pumice which averages only

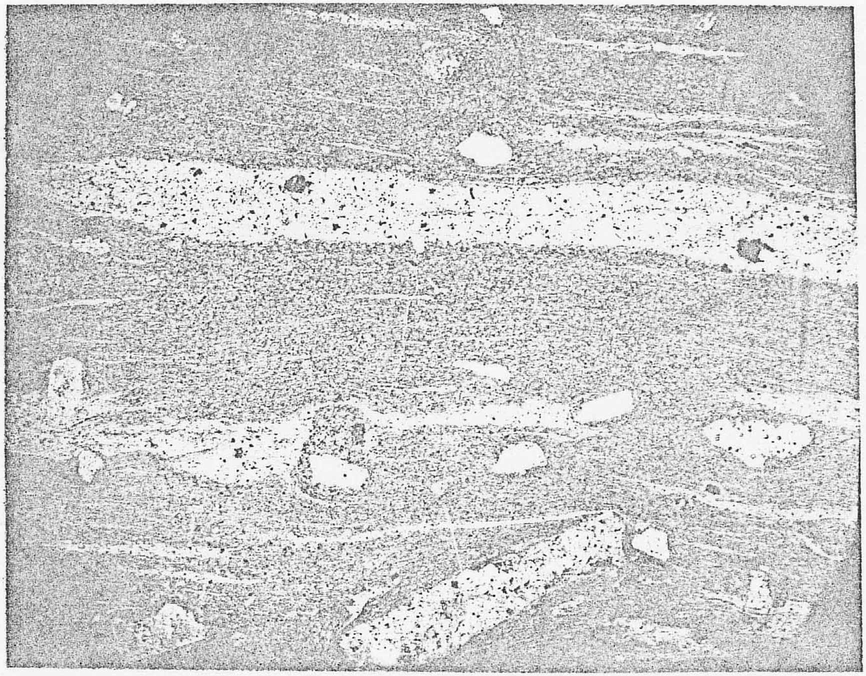


Figure 11. Contorted unit, lower tuff of Bear Springs, showing laminar-viscous flow textures and crystal-poor character. White bands and streaks are highly compressed pumice. Note large imbricated pumice in lower center. (12X)

2 mm. thick and ranges up to several inches long. The most highly compressed bands have a maximum length-to-thickness ratio of 300:1 which indicates that the pumice was radially stretched. Some of the larger streaks may represent the accumulation of volatiles along shear planes during laminar flowage and welding of the ash flows. Outcrops of the contorted ash flows usually have a platy fracture parallel to the foliation, and the banding is often contorted into tight asymmetric folds.

Microscopically, the ash flows are densely welded and composed mainly of highly flattened pumice in a glassy, partly devitrified groundmass. Pumice is often molded around the broken and rotated crystal fragments.

Above the contorted unit is an inconspicuous poorly-welded ash flow (PW) about 35 feet thick. It is soft,pinkish-gray, and contains abundant partially collapsed cellular pumice stained greenish-black by a manganese-bearing mineral. This tuff, which has only about two percent crystals, may represent the last weak pulse of ash to be erupted.

Just south of La Jencia Creek the lower tuff of Bear Springs contains a thin crystal-rich tuff which is not present in the vicinity of the measured section. This unit has been informally designated the tuff of La Jencia Creek (Chapin, oral communication, 1971); it is very similar to the tuff of Goat Spring but it is welded within the gray massive unit. Typical specimens are densely welded and slightly pumiceous with a light lavender-gray color. Phenocrysts of smoky quartz, euhedral sanidine, plagioclase, and coppery biotite make up 30 to 40 percent of the rock by volume. The tuff of Goat Spring contains 10 to 20 percent more crystals and its matrix is crowded with small crystal fragments.

Judging from their low content of phenocrysts and highly glassy matrix, the ash flows in the tuff of Bear Springs were probably quenched from a very hot eruption which was near the liquidus temperature of the original melt, perhaps as much as 900°to 950°C. based on the calculations of Boyd (1961, p. 414). This high temperature, together with their high volatile content, made the upper pumiceous ash flows particularly fluidal. As the ash flows began to lose momentum, exsolved gases may have acted as fluidizing agents causing them to develop laminar flow structures during the final stage of their emplacement (Noble, 1968). Pumice became highly stretched in the direction of flowage and wave-like flow folds and some ramp thrusts developed at right angles to the pumice lineation. In the Bear Mountains, the pumice lineation trends about S 10°W and the axial planes of flow folds and the ramp thrusts dip to the south. These data indicate a northward transport direction for the ash flows, which is consistent with the recent discovery by Deal and Rhodes (1971, oral communication) of a major cauldron in the Mount Withington area. A great thickness of ash-flow tuffs of similar stratigraphic position and lithology were deposited within the cauldron (op. cit.).

Upper Cooling Unit

The upper tuff of Bear Springs is a welded rhyolite ash-flow tuff sequence which crops out over about two square miles in the thesis area. Most of the exposures occur northwest of Bear Springs and along a ridge extending two miles south from Bear Springs. The upper and lower units of the tuff of Bear Springs are separated by five to seventy feet of andesite flows. Except for the presence of this cooling break, it would be difficult to distinguish the two since they are very similar lithologically.

The upper unit crops out as cliffs and rounded pinnacles which weather to reddish-brown platy surfaces, often highly fractured and hackly. The base is characterized by a zone with egg-shaped spherulites up to several inches long. Large slump blocks are common over the underlying, relatively soft andesites.

Fresh hand specimens are pinkish-gray and weather gray to reddish-brown. The groundmass is aphanitic and has a compaction foliation outlined by small, white, compressed pumice. Pink, silicified and contorted pumice up to 5 cm. long form up to three percent of some specimens. Phenocrysts are noticeably less abundant than in the lower unit and include white euhedral sanidine and occasional smoky quartz. Small angular lithic fragments comprise less than one percent of most samples and are similar to the lithics in the lower tuff of Bear Springs.

Microscopically, the upper unit contains from 0.1 to about 5 percent subhedral, broken sanidine phenocrysts which range from 0.2 mm. to 1.5 mm. in length. Usually, the sanidine is only incipiently altered along cracks and cleavages but some grains are completely albitized or altered to clay. Anhedral, broken quartz grains and opaque biotite pseudomorphs amount to less than one percent of the samples. Plagioclase was not found in any of the thin sections. The aphanitic groundmass is largely devitrified and consists of a mixture of glass and small crystallites of quartz and alkali feldspar.

A stratigraphic thickness of 280 feet was measured for the upper tuff of Bear Springs approximately two miles southeast of Bear Springs (T. 1 S., R. 4 W., Sec. 22 and 27). As shown diagrammatically in Figure 12, the unit seems to consist

Table III. Modes in volume percent from the upper tuff of Bear Springs

Sample Number		Total pheno- crysts	Phenocryst Proportions					
			Sani- dine	Plagio- clase	Quartz	Mafics and opaques	Pumice	Total points counted
Top of unit								
1	M-24-88*	7.0	5.5	0.0	0.6	0.9	12.7	1862
2	M-24-87*	5.1	3.7		0.8	0.6	12.1	2015
3	M-24-86*	5.4	3.7		0.7	1.0	6.6	1718
4	M-24-84*	4.3	2.9		0.8	0.6	18.3	2452
5	M-24-83*	3.9	3.0		0.6	0.3	11.6	2147
6	M-24-82	3.0	2.1		0.6	0.3	16.1	2500
7	M-24-81*	2.6	2.0		0.3	0.3	13.9	1920
8	M-24-80*	2.7	1.8		0.4	0.5	19.0	2480
9	M-24-79*	5.2	4.3		0.6	0.3	4.3	2170
10	M-24-78	0.2	0.1		0.0	0.1	9.0	1806
11	M-24-77	0.8	0.4		0.2	0.2	6.1	2062
12	M-24-76	0.1	0.1		0.0	tr.	13.0	1971
13	M-24-75	0.7	0.3		0.1	0.3	5.9	2225
14	M-24-73	2.4	1.4		0.8	0.2	7.8	2500
15	M-24-72	0.5	0.2		0.2	0.1	7.0	1922
Base of unit								

* Excluding crystal-rich clots

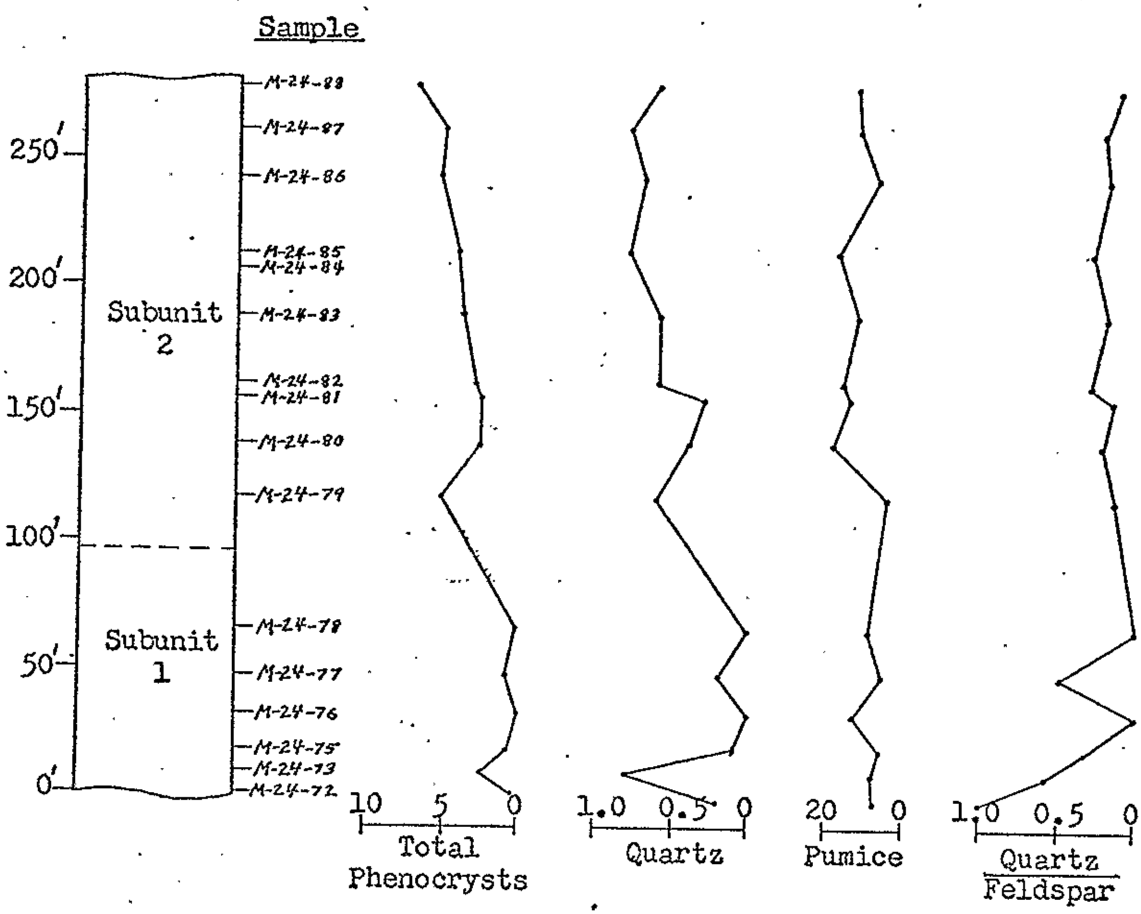


Figure 12. Measured section of the upper tuff of Bear Springs showing mineralogical variations (modal data are in volume percent, taken from Table III).

