NEVADA BUREAU OF MINES AND GEOLOGY

BULLETIN 92

GEOLOGY OF THE TONOPAH, LONE MOUNTAIN, KLONDIKE, AND NORTHERN MUD LAKE QUADRANGLES, NEVADA

HAROLD F. BONHAM, JR.
LARRY J. GARSIDE

MACKAY SCHOOL OF MINES
UNIVERSITY OF NEVADA · RENO
1979

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Headframe of Victor shaft, Tonopah, Nevada.

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ABSTRACT

This report describes the geology and mineral resources of an area of approximately 1,600 km^2 in Nye and Esmeralda Counties, Nevada. The topography is typical of the Basin and Range province with northerly trending mountain blocks separated by alluviated valleys. The highest point in the area is Lone Mountain at an elevation of over 2,775 m and the lowest point is 1,462 m in Big Smoky Valley. The well-known bonanza silver-gold deposits of the Tonopah district are located in the central portion of the mapped area.

Rocks of igneous, metamorphic, and sedimentary origin, ranging in age from late Precambrian to Holocene are present in the area. Rocks of late Precambrian and Cambrian age consist of quartzite, schist, phyllite, hornfels, dolomite, limestone, argillite, and chert and belong to an assemblage deposited in an environment that is transitional between miogeosynclinal to the east and eugeosynclinal to the west. Ordovician rocks consist of chert, quartzite and sandstone, siltstone, limestone and greenstone deposited in a eugeosynclinal environment and limestone, slate and argillite, sandstone and chert of the transitional assemblage. Rocks of Mississippian age include limestone, in part silicified, and black shale apparently deposited in a shallow marine trough.

Mesozoic rocks in the area are of igneous origin, mainly Cretaceous epizonal plutons ranging in composition from gabbro to granite. One small section of metamorphosed ash-flow tuffs, probably also of Mesozoic age, occurs in the southeastern part of the map area.

Tertiary volcanic rocks of early Oligocene to late Miocene age form the bulk of the exposed bedrock in the area. They range in composition from trachyandesite to rhyolite and include flows, flow breccias, intrusives, pyroclastic breccias and ash flows, and mud flows. Extensive exposures of sedimentary rocks of Miocene age are also present. They include waterlain tuffs, sandstones, siltstones, conglomerates, and limestones deposited in lacustrine and fluvial environments. The sedimentary rocks interfinger with, and are intruded by, the volcanic rocks.

Quaternary deposits, ranging from pediment gravels and alluvial fan deposits to eolian sand and playa deposits, fill most of the basinal areas.

The Paleozoic rocks were folded and faulted during one or more orogenic episodes of Mesozoic age. Several thrust faults that emplace younger Paleozoic rocks over older Paleozoic rocks formed during the Mesozoic. The Mesozoic intrusive rocks in the map area cut the thrust plates.

High-angle normal faulting associated with the development of basin-and-range structure commenced about 16 to 17 million years ago and has continued intermittently into the Quaternary.

Silver ore was discovered at the present site of Tonopah in 1900. Between 1900 and 1961 the Tonopah district produced 1,861,200 ounces of gold and 174,152,628 ounces of silver. The ore deposits at Tonopah are typical of the epithermal bonanza precious metal deposits of the western cordillera of North America. They occur as vein deposits in Tertiary volcanic rocks. The chief ore minerals are silver sulfides and sulfosalts, galena, sphalerite, and chalcopyrite in a quartz gangue.

The Divide district, a few kilometers south of Tonopah, produced over 3 million ounces of silver and 30,000 ounces of gold from lode deposits in intrusive rhyolite and rhyolitic ash-flow tuff of Tertiary age. The Klondyke district produced over 400,000 ounces of silver and 2,000 ounces of gold, plus some copper and lead, from vein deposits in lower Paleozoic rocks. The ore deposits at Klondyke are spatially and probably genetically related to muscovite granite of Cretaceous age.

Minor amounts of gold, silver, lead, copper, and zinc have been produced from several small mines in Paleozoic rocks in the Rays and Lone Mountain areas and a scheelite-molybdenite-bearing tactite is present at the Peg-Leg Mine a few kilometers north of Tonopah.

INTRODUCTION

This report describes the geology and mineral resources of the Tonopah and Lone Mountain 15-minute quadrangles, the north half of the Mud Lake 15-minute quadrangle and the Klondike 7.5-minute quadrangle (pl. 1).

One of the main objectives of this study was to prepare surface geologic maps of the Tonopah and Divide districts on modern topographic bases. Except for Spurr's (1905b) geologic map of the Tonopah district and Knopf's (1921) geologic sketch map of the Divide district, no published geologic map on a scale larger than 1:250,000 exists of these areas. We believe that recent advances in the geologic knowledge of volcanic rocks make a modern study of the districts highly desirable. The primary purpose was to establish the regional geologic setting of the districts and to delineate the Tertiary stratigraphy of this geologically complex area.

We did not restudy the underground geology of the Tonopah district because a comprehensive report (Nolan, 1935) on this subject is already available. Similarly, no attempt was made to restudy the ore mineralogy of the district, as a number of excellent papers have been published. (See Bibliography.)

Unfortunately, most of the underground workings in the Divide district, including the main productive mine, the Tonopah Divide, were not accessible when this study was made.

Primarily, this is a study of the geology of an extensive area surrounding the Tonopah district, the second largest silver-producing district in Nevada, and is complementary to existing detailed studies of the geology of the Tonopah district's mines and ores (Nolan, 1935; Bastin and Laney, 1918).

Acknowledgments

The fieldwork benefited from discussions and field trips with F. J. Kleinhampl, F. G. Poole, R. P. Ashley, and M. L. Silberman. J. R. Firby was of assistance in identifying Tertiary gastropods. J. G. Quade provided some of the aerial photographs used in the field work. P. E. Chapman contributed underground maps of the Klondyke district. John Livermore and P. Dircksen of Cordex provided us with useful information on the Hasbrouck precious metal prospect in the Divide district. Our colleague, K. G. Papke, was most helpful in identifying zeolites, clay minerals, and alteration micas.

We would particularly like to thank M. L. Silberman for providing us with most of the K-Ar dates listed, which materially benefited both the field work and the report. We

owe special thanks also to R. P. Ashley for providing us with the fission-track dates listed in the report.

The manuscript was greatly improved by the reviews of E. C. Bingler, R. B. Jones, J. H. Stewart, and L. T. Larson.

Location, Accessibility, and Extent of Area

This report describes the geology of an area of approximately 1,600 km^2 in Nye and Esmeralda Counties, Nevada. The geologic map (pl. 1) includes an area of 2½ 15-minute topographic sheets, plus one 7½-minute sheet. The scale of the geologic map is 1:48,000 (1 cm = 0.48 km). In addition to the three published 15-minute topographic maps of the area (Tonopah, Lone Mountain, and Mud Lake) and the one published 7½-minute sheet (Klondike), the northern portion of the area is covered by unpublished 7½-minute sheets which are available in preliminary form from the U. S. Geological Survey.

Tonopah, the only town in the mapped area, is located at the junction of U. S. Highway 6, which passes in an east-west direction across the area, and US 95, Nevada's major north-south highway (fig. 1). Except for the higher part of Lone Mountain and certain areas north of Lime Mountain, the area is reasonably accessible from numerous dirt roads. Many of these roads require a four-wheel-drive vehicle, although several are well traveled. A graveled road, State Route 89, also connects US 6 and 95 near Tonopah with the town of Gabbs about 112 km to the north.

The major mining districts in the mapped area include Tonopah, Divide, and Klondyke in the San Antonio Mountains. Smaller districts or mines are also present near the site of Rays in the northern part of the area, and on the east flank of Lone Mountain.

The Tonopah and Goldfield Railroad once ran down Montezuma Valley to the west of Tonopah, with a spur line to Tonopah. The roadbed still remains but the rail and trestles were taken up in 1948.

Aerial Photography

The San Antonio Mountains and adjacent areas described in this report have been included in a variety of aerial photographic projects. The following is a list of companies and agencies which have photography available for all or part of the mapped area:

1. InfraSearch, Inc., 1600 Ogden St., Denver, CO 80218. 1:20,000 B&W; 1:24,000 color.
2. Pacific Region Engineer, U. S. Geological Survey, Topographic Division, 345 Middlefield Rd., Menlo Park, CA 94025 (or EROS Data Center, Sioux Falls, SD 57198). 1:60,000 B&W; 1:40,000 B&W; 1:24,000 B&W.
3. Audio-Visual Research, Directorate for Defense Information. Office of the Assistant Secretary of Defense, Washington, DC 20301. Tonopah Bombing Range 1:29,000 B&W (1943).
4. Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557. 1:26,000 B&W.
5. U. S. Geological Survey, EROS Data Center, Sioux Falls, SD 57198. Various B&W and color flight lines at several scales.

A complete computer printout listing of available U. S. Government photography can be obtained for any particular area of the United States by contacting the EROS Data Center at the address listed above.

Physiography

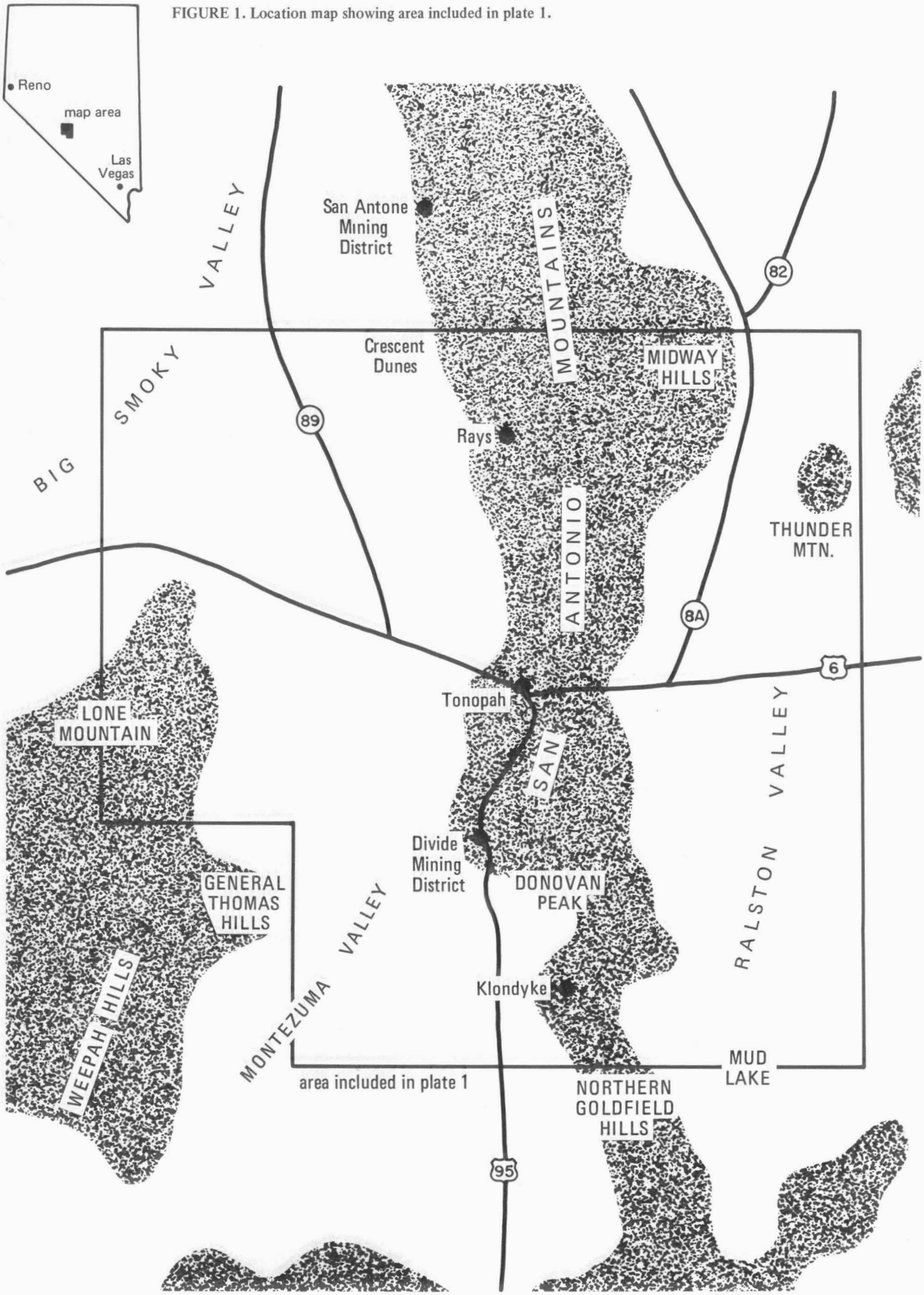
Topography of the mapped area, typical of much of the Basin and Range province, consists of linear valleys and mountain ranges oriented in a northerly or northeasterly direction. The San Antonio Mountains in the central part of the area reach elevations of about 2,100 m a few miles north of Tonopah, and over 2,400 m at the north end of the range, just out of the mapped area. Numerous dry washes and ephemeral streams drain the range, but they flow only during rare periods of heavy runoff.

Ralston Valley to the east of the San Antonio Mountains is a topographically closed basin, except for an ephemeral stream channel which enters the north end of the valley to the northwest of Thunder Mountain. Runoff in this channel rarely reaches Mud Lake (a playa in the south end of Ralston Valley), because it seeps into the channel bed or evaporates in its southward course (Eakin, 1962). The ultimate source of most of Ralston Valley's ground water is precipitation within the drainage basin. Apparently there is a significant amount of ground-water flow toward the southern end of the valley, and discharge probably occurs as underflow through Paleozoic and Tertiary rocks in this area (Eakin, 1962). The depth to water is about 73 m at Mud Lake (Ball, 1907, p. 83). The main area of evapotranspiration from ground water is west of Thunder Mountain at Rye Patch wells. This area is also favorably situated for the occurrence of water of relatively good quality within 3 to 4.5 m of the land surface. It is from this area that the town of Tonopah acquires its water, about 190 million liters (50 million gallons or 150 acre-feet) per year. The water is pumped from wells and piped about 24 km to Tonopah across the San Antonio Mountains. The Nye County Airport is also located in Ralston Valley just south of U. S. Highway 6. This airport was the site of the Tonopah Air Base, active during World War II. It is now used for commercial and private aviation.

Two valleys are adjacent on the west to the San Antonio Mountains and the Southern Klondyke Hills. Big Smoky Valley lies to the west of the northern San Antonio Mountains, and runs southwestward, passing to the west of Lone Mountain. Montezuma Valley (Alkali Spring Valley) is a closed topographic basin with a playa just to the southwest of the area described in this report (south of the General Thomas Hills). Depth to ground water in the portions of the valley having soils suitable for farming is 9 to 15 m (Rush, 1968). Big Smoky Valley is one of Nevada's longest, over 210 km. The Tonopah area is adjacent to the southern portion of Big Smoky Valley. A playa is also present in this valley, between Emigrant Peak and Lone Mountain, to the west of the area described in this report. The valley is named for the haze that often occurs in the area due to the presence of fine wind-blown dust in the air on windy days. Active and stabilized sand dunes are present in several areas, especially at Crescent Dunes along the west side of the San Antonio Mountains (see the section on Quaternary Deposits in this report).

Lone Mountain, in the west part of the mapped area, is a prominent topographic feature, lying somewhat isolated from the north end of the Weepah Hills. The highest point on Lone Mountain is over 2,775 m above sea level. Its topography is rugged and steep, and the roads in the area end at the base of the mountain.

FIGURE 1. Location map showing area included in plate 1.



Climate, Vegetation, and Wildlife

Air masses that move across this part of Nevada characteristically are deficient in moisture. Thunderstorms provide most of the precipitation during the summer (Rush, 1968). The precipitation in Nevada is essentially controlled by elevation, although local conditions may modify the pattern. The valleys are arid, whereas the higher mountains are subhumid and receive more precipitation, especially in the winter. In general, the average annual rainfall increases nearly 7.62 cm for every 305 m increase in elevation. The valleys in the Tonopah area receive 7 to 12 cm per year, while the higher mountains may have an average annual precipitation of 38 cm or more (Rush, 1968). The average yearly precipitation at Tonopah, where the station is at an elevation of 1,857 m, was 12.65 cm for the years 1907–1953. At the Nye County airport 5 km east of Tonopah, at an elevation of 1,599 m (Rush, 1968), the 1954–1966 yearly average was 9.80 cm.

The seasonal and daily range in temperature in this area is impressive. The maximum recorded temperature at the Nye County airport was 40°C on July 18, 1960 and the minimum recorded was -24.5°C on January 13, 1955 (Eakin, 1962). The average number of frost-free (greater than 0°C) days is about 150 for the airport and 129 for Tonopah (Rush, 1968), although this number may vary considerably from year to year. The average annual temperature is 10.5°C (see table 1 for monthly averages).

Vegetation in the Tonopah area, like that over much of central Nevada, consists of sagebrush (*Artemisia tridentata*) and other desert plants on the lower slopes and in the valleys. Rabbit brush (*Chrysothamnus grareolens*) and big greasewood (*Sarcobatus vermiculatus*) are often indicators of ground water at shallow depths. Shadscale (*Atriplex confertifolia*), white sage (*Eurotia lanata*), and the small, dry species of greasewood (*Sarcobatus baileyi*) occur with sagebrush on the drier slopes and hills (fig. 2). A number of small cacti, including the prickly pear and small barrel types are found in many places. Cholla cacti are quite common on Lone Mountain. Sparse Joshua trees are seen only in the southernmost parts of the mapped area south of Klondyke, although they are common in the Goldfield area a few miles further south. A single Joshua tree is present just south of Mount Butler, about 1 mile south of Tonopah, which is a somewhat rare occurrence at this latitude. In the higher parts of the mountains, piñon pine and juniper are abundant. Mountain mahogany is present on the upper slopes of Lone Mountain.

TABLE 1. Average temperatures for Tonopah and the Nye County airport.

[Compiled from published records of the U. S. Weather Bureau (Eakin, 1962, table 3).]

	°F	°C
January	30.3	−0.9
February	35.1	1.7
March	39.9	4.4
April	48.7	9.3
May	56.6	13.6
June	65.3	18.5
July	74.1	23.4
August	71.3	21.8
September	64.6	18.1
October	52.2	11.2
November	40.3	4.6
December	33.0	0.5
Average	50.9	10.0

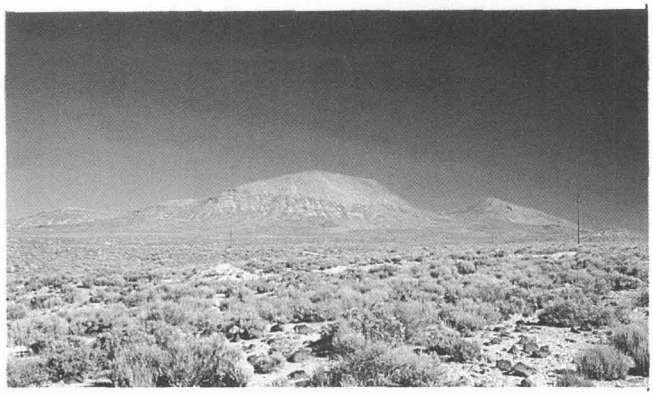


FIGURE 2. Typical vegetation, Tonopah area.

Wildlife is scarce in this area, partially due to the low rainfall, sparse vegetation, and lack of springs. Although cattle graze in the valleys, the area is marginal for livestock grazing. Small animals found in the area, include jackrabbits, cottontail rabbits, mice and other rodents, rattlesnakes, and several species of lizards. Chukkar partridge are present locally, especially on Lone Mountain. Deer and desert bighorn sheep live on Lone Mountain, and probably ranged in the past into the San Antonio Mountains, as an old bighorn skull was found there by the authors.

History

Tonopah is an Indian name, and has been interpreted to mean "hidden spring," "brush water springs," "greasewood spring," "little water," or "water brush." The name appears to mean "greasewood water (spring)," derived from either the Shoshone of northern Paiute dialects (Carlson, 1974, p. 233–234).

Jim Butler, the discoverer of the mineral deposits at Tonopah reports that the Indians, on their periodical trips from the Kawich and other places to Rhodes' Salt Marsh, camped at the spring (Carlson, 1974, p. 233) for which Tonopah is named (this is most likely a spring about 5 km north of the present town of Tonopah).

The first white men to see the Tonopah region were probably in the party of the fur trapper, Jedediah Smith. Smith's party crossed the entire State of Nevada from west to east in 1827, probably along a route near the present position of U. S. Highway 6 (Elliot, 1973, p. 36). The area was largely avoided by later explorers and emigrants, until the mid-1860's, when Mexican miners prospected for gold at Lone Mountain and at the San Antonio mining district, 25 km north of Tonopah (Thompson and West, 1881). Kral (1951) reports that the Spanish mine, 1 km southeast of Liberty, was worked in 1854 by Mexican miners.

Vanderburg (1936, p. 79) states that Chinese placer miners were working in the Klondyke area in the middle 1870's, although the veins were not discovered until March of 1899 by J. G. Court and T. J. Bell (Chipp, 1969). Most of the Klondyke mining activity occurred in the years

prior to 1905, and from 1908 to 1910, and 1912 to 1925 (Chipp, 1969).

In May of 1900, James L. "Jim" Butler, on his way to Klondyke, wandered off the chosen Ralston Valley route and took samples from a ledge that was later to become known as the Mizpah vein. Butler may have been told of the ledges at Tonopah by Indians, for he is said to have spoken the Shoshone dialect and been looked on as a friend (Carlson, 1974, p. 233). The ledges at Tonopah had also been sampled by sheepherders in the 1890's while they were camped at springs near Tonopah. However, these samples were apparently either lost or never analyzed (Carpenter and others, 1953).

Following the discovery, the mines at Tonopah developed rapidly, and because Butler and his partners were financially unable to develop their claims, they turned to a system of leases. Forty to 50 lessees were working the claims in 1901, and in that year they mined about $4 million in ore. By 1903 Tonopah stocks were listed on the San Francisco Mining Exchange, and by 1904 the Tonopah Mining Co. had completed a railroad from Sodaville.

Tonopah had essentially steady production from 1902 until 1930, by which time the price of silver had fallen to 38 cents per ounce. From 1930 until the late 1940's, Tonopah's yearly production was sporadic and exceeded $1 million only in 1935 and in 1937. There has been no recorded production from the Tonopah district since 1961. Total production from Tonopah was $154 million (table 29).

In 1969, Hughes Tool Co. (Summa Corp.) purchased mining claims that comprise a substantial part of the Tonopah district. Although some reconditioning of the workings was undertaken, no extensive exploration program was begun. Summa Corp. holdings in the Tonopah district were acquired by Houston Oil and Minerals Corp. in 1977. Tonopah's population today is about 1,500.

The Divide mining district is centered around Gold Mountain, which has been worked intermittently for gold since 1902. In 1917 a rich silver vein was cut by a crosscut which was being driven to intersect a gold vein. By February of 1919 a great boom had begun, with claims staked in a 130 km^2 area centered on Gold Mountain. By midsummer of that year, 80 to 100 hoists were in operation (Knopf, 1921). The district was active for about 30 years (Albers and Stewart, 1972).

Previous Work

The first geological investigations in the Tonopah area were conducted shortly after the discovery of ore at Tonopah. Spurr's reports (1903a, b, c; 1904a, b; 1905a, b, c; 1906a; 1911; 1915) summarize the geology of the district as it was known during its early development. Later work by Locke (1912), Bastin and Laney (1918), and Burgess (1909; 1911) more clearly define the geology and ore mineralogy of the district. Nolan's reports (1930; 1935) were written when the underground workings of the Tonopah district were most extensive and accessible, and are the most complete study of the underground portion of the district. Later studies include those by Campbell (1931; 1933), Broderick (1949), Cornwall and others (1967), and Bonham and Garside (1974a, b).

Knopf's (1921) report on the Divide mining district is the principal study on that area, although Sizer (1919), Young (1920), Carpenter (1919), and Mining and Scientific Press (1919) also contain published information on the district. Chipp (1969) has studied the Klondyke district to the south.

Geologic mapping at a scale of 1:250,000 has been published on Esmeralda County and the southern portion of Nye County (Albers and Stewart, 1972; Cornwall, 1972). In addition, a preliminary U. S. Geological Survey open file map is available for northern Nye County (Kleinhampl and Ziony, 1967). Davis and others (1971) have included a generalized geologic map of the San Antonio Mountains with their aeromagnetic study of the area, and Erwin's (1968) gravity map covers a large part of the area included in this report.

The bibliography at the end of this report is an attempt to list all geologic articles pertinent to the mapped area. Not all of these articles are cited in the text.

Present Investigation

Field investigations were conducted from 1967 to 1974. The geologic mapping was done on aerial photographs at a variety of scales (see Aerial Photography, p. 6). Data were then transferred to 1:24,000 preliminary topographic maps. This copy was reduced to match a 1:48,000 base map (an enlargement of the 15-minute series maps). Some additional geographic names were added to this base (pl. 1).

Over 500 rock specimens were collected during the mapping project, and approximately 400 thin sections were examined. Modal compositions were determined for approximately 35 rock specimens by point-counting methods on standard 25-x-40-mm thin sections. Between 1,000 and 1,500 points were counted on each thin section. Plagioclase determinations were made by determination of maximum extinction angles normal to 010, utilizing the charts of Tobi and Krall (1975).

Ninety-five new major oxide chemical analyses on volcanic and plutonic rocks are listed in a series of tables in the text. Three of these analyses were done in U. S. Geological Survey laboratories by standard rapid rock analysis techniques of Shapiro and Brannock (1962). The remaining 92 analyses were done at the Nevada Bureau of Mines and Geology and the Nevada Mining Analytical Laboratory by a combination of X-ray fluorescence (XRF), atomic absorption spectrophotometry (AA), and wet chemical techniques. SiO_2, CaO, K_2O, Fe_2O_3, Al_2O_3, and TiO_2 were determined by XRF; Na_2O and MgO by AA; and FeO and MnO by wet chemical methods. P_2O_5 was not determined. (FeO, MnO, Na_2O, MgO: analyst, P. Beaulieu, Nevada Mining Analytical Laboratory; SiO_2, CaO, K_2O, Al_2O_3, TiO_2, Fe_2O_3: analyst, H. F. Bonham, Nevada Bureau of Mines and Geology). All of the major oxide analyses were recalculated to a 100-percent volatile-free basis in order to facilitate comparisons between samples.

Assigning names to the volcanic rocks in the Tonopah area presents the usual nomenclatural problems associated with rocks that are partly to wholly aphanitic or glassy. Names can be assigned on the basis of field study, microscopic studies, or chemical analyses.

Since chemical analyses are available for most of the volcanic rock types present in the Tonopah area, and since we believe a nomenclatural system based upon chemical analyses is the most satisfactory for volcanic rocks, this is

the approach we have utilized. Unfortunately, no single classification system of this type is, at present, widely used. We use, in this report, the classification system of Segerstrom and Young (1972, p. 34–35) based on the Felsic-Mafic Index which they define as:

$$\frac{SiO_2 + Na_2O + K_2O}{FeO + Fe_2O_3 + MgO + CaO}$$

Utilizing the felsic-mafic ratio results in the following classification scheme:

Rock type	*Felsic-Mafic index*
Extreme alkali granite (rhyolite)	> 50
Alkali granite (rhyolite)	25 –50
Granite (rhyolite)	15 –25
Quartz monzonite (quartz latite)	10 –15
Granodiorite (rhyodacite)	7 –10
Quartz diorite (dacite)	5 –7
Monzonite (latite) $K_2O > 3\%$	3 –5
Trachyandesite $K_2O < 3\%$	3 –5
Diorite (andesite)	2.1–3
Gabbro (basalt)	1.4–2.1
Ultramafics	< 1.4

This version of the classification reflects minor changes suggested by G. J. Young in 1976; addition of extreme alkali granite and revision of the numerical values for diorite, gabbro, and ultramafics. We have also incorporated several minor changes from the original. We call the volcanic equivalent of quartz diorite dacite rather than quartz andesite. We have also added the name "trachyandesite" for rocks with felsic-mafic indexes of 3 to 5 and with K_2O contents of less than 3 percent, as we believe that these rocks more nearly match Nockolds' (1954) average trachyandesite than they do his average latite.

Terminology of ash-flow tuffs is essentially that of Smith (Smith, 1960a, b; Ross and Smith, 1961). The classification of volcaniclastic rocks and sediments follows Fisher (1961, p. 1409–1414).

Cook's (1965) classification scheme, shown as figure 3, is also used in this report for describing ash-flow tuffs. In this context it is important to remember that the adjective "vitric" does not mean that the tuff so described is necessarily still glassy. It is applied to both glassy and devitrified rock in accordance with the particle composition triangle of figure 3. The term "glass" or "glassy" is applied to pyroclastic rocks in which the pumice and shards are not devitrified regardless of the degree of welding. Vitrophyre, as applied to pyroclastic rocks in this report, refers to a glassy, densely welded tuff.

Phaneritic plutonic rocks are classified according to the IUGS (1973). Petrologic calculations, including normative data, were computed by the PETCAL computer program (Bingler and others, 1976).

The time scale for the various epochs of the Tertiary period follows Berggren (1972), except for the Miocene–Pliocene boundary. Because there is still some substantial disagreement about the age that should be assigned to this boundary, we prefer to use radiometric age, and/or North American Land Mammal ages (Evernden and others, 1964) for rock units that fall in this interval.

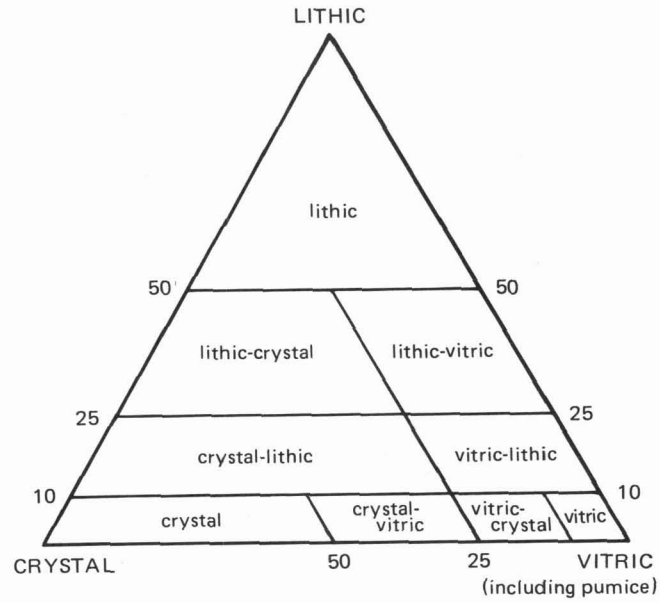


FIGURE 3. Mechanical composition triangle for ignimbrite rock types. *From Cook, 1965.*

GEOLOGIC UNITS

Precambrian Strata

Precambrian strata of the Wyman Formation, Reed Dolomite, and Deep Spring Formation crop out to the northeast of the Lone Mountain pluton (pl. 1).

WYMAN FORMATION (Zw)

The name Wyman Formation was proposed by Maxson (1934) for approximately 1,100 m of spotted schists and phyllites with a few interbedded dolomites. It underlies the Reed Dolomite at the type area in Wyman Canyon of the Inyo Mountains, Calif. Where unmetamorphosed, it consists of siltstone and sandstone with interbeds of limestone or dolomite (McKee and Moiola, 1962). Commonly calc-silicate hornfels is present (Stewart, 1966). The Wyman Formation as redefined by Nelson (1962) in the type area, has a minimum thickness of 2,700 m; no stratigraphic base is exposed.

The Wyman Formation is exposed on the northeast flank of Lone Mountain in a 0.5-to-1-km-wide band about 5 km long. There, a maximum thickness of slightly less than 915 m of Wyman is present below the Reed Dolomite, and the base of the formation is not exposed. Usually, only 300 to 600 m of the Wyman Formation are present as the lower part of the Wyman has been cut out by the intrusion of the main granite mass of the Lone Mountain pluton. Stewart (1970) reports a 413-m continuous measured section of Wyman from this area of Lone Mountain.

The Wyman at Lone Mountain consists of approximately 50 percent marble, interbedded in 2-to-5-cm layers with phyllite, quartzite, and calc-silicate hornfels. The bedding is usually quite regular, with interstratified layers of limestone and evenly laminated phyllite (fig. 4). Regional metamorphism is widespread and the unit has been affected by contact metamorphism near contacts with plutonic rocks. Rock that was originally shale is now phyllite composed of fine grains of quartz and muscovite with porphyro-

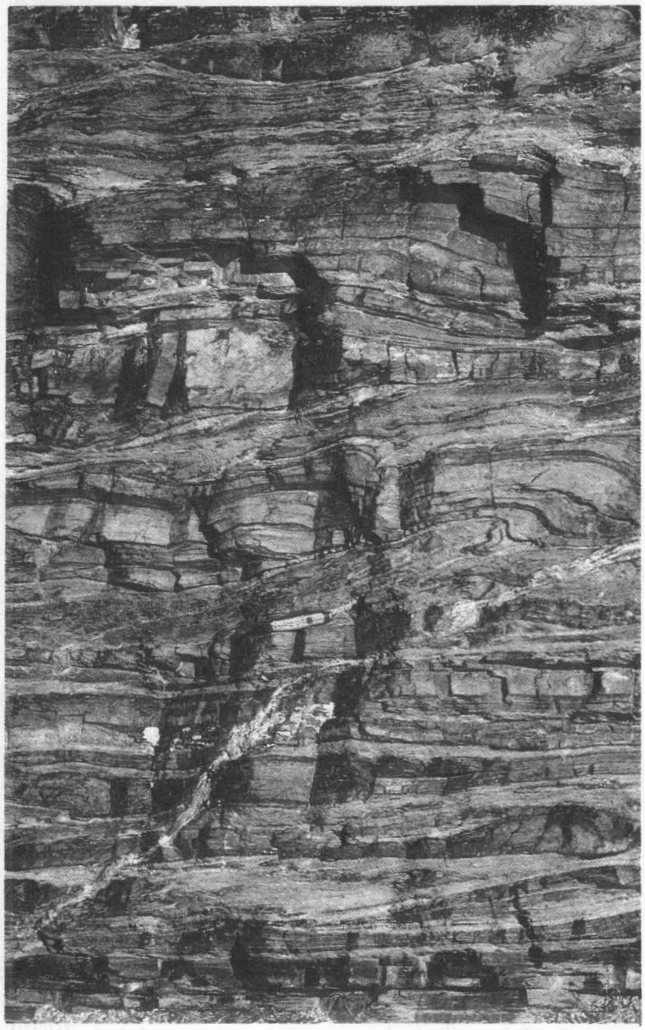
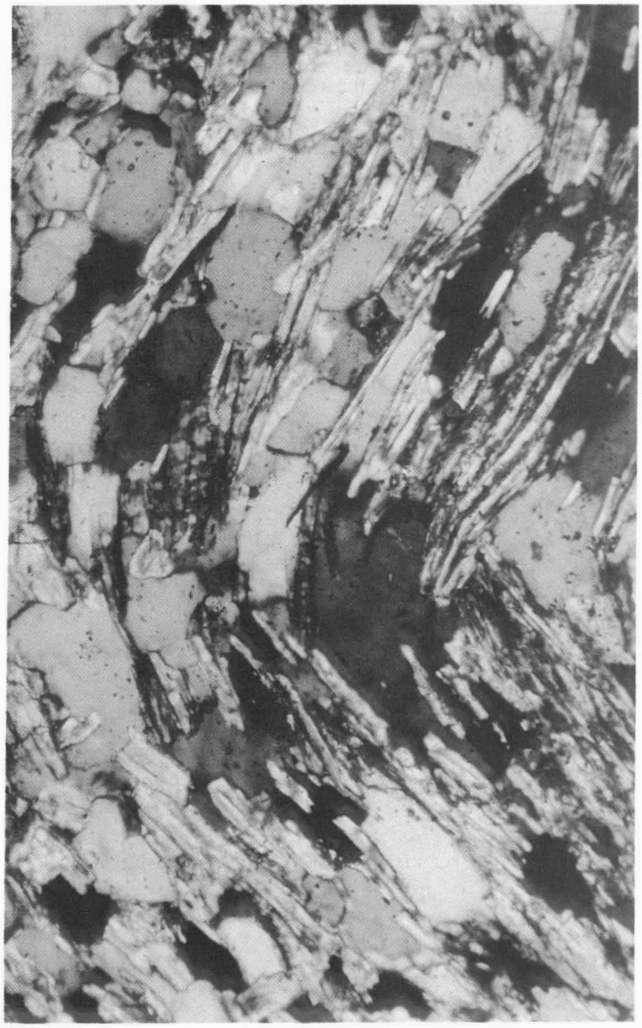


FIGURE 4. Interstratified limestone and phyllite of the Wyman Formation at north end of Lone Mountain. Pocket knife is 10 cm long.