of two ash flows welded together. The two ash flows have subtle differences in outcrop characteristics and in modal percentages which are plotted to the side. The lower tuff is more massive and contains fewer crystal fragments than the upper tuff, which is platy and contains distinctly more pumice (as much as 20 percent) and more crystals.

For the cooling unit as a whole, the total crystal content increases steadily from less than one percent at the base to about seven percent near the top. The quartz/feldspar ratio increases sharply in the basal thirty feet and then remains nearly constant to the top. Figure 10 shows that the two cooling units in the tuff of Bear Springs are quite similar petrographically. The most noticeable difference is a slightly higher quartz/feldspar ratio for the upper cooling unit.

<u>Andesites Interbedded in the Hells Mesa</u>. Two distinctly different types of andesite flows are found interbedded with the Hells Mesa ash flows: (1) porphyritic "turkey-track" andesites containing abundant large plagioclase phenocrysts, similar to some of the andesites in the upper member of the Spears Formation, and (2) fine-grained, relatively non-porphyritic andesites lacking plagioclase phenocrysts.

The first type forms a distinct cooling break between the tuff of Goat Spring and the tuff of Bear Springs. The main outcrops form a narrow band extending from hill "7090", where its thickness was measured as 90 feet, north to Bear Peak where it appears to pinch out. These andesites have not been observed in the western half of the area.

Megascopically, the andesite is porphyritic and bluish-gray on fresh surfaces with abundant flow-oriented plagioclase phenocrysts and reddish-brown pyroxene pseudomorphs. Locally, it contains numerous amygdules filled with calcite and quartz.

Microscopically, the texture is holocrystalline and porphyritic-aphanitic. Plagioclase phenocrysts make up about 20 percent of the rock and occur as euhedral laths averaging 2.0 mm in length. Alteration is restricted to minor clays and epidote. An average composition of four plagioclase phenocrysts determined by the Fouqué method is An_{55}. Three grains exhibiting normal zoning were also measured by the Fouqué method; on the average, they range from An_{53} at the center to An_{49} at the rim. About ten percent reddish-brown pyroxene pseudomorphs occur as subhedral grains up to 1.5 mm in diameter. The pyroxene has been replaced by a fine-grained aggregate of calcite, epidote, and silica in the center and by hematite around the edges of the grains. The groundmass is made of felty plagioclase microlites about 0.2 mm long and small magnetite grains which may represent altered pyroxene. The approximate composition of groundmass plagioclase, determined from fifteen grains by the Michel-Levy method, is An_{57}.

The second variety of andesite occupies a cooling break between the upper and lower cooling units of the tuff of Bear Springs; they are present at this stratigraphic position on Hells Mesa but are not shown on Tonking's measured section. Andesite flows also occur between the tuff of Bear Springs and the tuff of Allen Well. Outcrops usually weather as dark talus-covered slopes or swales between hogbacks of welded tuff. Lineated amygdules filled with quartz, chalcedony, and calcite are common and are sometimes stained by greenish-blue celadonite. Thin volcaniclastic sandstone layers are locally intercalated with the flows. The fresh color of hand specimens varies from gray to reddish-brown while weathered surfaces are usually greenish-brown. Usually, the flows are dense and aphanitic with only a few phenocrysts of oxidized pyroxene but some flows are vesicular or autobrecciated. The thickness is quite variable, possibly because of some minor erosional topography developed in the underlying ash flows. Total thickness varies from less than ten feet to more than seventy feet.

Microscopically, these andesites contain about ten percent reddish-brown opaque phenocrysts which appear to be hematized pyroxene. The groundmass contains altered, trachytic plagioclase microlites and interstitial opaque grains of iron oxides and hematized pyroxene. The plagioclase is commonly argillized and the groundmass is often replaced by aggregates of calcite and quartz.

Tuff of Allen Well. The youngest ash flow present in the study area is a quartz latitic crystal-rich tuff which was observed in three small outcrops along Dry Lake Canyon in the southwest corner of the study area. The outcrops are located in section 36, T. 1 S., R. 5 W., downstream from the Allen Well. The tuff of Allen Well is separated from the upper cooling unit of the tuff of Bear Springs by a series of andesite flows and thin sandstones.

In hand specimen the tuff of Allen Well is pinkish-gray and contains as much as 30 percent phenocrysts of sanidine, plagioclase, coppery biotite, and quartz in a vitroclastic matrix. It strongly resembles the tuff of Goat Spring, but upon close inspection can be distinguished by the more abundant matrix, which is not crowded with small crystal fragments as in the tuff of Goat Spring. The tuff of Allen Well is also similar to the tuff of La Jencia

Creek but the former contains fewer total crystals and proportionately less sanidine.

Petrographically, the tuff of Allen Well consists of phenocrysts of sanidine, plagioclase, quartz, and biotite combined with flattened pumice and a few lithics in a reddish-brown devitrified groundmass. A modal count on one thin section yielded 14 percent sanidine, 7 percent plagioclase, 4 percent quartz, 4 percent biotite, 13 percent pumice, and 58 percent groundmass. Trace amounts of apatite and pyroxene are also present. The crystals range in size from 0.1 mm to 3.0 mm, with an average size of 0.5 mm.

La Jara Peak Formation

The La Jara Peak Formation forms the higher elevations in the Bear Mountains and crops out over about six square miles in the northwest part of the study area. The unit was described in detail by Tonking (1957, p. 44-46; p. 57) who named it after La Jara Peak, a prominent volcanic neck in the Puertecito Quadrangle, and designated it as the upper member of the Datil Formation.

The lower part of the La Jara Peak Formation is a series of relatively soft autobrecciated flows and thin volcaniclastic sandstones and conglomerates which form the low hummocky topography between Bear Springs and the eastern escarpment of the Bear Mountains. The upper part is a well-stratified, resistant sequence of thin basaltic-andesite flows which form the main escarpment of the Bear Mountains. The complete thickness of the La Jara Peak can only be approximated because of a major fault which has dropped the Bear Mountains over 1000 feet and has placed La Jara Peak andesites in juxtaposition across the fault. A minimum thickness of about 1600 feet has been estimated from structure cross-section A - A′ (Plate I), but the maximum thickness may be as much as 2900 feet. In the Puertecito Quadrangle, Tonking (1957, p. 31) estimated the maximum thickness as 2500 feet and measured 1205 feet at the type section.

Dips west of the Hells Mesa Fault range from seven to fifteen degrees to the west. The basal part, exposed on the upthrown east side of the fault, is relatively flat-lying and rests unconformably on the tuff of Bear Springs. The area west and southwest of Bear Springs appears to be part of an old erosional surface on the Hells Mesa ash flows which was later flooded by La Jara Peak andesites. In the vicinity of Deer Spring and Bear Springs, the contact between the andesites and the welded tuffs is partly depositional and partly a fault contact.

Figure 13. Typical outcrop of La Jara Peak Andesite. The massive core of a basaltic andesite flow at the top of the picture grades abruptly downward into an autobrecciated base. A thin ledge of fine-grained sandstone is sandwiched between the base of this flow unit and the upper rubble zone of another flow unit.

Talus, soil, and slump blocks partially obscure the lower outcrops and individual flow units cannot be traced for any appreciable distance. The flows are medium-gray, aphanitic, and sometimes scoriaceous. The lower part has a distinctive speckled appearance from the presence of small hematized pyroxene grains and contains almond-shaped amygdules filled with calcite and quartz. The lower flows have autobrecciated tops and bottoms which are often oxidized to a reddish-brown color. Sheeting parallel to the foliation is common in the vesicular flows. Intercalated with the flows are reddish-brown sandstones and conglomerates which contain reworked fragments of the underlying andesite.

The flows in the upper part are more massive and often contain fresh pyroxene along with the hematite pseudomorphs. Red glassy flows and bombs are present near the top of the formation. One feature characteristic of the entire La Jara Peak Formation is the absence of any plagioclase phenocrysts.

Many of the massive flows have elongated, lineated vesicles which have been plotted on the map as indicators of flow direction. The lineations trend an average of N 50°E in the western and northern parts of the outcrop area and about S 50°E to the south and east.

In the lower part of the formation there are a number of north-northeast-trending dikes which are identical to the La Jara Peak flows. These dikes could occupy local feeder vents for the flows. The basaltic-andesite flows may have been formed in coalescing eruptions from widely scattered fissures which lay partly within the study area, but largely to the west and southwest.

In thin section, the andesites have an aphanitic groundmass composed of trachytic to felty plagioclase microlites with an average length of less than 0.05 mm. In a few samples the plagioclase laths range up to 0.5 mm long and display carlsbad, albite, and carlsbad-albite twinning; the range in composition of these grains was measured as An_{40} to An_{55} with an average composition of An_{48} (average of fifteen determinations by the Michel-Lévy method). The groundmass also contains microlites of pyroxene, magnetite, and hematite.