0.1 mm

FIGURE 5. Crenulation folds in a thin section of andalusite phyllite in the Wyman Formation.

blasts of andalusite and, rarely, garnet. Feldspars are uncommon constituents, although a few limy sandstones and siltstones that originally contained potassium feldspar grains have been changed by contact metamorphism to calc-silicate hornfels composed of calcite, diopside, zoisite, quartz, potassium feldspar, hornblende, biotite, and muscovite.

Rocks of the Wyman Formation are complexly folded. Crenulation folds with amplitudes of 2 to 3 mm are common in the phyllitic rocks (fig. 5), and thin beds of calc-silicate hornfels and marble form flexural-slip folds with amplitudes of 10 to 30 cm (fig. 6). Intervening thicker, massive beds do not usually exhibit smaller folds, but may be involved in folds having amplitudes of several hundred meters. These larger folds are best seen at the north end of Lone Mountain, in S33,T3N,R40E. Boudinage is often well developed in the calc-silicate hornfels and interbedded marble.

The base of the Wyman is not exposed, and the unit has been intruded by the granite which underlies the higher part of Lone Mountain. Contact metamorphism has changed limestones and shales at the contact to calc-silicate hornfels and garnet-tremolite-diopside skarn. The contact effects usually extend only a few meters outward from the granite.

The contact between the Wyman Formation and the overlying Reed Dolomite appears conformable. Stewart (1970) reports that "lithologic similarities between the strata near the top of the Wyman and the strata in the lower part of the Reed suggest a transitional sequence from one to the other." We place the contact at the point where marble and calc-silicate hornfels change to massive, tan dolomite.

FIGURE 6. Flexural slip folds in interbedded marble and calc-silicate hornfels of the Wyman Formation. Pocket knife is 10 cm long.

The Precambrian Wyman Formation is believed to be a fine-textured equivalent of the Johnnie Formation and the lower part of the Stirling Quartzite in the central and southern Great Basin, although correlations are difficult due to rapid lithologic variations (Stewart, 1970). Moore (1974) suggests that a shallow sea with local reef-like areas and low-lying temporary islands was the site of deposition for the Johnnie and Wyman Formations.

REED DOLOMITE (Zr)

The Reed Dolomite was named by Kirk (*in* Knopf, 1918, p. 27) for exposures along the east side of Reed Flat in the Blanco Mountain quadrangle, Inyo Mountains, Calif. The unit is composed mostly of white to medium-gray, yellowish-gray, and pale yellowish-brown, medium to coarsely crystalline dolomite (Stewart, 1970). In the White and Inyo Mountains and in southern Esmeralda County, a clastic unit, the Hines Tongue, is present (Nelson, 1962). Only a few thin quartzite beds crop out in the section exposed on the east side of Lone Mountain. Phariss (1974) has described siltstone beds in the Reed exposed on the west side of Lone Mountain.

The Reed Dolomite crops out in a band parallel to the Wyman Formation along the northeast edge of Lone Mountain (pl. 1). The unit appears to be structureless and of uniform compositon throughout; however, structural movement may have obliterated any original bedding. Nearly the entire formation consists of light-tan-weathering, white, sugary, massive recrystallized dolomite. However, in the center of S33,T2N,R40E, some marble beds included in the Reed are incompletely dolomitized and display progressive dolomitization. In thin section, representative samples of the Reed consist entirely of dolomite having a polygonal mosaic texture. Twinning in individual dolomite crystals is common, and is probably the result of deformation.

The Reed is estimated to be 600 to 900 m thick, based on the outcrop width and attitudes interpreted from adjacent formations. However, duplication of the section is possible, and although Stewart (1970) reports over 790 m of Reed on Lone Mountain, he suggests that the top 300 m may be a duplication, and the actual thickness may be only about 520 m.

The contact between the Reed Dolomite and the overlying Deep Spring Formation was placed at the change from massive, structureless dolomite to distinct bedded dolomite, limestone, and sandstone. This contact is difficult to locate precisely at Lone Mountain, as it is elsewhere in Esmeralda County (Albers and Stewart, 1972, p. 9), but nevertheless represents a distinct lithologic change. It is particularly difficult to distinguish massive dolomitized limestones in the lower Deep Spring from the uppermost Reed beds in an area about 2.4 km east of Willow Spring.

Stewart (1970), has interpreted the Reed Dolomite as either Cambrian or Precambrian, but he believes it to be Precambrian because it lies 600 to 900 m below the lowest occurrence of fossils used to define the Precambrian-Cambrian boundary (olenellid trilobites and archeocyathids). Other geologists (Cloud and Nelson, 1966) think that the Reed is at least partly Cambrian. It is probably a carbonate-rich westward facies of the upper part of the Stirling Quartzite of the central region of the southern Great Basin.

DEEP SPRING FORMATION (Zds)

The Deep Spring Formation was named by Kirk (*in* Knopf, 1918, p. 24) for a lithologically variable unit exposed on the west side of Deep Spring Valley, Inyo Mountains, Calif., where it includes 450 to 490 m of interbedded limestone, quartzite, and dolomite.

The Deep Spring Formation is exposed on the flanks of Lone Mountain in S2,12,13,T12N,R40E (unsurveyed). The outcrop area is approximately 2.6 km^2 and less than that of either the underlying Wyman or Reed Formations.

The formation consists of alternating gray thin-bedded marble, mica schist, and lesser amounts of light-gray quartzite. Some tan-colored dolomite (similar to beds in the Reed Dolomite) occurs near the base, making exact location of the lower contact difficult. The formation is metamorphosed throughout its outcrop area. Marble (originally limestone) consists of calcite, dolomite, and varying amounts of tremolite. Some impure limestone near intrusive contacts is metamorphosed to calc-silicate hornfels, consisting of calcite, tremolite, zoisite, chlorite, sericite, and potassium feldspar. Quartzite beds are light gray, fine grained (grains up to 0.15 mm) and evenly laminated or, less commonly, crossbedded. The quartzites were originally calcareous and somewhat arkosic, and now consist of a mosaic of xenomorphic quartz, potassium feldspar, sericite, calcite, and actinolite. Detrital zircon (3 percent or more) is a common accessory, and minor apatite and sphene are also present. Schists consist of fine-grained quartz, potassium feldspar, and sericite.

The outcrop width and attitude of the Deep Spring Formation indicate a maximum thickness of over 300 m at Lone Mountain. However, the unit is almost certainly repeated or interrupted by faults and folds, and it is possible that only about 180 m of stratigraphic section is present here below a thrust fault which places the Cambrian Harkless Formation over the Deep Spring. To the north of the outcrop area of Deep Spring this thrust fault has entirely cut out the unit, and the Harkless Formation rests directly upon the Reed Dolomite. Elsewhere in Nevada, the Deep Spring has considerably more carbonate beds in its lower member than in the middle and upper members. Possibly only the lower member of the Deep Spring is represented at Lone Mountain. The thrust fault has apparently cut out about 1,500 m of section, including the middle(?) and upper Deep Spring, and the Cambrian Campito and Poleta Formations which would be present in a complete stratigraphic sequence.

The Deep Spring Formation is predominantly the westward equivalent of the lower member of the Wood Canyon Formation of the central region of the southern Great Basin (Stewart, 1970). Because it is at least 300 m below the lowest occurrence of olenellid trilobites and archeocyathids, it is believed to be of Precambrian age (Stewart, 1970). Cloud and Nelson (1966) believe it to be Cambrian, based on other fossil evidence. Raymond (1975) suggests that the depositional environment was tidal flat and shallow subtidal.

Cambrian Strata

Cambrian strata in the mapped area include the Harkless Formation, which is present at Lone Mountain and Klon-

dyke, and the Mule Spring Limestone and Emigrant Formation, both present mainly at Klondyke.

HARKLESS(?) FORMATION (€h?, €hl?)

The Harkless Formation is named for exposures present at the divide south of Harkless Flat, Inyo Mountains, Calif. There, the unit consists of siltstone, fine- to medium-grained quartzite, and, in places, minor amounts of limestone (Nelson, 1962). The formation is 600 m thick in the White and Inyo Mountains and 1,100 m thick in the Weepah Hills, Esmeralda County, about 16 km to the southwest of Lone Mountain (Albers and Stewart, 1972).

The Harkless(?) Formation is exposed in an 11 km-long band along the northeast side of Lone Mountain. A few small exposures are also present near Klondyke, below the Mule Spring Limestone. The Harkless(?) Formation in the mapped area is predominantly a detrital unit that includes dark-brown, black, and olive hornfels with minor amounts of thin, gray-to-black quartzite, impure sandstone, and recrystallized, gray-blue limestone. The quartzites are thinly laminated and rarely arkosic. The limestone beds are shown separately on plate 1. The unit is metamorphosed everywhere in the mapped area; rocks that were originally siltstone are now spotted andalusite hornfels and quartz-biotite-muscovite phyllite and schist. Barnes (1973) believes that the Harkless was deposited on intertidal flats and shallow subtidal sand bodies.

Neither the stratigraphic top nor base of the Harkless(?) is exposed on Lone Mountain, and because of structural complications, its thickness is very difficult to estimate. As much as 300 m may be present, but an unknown amount of the basal part of the formation is missing due to a thrust fault which emplaces the Cambrian Harkless over the Precambrian Deep Spring Formation. Elsewhere in Esmeralda County a complete stratigraphic section includes two additional units, the Campito and Poleta Formations, between the Deep Spring and Harkless. These formations consist of siltstone, sandstone, and limestone and are lithologically similar to parts of the Harkless. The upper part of the exposed section of Harkless(?) at Lone Mountain is intruded by a variety of granitic and gabbroic rocks and covered by alluvium; no stratigraphic top is seen. At Klondyke, the upper contact of the Harkless Formation with Mule Spring Limestone is marked by the change from dark hornfels to massive gray limestone and is best exposed in the SW/4 S24,T1N,R42E.

The Harkless Formation is Early Cambrian in age, based on trilobite fossils (see Albers and Stewart, 1972). No fossils were found in exposures of this formation in the mapped area, possibly due to the pervasive metamorphism. Because strata of the Campito Formation resemble the Harkless (Albers and Stewart, 1972, p. 16), the correlation of hornfels, dark quartzites, and limestones exposed at the northeast end of Lone Mountain with the Harkless Formation is somewhat tentative, and the strata could be Campito rather than the Harkless.

The Harkless Formation is the lateral equivalent of the uppermost part of the Wood Canyon Formation and the overlying lower and middle parts of the Zabriskie Quartzite in the central region of the southern Great Basin (Stewart, 1970). In Esmeralda County, the Saline Valley Formation is virtually indistinguishable from the Harkless Formation, and Albers and Stewart (1972) have included the lithologically similar and possibly correlative Saline Valley units within the Harkless. The Campito Formation, the alternative designation possible for the strata on Lone Mountain, is equivalent to the middle member and part of the upper member of the Wood Canyon Formation (Stewart, 1970).

MULE SPRING LIMESTONE (€ms, €msh)

The Mule Spring Limestone was named by Nelson (1962) for a 150-to-300-meter-thick sequence of gray, fine-grained, crystalline limestone exposed in the Inyo Mountains, Calif. It characteristically contains concretionary algal structures (*Girvanella*) 1.3 cm in diameter (Stewart, 1970). Limy siltstone and silty limestone occur in the lower part of the unit. The amount of *Girvanella* present in the formation is quite variable (Albers and Stewart, 1972).

The Mule Spring Limestone is present in the southern part of the mapped area in the Klondyke Hills, and to the west across Montezuma Valley in the General Thomas Hills (S9,10,T1N,R41E). The Mule Spring in the Klondyke Hills consists of approximately 120 m of massive- to thick-bedded, blue-gray limestone. The limestone is finely crystalline, and commonly displays concretionary algal structures (*Girvanella*) as white calcite replacements in a medium-gray, finely crystalline limestone. Bedding in the Mule Spring varies in thickness from several cm to more than 3 m (Chipp, 1969). To the west of Klondyke, in the General Thomas Hills, the Mule Spring Limestone consists of massive limestone with minor interbedded dark-colored siltstone (now metamorphosed to hornfels). This hornfels resembles hornfels in the Harkless Formation, but the Mule Spring hornfels beds are less than 30 m thick, with the majority of the formation consisting of limestone. This outcrop in the General Thomas Hills may represent the lower part of the Mule Spring, since shales and limy siltstones are more common in the lower 30 to 45 m of the formation in Esmeralda County (Albers and Stewart, 1972).

The Mule Spring is latest Early Cambrian and laterally equivalent to the lower third of the Carrara Formation in the Spring Mountains and Death Valley areas (Stewart, 1966). The Mule Spring lies conformably on the Harkless in the Klondyke area, and underlies the Emigrant Formation. The Mule Springs-Emigrant contact is placed at the change from massive limestone below to an overlying argillite.

EMIGRANT FORMATION (€e)

The Emigrant Formation was named by Turner (1902, p. 265) for exposures near Emigrant Pass at the north end of the Silver Peak Mountains, Esmeralda County, Nev. Albers and Stewart (1972, p. 20) divided the Emigrant into three members named informally from bottom to top: (1) the limestone and siltstone member, (2) the shale member, and (3) the limestone and chert member. In the Klondyke Hills, Chipp (1969) describes over 900 m of the formation and divides it into five units. From bottom to top they are: (1) an argillite unit, 5 m thick, (2) an argillaceous limestone unit 60 to 120 m thick, (3) a spotted siltstone unit, about 90 m thick, (4) a limestone unit over 600 m thick, and (5) a banded unit, 150 to 200 m thick. These subdivisions roughly correspond to the informal

members of Albers and Stewart (1972) in that Chipp's number 1 and 2 units correlate with the limestone and siltstone member, the number 3 unit is equivalent to the shale member, and units 4 and 5 correspond to the limestone and chert member.

The basal 15 m of the Emigrant Formation in the Klondyke Hills consist of light-brown to gray argillite. This argillite may correspond to an 18-m thick fossiliferous basal unit reported by Albers and Stewart (1972) from the Goldfield Hills and on Clayton Ridge south and southwest of the Klondyke Hills. No fossils were found in the argillite in the Klondyke Hills, possibly because of shearing within the unit. The argillite is overlain by dark-gray, thin-bedded, locally silicified, argillaceous limestone, 60 to 120 m thick (Chipp, 1969). Above the argillaceous limestone, in the NW/4 S25,T1N,R42E, is a spotted hornfels consisting of fine-grained quartz with sparse biotite and muscovite. Above this is a unit of interstratified thin beds of limestone and chert about 600 m thick. The limestone is medium gray, finely crystalline, and occurs in beds 2 to 10 cm thick interlayered with 2-to-8-cm-thick beds of brown-weathering, medium-gray chert. These beds are exposed in the Klondyke Hills and on the edge of the General Thomas Hills to the west across Montezuma Valley where they underlie a thrust slice of Palmetto Formation. Above the limestone and chert is a sequence of interbedded siltstone and limestone (the banded unit of Chipp, 1969). This unit is 150 to 210 m thick, and has a distinctive appearance on the weathered surface due to alternating thin (1 cm) colored bands of various shades of brown and gray.

The stratigraphic top of the Emigrant Formation is not exposed in the Klondyke Hills because the formation lies under an allochthonous block of Ordovician Palmetto Formation. Other minor thrust faults are present within the Emigrant Formation in this area (pl. 1, Chipp, 1969). The majority of the formation is probably present here, as determined by comparison of the section with surrounding areas. Albers and Stewart (1972) estimate the Emigrant might be up to 1,500 to 1,800 m thick in Esmeralda County. Probably over 900 m of section are present at Klondyke.

No fossils were found in the Emigrant, but fossil evidence elsewhere in Esmeralda County indicates that the unit is of Middle and Late Cambrian age (Albers and Stewart, 1972) and is correlative with the Monola and Bonanza King Formations in the Inyo and White Mountains of California (Stewart, 1970, p. 64).