Phenocrysts include 10 to 20 percent clinopyroxene and occasional xenocrysts of plagioclase and quartz. Clinopyroxene occurs as colorless to pale green, anhedral to euhedral grains from 0.2 to 1.5 mm in length. Basal sections often display polysynthetic twinning and a few grains are zoned. As much as half of the pyroxene is altered to hematite. Tonking (1957, p. 46) measured the refractive indices of the pyroxene and identified it as intermediate between diopside and hedenbergite.

Chemical analyses by Tonking (1957, p. 50) and Chapin (1971-a, p. 44) indicate that the La Jara Peak flows are quite rich in potassium which suggests that they may be alkalic in composition. Experimental studies by Green and Ringwood (1967, p. 142-148) on the fractional crystallization of basaltic magmas show that at a depth of 15 to 35 km, the liquidus phase of an alkali basalt magma is olivine in the early stages of fractionation followed closely by clinopyroxene. Plagioclase appears only at temperatures very near the solidus. If the La Jara Peak magma differentiated into basaltic andesite along an alkali trend, then the absence of plagioclase phenocrysts is explained by the late crystallization of plagioclase from the melt.

Tertiary Intrusive Rocks

Mafic Dikes

A large number of dark, aphanitic mafic dikes are found throughout the area. They are equivalent to the north-trending lamprophyre dikes in the Kelly district (Laughlin and Koschmann, 1942, p. 43) and to the basaltic dikes found in the Puertecito Quadrangle (Tonking, 1957, p. 32). Most of the dikes occupy a major fault zone which trends northward through the Kelly district and along the eastern edge of the Bear Mountains, varying from 1.5 to 2 miles in width. Although none have been found to cut the monzonite stock, the lower part of the La Jara Peak Formation is intruded by these mafic dikes in places. They were probably intruded over a considerable span of time, since different types are commonly emplaced side by side into the same fault zone. Most of the dikes were probably emplaced during the formation of this major fault zone in the Oligocene.

Individual dikes generally vary from a few feet to a thousand feet in length and one dike is over a mile long. They are generally narrow but range from 2 to 50 feet in width and probably average about 6 feet. Most of the dikes trend either north-south or about N 10°E, but a few trend almost east-west. Dips are predominantly eastward at angles from 70 degrees to vertical. In outcrop the dikes weather to shallow depressions deficient in vegetation and thus, tend to form visible lineaments on aerial photographs.

In hand specimen, a number of different varieties can be distinguished, but most are very aphanitic, black to greenish-gray on fresh surfaces, and stained rusty brown by limonite on weathered faces. Phenocrysts of pyroxene, hornblende, biotite, and plagioclase are present in some varieties and xenocrysts of quartz and plagioclase are common. A porphyritic variety contains plagioclase phenocrysts up to 5 mm long. Most of the varieties are too fine-grained and altered to be identified petrographically and they are best described as lamprophyres in the sense that they are dark, fine-grained rocks in which only ferromagnesian minerals usually occur as phenocrysts. The lamprophyres have an aphanitic groundmass composed of felty plagioclase microlites, pyroxene, iron oxides, and accessory amounts of biotite and slender apatite prisms. Plagioclase, which forms approximately 70 percent of the groundmass, occurs as subhedral laths from 0.05 to 0.2 mm long. The composition of the groundmass plagioclase in one unusually fresh sample was measured as An_{55} (average of 15 determinations by the Michel-Levy method). In most samples the groundmass is highly altered with the plagioclase altering to clays and the pyroxenes to chlorite and calcite. Pale green augite is the most common mineral and occurs both as groundmass microlites and as subhedral to euhedral phenocrysts from 0.1 to 2.0 mm long. The maximum extinction angle ($Z' \wedge c$) in the phenocrysts is about 45°.

Most grains show slight alteration to calcite, chlorite, and epidote along cracks and cleavages. Some augite is intergrown with plagioclase as glomeroporphyritic aggregates. The boundaries between the plagioclase and pyroxene grains are often resorbed and the plagioclase is sometimes penetrated by the pyroxene; however, some plagioclase contains poikilitic inclusions of pyroxene. Thus, the two minerals probably crystallized concurrently, at least in part.

There seem to be two varieties of plagioclase phenocrysts: (1) fresh, euhedral laths with sharp albite twinning, and (2) composite, often zoned crystals with irregular, partially resorbed boundaries. The zoned grains may be xenocrysts which crystallized at great depth since they are usually broken and have an undulatory extinction. The average composition of the zoned plagioclase is An_{55} with slightly more calcic cores. The composition of the uncorroded plagioclase averages An_{42}.

Tonking reported the presence of hornblende in some of the dikes of the Puertecito Quadrangle but none has been found in this area. A few dikes contain up to ten percent biotite as subhedral phenocrysts partly replaced by magnetite and chlorite. Xenocrysts of quartz occur as rounded and resorbed grains surrounded by reaction rims.

The nearly ubiquitous alteration of the dikes, together with the presence of alteration zones in the adjacent wall rocks, suggests that the dikes were either quite wet and reactive during emplacement or that the fractures occupied by the dikes were utilized by later hydrothermal solutions. The composition of the dikes argues against the first possibility; the intrusion of monzonite stocks following dike emplacement and the presence of mineralization along the edges and within some of the dikes supports a hydrothermal origin of the alteration. Immediately adjacent to the dikes the wall rocks are baked and silicified but the wall rocks are often bleached as much as fifty feet from the dikes. Sanidine phenocrysts in the ash flows are commonly replaced by limonite and epidote.

Larger Mafic Intrusives

Two elongate andesitic stocks occur in the southeastern part of the area along the margins and to the north of the monzonite stock. These intrusives represent the northern end of a line of augite andesite plugs and stocks which continues southward along the crest and west side of Granite Mountain. The stocks are 300 to 1200 feet wide and one to two miles long and were intruded into the major north-south fault zone (page 56) prior to emplacement of the monzonite stock and white rhyolite dikes.

The andesite which forms the stocks is very similar to the dark mafic dikes in the area and the stocks appear to be approximately contemporaneous with most of the dikes. Near Goat Spring the margins are autobrecciated and intruded by mafic dikes. Fresh hand specimens are purplish-gray and very fine-grained with abundant small plagioclase phenocrysts and about 10 percent greenish-black pyroxene phenocrysts.

In thin section, the texture varies from porphyritic-aphanitic to seriate. Phenocrysts include 5 to 10 percent subhedral plagioclase and 10 to 15 percent subhedral to anhedral clinopyroxene set in an aphanitic groundmass of trachytic plagioclase microlites and magnetite grains. The plagioclase phenocrysts average only 0.5 mm long and are partly altered to clays and epidote. The clinopyroxene has a maximum extinction angle of about 48° and may be an augite. The pyroxene grains are typically anhedral, average about 0.3 mm in size, and are completely replaced by calcite in the more altered samples.

Monzonite

In the southeastern part of the area, a monzonite intrusive crops out in sections 34 and 35, T. 1 S., R. 4 W. and sections 2 and 3, T. 2 S., R. 4 W. Because of its proximity to La Jencia Creek, it is herein referred to as the La Jencia stock. The stock includes a few dikes and apophyses with a total outcrop area of approximately ¼-square mile. Much of the monzonite has been buried by windblown sand and its total areal extent north of La Jencia Creek is probably more than one square mile. The La Jencia stock is roughly oval-shaped and is actually the northernmost end of an elongate monzonite body intruded into a major zone of weakness along the west side of Granite Mountain. The monzonite intrudes the tuff of Goat Spring and the lower tuff of Bear Springs; the latter has been silicified and warped up into a prominent ridge along the western margin of the stock. Small, isolated ash-flow outcrops which occur near the margins of the stock appear to be remnants of fault blocks formed by intrusion of the monzonite.

The monzonite is the youngest intrusive in the area with the exception of the white rhyolite dikes, a few latite dikes, and some of the youngest mafic dikes. Similar monzonite bodies in the Kelly district, the Nitt and

Anchor Canyon stocks, have been dated by the K-Ar method as 28.0 $\pm$ 1.4 m. y. and 28.3 $\pm$ 1.4 m. y., respectively (Weber and Bassett, 1963, p. 220). Monzonite dikes related to the La Jencia stock cut the surrounding andesite intrusives and since the monzonite is not cut by mafic dikes in the study area, most of the andesitic and lamprophyric intrusives are probably older than 28 m. y. Those mafic dikes which cut the La Jara Peak Andesite are, of course, younger.

The stock outcrops as angular, jointed cliffs or spheroidal boulders with a fine to medium-grained texture, whereas the monzonite dikes are generally fine grained. Hand specimens are light olive gray on fresh surfaces and weather to a yellowish-brown while more mafic varieties are finer grained and darker green. The texture varies from equigrangular to porphyritic-phaneritic. Grain size varies from 1 to 4 mm and the porphyritic varieties have chalky-white plagioclase phenocrysts up to 5 mm long. Phenocrysts visible in hand specimen include large plagioclase grains, smaller pink orthoclase, olive green pyroxene, biotite, and a few rounded quartz grains.

The monzonite is cut by a few small pink aplite dikes and near the west side of the stock the monzonite has incorporated some blocks of a dark siliceous rock, which may be xenoliths of Precambrian felsite (Loughlin and Koschmann, 1942, p. 9). Along the western margin of the stock, the typical monzonite grades over a distance of several feet into a dark greenish-black border facies which is more dioritic in mineralogical composition. The diorite contains more pyroxene and biotite than feldspars and has about twice as much plagioclase as orthoclase. Small steeply-dipping xenoliths of a dark mafic rock similar to the border facies are found in the interior of the stock, which indicates that the diorite may be an earlier intrusive that was later displaced and assimilated by the monzonite.