Ordovician Strata

PALMETTO FORMATION (Op, Opl)

The name "Palmetto Formation" was applied by Turner (1902, p. 265) to outcrops in the Palmetto Mountains in southwestern Esmeralda County. It crops out extensively in Esmeralda County, and consists mainly of shale, siltstone, and lesser amounts of chert and limestone. Near intrusives, the rocks are metamorphosed to hornfels and argillite. The exact thickness of the formation is unknown because it is everywhere folded and faulted, but it must be over 1,000 m thick (Albers and Stewart, 1972). The Palmetto may be transitional between rocks of the miogeosynclinal and eugeosynclinal facies (John Stewart, personal commun., 1975), because it includes Emigrant-like rocks and is in normal depositional contact with the Emigrant Formation at several localities in Esmeralda County (Albers and Stewart, 1972, p. 21, 23). Stewart and Poole (1964) have proposed that the Palmetto in northernmost Esmeralda County and the adjacent part of Mineral County is allochthonous, whereas to the south in the remainder of Esmeralda County it is autochthonous or para-autochthonous.

Rocks of the Palmetto Formation are exposed in the central part of the Klondyke Hills, and near the Midway Mine in the northeastern part of the mapped area. The outcrops near the Midway Mine occupy slightly less than 1 km^2, and consist of spotted chiastolite slate, black chert and a few 1.2-to-1.5-m-thick beds of sandy limestone. Graptolites, especially *Climacograptus bicornis* Hall were found in the slate. The Midway Mine exposures are over 75 percent medium-gray slate and argillite, 10 to 15 percent black chert, and less than 5 percent medium- to dark-gray sandy limestone and calcareous sandstone. Sand-size quartz grains in the calcareous sandstone and sandy limestone are well rounded, up to 1 mm in diameter, and not well sorted. Rocks assigned to the Palmetto Formation in the Klondyke Hills are similar to those near the Midway Mine. Some light-gray shales here contain grapolites, tentatively identified as *Orthograptus* sp. Probably three-quarters of the rock exposed in the Klondyke area (about 2 km^2) is dark-gray slate, argillite, and black chert. The remainder consists of discontinuous beds of tan and gray limestone and black quartzite (Chipp, 1969, p. 18). A limestone and chert unit, 150 to 180 m thick and mapped separately (pl. 1) at Klondyke, crops out in the SW/4 S30,T1N,R42E. This unit strongly resembles the limestone and chert member of the Emigrant Formation but seems to be interbedded with dark slate and quartzite of the Palmetto. Albers and Stewart (1972, p. 23) describe similar rocks within the Palmetto in the General Thomas Hills about 19 km west of Klondyke.

Neither the basal nor upper contacts of the Palmetto Formation are exposed in the mapped area. At the Midway Mine, Tertiary volcanic rocks and Quaternary alluvium overlie the Palmetto, and near Klondyke the Palmetto is always in thrust contact with the underlying Emigrant Formation. Movement on the thrust is not necessarily of great extent, since it does not juxtapose rocks of different depositional environment (the Palmetto and Emigrant are both essentially transitional assemblage rocks). Stewart and Poole (1974) have suggested that the Palmetto is autochthonous or para-autochthonous in this part of Esmeralda County.

The Palmetto Formation ranges in age from Early to Late Ordovician, based on numerous graptolite collections. (See Albers and Stewart, 1972.) It is part of a shale and chert facies of Ordovician rocks in north-central and western Nevada which also includes the Vinini and Comus Formations (Stewart and Poole, 1974), and is possibly correlative with these formations. The Palmetto is also somewhat similar to the Broad Canyon Formation in the central Toiyabe Range, 80 km north of Tonopah (Washburn, 1970, p. 276).

VALMY(?) FORMATION (Ov?, Ovl?)

The Valmy Formation was named by Roberts (1951) for exposures on the north side of Battle Mountain, Humboldt

County. North of the San Antonio Mountains, in Lander County, the Valmy occurs in thrust sheets within the upper plate of the Roberts Mountains thrust and consists mostly of chert, quartzite (or sandstone), siltstone, shale, and minor to sparse greenstone and limestone (Stewart and others, 1977). A similar sequence of marine rocks of probable early Paleozoic age is exposed in an 8 to 10 km^2 area approximately 12 km north of Tonopah. We believe these rocks are Ordovician in age and they closely resemble the Valmy Formation elsewhere in western Nevada. Neither the bottom nor the top of the unit is exposed in the San Antonio Range. The apparent lowermost beds are limestones seen near the south margin of the area of exposure, where the rocks have been intruded by Cretaceous granodiorite. The formation is separated from an overlying Mississippian limestone by a thrust fault, exposed near the abandoned mining camp of Rays (pl. 1).

The Valmy(?) Formation in the map area is over two-thirds quartzite and siltstone; the remainder includes chert and minor conglomerate, limestone, dolomite and greenstone. Many samples indicate low rank metamorphism to schist, argillite, and hornfels. Limestone beds within the formation are exposed near the north and west margins of the granodiorite intrusive, and are recrystallized to coarse-grained, light- to medium-gray marble. Near the granodiorite contact the rocks are extensively sheared. Very thin bedding (1 to 2 cm) is seen at a few localities. The limestone is locally altered to tactite; some tactite contains scheelite and molybdenite (See the Peg Leg Mine). Garnet is the most abundant calc-silicate mineral in the tactite, although pyroxene is also present.

Fine-grained quartzite and argillite make up the bulk of the exposures between the granodiorite and the Rays area. The quartzite is thin-bedded, thinly laminated, light to dark gray on fresh broken surfaces and weathers to a yellowish-brown color. Poorly preserved trace fossils ("worm trails") were noted on bedding surfaces of a quartzite exposed at a locality 2 km northeast of Fraziers well. Quartzite is strongly cemented by calcite, or, less commonly, by silica; in thin section, it is strongly bimodal in the size range of grains. Larger (0.3 to 0.6 mm) grains are well rounded and the smaller (up to 0.1 mm) are subangular to subrounded. Argillite and very fine-grained quartzite contain several percent muscovite. The detrital grains in the quartzites consist entirely of quartz except for accessory apatite, zircon, and magnetite. In one thin section of coarse-grained, thinly laminated, calcareous siltstone a few (less than 1 percent) 0.1- to 0.5-mm grains of plagioclase and microcline were seen. A small number of conglomerate beds, consisting of well-rounded chert or quartz pebbles, are present in the section.

Chert beds make up as much as one-fifth of the exposures between the granodiorite and Rays, and most are dark gray to black (fig. 7). In thin section the chert consists of a dense mosaic of microcrystalline silica and very fine-grained opaque minerals. Some of the chert includes a small amount of silt-size detrital quartz and finely crystalline sericite. The chert is interbedded with siltstone, argillite, and rare dolomite and greenstone. The dolomite occurs as thin beds, weathers reddish to yellowish brown and is recrystallized. The greenstone was originally vesicular basaltic breccia and pillow lava, but now is completely altered to saussurite, sericite, and calcite. The chemistry

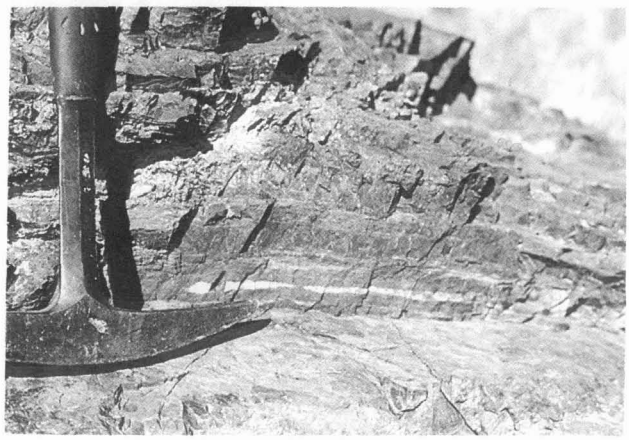


FIGURE 7. Dark-gray to black chert beds in the Valmy(?) Formation east of Rhyolite Peak.

of the greenstone indicates that it is probably related to tholeiitic basalt (Miyashiro, 1974) that was erupted on a crust of dominantly oceanic composition. The analysis in table 2 is similar to analyses from tholeiitic basalt in the Valmy elsewhere (Rogers and others, 1974). A sample of unmineralized argillite from the Valmy(?) near Rays contained over 12,000 ppm barium, and the greenstone in the Valmy reportedly contains 30,000 ppm (table 2). Anomalous barium is also common in other Ordovician rocks (including pillow lavas) in western Nevada (Wrucke and others, 1978). Valmy(?) greenstones are exposed in the vicinity of Rays where they are cut by numerous thrust faults which are probably of minor displacement. These thrust faults increase in number toward the major thrust at Rays (fig. 8). Some of the Valmy(?) is thermally meta-

TABLE 2. Chemical composition of greenstone from the Valmy(?) Formation near Rays, Nye County. Approximate location, S23,T4N,R42E.

[Analysis by U. S. Geological Survey; sample collected by F. G. Poole (No. 68 FP–443)]

	Weight percent	Volatile-free percent		ppm
SiO_2	44.5	49.0	Ba	30,000
Al_2O_3	16.7	18.4	Co	50
Fe_2O_3	1.4	1.5	Cr	500
FeO	9.6	10.6	Cu	150
ΣFeO	10.8	11.9	La	50
MgO	7.5	8.3	Mo	10
CaO	4.1	4.5	Nb	20
Na_2O	2.2	2.4	Ni	200
K_2O	1.8	2.0	Sc	20
H_2O^+	5.1		Sr	300
H_2O^-	0.13		V	200
TiO_2	2.4	2.6	Y	30
P_2O_5	0.43		Zr	200
MnO	0.11			
CO_2	2.8			
Total	99.0	99.3		

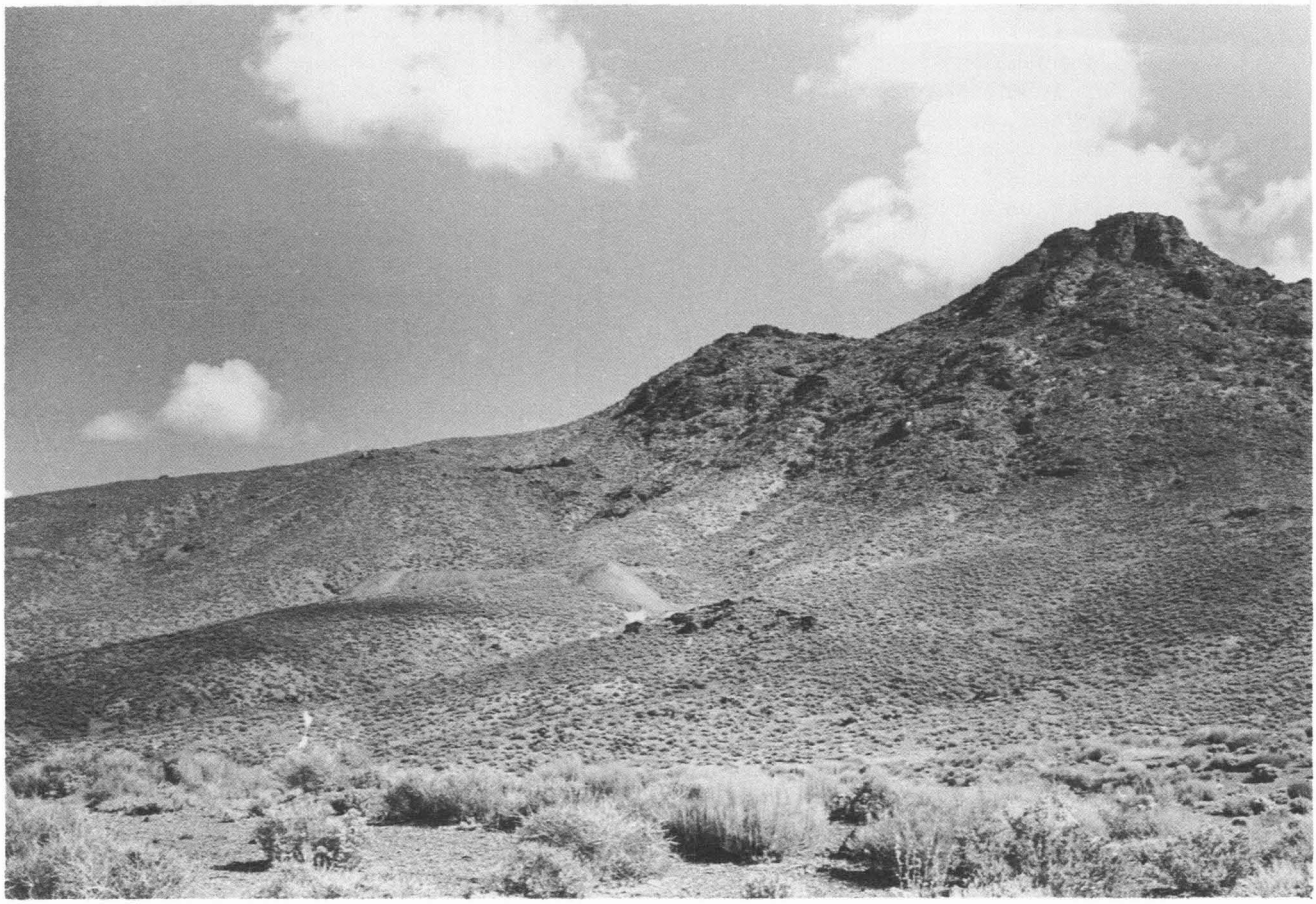


FIGURE 8. Mississippian Limestone (rough, craggy outcrop) overlying Ordovician rocks on a low-angle thrust fault at Rays.

morphosed in the map area. Tactite and calc-silicate hornfels occur near the contact with Cretaceous granodiorite, and quartz-muscovite-andalusite hornfels are relatively common. The andalusite in many samples is completely sericitized.

The age of the rocks in the mapped area we place in the Valmy(?) is not definitely known because no fossils were found. Broderick (1949) reports that H. G. Ferguson found Ordovician fossils in rocks exposed near the Rays district. Unfortunately, this locality was not described in any publication by Ferguson, and no collections could be found in the files of the U. S. Geological Survey (F. J. Kleinhampl, oral commun., 1976). Ferguson and Muller (1949, p. 4) also describe these rocks as Ordovician without citing any direct evidence. F. G. Poole (written commun., 1973) collected possible plant impressions from the Valmy(?) near Rays which were identified by S. H. Mamay (written commun., 1973) as probable impressions of woody plant stems, Devonian or younger in age. However, after further field checking, we believe that these are more likely impressions of shale fragments, and not useful in age determination. Quartzite from the Valmy(?) in the mapped area strongly resembles quartzite in the Valmy Formation at the type section, in that both are rich in quartz and display the characteristic texture of rounded larger grains surrounded by more angular small ones. Gilluly and Masursky (1965, p. 40) mentioned that this characteristic is distinctive of the Valmy. Also the general lithologic character of the Valmy in many areas of western Nevada resembles that of these rocks near Rays (for example see Gilluly and Gates, 1965). In summary, we believe that the association of greenstone with distinctive quartzite beds is more likely found in the Valmy Formation than in other lower Paleozoic units such as the Vinini or Palmetto Formations.

Mississippian Strata

LIMESTONE AND SHALE NEAR RAYS (Ml, Mls)

An allochthonous block (about 2.6 km^2) of massive limestone and minor shale of Mississippian age overlies the Valmy(?) Formation about 12 km north of Tonopah (fig. 8) near the site of the abandoned mining camp of Rays. The unit is separated from the underlying Ordovician? cherts, quartzites, and siltstones by a nearly flat-lying thrust fault (fig. 8).

The limestone, which makes up about 90 percent of the outcrop area, is a medium- to dark-gray calcarenite that is commonly recrystallized. Bedding is uncommon in the limestone, making the determination of any structure in the unit difficult. At some localities the rocks contain numerous crinoid columnals, solitary and colonial corals, some brachiopods, and *foraminifera*, which are described below. The surfaces of many outcrops, especially on the higher areas of the peak above the old mining camp of Rays, consist of light-gray to reddish jasperoid. This extensive silicification seems to be mainly a near-surface phenomena—that is, outcrops of unsilicified limestone can usually be found in the deeper canyons, while the higher areas more commonly consist of massive jasperoid. The

thickness of the limestone is unknown, because neither the base nor top of the unit is exposed and bedding features are scarce.

A distinctive black siltstone unit crops out at the northwest corner of the outcrop area of Mississippian rocks. It is interbedded with limestone and separated from the main mass of limestone outcrop by a high-angle fault. The siltstone weathers into thin "pencils," which litter the outcrop area. Because of the association with limestone that is essentially identical to the main outcrop, the siltstone is considered part of the same Mississippian unit. About 60 to 90 m of the siltstone are exposed in any single uninterrupted section.

Corals collected from limestone beds exposed in the northern San Antonio Mountains indicate a probable early Late Mississippian age for these rocks (Helen Duncan, written commun., 1964). Two of the fossil groups identified below were collected by Frank J. Kleinhampl of the U. S. Geological Survey in 1963 and 1965; the third (USGS 14666-PC) is a re-examination of a 1951 collection of H. G. Ferguson of the U. S. Geological Survey. Fossil identifications are by Helen Duncan and Betty Skipp of the U. S. Geological Survey.

15084-F2 (USGS 19778-PC, shipment SW-63-2), NE/4 S23,T4N,R42E (unsurveyed); about 1.2 km southeast of the site of Rays.

Siphonodendron sp.
pelmatozoan columnal
horn coral, indeterminable fragment

Age: The lithostrotionoid coral *Siphonodendron* appears in American faunas about the beginning of Late Mississippian time and is, so far as we know, diagnostic of the Upper Mississippian (Helen Duncan, written commun., 1964).

63-F1 (USGS 14666-PC) "Ferguson collection," 13 km north of Tonopah, from limestone east of Rays, T4N,R42E.

Siphonodendron sp.
Syringopora sp.
Schizophoria sp.
Cleiothyridina sp.