In thin section the monzonite has a hypautomorphic-granular texture of interlocking subhedral minerals with an average grain size of about 0.75 mm. The component minerals are about 80 percent feldspars with plagioclase in excess of orthoclase and accompanied by 10 to 15 percent biotite, from 0 to 5 percent augite, about 2 percent quartz, about 3 percent magnetite, and minor amounts of apatite and zircon. Plagioclase occurs as subhedral grains as much as 5 mm. in length with a compositional range from An_{27} to An_{48}. Most grains show argillic alteration. Orthoclase occurs with quartz as irregular grains interstitial to the plagioclase and pyroxene; some orthoclase is graphically intergrown with quartz. The augite is pale green, anhedral to subhedral in shape, and is sometimes micrographically intergrown with magnetite.

The monzonite intrudes rocks of very similar chemical composition, thus contact effects are minimal. Near the margins of the stock, the lower tuff of Bear Springs is baked to a dark greenish-gray hornfels. The dark color is caused by the presence of fine-grained epidote replacing part of the groundmass. The wall rocks are silicified as much as several hundred feet from the contact and are cut by numerous small quartz veinlets; a number of quartz-carbonate veins are present near the contacts. In addition to silicification, other alteration effects include bleaching, argillization of feldspars in the tuffs, and hematite staining adjacent to fractures.

Porphyritic Latite Dikes

A few small latite dikes are present in the southeastern corner of the area. All of the dikes occur within a two-mile radius of the La Jencia stock which some of them intrude; the latite is very similar to the monzonite except for grain size. The dikes are similar to the three small latite dikes mapped by Laughlin and Koschmann (1942, p. 33).

The longest dike crops out in an *en echelon* pattern for about 0.6 mile on the west slope of Nipple Mountain.

The dike trends approximately N 20 E and dips from 60 to 70 degrees east. The other latite dikes intrude the monzonite stock and the tuff of Goat Spring in Goat Spring draw and along La Jencia Creek. The latite is grayish green on fresh surfaces and is usually highly altered and disintegrated. Hand specimens are fine-grained and porphyritic with scattered, chalky plagioclase phenocrysts. Microscopically, the latite contains 10 to 20 percent plagioclase phenocrysts which average about 3 mm in length and are largely replaced by aggregates of clays, calcite, and epidote. About 10 percent clinopyroxene phenocrysts occur as anhedral grains almost entirely replaced by epidote, chlorite, and magnetite. The groundmass is a fine-grained intergrowth of about 80 percent argillized plagioclase microlites and about 15 percent orthoclase which is clearly interstitial to the plagioclase. The remainder of the groundmass is epidotized pyroxene grains.

White Rhyolite Dikes

The youngest intrusive rocks in the study area are white rhyolite dikes. Outcrops are restricted to the southeastern part of the area where dikes and small plugs have been intruded along the eastern half of the major north-trending fault zone. Individual dikes vary from 10 to 200 feet in width and from several hundred feet to over a thousand feet in length.

Multiple dikes are common within which the white rhyolite occurs adjacent to an older mafic dike. Outcrops are often flow-banded and many contain up to 10 percent limonite pseudomorphs after pyrite. The rhyolite is light pinkish-gray on fresh surfaces and weathers yellowish-gray to brown. Phenocrysts of quartz make up about 10 percent of the rock and small altered orthoclase crystals are sometimes visible.

In thin section, the rhyolite has a dense, microgranular groundmass made of irregular quartz and feldspar grains largely replaced by sericite. Quartz phenocrysts vary from 0.5 to 1.0 mm in diameter and occur as rounded, resorbed grains with reaction rims. Orthoclase phenocrysts are highly altered to calcite and sericite. Biotite is rare and occurs as subhedral grains replaced by muscovite and limonite.

Postvolcanic Deposits

Tertiary Deposits

Fanglomerate of Dry Lake Canyon. A series of soft, poorly-sorted volcaniclastic sedimentary rocks occurs interbedded with and overlying the La Jara Peak Formation. These rocks are extensively exposed in the southern part of the Puertecito Quadrangle where Tonking (1957, p. 34) designated them as the equivalent of either the Santa Fe Group or the Popotosa Formation. In the Silver Creek area, 15 miles to the east, basaltic andesites interbedded with the Popotosa Formation have been dated at 15.8 m. y. (Weber, 1971) which is considerably younger than the 23.8 m. y. age of the La Jara Peak Formation (Chapin, 1971-a). The Popotosa Formation (Denny, 1940), a basal unit of the Santa Fe Group, was deposited in middle Miocene to Pliocene time in block-faulted basins along the Rio Grande rift in central New Mexico. It consists of fanglomerates, playa deposits, and interbedded volcanic rocks; the clasts represent an inverted section of the Datil Group with older rocks becoming more abundant upward as erosion cut deeper into the bordering uplifts. The fanglomerate of Dry Lake Canyon contains mostly detritus from the La Jara Peak Formation but is similar in mode of deposition and perhaps age to the Popotosa.

The formation outcrops along the western margin of the study area in the vicinity of Dry Lake Canyon and in the low area west of the main Bear Mountains divide. The lower part is interbedded with flows in the upper La Jara Peak Formation. The formation dips about 6 degrees to the

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―――――――, 1971, K-Ar ages of Tertiary igneous rocks in central and western New Mexico: Isochron/West, n.1, p. 33-45.

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Willard, M. E., 1959, Tertiary stratigraphy of northern Catron County, New Mexico, in Guidebook of west-central New Mexico: N. Mex. Geol. Soc., Guidebook, 10th Field Conf., p. 92-99.

Winchester, D. E., 1920, Geology of Alamosa Creek Valley, Socorro County, New Mexico, with special reference to the occurrence of oil and gas: U.S. Geol. Survey Bull. 716-A.

west and has been eroded into strike ridges covered with heterolithic clasts of the underlying volcanic rocks.

The deposits consist of siltstones, sandstones, conglomerates, and mudflow breccias most likely deposited as westward-sloping alluvial fans along the margin of the Bear Mountains uplift. Outcrops range in color from pink to light brown and are generally poorly sorted and loosely cemented by calcite in a silty matrix. The conglomerates contain subrounded pebbles, cobbles, and boulders as much as one foot in diameter. Most of the clasts are derived from the La Jara Peak Formation but fragments from all parts of the Datil Group are present in minor amounts. Cross-bedding and channeling are common structures. In a roadcut just east of Dry Lake Canyon, a white airfall tuff and some stratified tuffaceous sandstones are interbedded with the other deposits. The airfall tuff contains white pumice lapilli up to one inch long cemented by reddish-brown silty material.

Quaternary Deposits

Pediment Gravels. The oldest surficial deposits in the area are thin veneers of poorly-consolidated pediment gravels. The most extensive pediment surfaces occur along the eastern margin of the area as gentle eastward-dipping surfaces at the edge of the La Jencia basin (Snake Ranch Flats). The pediments contain volcanic pebbles and cobbles derived from the underlying Datil Group, and in the extreme southeastern corner, clasts of Paleozoic and Precambrian rocks. A prominent caliche zone caps the pediment gravels and extends onto the talus cones along the east side of the southern Bear Mountains.

Talus, Landslides, and Colluvium. For the purposes of this study, talus, landslides, and colluvium were mapped collectively to delimit the aprons and fans derived from mass-wasting. The talus deposits are stabilized by a mantle of soil and grass and most are being dissected by shallow gulleys. They are relatively old deposits of probably Pleistocene age, have a well-developed caliche zone on their lower slopes, and merge downslope into the pediment surfaces.

Boulders as much as ten feet in diameter have slumped downhill from the cliff-forming ash-flow tuffs and have been partially buried by colluvium. The upper tuff of Bear Springs is particularly susceptible to slumping over the relatively incompetent andesites. The rotated slump blocks range in size to as much as several hundred feet in length and they often leave cirque-like scars at their heads.

Aeolian Sand. The pediment surfaces in the southern half of the area have been largely buried by a veneer of windblown sand. The sand shows up clearly on the aerial photos as light-colored areas with a definite northeast-trending grain. The thickest accumulations occur along La Jencia Creek, where up to twenty feet of the sand overlies pediment gravels, and in dunes which have developed on the windward side of some ridges. The windblown sand provides a shallow ground-water reservoir by trapping meteoric water above the relatively impermeable adobe soils and caliche of the pediment surfaces and usually supports a thick growth of juniper and sage.

Alluvium. In this report, alluvium is used to indicate recent stream gravels which have been deposited in the major drainages. It also includes deposits of deeply weathered valley fill which have obscured the bedrock. The older alluvium interfingers with and is approximately the same age as the windblown sand.

Petrogenesis of the Ash Flows

The purpose of this section is to summarize and interpret some of the petrographic and field data pertaining to the ash flows in the study area in order to reconstruct part of the area's volcanic history. The data is restricted to the Hells Mesa ash flows which have widespread outcrops in the area and have been sampled in some detail during the mapping. A more comprehensive petrologic study of the entire suite of volcanic rocks necessitates systematic chemical analyses but some preliminary conclusions can be drawn in the present investigation.

Petrographic Data

Figure 14 is a composite section which compares the mineralogy and abundance of crystals in each of the ash-flow cooling units. The diagram shows that there is a distinct gap in the abundance of phenocrysts between the crystal-poor ash flows and the crystal-rich ash flows. The former have an upper limit of 8.0 percent while the latter have a lower limit of about 30 percent. The relative percentages of the component minerals are designated by the histograms which also display a marked difference between the crystal-poor samples from the tuff of Bear Springs and the crystal-rich samples. The two cooling units in the tuff of Bear Springs are almost identical to each other but contain practically no plagioclase and relatively more sanidine than the crystal-rich units which are also quite similar to each other.