Age: Early Late Mississippian (re-examination by Helen Duncan, 1964)

15084-6 (shipment SW-65-4), NW/4 S24,T4N,R42E (unsurveyed), about 1.2 km east of the site of Rays.

Globoendothyra aff. *G. baileyi* Hall 1854
Endothyra bowmani Brady 1876, emend. 1C2N 1965
Priscella sp.
Eoturberitina sp.
Earlandia spp.

Age: This fauna is representative of Mamet's foraminiferal zones (F.Z.) 10 through 12 (Mamet and Skipp, 1971) and is of late Early Mississippian (Brenckle and others, 1974) to early Late Mississippian age (Betty Skipp, written commun., 1977).

The Mississippian limestone at Rays is believed to have been deposited within the Antler highland or orogenic belt, where that highland was locally reduced to sea level and partly submerged by Late Mississippian time (Poole and Sandberg, 1977). Exposures of rocks similar to those found near Rays are present about 13 km to the north in the vicinity of the Hall Mine (Davis and others, 1971). Correlative strata are found further to the north, in the Toiyabe Range, and in the Candelaria Hills 80 km west of Tonopah (Poole and Sandberg, 1977, fig. 26; Speed and others, 1977). These limestone and dolomitized limestone units (of which the limestone at Rays is a part) locally contain mudstone, siltstone, sandstone, and conglomerate, and are believed to have a shallow subtidal and intertidal depositional environment (Poole and Sandberg, 1977).

Mesozoic Rocks

Nearly all rocks of Mesozoic age that occur within the boundaries of the area covered in this report are epizonal plutonic rocks. One small area of Mesozoic(?) welded tuff and associated volcaniclastic sedimentary rocks is present in the northeast part of the area.

MESOZOIC(?) ASH-FLOW TUFF (Mzt)

Metamorphosed dacite and rhyodacite ash-flow tuff of probable Mesozoic age is exposed in the NE/4 S12,T4N, R43E, approximately 3 km southeast of Rye Patch Ranch. A few thin beds of epiclastic volcanic pebble conglomerate and sandstone are interlayered with the ash-flow tuffs. The Mesozoic(?) rocks are approximately 100 m thick; the base of the section is not exposed. The rocks are intruded by coarse-grained hornblende diorite and are unconformably overlain by pyroclastic rocks of late Oligocene age (tuffs of Rye Patch) and by Quaternary alluvium.

The pyroclastic rocks are vitric-crystal, moderately to densely welded ash-flow tuffs with an SiO_2 content ranging from 63 to 66 percent (table 3, fig. 9). Two of the analyzed samples are dacites and two are rhyodacites. The rhyodacite welded tuff is a yellowish to greenish-gray, hard, resistant rock, which usually shows well-developed eutaxitic texture in hand specimen. The tuff contains between 15 and 20 percent phenocrysts of plagioclase (An_{35-50}), potassium feldspar, biotite, sparse quartz, and accessory Fe-Ti oxides, apatite, and zircon. Plagioclase commonly comprises up to 80 percent of the total amount of phenocrysts. The phenocrysts range up to 3 mm in maximum dimension, but seldom exceed 2 mm in length. Many of the phenocrysts are corroded. The dacite welded tuff is olive gray to yellowish gray and has a crystal content of between 15 and 25 percent, of which 75 to 80 percent is plagioclase (An_{40-45}), and the remainder is made up of approximately equal amounts of potassium feldspar, hornblende, biotite, and clinopyroxene. Accessory minerals are Fe-Ti oxides, apatite, and zircon. Phenocrystic quartz is rare to absent in the dacite tuff. Approximately half of the phenocryst minerals are corroded. The size range of the phenocryst minerals in the dacite tuff is nearly identical to that of the rhyodacite tuff.

The lithic content of the ash-flow tuffs ranges from about 1 to 10 percent and presumably reflects differences in the lithic content of individual cooling units. The most abundant lithics are chert, quartzite, limestone, welded tuff, and plutonic rocks.

Low-grade greenschist to epidote-amphibolite facies metamorphism of the dacite and rhyodacite has resulted in the partial alteration of plagioclase to mixtures of albite, sericite, and calcite; biotite to chlorite and Fe-Ti oxides;

TABLE 3. Chemical analyses, Mesozoic(?) ash-flow tuff.

Sample	T190 Dacite	SS114 Rhyodacite	T188A Dacite	T189 Rhyodacite
Location number	1	2	3	4
		Normalized oxide values		
SiO_2	62.9	65.4	64.8	66.0
Al_2O_3	14.6	15.9	16.3	15.9
Fe_2O_3	2.4	2.8	2.9	0.5
FeO	4.1	2.2	2.8	4.2
MgO	2.4	1.2	1.5	1.3
CaO	4.4	3.1	3.4	2.9
Na_2O	4.7	4.2	3.1	3.7
K_2O	3.6	4.2	4.4	4.8
TiO_2	0.7	0.8	0.9	0.8
MnO	0.45	0.05	0.55	0.06
		Normative minerals		
Quartz	9.7	17.0	20.1	15.5
Corundum			0.4	
Orthoclase	21.1	25.0	25.8	28.3
Albite	39.8	35.3	26.1	31.5
Anorthite	8.0	12.3	16.6	12.5
Diopside	11.3	2.7		1.7
Hypersthene	5.2	2.3	5.0	8.5
Magnetite	3.6	4.0	4.2	0.7
Hematite				
Ilmenite	1.3	1.5	1.7	1.4
Wollastonite (diopside)	5.8	1.4		0.8
Enstatite (diopside)	3.1	1.1		0.3
Ferrosilite (diopside)	2.4	0.2		0.6
Enstatite (hypersthene)	2.9	1.9	3.7	2.9
Ferrosilite (hypersthene)	2.3	0.4	1.4	5.6
		Petrologic indices		
Differentiation index	70.6	77.2	72.1	75.3
Felsic-mafic index	5.3	7.9	6.9	8.5

Locations: 1. N/2 S12,T4N,R43E
2. N/2 S12,T4N,R43E
3. NE/4 S12,T4N,R43E
4. N/2 S12,T4N,R43E

and hornblende and clinopyroxene to actinolite, clinozoisite, and Fe-Ti oxides. The original matrix of pumice, shards, and dust in the welded tuffs is completely recrystallized to fine-grained aggregates of quartz, actinolite, alkali feldspar, biotite, chlorite, albite, and calcite. Primary tuff structures are almost completely destroyed in these rocks by recrystallization, but ghosts of pumice and shards are recognizable in some specimens. The pyroclastic textures in these rocks, principally flattened pumice are more obvious in hand specimen than in thin section.

The volcanic pebble conglomerate and sandstone are pale reddish brown, well indurated, poorly sorted rocks. The pebble conglomerate contains subangular to subrounded pebbles up to 1 cm in diameter in a sandy matrix. The pebbles consist predominantly of intermediate volcanic flow rock, welded tuff, and quartzite. The sand-size matrix consists of 0.1 to 2 mm grains of quartz, plagioclase, potassium feldspar, and volcanic rock fragments. The volcanic sandstones are poorly sorted, medium to coarse grained and are lithologically identical to the sand-size matrix of the pebble conglomerates.

A plagioclase separate from the Mesozoic(?) welded tuffs yielded a K-Ar age of 17.3±0.8 m.y. This age is certainly too young, because the tuffs of Rye Patch, which unconformably overlie the Mesozoic(?) rocks, are at least 25 m.y. old. Many of the Tertiary volcanic rocks and most of the hydrothermal alteration in the map area give K-Ar ages near 17 m.y. (table 4) and it seems quite likely that the 17.3 m.y. plagioclase age reflects a thermal or hydrothermal event related to Tertiary volcanism.

We believe that the most probable age for the welded tuffs and associated sediments is Mesozoic, primarily

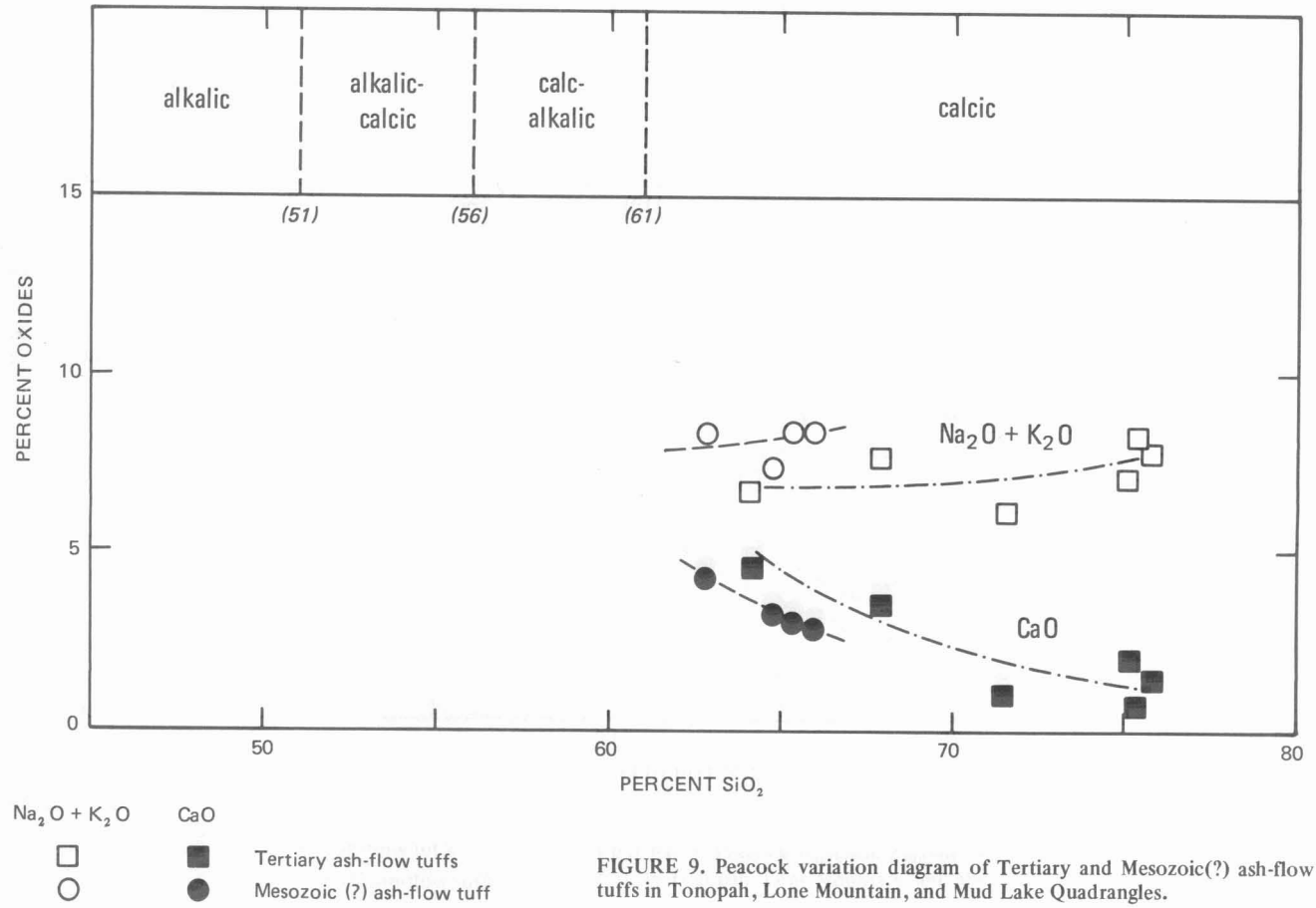


FIGURE 9. Peacock variation diagram of Tertiary and Mesozoic(?) ash-flow tuffs in Tonopah, Lone Mountain, and Mud Lake Quadrangles.

because the rocks are intruded by coarse-grained hornblende diorite of a type relatively common in intrusive rocks of Mesozoic age in this portion of Nevada (100 km radius). Coarse-grained diorite is not known to occur in Tertiary intrusive rocks from the same area. Secondly, rocks of known Tertiary age within a 100-km radius are unmetamorphosed, with the possible exception of the Darrough Felsite (Speed and McKee, 1976, p. 75–81). The Mesozoic(?) welded tuffs and clastic sedimentary rocks, on the contrary, are definitely metamorphosed, and it seems unlikely, from Speed and McKee's lithologic description of the predominantly crystal-rich, rhyolitic ash-flow tuffs of the Darrough Felsite (1976, p. 78–79), that the Mesozoic(?) ash-flow tuffs in the Tonopah area are correlative with the Darrough Felsite.

HORNBLENDE DIORITE (Kd)

Diorite crops out in an area approximately 600 m long and 240 m wide in S12,T4N,R43E. The diorite intrudes Mesozoic(?) ash-flow tuff and is unconformably overlain by the tuffs of Rye Patch.

The diorite is a greenish-gray, coarse-grained rock with a hypautomorphic-granular texture. It is less resistant to erosion than the Mesozoic(?) ash-flow tuffs and weathers to gruss-mantled slopes.

The diorite consists predominantly of plagioclase (An_{45-55}) and hornblende in subequal amounts with minor interstitial orthoclase and quartz. Fe-Ti oxides and apatite are ubiquitous accessory minerals. Plagioclase occurs as euhedral to subhedral crystals up to 6 mm long, which are partially altered to sericite. The hornblende is euhedral to subhedral and is altered to a mixture of actinolite and chlorite. Orthoclase is anhedral and is partially altered to clay minerals.

The age of the hornblende diorite is known only within broad limits. The diorite is older than the tuffs of Rye Patch (25 m.y.) and younger than the Mesozoic(?) ash-flow tuffs. It is therefore older than 25 m.y. and is very probably no older than Triassic, since plutonic rocks of Paleozoic age are not known to occur in Nevada.

LONE MOUNTAIN PLUTONIC ROCKS

Plutonic rocks crop out over an area of approximately 50 km^2 in T2,3N,R40E in the southwestern part of the Lone Mountain quadrangle. The plutonic rocks range in composition from gabbro through quartz monzodiorite to granite. Granite is the most abundant plutonic rock type. The plutonic rocks intrude Precambrian and Cambrian metasedimentary rocks and are intruded by a silicic porphyry dike swarm of Tertiary age.

Gabbro (Kgb)

Hornblende gabbro is the oldest plutonic rock exposed in the Lone Mountain area. The gabbro intrudes the Harkless(?) Formation and is intruded by quartz monzodiorite and by a swarm of granite and rhyolite porphyry dikes. The resulting outcrop pattern (pl. 1) is very complex with many bodies of gabbro and Harkless(?) Formation, ranging from a few meters to a 1,000 m in length, occurring as isolated roof pendants in the silicic intrusions.

The contact between the gabbro and the Harkless(?) Formation is sharp, discordant, and intricate in detail,

TABLE 4. Age dates from the Tonopah, Lone Mountain, Klondike, and northern Mud Lake quadrangles.

[Except where noted, all K-Ar age determinations by M. L. Silberman, U. S. Geol. Survey, Menlo Park, Calif. All fission-track age determinations by R. P. Ashley, U. S. Geol. Survey, Menlo Park, Calif. Some dates previously reported in Bonham and others (1973) and Silberman and others (1975).]

Age m.y.	Mineral	Method[1]	Unit	Sample no.	Location	Comments
10.5±0.3	Alkali feldspar	K-Ar	Rhyolite of Klondyke	K-1	NW/4 NW/4 NW/4 S31,T1N,R43E	
12.0±0.5	Whole rock	K-Ar	Trachyandesite of Mud Lake(?)	Y-58441	SE/4 NW/4 NW/4 S11,T2S,R43E	Age determination by R. L. Armstrong and H. Dick, Yale Univ. (Armstrong and others, 1972).
14.7±0.3	Alkali feldspar	K-Ar	Rhyolite of Millers	Millers-1	SE/4 SW/4 S13,T3N,R40E	
14.7±0.5	Hornblende	K-Ar	Trachyandesite of Red Mountain	RMB-2	NE/4 SW/4 NW/4 S29,T3N,R43E	Probably close to true age.
17.9±3.0	Whole rock	K-Ar	Trachyandesite of Red Mountain	Y-57233	Incorrect location given as SE/4 SE/4 T4N,R42E	Age determination by R. L. Armstrong and H. Dick, Yale Univ. (Armstrong and others, 1972). Sample probably from flows along Military Station road, S6, T3N,R43E. Compare with RMB-2.
15.8±2.0	Whole rock	K-Ar	Trachyandesite of Red Mountain(?)	Y-5780	NE/4 NE/4 NW/4 S23,T4N,R43E, unsurveyed	Age determination by R. L. Armstrong and H. Dick, Yale Univ. (Armstrong and others, 1972).
16.1±0.5	Whole rock	K-Ar	Trachyandesite of Thunder Mountain	TM-1	C NW/4 NW/4 NE/4 S22,T4N,R44E	
18.9±1.5	Whole rock	K-Ar	Trachyandesite of Thunder Mountain	Y-B3-13	NE/4 NE/4 SE/4 S28,T4N,R44E	Age determination by R. L. Armstrong and H. Dick, Yale Univ. (Armstrong and others, 1972); age probably too old, compare with TM-1.
16.1±0.5	Biotite	K-Ar	Brougher Rhyolite	BQL-1	SE/4 NW/4 SE/4 S2,T2N,R42E	Mt. Butler, along road to radio tower.
16.3±0.5	Alkali feldspar	K-Ar	Brougher Rhyolite	BQL-1	SE/4 NW/4 SE/4 S2,T2N,R42E	Mt. Butler, along road to radio tower.
16.2±0.4	Biotite	K-Ar	Brougher Rhyolite	659-66	C S10,T1N,R42E	Age determination by M. A. Lanphere and J. C. Engles, U.S.G.S. Isotope Lab. Menlo Park (Albers and Stewart, 1972).
16.2±0.4	Alkali feldspar	K-Ar	Brougher Rhyolite	659-66	C S10,T1N,R42E	Age determination by M. A. Lanphere and J. C. Engles, U.S.G.S. Isotope Lab. Menlo Park (Albers and Stewart, 1972).
13.2±0.4	Biotite	K-Ar	Brougher Rhyolite	BQL-2	C S/2 S27,T4N,R42E, unsurveyed	Younger than Brougher intrusions near Tonopah.
14.6±0.4	Alkali feldspar	K-Ar	Brougher Rhyolite	BQL-2	C S/2 S27,T4N,R42E, unsurveyed	Younger than Brougher intrusions near Tonopah.
14.8±0.5	Hornblende	K-Ar	Rhyodacite, volcanics of Donovan Peak	HL-1	SW/4 NW/4 S32,T2N,R43E	
15.9±0.5	Whole rock	K-Ar	Quartz latite, volcanics of Donovan Peak	L-1		
16.3±0.7	Biotite	K-Ar	Rhyolite, volcanics of Donovan Peak	FBR-2	SW/4 NW/4 S32,T2N,R43E	
15.3±0.6	Sericite	K-Ar	Hydrothermal alteration Divide district	TD-3	NW/4 SW/4 NW/4 S27,T2N,R42E	
15.8±0.5	Muscovite	K-Ar	Hydrothermal alteration Divide district	THA-6	SE/4 SW/4 SE/4 S28,T2N,R42E	Tonopah Hasbrouck Mine.