Peterson and Roberts (1963) studied a number of ash-flow sheets throughout the Basin and Range province of the

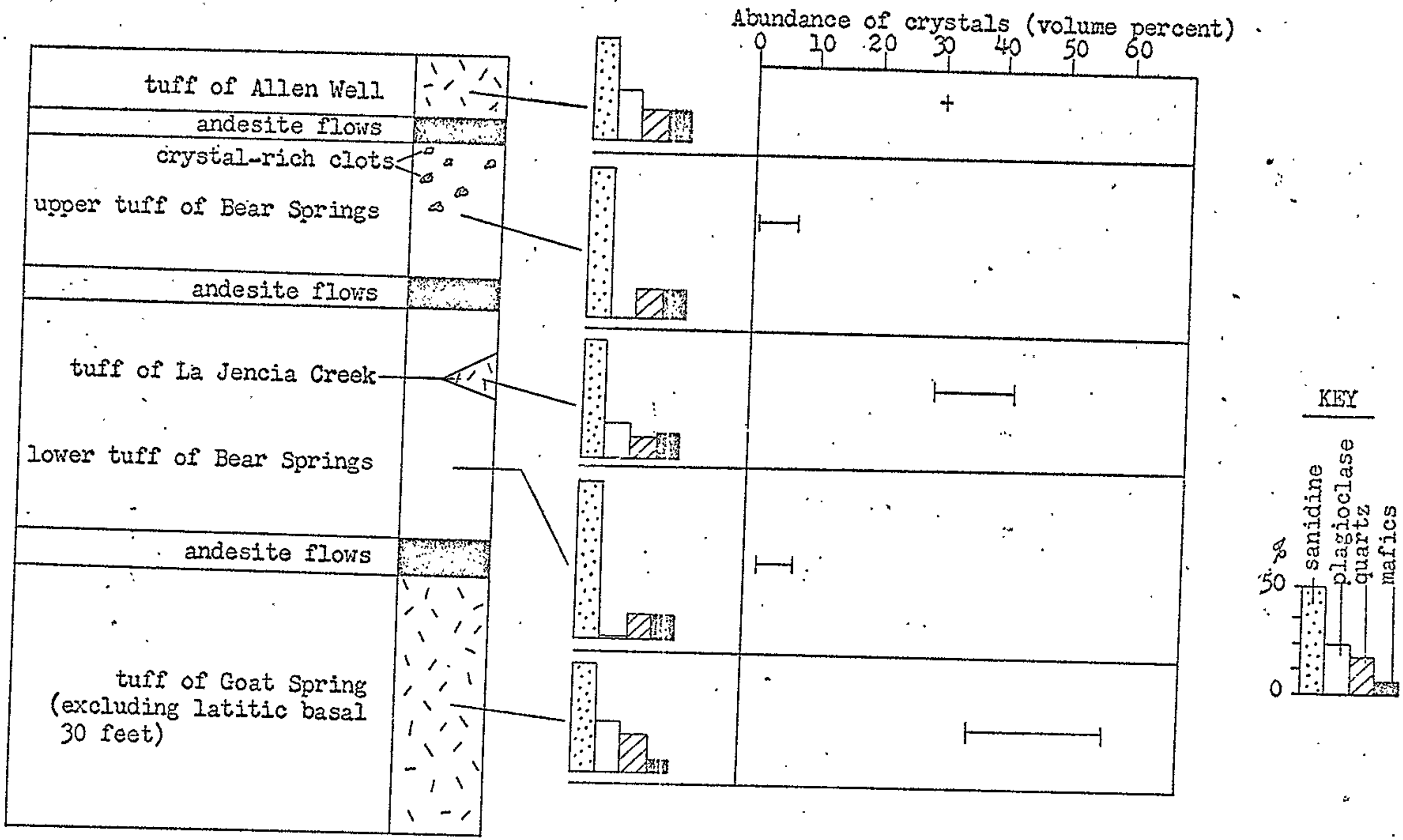

Figure 14. Composite section of the ash-flow cooling units, showing their average mineralogical composition and range in abundance of crystal fragments. (short dashes represent crystal-rich units.)

western United States and found that there is a relationship between the chemical composition and the crystal content of the tuffs. The crystal-poor welded tuffs contain less than 25 percent crystals and chemically are rhyolites. The crystal-rich welded tuffs have more than 25 percent phenocrysts and chemically range from quartz latite to dacite. The rhyolitic ash flows are also composed of smaller sized vitric fragments than the quartz latitic ash flows. Although the ash flows in the study area have not yet been chemically analyzed, the mineralogical compositions indicate that the crystal-poor ash flows in the Hells Mesa Formation are rhyolitic (Figure 10) while the crystal-rich ash flows plot close to the rhyolite-quartz latite boundary (Figure 8). Furthermore, petrographic examination shows that the crystal and vitric fragments are generally smaller in the crystal-poor tuffs.

Peterson and Roberts (op. cit.) suggested two possible hypotheses to explain these relationships: (1) differentiation by crystal settling and/or upward-migrating volatiles, and (2) partial melting. The end result of either process would be the formation of a crystal-poor rhyolite, high in silicas and alkalis, and a crystal-rich quartz latite or dacite, poor in silica and alkalies. Although it is difficult to demonstrate whether fractional crystallization or partial melting has formed a particular suite of rocks, the euhedral faces on many of the crystals and the presence of possible differentiation trends in the modal compositions suggest that the ash flows in the Hells Mesa were formed by differentiation in a shallow magma chamber although the original magma may have been derived by anatectic melting in the upper mantle or lower crust. The following sequence of events is postulated by the writer as a model of the crystallization history:

1. A melt of intermediate composition was emplaced into a relatively shallow holding chamber and began crystallizing. Early-formed mafic and calcic minerals settled toward the bottom of the magma chamber while volatiles and alkalies ascended toward the top. Gradually the magma segregated itself into an upper crystal-poor rhyolitic part and a lower crystal-rich level of quartz latitic composition.
2. Fissures tapped the lower level and crystal-rich ash flows (the tuff of Goat Spring) were erupted. These ash flows were latitic to quartz latitic in composition and contained relatively high percentages of mafic minerals and plagioclase.
3. Later, another set of fissures tapped the upper level of the magma chamber and erupted a series of crystal-poor ash flows (the tuff of Bear Springs).

These ash flows were rhyolitic in composition and were deficient in plagioclase and mafic minerals. In addition, they were rich in volatiles and hence more pumiceous and more fluidal as evidenced by their lineated pumice and other laminar flow structures.

4. From time to time the first set of fissures were reopened and more crystal-rich ash flows (the tuffs of La Jencia Creek and Allen Well) were erupted almost simultaneously with the crystal-poor ash flows.

Although this model is undoubtedly oversimplified, it does provide a reasonable conception of the mechanisms which may have produced the observed petrographic and field relationships. The composite section in Figure 14 supports the hypothesis by showing that crystal-poor and crystal-rich ash flows alternate with each other in a somewhat cyclical manner. The clots of crystal-rich material near the top of the tuff of Bear Springs suggests mixing of the two types of magma during the waning stages of that eruption. Except for the upper part of the tuff of Bear Springs, the two varieties of ash flows appear to have been erupted in intermittent pulses from two different sets of feeder vents. The data is insufficient to determine whether these vents were part of a plumbing system which tapped different levels of a single magma chamber or entirely different magma bodies. The general location of the ash-flow source or sources is discussed in more detail in the following section.

Directional Significance of Laminar Flow Structures

Ash-flow tuffs are thought to be emplaced in a highly turbulent gas-charged eruption but descriptions of laminar-flow structures in ash flows are becoming common in the literature. Most of these structures, which include lineations, folds, and flow banding have been attributed to secondary flowage caused by remobilization of the ash flows after deposition. However, some primary flow structures are produced by laminar flowage just before the ash flows came to rest and these structures may be used to determine the direction of movement (Schmincke and Swanson, 1967; Noble, 1968; Lowell, 1969; Elston and Smith, 1970). These primary laminar flow structures were first described by Schmincke and Swanson (1967) and include: (1) stretched pumice fragments; (2) rotated and broken pumice fragments; (3) tension cracks in the matrix; (4) hollows around rotated inclusions; (5) folds; (6) imbricated crystals, lithic, and pumice fragments; and (7) ramp structures. The ash flows in the study area contain some of these features, which are described and interpreted individually below.

Lineated Pumice. Compressed pumice ellipsoids and cavities left by the weathering of pumice are common in each of the cooling units. These ellipsoids bulge in the center and taper at either end. The long axes are parallel and define a lineation which trends consistently north-south in the tuff of Goat Spring and from north-south to N 30° E in the tuff of Bear Springs. Assuming that these lineations were produced during emplacement of the ash flows, the sense of movement appears to have been almost north-south with a slightly more northeasterly sense for the tuff of Bear Springs.

Rotated Inclusions. Schmincke and Swanson (1967, p. 653) described flow structures produced by differential flowage in the matrix around rotated inclusions. The structures are typically spindle-shaped and are defined by two cavities on diagonally opposite sides of the inclusion. The asymmetry of these cavities has directional significance since the hollow on the downslope side of the inclusion is consistently higher than the one on the upslope side.

The ash flows of the thesis area locally contain abundant lithic fragments up to several centimeters in diameter. In places, pumice has molded around these lithics or around phenocrysts to form a crudely spindle-shaped structure similar to these described above. The inclusions are slightly imbricated relative to the compaction foliation, and the deformed pumice is often highly crenulated on the downslope side of the imbrication where the foliation was jammed against the inclusion at the point of greatest pressure. When viewed in a vertical plane parallel to the lineation, the long axes of these spindle-shaped structures dip southward, presumably toward the source.

Folds and Ramp Structures. In places, the compaction foliation in the contorted ash flow has been warped into anticlines and synclines with amplitudes ranging from several inches to several feet. The shape of these folds varies from broad, wavelike undulations to tight, V-shaped flexures. The axes of all the folds observed are oriented west-northwest, normal to the pumice lineation. Axial planes of the asymmetric folds usually dip steeply southward. The broad warps have wavelengths up to several feet and may be ramp structures, so named by Schmincke and Swanson (1967; p. 656). One of these ramps, found near Bear Springs, is about six feet long and highly asymmetric with the steep side southward and with an axis which trends about twenty degrees north of west.

The folds are probably primary features produced by the compressional buckling of the contorted ash flow after the

Figure 15. Wavelike folds in the contorted unit, lower tuff of Bear Springs. View is looking west, perpendicular to the sense of movement.

pumice had largely collapsed and the ash flow was moving in a laminar manner just before coming to rest. The southward dip of the axial planes indicates that the ash flows of the tuff of Bear Springs advanced from south to north and their foliation began to wrinkle like a rug as the flow front lost momentum. Similar flow structures which indicate the same sense of movement have been mapped by Richard Chamberlin (oral communication, 1971) in the Gallinas Mountains. A possible source cauldron for the tuff of Bear Springs has recently been discovered by Ed Deal and Rodney Rhodes (oral communication, 1971) in the Mount Withington area of the San Mateo Range which is located about 30 miles to the south-southwest of the study area. A source in that general area is consistent with the laminar flow structures described in this report.

STRUCTURE

Regional Structure

The regional structural framework of west-central New Mexico has not been studied in detail. According to Eardley (1962), the area is part of the Sonoran-Chihuahua system, a subdivision of the Basin and Range province characterized by late-Cenozoic block faulting and volcanism. The Bear and Magdalena Mountains represent a north-northwest-trending, westward-tilted uplift bordered on the east by a downfaulted basin known as the Snake Ranch Flats or La Jencia basin. The late Cenozoic block faulting related to the Rio Grande rift zone has been superimposed on Laramide uplifts and basins which were beveled by a pre-volcanic erosion surface of regional extent. Within the framework of the Mogollon Plateau volcanic province the type-Datil rocks of the Bear Mountains are thought by Elston (1968) to occupy the outer rim of a large volcano-tectonic depression centered in the Mogollon Plateau.

Laramide forces warped the pre-volcanic rocks of the area into a series of plunging homoclinal folds and thrust belts (Darton, 1928; Kelley and Wood, 1946; Tonking, 1957; Kelley and Clinton, 1960). Laughlin and Koschmann (1942) found evidence that the Paleozoic rocks in the Magdalena District were arched into an elongated anticline which was beveled by erosion prior to deposition of the Tertiary volcanic rocks. Earlier writers attributed these folded structures to east-west compressive forces but Eardley (1962, p. 402) favors the role of vertical uplift due to a rising column of magma during the Laramide orogeny.

Since middle Miocene time, the Colorado Plateau and surrounding Basin and Range province have been subjected to crustal distension accompanied by volcanism. The cause of tensional forces may be a northwestward drift of the Colorado Plateau block, which has opened up the Rio Grande rift (Eardley, 1962; Chapin, 1971-b).

Local Structure

The area of investigation has had a long and complex history of recurrent faulting from middle Tertiary time until the present. An interpretation of the structure must explain several anomalous features of the area. First, Figure 16 shows that the study area occupies a low saddle between the Magdalena Mountains on the south and the Bear Mountains on the north. Second, there is a marked discordance between the general west-southwestward tilt of the rocks and the north-south alignment of the individual fault-block ridges. Third, reversals of the regional westward dip are present in places.

Oligocene Faults. The oldest deformation exposed at the surface within the study area is a series of closely spaced normal faults which have broken the eastern part of the area into a number of tilted blocks progressively stepped down to the east. These faults were developed during the Oligocene because they cut ash-flow tuffs dated at about 30 m. y. and are intruded by monzonite stocks dated at 28 m. y. The individual faults trend from about north-south to N 15 W. The fault planes dip steeply to the east at angles from 60 degrees to nearly vertical. The out-crop pattern of the map suggests that some blocks are bounded at either end by transverse faults which trend approximately east-west.

Some of the fault zones in this system have localized the emplacement of the andesite and monzonite stocks as well as numerous smaller dikes. Most of the dikes trend about north-south and dip steeply east, but many form a criss-cross pattern, trending from N 30 E to N 10 W. This pattern may be related to a conjugate set of fractures developed contemporaneously with the faults. The dike pattern, together with the predominant north to north-northwest trend of the faults, indicates that the tensional stresses which produced the fracturing were oriented east-northeast to east-west. This system of faults and dikes is part of a major zone of Oligocene faulting and intrusion which has a known length of over 25 miles from the central portion of the Magdalena Mountains through the Kelly mining district and northward along the east edge of the Bear Mount-ains to north of Riley (Chapin, oral communication, 1971). The zone is about 1½ miles wide in the Kelly district, 3 miles wide in the thesis area, and about 5 miles wide in the Riley area. It is characterized by closely spaced normal faults intruded by mafic dikes and by monzonite stocks and their related latitic to rhyolitic dikes. The regional extent and significance of this structural zone is only partly known but it was a major factor in the localization of monzonite stocks and ore deposits in the Magdalena area.

Basin and Range Faults. During the period of Basin and Range faulting, the Magdalena Range was uplifted into a westward-tilted horst bounded on the east side by the La Jencia basin. During the early stages of uplift a set of northeast-trending faults dropped the study area into a graben oriented obliquely to the Magdalena-Bear Mountains horst. The main period of uplift probably took place during late Miocene to Pliocene time because the faulting postdates the La Jara Peak Formation (24 m. y.) and both accompanied and followed deposition of the Popotosa Formation (the Silver Creek Andesite interbedded in the lower part of the Popotosa has been dated at 16 m. y. (Weber, 1971). Outcrops of the Popotosa Formation have been found on both sides and on the crest of the Magdalena Range and playa deposits of the Popotosa have been uplifted along the Socorro-Lemitar Mountains (Chapin, 1971-b). The major expression of this faulting in the southern Bear Mountains is a prominent north-northwest trending escarpment along the western margin of the La Jencia basin. This escarpment probably represents a zone of closely spaced normal faults progressively stepped down to the east. The presence of a recent fault scarp just outside the mapped area indicates that movement along this fault zone has continued up to the present.

Normal Faults

Faults of this system generally trend from N 10° E to N 20° W. Some of the northwesterly-trending faults may represent renewed movement along the Oligocene zones of weakness. The fault zones are often free of dikes, but contain fault breccia, calcite, and spring deposits. Evidence from slickenside surfaces and stratigraphic displacement indicate that the fault planes of the northeast-trending set dip an average of 75 degrees to near-vertical, and are downthrown to the west.

The Hells Mesa fault (Tonking, 1957, p. 38) extends for fifteen miles in a north-northwesterly direction through the Puertecito Quadrangle and its southern continuation has been traced for an additional six miles in the present area where it trends approximately north-south along the east side of the high Bear Mountains axis. The west side of this normal fault has dropped the La Jara Peak Formation down more than one thousand feet. In the Puertecito Quadrangle, Tonking estimated the throw as 500 to 600 feet and the horizontal displacement as greater than one mile. The Hells Mesa fault appears to be part of a system of subparallel faults which are progressively stepped down toward the west into a graben which lies between the Bear-Magdalena and Gallinas-San Mateo uplifts.

Oblique-Slip Faults

In the northeast corner of the area, a prominent fault-controlled ridge along the south side of Bear Springs draw juts out into the La Jencia basin transecting the regional northwesterly structural grain. The whole area south of Bear Springs draw is physiographically and structurally low and appears to have been moved down and to the east with respect to the main Bear Mountains to the northwest. As the Bear Springs area is approached from the north and south the strike of the outcrops swings from the regional N 15 W trend and becomes almost east-west. The ridges wrap around and are truncated at their northern ends. Many outcrops are warped up or down by drag next to the faults and tilted eastward on the downthrown blocks.

The cause of these physiographic features is a zone of northeast-trending faults in the vicinity of Bear Springs. The zone is about one mile wide and the aggregate vertical throw is approximately one thousand feet. Individual faults trend from thirty to forty-five degrees east of north and display a left-lateral sense of movement in plan view. It is not possible to prove strike-slip displacement in the study area because no dikes or other vertical structures are offset by the faults. However, left-lateral movement can be demonstrated along the southermost oblique-slip fault zone near Highway 60, where a zone of Oligocene dikes and faults has been offset about 0.8 mile. Part of the apparent strike-slip offset may be caused by the regional southwesterly dip of the rocks. The northeast-trending faults in the study area are part of a major oblique-slip fault system which has dropped the Tertiary volcanic rocks into a low saddle bounded on the south by the Magdalena Mountains and on the north by the main Bear Mountains (Figure 16; Chapin, 1971-b, p. 199).

The original fault traces of the oblique-slip system have been largely obscured by more recent uplift along the north-trending Basin and Range faults and their major surface expression is a strike-slip displacement of about 1.5 miles across Bear Springs Draw. Complex, mutually cross-cutting relationships between the two fault systems are suggested by the geologic map, which implies that the oblique-slip faults are genetically related to the tensional forces which have uplifted and tilted the Magdalena and Bear Mountains since Miocene time. The oblique-slip faults probably became dormant some time ago while the north-trending normal faults have continued to uplift the study area relative to the La Jencia graben.

The two major faults in the oblique-slip system are Deer Spring fault and Bear Springs fault. The block between these two structures is a northeast-trending graben which has displaced a section of the La Jara Peak Formation down and to the east. Deer Spring fault trends northeasterly across Deer Spring Canyon and offsets rocks of the Datil Group about 1000 feet down along its southeast side. South of Deer Spring the fault follows a topographic lineament through the La Jara Peak Formation in a north-northeasterly