16.1±0.5	Adularia	K-Ar	Hydrothermal alteration Divide district	A-1[2]	NE/4 SE/4 S28,T2N,R42E	North of Hasbrouck Mountain.
15.7±0.3	Sericite	K-Ar	Hydrothermal alteration Divide district	TD-2	C SW/4 S26,T2N,R42E	At Gold Zone Shaft.
16.3±0.5	Adularia	K-Ar	Hydrothermal alteration Divide district	THA-25C	NW/4 NE/4 S33,T2N,R42E	Hasbrouck Mountain area.
16.4±0.5	Adularized whole rock	K-Ar	Hydrothermal alteration Divide district	THA-25R	NW/4 NE/4 S33,T2N,R42E	Hasbrouck Mountain area.
15.6±1.0	Hornblende	K-Ar	Divide Andesite	D-1	NW/4 SW/4 NW/4 S33,T2N,R43E	
14.9±0.4	Plagioclase	K-Ar	Divide Andesite	D-1	NW/4 SW/4 NW/4 S33,T2N,R43E	
16.8±0.5	Biotite	K-Ar	Divide Andesite	D-1	NW/4 SW/4 NW/4 S33,T2N,R43E	Probably close to true age.
16.9±0.7	Hornblende	K-Ar	Divide Andesite	D-3	NW/4 NW/4 S33,T2N,R43E	Probably close to true age.
16.4±0.5	Biotite	K-Ar	Oddie Rhyolite	Od-1 Bo	C SE/4 NE/4 S35,T3N,R42E	
16.9±0.5	Biotite	K-Ar	Oddie Rhyolite	11550-1		
15.5±1.6	Biotite	K-Ar	Siebert Formation	AD-34	SW/4 SE/4 S20,T2N,R42E	Age determination by Geochron Labs., Inc. (Silberman and McKee, 1972).
19.5±0.4	Alkali feldspar	K-Ar	Siebert Formation	S1E-1	SW/4 SW/4 NE/4 S3,T2N,R42E	K-Ar age too old.
16.1±1.0	Biotite	K-Ar	Siebert Formation	S1E-1	SW/4 SW/4 NE/4 S3,T2N,R42E	
16.2±0.6	Whole rock	K-Ar	Siebert Formation, trachyandesite	S1E-2	SW/4 S3,T2N,R42E	
13.5±0.4	Plagioclase	K-Ar	Trachyandesite, volcanics of Lime Mountain	LM-1	NW/4 NW/4 SW/4 S7,T4N,R42E, unsurveyed	Age date is too young.
9.7±0.5	Plagioclase	K-Ar	Trachyandesite, volcanics of Lime Mountain	LM-1	NW/4 NW/4 SW/4 S7,T4N,R42E, unsurveyed	Age date is too young.
10.0±1.0	Whole rock	K-Ar	Trachyandesite, volcanics of Lime Mountain	LM-1	NW/4 NW/4 SW/4 S7,T4N,R42E, unsurveyed	Age date is too young.
15.6±0.5	Hornblende	K-Ar	Trachyandesite, volcanics of Lime Mountain	LM-2	SE/4 NE/4 S4,T4N,R42E, unsurveyed	Probably close to true age.
16.8±0.5	Plagioclase	K-Ar	Trachyandesite, volcanics of Lime Mountain	LM-2	SE/4 NE/4 S4,T4N,R42E, unsurveyed	Probably close to true age.
15.8±0.5	Hornblende	K-Ar	Trachyandesite, volcanics of Lime Mountain	LM-3	SW/4 S4,T4N,R42E, unsurveyed	Probably close to true age.
16.9±0.3	Alkali feldspar	K-Ar	Heller Tuff	USGS(M) 11549-1	NE/4 S2,T2N,R42E	
17.1±0.3	Biotite	K-Ar	Heller Tuff	USGS(M) 11549-1	NE/4 S2,T2N,R42E	
18.9±0.4	Alkali feldspar	K-Ar	Rhyolite of the Cleft	R-1	NW/4 S3,T4N,R42E, unsurveyed	
17.0±0.7	Adularized whole rock	K-Ar	Mizpah Formation (altered)	T229	C W/2 S35,T4N,R42E, unsurveyed	Fraziers Well area.
18.1±0.7	Adularized whole rock	K-Ar	Mizpah Formation (altered)	T291	C SE/4 S35,T3N,R42E	Tonopah district.
19.1±0.4	Adularia	K-Ar	Tonopah district vein	USGS(M) TV-1	W/2 S36,T3N,R42E	
20.4±0.6	Biotite	K-Ar	Mizpah Formation	USGS(M) T219	SE/4 SE/4 S15,T3N,R42E	
20.5±0.8	Biotite	K-Ar	Mizpah Formation	GC-135	NE/4 SW/4 SE/4 SE/4 S26,T3N,R42E	

TABLE 4. Age dates from the Tonopah, Lone Mountain, Klondike, and northern Mud Lake quadrangles.–Continued

Age m.y.	Mineral	Method[1]	Unit	Sample no.	Location	Comments
18.7±0.6	Alkali feldspar	K-Ar	Upper unit, King Tonopah Member of Fraction Tuff	TV-1	SE/4 NW/4 S24,T3N,R42E	
20.4±0.6	Alkali feldspar	K-Ar	Lower unit, King Tonopah Member of Fraction Tuff	TV-2	SW/4 SE/4 S15,T3N,R42E	
19.6±0.4	Glass	K-Ar	Lower unit, King Tonopah Member of Fraction Tuff	SS-25	C SE/4 SW/4 SW/4 S22,T3N,R42E	
19.7±0.6	Alkali feldspar	K-Ar	Lower unit, King Tonopah Member of Fraction Tuff	TFR-1	NE/4 SW/4 SW/4 S24,T3N,R24E	
21.5±0.9	Biotite	K-Ar	Lower unit, King Tonopah Member of Fraction Tuff	TFR-1	NE/4 SW/4 SW/4 S24,T3N,R42E	
17.3±0.5	Biotite	K-Ar	Tonopah Summit Member of Fraction Tuff	74MLS-1	NW/4 SW/4 S17,T2N,R43E	K-Ar age too young, probably affected by younger rhyolite intrusions.
17.0±1.3	Zircon	FT	Tonopah Summit Member of Fraction Tuff	74MLS-1	NW/4 SW/4 S17,T2N,R43E	
18.4±3.1	Apatite	FT	Tonopah Summit Member of Fraction Tuff	74MLS-1	NW/4 SW/4 S17,T2N,R43E	
16.8±0.7	Biotite	K-Ar	Tonopah Summit Member of Fraction Tuff	TFR_2-(1)	SW/4 NW/4 NE/4 S11,T2N,R42E	K-Ar age too young, probably affected by younger rhyolite intrusions; rock is somewhat altered.
16.2±0.5	Alkali feldspar	K-Ar	Tonopah Summit Member of Fraction Tuff	TFR_2-(1)	SW/4 NW/4 NE/4 S11,T2N,R42E	K-Ar age too young, probably affected by younger rhyolite intrusions; rock is somewhat altered.
22.1±3.2	Zircon	FT	Silicic porphyry dike, Lone Mountain	GRP-1	SE/4 SW/4 SW/4 S2,T2N,R40E, unsurveyed	
25.2±0.7	Biotite	K-Ar	Tuff of Murphy's Camp	MC-1	SW/4 S3,T5N,R46E, unsurveyed	Overlies the tuffs of Rye Patch.
24.0±0.7	Plagioclase	K-Ar	Tuff of Murphy's Camp	MC-1	SW/4 S3,T5N,R46E, unsurveyed	Overlies the tuffs of Rye Patch.
26.0±0.8	Biotite	K-Ar	Tuffs of Antelope Springs(?)	Taf_2-(1)	NW/4 SW/4 SE/4 S5,T1S,R43E	
24.3±2.8	Zircon	FT	Tonopah Formation	TF-1	SW/4 S24,T3N,R42E	
34.8±4.2	Zircon	FT	Tonopah Formation	TF-2	NW/4 S31,T4N,R43E	
18.0±0.4	Alkali feldspar	K-Ar	Tuff of Ralston Valley	OWT-1	SE/4 NE/4 NE/4 S21,T4N,R42E	Alteration age.
31.4±3.8	Zircon	FT	Tuff of Ralston Valley	OWT-1	SE/4 NE/4 NE/4 S21,T4N,R42E	
59.3±7.4	Sphene	FT	Fraziers Well pluton	SAgd-1	C SW/4 SW/4 S36,T4N,R42E	
67.9±8.4	Zircon	FT	Fraziers Well pluton	SAgd-1	C SW/4 SW/4 S36,T4N,R42E	
71.1±1.4	Muscovite	K-Ar	Lone Mountain pluton	Spr-1	SE/4 NW/4 S15,T2N,R40E unsurveyed	From a pegmatite dike in the Lone Mountain pluton.
69.2±1.4	Biotite	K-Ar	Lone Mountain pluton	Spr-1A	SE/4 NW/4 S15,T2N,R40E unsurveyed	
67.2±3.0	Biotite	K-Ar	Lone Mountain pluton	1017	Lone Mountain	Age determination by J. D. Obradovich, U.S.G.S. Isotope Lab., Denver (Albers and Stewart, 1972). Probably close to true age.

19.5±1.0	Biotite	K-Ar	Lone Mountain pluton	SP-3	Lone Mountain	Probably affected by silicic porphyry dikes (22 m.y.). Age determination by R. W. Kistler, U.S.G.S. Isotope Lab., Menlo Park (Albers and Stewart, 1972).
63.0±7.0	Biotite	K-Ar	Lone Mountain pluton	S-EPR 40850/ 1010	S10?,T2N,R40E	Age determination by Shell Development Co., Houston; compare with Spr-1, Spr-1A and 1017. (Edwards and McLaughlin, 1972).
104.0±2.0	Muscovite	K-Ar	Muscovite granite of Klondyke	MG-1	SW/4 NW/4 NE/4 S25,T1N,R42E	
113.0±3.0	Hornblende	K-Ar	Gabbro, Lone Mountain	gb-1	NE/4 SE/4 SE/4 S35,T3N,R40E	Minimum age.
17.3±0.8	Plagioclase	K-Ar	Mesozoic(?) welded tuff	Mzwt-1	NW/4 NE/4 S12,T4N,R43E	Alteration age, not crystallization age.
367.0±18.0	Hornblende	K-Ar	Lamprophyre dike, Lone Mountain	1016	Lone Mountain	Age determination by J. D. Obradovich U.S.G.S. Isotope Lab., Denver (Albers and Stewart, 1972). K-Ar age much too old.

[1] K-Ar, potassium argon; FT, fission track.
[2] Sample collected by Cordex Exploration Co.

although there is a crude parallelism between the elongation of the gabbro bodies and the strike of the bedding in the Harkless(?) Formation. The gabbro seems to have been emplaced approximately parallel to the regional grain of the rocks it intrudes.

The gabbro is a medium- to coarse-grained rock, which in hand specimen appears to consist almost entirely of greenish-black hornblende and very light-gray plagioclase. In thin section eight of ten specimens contain plagioclase (An_{50} average), pleochroic green-brown hornblende, augite rimmed with hornblende, together with accessory apatite, Fe-Ti oxides, and sphene. The other two specimens lacked augite. Quartz and biotite are present as rare accessory minerals in a few samples. Sparse veinlets of microcline are also present in several samples of the gabbro and may well be related to potassium metasomatism produced by the silicic rocks that intrude the gabbro.

Plagioclase forms euhedral to subhedral crystals 2 to 5 mm in length. Hornblende also forms subhedral to euhedral crystals which range in length from less than 1 mm to about 1 cm. Microcline and quartz are anhedral; biotite forms euhedral books. The texture of the gabbro is typically subophitic to poikilitic with hornblende partially to completely enclosing crystals of plagioclase, augite, and accessory minerals (fig. 10).

Modal analysis from thin sections and stained plugs show 50 to 55 percent plagioclase, 40 percent hornblende, and 5 to 10 percent augite. Fe-Ti oxides, sphene, apatite, and minor microcline, quartz, and biotite constitute the remainder of the rock.

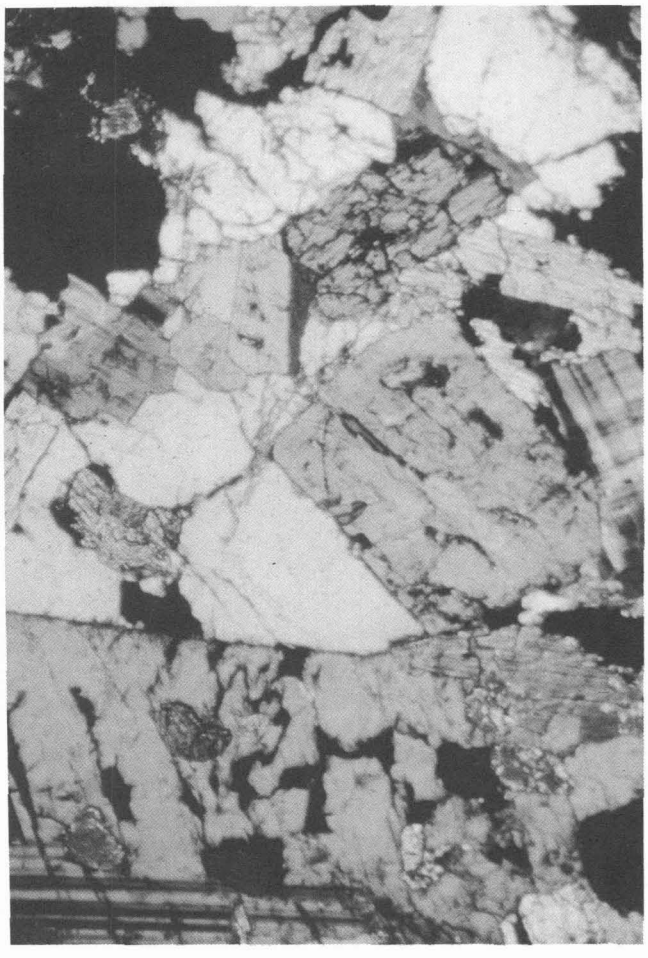


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FIGURE 10. Photomicrograph of Mesozoic gabbro, Lone Mountain area. Crystals of plagioclase, hornblende, and augite. Microcline and epidote replace plagioclase.

A chemical analysis of the gabbro is shown in table 5. This analysis is quite similar to the average hornblende gabbro of Nockolds (1954, p. 1020, col. 1) except for its higher potassium content. As discussed earlier, we believe that part of the potassium in the gabbro is of metasomatic origin.

Hornblende from the gabbro has yielded a potassium-argon age of 110 m.y. (table 4). This must be considered a minimum age because the gabbro occurs as roof pendants in younger silicic intrusives, and the heating of the gabbro during the emplacement of these younger intrusives may have resulted in some loss of radiogenic argon from the hornblende.

Quartz Monzodiorite (Kqm)

Equigranular, medium-grained quartz monzodiorite crops out in the low hills north and east of Lone Mountain. The quartz monzodiorite intrudes the Harkless(?) Formation and the hornblende gabbro and it is intruded by granite and rhyolite porphyry dikes of Miocene age. Like the gabbro, the quartz monzodiorite occurs in a number of isolated bodies as a result of the intimate intrusion of the quartz monzodiorite by granite and rhyolite porphyry dikes in a complex anastomosing pattern.

The quartz monzodiorite and the hornblende gabbro are present only in the upper plate of a thrust which has placed the Harkless(?) Formation over the Reed Dolomite and the Deep Springs Formation. It is possible that the quartz monzodiorite and the gabbro were intruded into the Harkless Formation prior to the development of the overthrust fault, since they neither intrude the thrust nor any of the lower plate rocks.

The quartz monzodiorite occurs at the present level of erosion as a number of discrete, small intrusive bodies, which have sharp, discordant contacts with their wall rocks. The metamorphic grade of the rocks in the Harkless(?) Formation does not seem to change significantly with proximity to the contact with the quartz monzodiorite. The gabbro, however, is recrystallized adjacent to the contact with the quartz monzodiorite and is somewhat coarser grained than elsewhere. Potassium feldspar in the form of veinlets of microcline, also occur in the gabbro in a zone a few meters wide adjacent to the quartz monzodiorite contact.