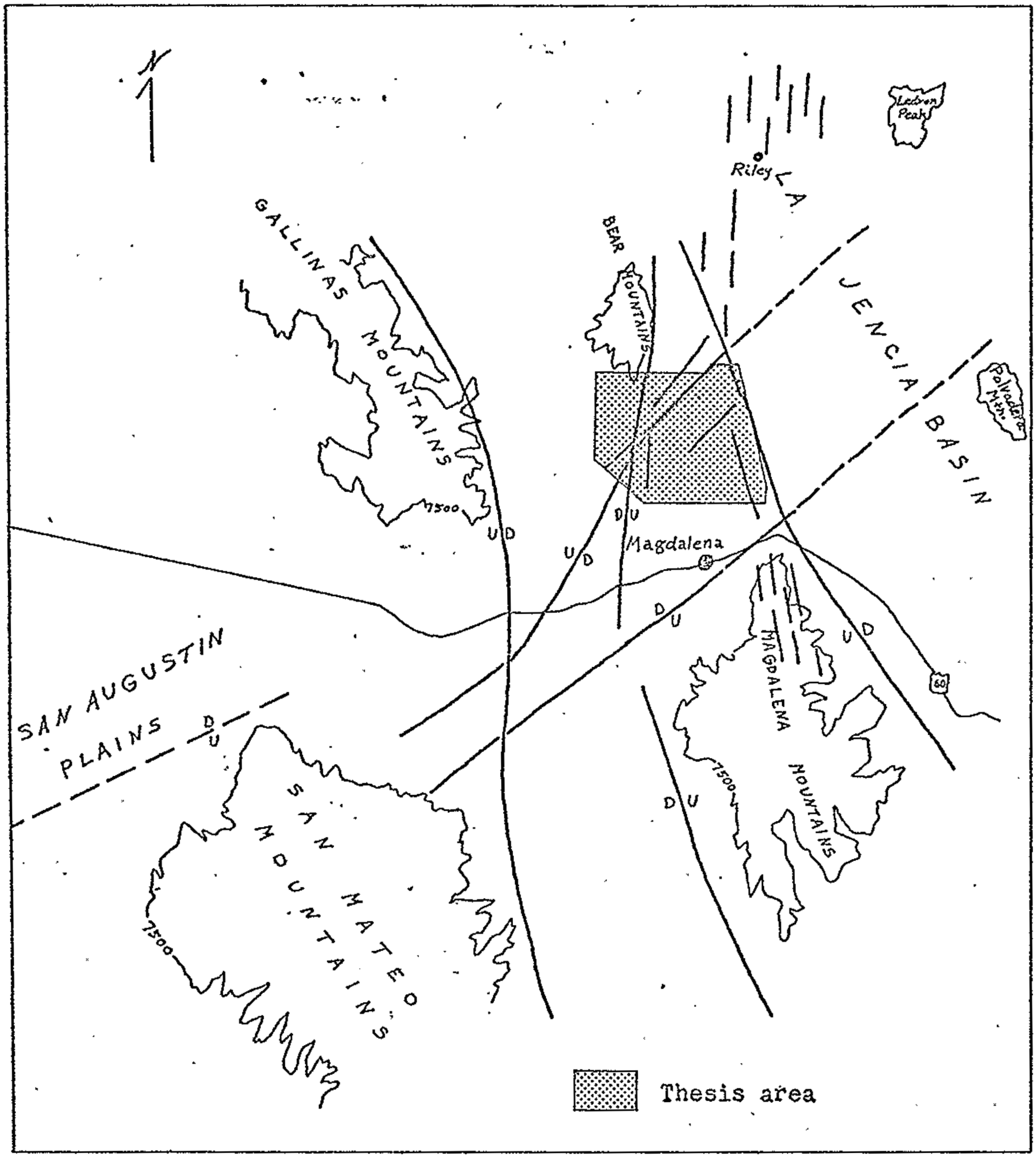

Figure 16. Location of thesis area with respect to the major structural elements in the Magdalena area. Dark lines represent major high-angle faults. Mountain ranges are outlined by the 7500-foot topographic contour.

direction, subparallel to the Hells Mesa fault. Bear Springs fault trends northeasterly in a topographic lineament along Bear Springs Canyon. South of Bear Springs ranch, this fault trends south-southwesterly for about one mile and then bends southwesterly again. The southeast side of the fault is upthrown and southward rotation of the upthrown block has flattened or reversed dips along the entire length. It is possible that Bear Springs fault was originally downthrown on the southeast side and the present sense of movement has resulted from reactivation of the fault zone during more recent uplift.

Folding

The only major fold visible at the surface is a broad, flat-bottomed syncline. The axis of this flexure trends in a north-northwesterly direction and bisects the southern half of the area into an eastern limb which dips to the southwest and a western limb which dips to the southwest. Near the axis the ash-flow tuffs are nearly horizontal. At least four explanations for this reversal of the regional westward dip occur to the author: (1) east-west compressional stresses, (2) compaction dips along the sides of a paleovalley, (3) intrusive doming, and (4) fault-block tilting. The first explanation, favored by Johnson (1955), seems least likely in view of the tensional stresses present since middle Tertiary time.

The original outcrop pattern of the fold has been considerably modified by faulting, which makes it difficult to evaluate the remaining possibilities. If the entire southern Bear Mountains are on the southwestern limb of a major southward-plunging arch (Tonking, 1957, p. 37), then it is possible that the Oligocene ash flows were emplaced along a northwest-trending synclinal valley. Ash flows are highly mobile and are known to fill in low areas like water. In support of this possibility, the axis of the fold is almost on trend with the axis of a synclinal paleovalley in the Puertecito Quadrangle (Tonking, 1957, p. 24). If the ash flows of the Datil Group were emplaced into this paleovalley, compaction dips along the sides would explain the reversal in the dip of the ash flows and the trend of the valley axis would explain the consistent north-south lineations in the ash flows. However, it seems likely that the low relief on the prevolcanic surface would have been largely filled and levelled by Spears sedimentation prior to eruption of the ash flows unless erosion exhumed part of the topography.

An alternative explanation for the fold is that the west limb of the syncline was domed up by a concealed intrusive similar to the La Jencia monzonite stock which warped up part of the east limb. The attitudes of the volcanic rocks in the southwestern part of the study area form a crudely arcuate pattern around the highest point on the north-trending ridge which forms part of the west limb. If such a dome originally existed, its form was largely obscured by normal faulting which collapsed the center of the intrusion into a graben bounded on the east side by the Hells Mesa fault. Although no surface exposures of any large intrusives have been found west of the La Jencia stock, the ash-flow tuffs in the vicinity of Allen Well are hydrothermally altered along fracture zones and most of the tuffs are silicified to some degree up to one mile north of La Jencia Creek. This alteration was probably produced by the localization of hydrothermal fluids along numerous faults, but evidence is lacking to determine whether the fluids ascended from an underlying intrusive.

Another explanation for the fold is tilting due to block faulting. The regional southwesterly dip reverses and becomes southeasterly along a line passing diagonally across the study area from Bear Springs draw on the northeast across the northern end of the synclinal structure and southwestward beneath the alluvium towards Allen Well. Immediately south of this line, which coincides with a zone of northeast-trending faults, the outcrops either flatten or dip southeastward as if tilting and/or drag has warped the strata out of their previous attitudes. The west limb of the synclinal structure is located at the intersection of north-trending Basin and Range faults with northeast-to-east trending transverse faults which have dropped the major portion of the study area into a northeast-oriented graben. Unfortunately, sand has covered the critical zone of intersection in the southwestern corner of the area but the topography and the repetition of units suggests that the west limb of the syncline is a horst bounded on the west and north by major downdropped blocks. The rotational sense of the horst would be away from these two grabens, which might produce the southeastward tilt observed along the ridge held up by the horst. However, the ridge is over 3 miles in length and the southeasterly dips persist to the south boundary of the map area. This seems too great a distance to explain by tilting along the northeast-trending faults.

A curious feature of the western limb of the syncline is that the strike of the beds is generally transverse to both the synclinal axis and to the north-trending faults which have truncated it on the west. This makes the structure difficult to explain by either compressional folding or block faulting and lends some credence to an origin by intrusive doming or compaction over buried topography. Further mapping to the south may shed some light on this problem.

ECONOMIC GEOLOGY

The study area is situated just north of the Kelly mining district, an important producer of lead, zinc, and silver ores until about 1949 (Titley, 1959). Most of the mineralization occurs along the west slope of the Magdalena Mountains in a major fault zone which trends N 10° W and is over a mile in width. Past production has been mainly from vein and replacement-type ore deposits extending to the south of the Nitt Stock for about three miles along the fault zone. The fault zone and the monzonite stocks extend northward along the west side of Granite Mountain into the southeastern corner of the study area where a number of weakly-mineralized epithermal veins occur in the vicinity of the La Jencia monzonite stock.

Most of the veins in the study area are located along the western and northern margins of the La Jencia stock. The veins vary in width from a fraction of an inch to zones as much as five feet wide. One set of veins roughly parallels the western contact of the stock; these trend from about due north to N 20° E and dip 70° to 85° east. A second set trends from about N 45° E to almost east-west and dips 55° to 75° southeast. A third set parallels a strong N 30° W joint set within the stock. Many of the veins are localized near contacts of the monzonite with the tuff of Bear Springs or with the andesite intrusives.

Gangue minerals include quartz, calcite, siderite, and barite. The quartz was deposited early in the form of small veinlets and massive silica. The carbonate minerals occupy veinlets and cavities in brecciated cherty quartz. Apparently the early quartz-filled veins were reopened and sealed with carbonate minerals and barite. Sulfide minerals are found primarily in veins which cut the tuff of Bear Springs where it is warped up and silicified along a ridge parallel to the contact. The sulfides include small grains of pyrite, galena, chalcopyrite, and sphalerite disseminated in the massive quartz. A trace of malachite is also present in some areas. Some of the calcite has a black color from the presence of internally disseminated cryptomelane, a potassium-bearing form of psilomelane (Charles Walker, oral communication, 1971). The sulfide-bearing veins in the tuff of Bear Springs have been mined to a shallow depth with shafts connected by drifts. The absence of significant amounts of ore minerals in the dumps indicates that the veins may have been worked for their gold or silver value.

The La Jencia monzonite stock and its associated veins appear to represent the roof zone of a large intrusive body which was emplaced within 2000 feet of the Oligocene surface (C. E. Chapin, oral communication, 1971). Evidence found in the study area which supports this conclusion includes the presence of roof pendants of the tuff of Goat Spring within the monzonite, the high stratigraphic position of the La Jencia stock, and the structurally low position of the study area relative to the Magdalena Mountains. Although the silicic ash-flow tuffs now exposed at the surface were not very reactive to hydrothermal fluids, the Paleozoic limestones buried at depth might contain replacement deposits similar to those farther south, in the Kelly district. The present study indicates that such deposits would be buried beneath a Tertiary volcanic cover about 2000 to 2500 feet thick in the vicinity of La Jencia stock.

The La Jara Peak Andesite is also mineralized, but not within the study area. In the Silver Hill area to the southwest and at the Baca prospect near Hells Mesa, the andesites are cut by veins which follow brecciated fault zones. The veins contain quartz and calcite as gangue minerals and chrysocolla together with minor amounts of copper carbonates and chalcocite as ore minerals (Lasky, 1932, p. 38-41). The deposits are localized along the Hells Mesa fault zone, which suggests a second period of mineralization subsequent to deposition of the La Jara Peak Andesite (24 m. y., Chapin, 1971-a) and the beginning of Basin and Range faulting.

Another area of mineralization occurs in the La Jara

Peak Andesite south of the study area, between La Jencia Creek and Magdalena (Lasky, 1932, p. 41-42; Loughlin and Koschmann, 1942, p. 163). Mapping in this area by C. E. Chapin (oral communication, 1971) has revealed the existence of west-northwest, northwest, and northeast-trending veins containing quartz, barite, carbonates, and minor amounts of galena.

The exposed portion of the La Jencia monzonite stock is quite fresh and barren and offers little encouragement for finding disseminated sulfide mineralization. Loughlin and Koschmann (1942, p. 111-112) concluded that mineralization in the Kelly district is not related to the exposed stocks but rather to major faults which served as conduits along which the ore fluids ascended from a great depth.

A more favorable exploration target may exist just west of the study area, where two factors suggest the presence of a concealed intrusive: (1) the west limb of the synclinal structure (p. 90) may be related to magmatic doming, and (2) a small area of intense hydrothermal alteration occurs along Council Rock Arroyo, in the extreme southwest corner of the mapped area. The postulated intrusive would be located somewhere between the Bear and Gallinas Mountains.

GEOLOGIC HISTORY

Prevolcanic History

In late Cretaceous and early Tertiary time, Laramide orogenic forces uplifted the area to the north of the Bear Mountains to form the north-trending Lucero arch and Comanche thrust belt. Another major uplift formed to the south and southeast of the study area; its western flank trends northeastward through Magdalena and the southern Bear Mountains. Erosion of these highlands during early Tertiary time resulted in the deposition of as much as 1000 feet of arkosic sediments to form the Baca Formation of Eocene age (Kelley and Wood, 1946; Snyder, 1971).

By the end of the Eocene, erosion had beveled the uplifts and filled the basinal areas to form a low, undulating surface with northwest-trending synclinal valleys. One of the largest of these valleys probably headed west of the Lucero uplift and drained southeastward through the center of the study area (Tonking, 1957, p. 24).

Volcanic and Postvolcanic History

In early Oligocene time, a volcaniclastic alluvial apron spread across the Magdalena area as a result of erosion of andesite and latitic volcanic rocks being erupted in the heart of the Mogollon Plateau volcanic province to the south and southwest. After deposition of more than 1000 feet of alluvial detritus, the eruptions encroached on the Magdalena area and mudflows, ash flows, and lava flows from local centers spread over the alluvial apron. Porphyritic andesite flows and the tuff of Nipple Mountain spread over a wide area of the alluvial apron to form a very useful marker horizon above the thick and monotonous sequence of fluvial conglomerates. Continued transport of volcanic detritus away from the center of the field buried the tuff of Nipple Mountain. The nature of the eruptions, however, became increasingly violent so that fluvial deposition gave way to mudflows and then to culminating eruptions of latitic ash flows. An ensuing period of hydrothermal alteration and erosion is recorded in the hematite-stained conglomerate which marks the top of the Spears Formation in the southern Bear Mountains.

The ash flows in the upper Spears signaled the beginning of a period of catastrophic pyroclastic eruptions which buried the Magdalena area beneath nearly 2000 feet of tuffs. The first of these great eruptions formed the tuff of Goat Spring (30.6 $\pm$ 2.8 m. y., Weber and Bassett, 1963; 32.1 $\pm$ 1.5 m. y. and 32.4 $\pm$ 1.5 m. y., Weber, 1971, p. 40-41). Fissures tapped the lower part of a fractionally crystallizing magma chamber to form these very crystal-rich ash flows. The exact location of the source is not known, but flow structures suggest that it may have been to the south of Magdalena. In the study area, the ash flows may have flowed northward along a broad paleo-valley largely filled with Spears sediments.

Welding and cooling of the tuff of Goat Spring was followed by the eruption of porphyritic andesite flows. Partial collapse of the magma chamber roof may have sealed off the fissure vents temporarily. A period of relative quiessence was marked by minor erosional reworking of the surface and the deposition of andesite flows.

Renewal of pyroclastic volcanism began with the eruption of the tuff of Bear Springs which has not yet been dated. The source of this ash flow sequence appears to have been a major cauldron centered in the Mount Withington area at the north end of the San Mateo Mountains (Ed Deal, oral communication, 1971). A very hot, crystal-poor series of ash flows entered the study area from the southwest and welded together to form the lower cooling unit. The upper ash flows of this unit were pumiceous and very fluidal; they flowed in a laminar manner just before coming to rest as evidence by stretched pumice and abundant small flow folds whose axes are perpendicular to the pumice lineations. The tuff of La Jencia Creek was erupted contemporaneously with the non-pumiceous tuffs in the lower tuff of Bear Springs, but these crystal-rich ash flows advanced only as far as the southern margin of the study area.

A short period of quiescence followed and minor erosional relief was developed on the lower cooling unit. A series of thin andesite flows then entered the area along the low central axis of the paleovalley. Continuing eruptions from the Mount Withington cauldron deposited the upper cooling unit of the tuff of Bear Springs in the central part of the area.

Following the deposition of more andesite flows and thin volcaniclastic sandstones, the tuff of Allen Well was erupted. These crystal-rich ash flows represent the youngest Datil Group volcanic rocks found within the study area. Other ash flows may have been emplaced during the waning stages of volcanism and stripped by erosion from the study area. By the end of this period of volcanism, which may have spanned as much as four million years, the prevolcanic drainages were largely filled and the area was part of an extensive constructional plain.

In late Oligocene time, the volcanic rocks were broken and tilted by block faulting along a wide north-trending fault zone. Faulting may have been initiated by the upward movement of magma during the last stages of effusive activity. A number of dikes and stocks were intruded along this fault zone, including the Nitt and Anchor Canyon monzonite stocks (28.0 $\pm$ 1.4 m. y. and 28.3 $\pm$ 1.4 m. y., respectively; Weber and Bassett, 1963, p. 220). The La Jencia monzonite stock, which has not been dated, was emplaced close to the surface at this time. Hydrothermal fluids ascending along the margins of these stocks deposited quartz veins and minor low-temperature sulfides in fractures.

After this period of structural modification, erosion dissected the volcanic rocks into a low undulating topography. Volcanism began again in early Miocene time with the extrusion of the La Jara Peak Formation (23.8 ± 1.2 m. y. , Chapin, 1971-a). Thin basaltic andesite flows flooded the topography; these sporadic eruptions were separated by local surface reworking and sedimentation in lava-dammed streams.

After a period of time sufficient to deposit as much as two thousand feet of lava flows and sediments, the volcanic activity began to subside and faulting related to the opening of the Rio Grande rift began. The area was uplifted and tilted to the west by normal faults along the west boundary of the La Jencia graben. While the area was being uplifted, a set of oblique-slip faults dropped the southern Bear Mountains into a northeast-trending trough bounded by the high Magdalena Range on the south.

Concurrently with uplift, a great thickness of La Jara Peak Andesite was stripped by erosion from the high areas. A north-trending graben bounded on the east side by the Hells Mesa fault preserved a thick section of the La Jara Peak

Formation and became filled with the fanglomerate of Dry Lake Canyon. Airfall tuffs interbedded with the fanglomerates indicate that volcanism may have accompanied faulting in the nearby area.

During the last stage of deformation the fanglomerate of Dry Lake Canyon was uplifted, tilted, and partially removed by erosion. In Quaternary time, an extended period of erosion dissected the tilted fault blocks and developed extensive pediment surfaces which were later buried by sand blown into the area from the southwest, possibly from the San Augustin Plains and La Jencia Creek.

CONCLUSIONS

The southern Bear Mountains have been the site of at least two major periods of volcanism separated by a span of several million years: (1) an Oligocene period of early latitic and andesitic eruptions and later rhyolitic pyroclastic eruptions which produced the rocks known as the Datil Group, and (2) a Miocene period of basaltic andesite volcanism which produced the La Jara Peak Formation. The combined thickness of these Tertiary volcanic rocks and their clastic derivatives may be six thousand feet or more.

The Hells Mesa Formation, which forms the upper part of the Datil Group is thicker and more varied than previously described by Tonking (1957). Cooling breaks between ash flow units are occupied by thin andesite flows and clastic rocks. Crystal-poor rhyolites and crystal-rich quartz latites form two distinctly different types of ash-flow tuffs. These contrasting tuffs appear to fit the model of Peterson and Roberts (1963), by which the pumiceous rhyolites are thought to be erupted from vents which tap the volatile-rich upper level of fractionating magma chamber, while the crystal-rich quartz latites are thought to be derived from a crystal mush accumulating in the lower part of the magma chamber. The two varieties of ash flows were erupted by overlapping and partly simultaneous activity. Laminar flow structures indicate that the source of the tuff of Bear Springs lay somewhere to the south or southwest.

Following, or possibly accompanying, the last stages of Oligocene volcanism, north-trending normal faults tilted the rocks westward and localized the emplacement of hypabyssal intrusives. The largest of these intrusives in the study area, the La Jencia monzonite stock, was forcefully injected close to the surface and tilted the volcanic rocks along its western margin. Hydrothermal fluids later deposited epithermal veins in fractures and fault zones near the stock. The veins are generally barren of ore and the present study indicates that any lead-zinc replacement deposits in the Paleozoic limestones would be buried beneath a Tertiary volcanic cover about 2000- to 3500-feet-thick in the southeastern part of the area and from 4000- to 6000-feet-thick in the southwestern corner of the area where a thick section of the La Jara Peak Formation has been preserved by down-faulting.

Eruption of the La Jara Peak Andesite began in early Miocene time after an erosional hiatus of about four million years. The flows were erupted onto an erosional surface of low relief from fissure-type vents. Intermittent volcanism and minor sedimentation over an unknown time span deposited as much as 2500 to 3000 feet of material in the study area.

In late Miocene time the area was transected by two major fault zones related to the opening of the Rio Grande rift. The volcanic rocks were uplifted and broken into north-trending blocks by Basin and Range faulting along the west shoulder of the rift. At approximately the same time, northeast-trending faults at the northeast end of the San Augustin arm of the rift dropped part of the study area at least one thousand feet relative to the Bear and Magdalena uplifts.

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by
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