Modal analysis from thin sections and stained plugs indicate that the quartz monzodiorite has an average composition of 56 percent plagioclase (An_{15}), 16 percent quartz, 13 percent microcline, 11 percent biotite, 4 percent muscovite and accessory hornblende, Fe-Ti oxides, zircon, sphene, and apatite. The rock is a quartz monzodiorite, according to the I.U.G.S. (1973) classification. The texture is hypautomorphic granular. Deuteric(?) alteration of the quartz monzodiorite has resulted in the partial alteration of plagioclase to muscovite, fine-grained sericite and clinozoisite; biotite to muscovite, chlorite, and epidote; and hornblende to actinolite and epidote.

A chemical analysis of the quartz monzodiorite appears in table 5. The only unusual feature of the analysis is its relatively high Al_2O_3 content, which may be a reflection of the weak, but pervasive, alteration of the rock.

TABLE 5. Chemical analyses, Lone Mountain plutonic rocks.

Sample	T179D Gabbro	T184 Alkali granite	T176A Alkali granite	T181 Alkali granite	T208A Quartz monzodiorite	LM13 "Microcline" granite
Location number	1	2	3	4	5	6
			Normalized oxide values			
SiO_2	48.2	73.3	76.1	77.3	66.6	77.2
Al_2O_3	19.7	15.6	13.5	13.1	18.3	13.1
Fe_2O_3	2.9	0.2	10.0	9.1	0.9	0.2
FeO	5.7	0.6	0.7	0.4	2.1	0.5
MgO	7.2	0.2	5.0	0.1	0.8	0.2
CaO	10.9	1.2	1.1	0.8	2.6	1.1
Na_2O	2.3	4.3	3.9	4.0	5.0	3.5
K_2O	1.7	4.4	4.4	4.0	3.2	3.9
TiO_2	1.2	0.2	10.0	0.1	0.5	0.2
MnO	0.13	0.03	0.08	0.03	0.05	0.01
			Normative minerals			
Quartz		28.3	33.7	36.3	17.4	38.3
Corundum		1.6	0.4	0.7	1.9	0.9
Orthoclase	10.1	26.0	26.1	23.8	18.8	23.1
Albite	18.9	36.3	32.8	34.1	42.4	30.9
Anorthite	38.2	6.0	5.4	3.9	12.8	5.5
Nepheline	0.4					
Diopside	12.9					
Olivine	13.1					
Hypersthene		1.1	1.3	0.8	4.7	0.8
Magnetite	4.1	0.3	0.1	0.1	1.3	0.3
Hematite						
Ilmenite	2.4	0.4	0.2	0.2	0.9	0.4
Wollastonite (diopside)	6.7					
Enstatite (diopside)	4.6					
Ferrosilite (diopside)	1.6					
Enstatite (hypersthene)		0.5	1.1	0.3	2.1	0.4
Ferrosilite (hypersthene)		0.6	1.1	0.6	2.6	0.4
Forsterite (olivine)	9.4					
Fayalite (olivine)	3.7					
			Petrologic indices			
Differentiation index	29.4	90.7	92.6	94.2	78.6	92.2
Felsic-mafic index	2.0	37.8	43.9	61.0	11.7	42.0

Locations: 1. SW/4 S36,T3N,R40E
2. On ridge ½ km east of summit
3. 1 km north of Willow Spring
4. On ridge ¼ km north of summit of Lone Mountain
5. Ridge 2 km northeast of Mikes Well
6. S/2 S36,T3N,R40E

The quartz monzodiorite is not radiometrically dated. It is younger than the hornblende gabbro (minimum age 110 m.y.) and older than the granite-rhyolite porphyry dike swarm (22 m.y.). The 110-m.y., K-Ar age of hornblende from the gabbro may reflect reheating of the hornblende during emplacement of the quartz monzodiorite and may therefore be close to the emplacement age of the quartz monzodiorite.

Microcline Granite (Kgr)

Coarse-grained granite containing prominent moderate orange-pink microcline crystals, which impart a distinct color to the rock, crops out in the SE/4 of S36,T3N,R40E. The granite is intruded by rhyolite and granite porphyry and by a rhyolite porphyry breccia pipe of Tertiary age and is unconformably overlain by conglomerate and arkose of the Siebert Formation. No intrusive contact between the

microcline granite and older rocks is exposed at the present erosion surface.

The granite consists of subequal amounts of light-gray quartz, moderate orange-pink microcline, and light-gray plagioclase (An_{15}) with 1 to 2 percent biotite and accessory Fe-Ti oxides, zircon, and apatite. Microcline occurs as subhedral, perthitic crystals up to 1 cm long. Quartz forms anhedral crystals up to 6 mm in maximum dimension. Plagioclase, up to 6 mm in length, occurs as euhedral to subhedral crystals, some of which are normally zoned. The texture is hypautomorphic granular. Deuteric or hydrothermal alteration of the granite has resulted in complete sericitization of original biotite and partial sericitization of microcline and plagioclase. The microcline and plagioclase also contain small amounts of secondary calcite.

A chemical analysis of the microcline granite appears in table 5. The normative content of orthoclase, quartz, albite, and plagioclase, as well as the approximate modal data, clearly show that the rock is a granite by the I.U.G.S. (1973) classification.

The microcline granite was not radiometrically dated. It is older than the granite and rhyolite porphyry dikes (22 m.y.), which intrude it, and presumably is part of the 188-m.y. to about 40-m.y. Mesozoic to early Tertiary intrusive sequence widespread elsewhere in Esmeralda County (Albers and Stewart, 1972, p. 31).

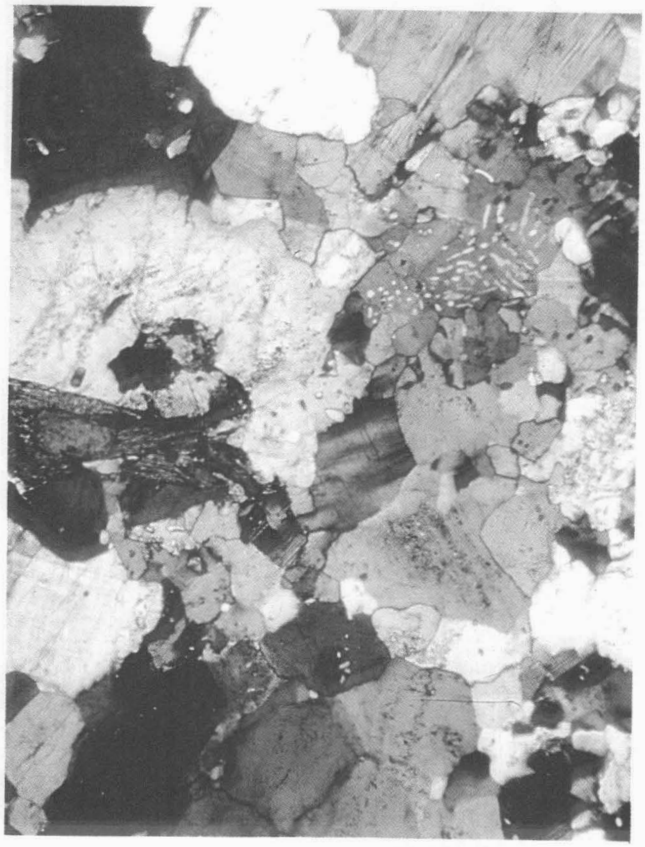
Lone Mountain Pluton (Klm)

The Lone Mountain pluton intrudes metasedimentary rocks of the Wyman Formation, Reed Dolomite, Harkless Formation, and Deep Spring Formation (fig. 11). It is intruded by lamprophyre, aplite-pegmatite, and by granite and rhyolite porphyry dikes. The intrusive contact of the pluton with the enclosing rocks is sharp and discordant in detail, but as Albers and Stewart (1972, p. 28) have pointed out, the Lone Mountain pluton occupies the core of a gently plunging, northwest-trending anticline developed in the Late Precambrian and Cambrian rocks. The granite of the Lone Mountain pluton exhibits a poorly developed gneissic foliation (fig. 12) along its margin. This foliation was apparently produced by protoclastic deformation within the outer shell of the pluton during emplacement and is approximately parallel to the bedding in the wall rocks.

There are two prominent joint sets in the Lone Mountain pluton. One strikes northwest and dips 40° to 75° SE; the second set strikes east to northeast and dips steeply to the north in the central part of the pluton and 60° to 75° S near the margins of the pluton. The joint sets cut each other without visible offset, suggesting that they formed at the same time. The prominent joint sets, when viewed from a distance, impart a layered appearance to the granite. Lamprophyre dikes, ranging from a few centimeters to tens of meters thick, were emplaced along both joint sets in the pluton. In places, the lamprophyre dikes form nearly right-angle bends where they pass from one joint set to the other.

Most of the pluton is very light-gray, coarse to medium-grained, hypautomorphic-granular biotite granite. A porphyritic phase is present locally along the margin of the pluton. It has orange-pink microcline phenocrysts up to 1

FIGURE 11. Lone Mountain, view from near Millers, looking in a southerly direction. Bedded rocks on right are Wyman Formation and Reed Dolomite intruded by granite of the Lone Mountain pluton, which forms the bulk of the mountainous area.



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A. Alkali granite, Lone Mountain pluton. Quartz, oligoclase, microcline, biotite, sphene, myrmekite.

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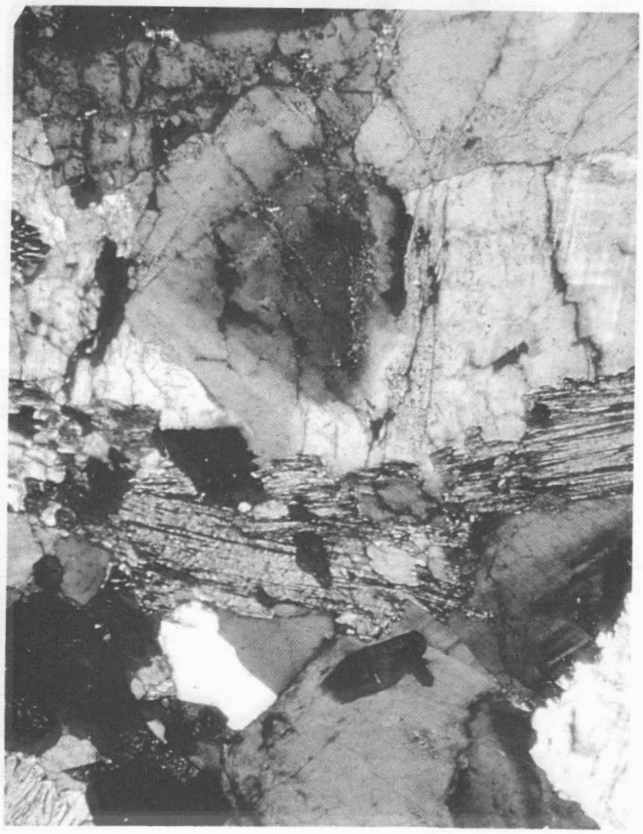
C. Aligned plagioclase crystals in a microcline phenocryst, same sample as B.



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B. Typical biotite crystals in alkali granite of Lone Mountain pluton. K-Ar age of biotite is 69.4±1.4 m.y.

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D. Spessartite dike. Plagioclase, hornblende, chloritized biotite, interstitial alkali feldspar, and quartz.

FIGURE 12. Photomicrographs.

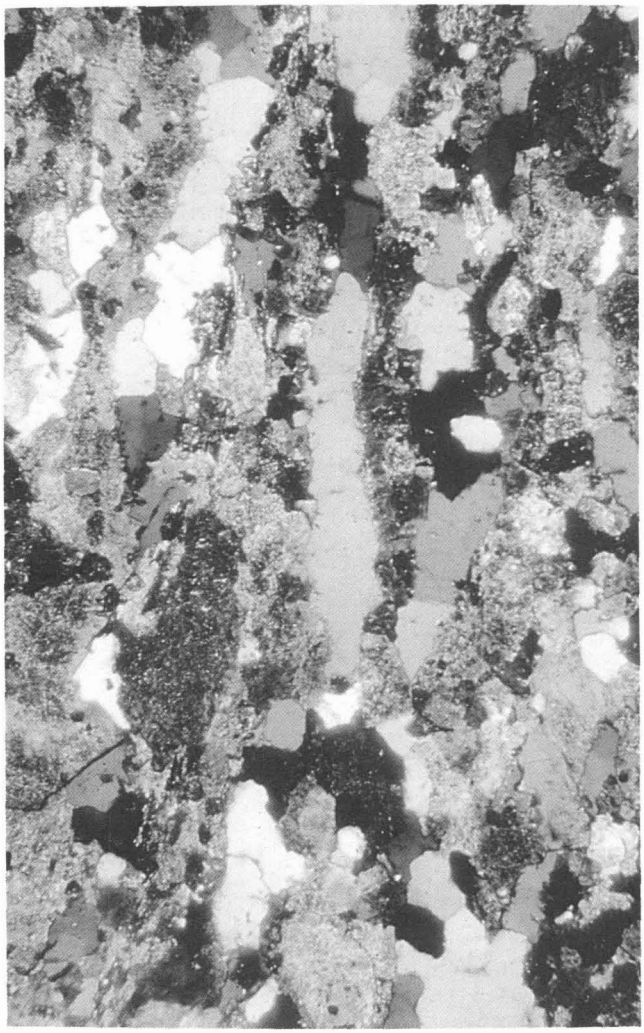

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FIGURE 12E. Protoclastic marginal phase of Lone Mountain pluton.

cm in length set in a xenomorphic granular matrix of quartz, microcline, plagioclase biotite, hornblende, and minor andradite. Modal analysis of the granite from thin sections and stained plugs average 25 to 30 percent quartz, 35 percent perthitic microcline, 35 to 40 percent oligoclase, and 2 to 3 percent biotite. A small amount of hornblende was seen in one thin section. Fe-Ti oxides, zircon, sphene, apatite, and tourmaline are present as accessories (fig. 12). Alteration minerals, probably deuteric in origin, include chlorite, muscovite, epidote, and sericite. In places, particularly adjacent to aplite-pegmatite dikes, biotite in the granite is altered to muscovite, and plagioclase is sericitized. In other areas, biotite in the granite is chloritized, and plagioclase is partially altered to epidote and sericite.

Modal analyses of the plutonic rock (fig. 13) plot in the granite field. The quartz-albite-orthoclase ternary diagram (fig. 14) shows that the chemically analyzed rocks of the Lone Mountain pluton plot near the ternary maximum for granites (Tuttle and Bowen, 1958, p. 75) and well within Tuttle and Bowen's granite field. The ternary plot of albite, orthoclase, and anorthite (fig. 15) shows that the analyzed rocks from the pluton plot near the albite-orthoclase sideline, again in the portion of the diagram where the majority of analyzed granites occur (Tuttle and Bowen, 1958, fig. 67, p. 136). (Peacock variation diagram of Mesozoic plutonic rocks in the area is shown on fig. 16).

Table 4 lists the dates obtained on the Lone Mountain pluton and on one spessartite dike that cuts it. The K-Ar dates on the Lone Mountain pluton listed here have also been reported by Silberman and others (1975, p. 13–21). The three essentially concordant K-Ar dates of 67±3 m.y., 71.1±1.4 m.y., and 69.2±1.4 m.y. indicate that the age of emplacement of the pluton is approximately 70 m.y. ago or latest Cretaceous. The 367-m.y. age date on the lamprophyre dike is clearly in error. The 20±1-m.y. date probably reflects reheating connected with the emplacement of the 22.1±3.2-m.y. porphyry dike swarm in the Lone Mountain block.

Moly Prospect Granite (Kmp), General Thomas Hills

Hydrothermally altered, medium-grained porphyritic granite crops out over an area of a few hundred square meters in S30,T2N,R41E on the southern edge of the Lone Mountain quadrangle in the northern part of the General Thomas Hills. The small area is part of a larger body of granite that is present just to the south of the quadrangle boundary. The granite intrudes the Harkless(?) Formation.

The least altered granite is very light gray and porphyritic. Phenocrysts of microcline up to 2 cm long occur in a medium-grained matrix of microcline, plagioclase, quartz, and biotite. Modal analysis from thin sections indicate that the granite contains about 40 percent microcline, 30 percent plagioclase (An_{15-20}), 25 percent quartz, and 5 percent biotite and muscovite. Fe-Ti oxides, sphene, and zircon are present as accessory minerals. The texture is hypautomorphic granular.

Plagioclase forms zones, subhedral to euhedral crystals up to 6 mm long, which are partially altered to sericite. Perthitic microcline forms subhedral to anhedral crystals, which commonly poikilitically enclose small crystals of plagioclase, biotite, and muscovite. Biotite is largely subhedral and occurs as ragged crystals interstitial to the other minerals or enclosed in microcline. It is partially altered to chlorite and/or muscovite.

Over 50 percent of the granite is altered to a rock consisting of quartz, microcline, sericite, and 5 percent or less of disseminated pyrite. A few hundred meters south of the quadrangle boundary a shaft about 100 m deep is present in the altered granite. About 10 to 15 percent of the granite on the shaft dump is veined with quartz that contains sparse flakes of molybdenite and small amounts of pyrite and chalcopyrite.

MUSCOVITE GRANITE OF KLONDYKE (Kmg)

Several small masses of muscovite granite intrude rocks of the Emigrant Formation and the Mule Springs Limestone in the northern part of the Klondyke Hills (pl. 1). The muscovite granite was intruded along the contact between the Emigrant Formation and the Mule Springs Limestone. The granite also cuts a thrust fault, which is located entirely within the Emigrant Formation, approximately 30 to 50 m above the base of the formation. It seems probable, in view of the wide contact metamorphic aureole surrounding the muscovite granite, that the discrete bodies of granite represent apophyses of a granite pluton, which may underlie much of the northern part of the Klondyke Hills.

The muscovite granite is coarse-grained, leucocratic, and equigranular. Quartz, potassium feldspar, plagioclase, and

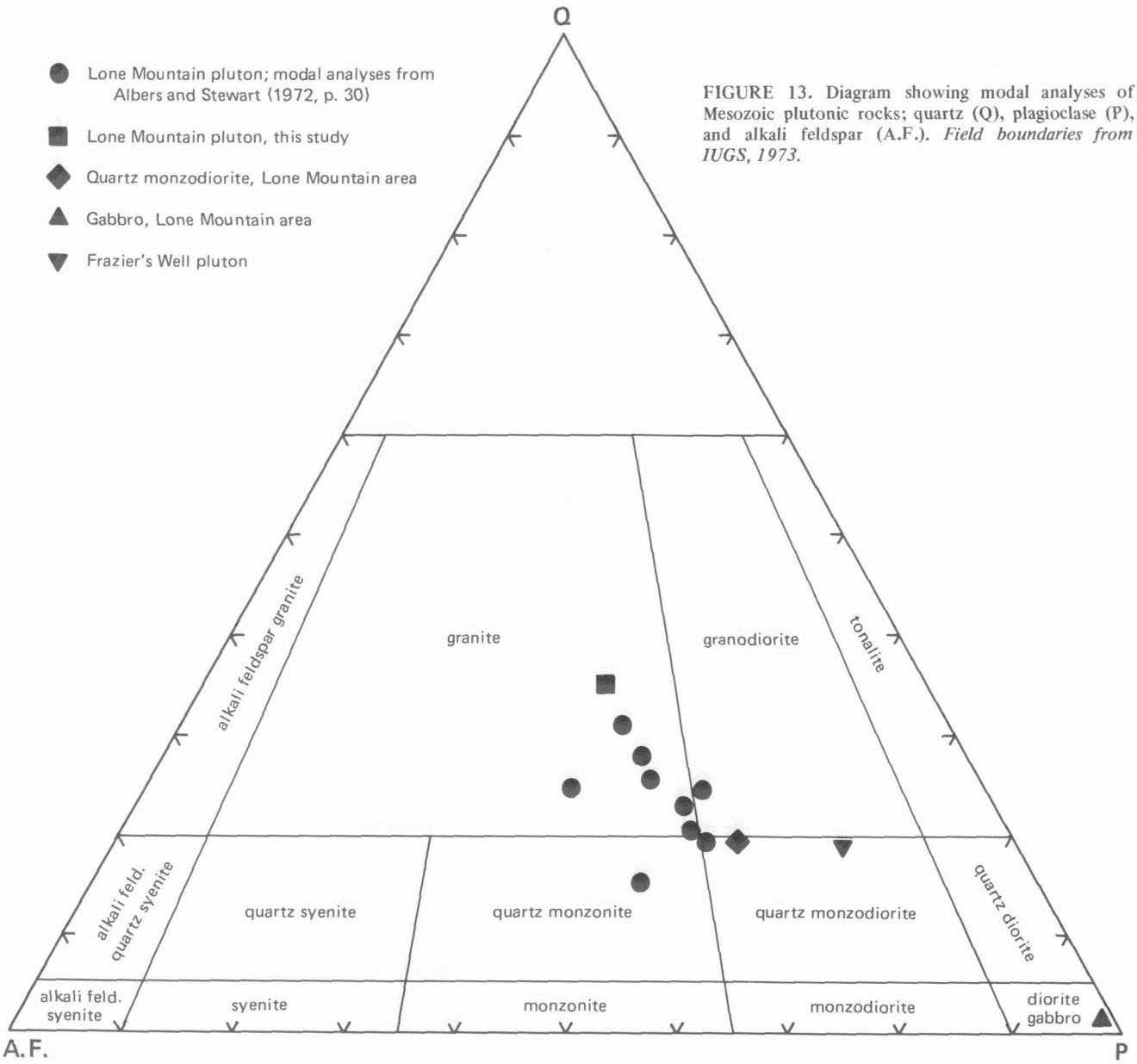


FIGURE 13. Diagram showing modal analyses of Mesozoic plutonic rocks; quartz (Q), plagioclase (P), and alkali feldspar (A.F.). *Field boundaries from IUGS, 1973.*

muscovite are recognizable in hand specimen. Modal analysis from thin sections reveal about 30 percent microcline, 30 percent quartz, 25 percent muscovite, and 15 percent albite. Fe-Ti oxides, zircon, apatite and garnet are accessories. Hydrothermal alteration of extensive areas of the granite have converted it into an aggregate of quartz, muscovite, and sericite. The texture is hypautomorphic granular.

Age. Muscovite of probable hydrothermal origin from the granite yielded a K-Ar date of 104±2.0 m.y. (table 2). We regard the 104-m.y. age as the minimum estimate for the time of emplacement of the muscovite granite, as most of the muscovite reacted with hydrothermal fluids during the alteration of the granite.

FRAZIERS WELL PLUTON (Kfw)

A granitic body that crops out over an area of about 5 km^2, approximately 8 km north of Tonopah in T3,4N,R42, 43E, is here named the Fraziers Well pluton. The pluton is elongated in a west-northwest direction. It intrudes Ordovician(?) metasedimentary rocks of the Valmy(?) Formation and it is unconformably overlain by Tertiary volcanic rocks. The pluton and the Ordovician(?) rocks are intruded by a west-northwest-trending porphyry dike swarm of Cretaceous or Tertiary age.

The Fraziers Well pluton was emplaced at a stratigraphic horizon in the Ordovician(?) rocks in which limestone is particularly abundant. Consequently, much of the country rock adjacent to the pluton is marbleized limestone. In the Peg Leg Mine area the limestone adjacent to the intrusion, has been metasomatically altered to tactite. Most of the Ordovician(?) rocks consist of quartzite, chert, and siltstone. The quartzite and chert are recrystallized, but exhibit little megascopic evidence of thermal metamorphism with proximity to the pluton, while the siltstone is recrystallized to hornfels and phyllite within 300 to 400 m of the plutonic contact.

The contact between the pluton and the Ordovician(?) rocks is sharp and discordant in detail, but is subparallel to

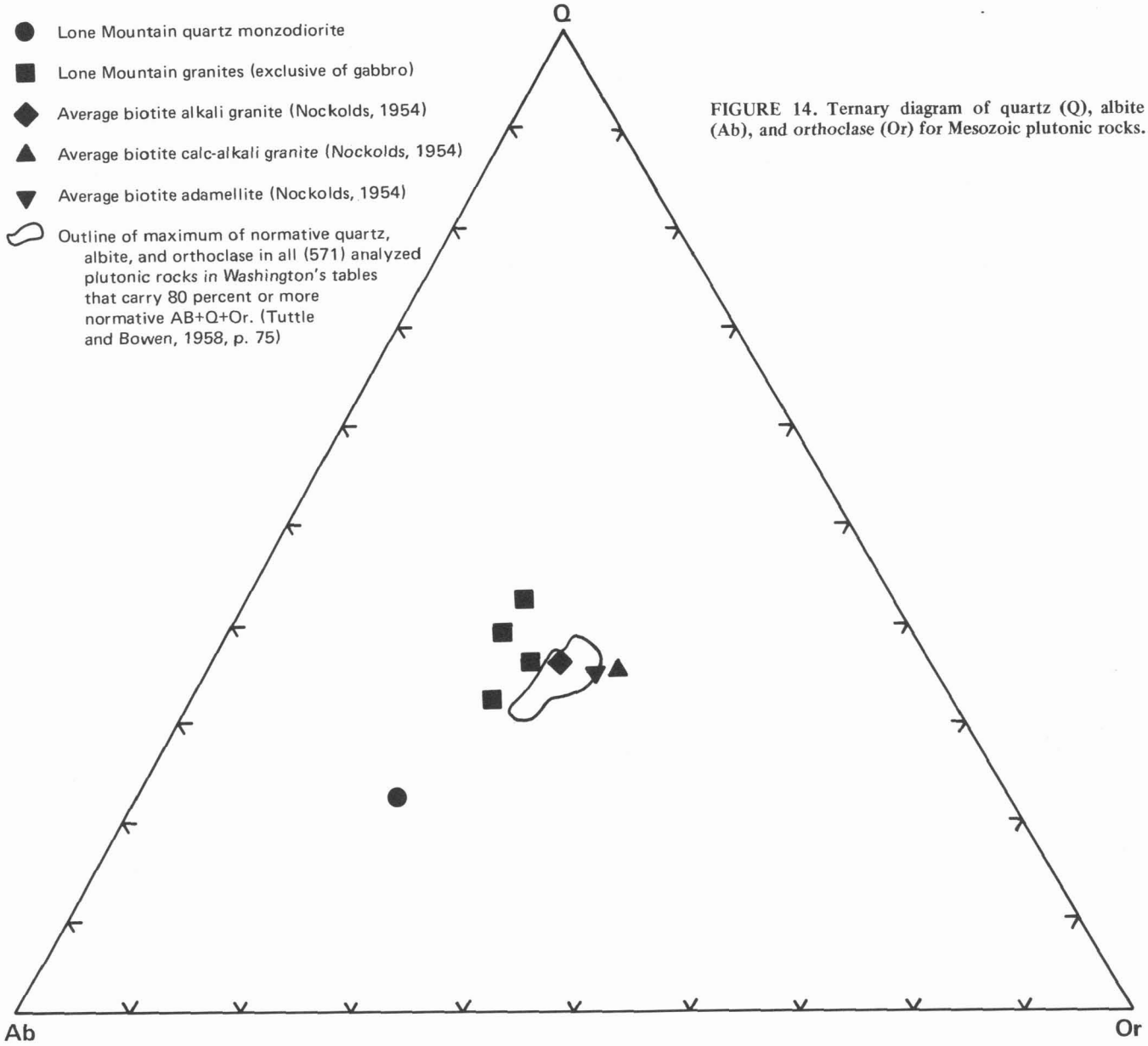


FIGURE 14. Ternary diagram of quartz (Q), albite (Ab), and orthoclase (Or) for Mesozoic plutonic rocks.

bedding in the Ordovician(?) rocks in general. The pluton and its enclosing wall rocks are exposed in a north-trending horst bounded by major normal faults on the east and west.

In outcrop, the Fraziers Well pluton is a coarse-grained, porphyritic rock which contains moderately abundant dark greenish-gray biotite and hornblende, prominent subhedral 1 to 5-cm phenocrysts of microcline, plus plagioclase and quartz (fig. 17). Modal analyses from thin sections show about 15 percent quartz, 45 percent plagioclase (An_{35-40}), 22 percent perthitic microcline, 12 percent hornblende, and 5 percent biotite. Fe-Ti oxides, apatite, sphene, and zircon occur as accessory minerals. The modal data for the pluton, plotted on figure 13, indicate that it is a quartz monzodiorite; however, the coarse-grained porphyritic nature of the rock makes taking representative samples difficult, and thus the bulk composition of the pluton could be either quartz monzodiorite or granodiorite.

Plagioclase forms subhedral to euhedral crystals which exhibit complex oscillatory zoning. It is altered, in part, to epidote, calcite, and sericite. Hornblende and biotite are replaced, in varying degrees, by epidote, chlorite, and clinozoisite. Many of the crystals in the quartz monzodiorite show the effects of cataclastic deformation. They are fractured and strained, and the mafic minerals are locally bent and squeezed into fractures.

Two chemical analyses of the quartz monzodiorite are listed in table 6. Normative data are plotted in figures 14 and 15.

Fission-track ages of 67.9±8.4 m.y. for zircon and 59.3±7.4 m.y. for sphene were obtained from the quartz monzodiorite of the Fraziers Well pluton (table 4). The error limits in the method would permit an age range of about 52 to 75 m.y. Wright (1976, p. 1177) recently reported a K-Ar age of 69 m.y. for the Hall pluton located approximately 19 km north of Fraziers Well. Silberman and others (1975, p. 19) reported a K-Ar age of 77.4±2.3 m.y. for this same pluton. The Lone Mountain pluton is also about 70 m.y. old (this report), and thus it seems highly probable that the Fraziers Well pluton is related to this magmatic episode and that the zircon age of 67.9±8.4 m.y. is more accurate.

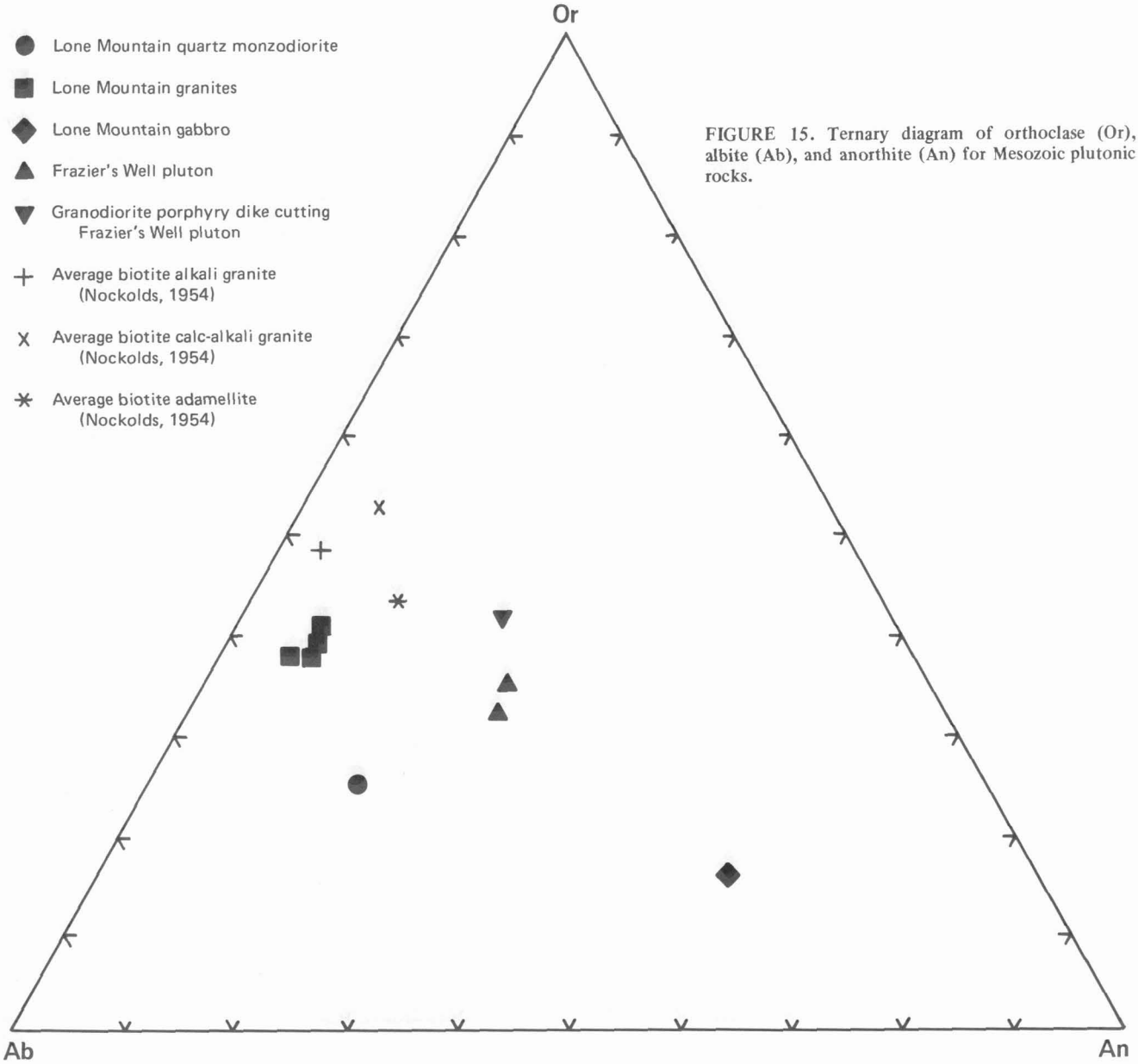


FIGURE 15. Ternary diagram of orthoclase (Or), albite (Ab), and anorthite (An) for Mesozoic plutonic rocks.

PORPHYRY DIKES (Kgdp, Kdp, Krp)

The Fraziers Well pluton and adjacent Ordovician(?) rocks are cut by a northwest-trending, nearly vertical swarm of porphyry dikes that range in composition from diorite to rhyolite porphyry. Some of the dikes that are called diorite porphyry in this report may contain enough matrix potassium feldspar actually to be monzonite porphyry.

Diorite porphyry dikes contain prominent phenocrysts of plagioclase (An_{35-40}), biotite, and hornblende in a fine-grained matrix of plagioclase, potassium feldspar, hornblende, and Fe-Ti oxides. A few diorite porphyry dikes also contain sparse clinopyroxene as a matrix mineral. Plagioclase and hornblende phenocrysts range up to 1 cm in maximum dimension. Biotite phenocrysts seldom exceed 5 mm in dimension. The granodiorite porphyry dikes are similar in mineralogy and phenocryst size to the diorite porphyry dikes. The main differences are that the granodiorite porphyry dikes contain more sodic plagioclase (An_{25-30}) and visible quartz in the matrix (occasionally as a phenocryst mineral), and potassium feldspar is more abundant. The rhyolite porphyry dikes have fewer and smaller phenocrysts (average size, 1 to 2 mm), lack hornblende, and are distinctly lighter in color than the diorite and granodiorite porphyries. Phenocrysts consist of quartz, potassium feldspar, oligoclase, and sparse biotite in a fine-grained matrix of quartz and potassium feldspar (fig. 18).

The porphyry dikes are pervasively propylitized and very little relatively fresh rock remains. The mafic minerals are partially to completely altered to chlorite, epidote, clinozoisite, and sericite; plagioclase is albitized and replaced by sericite, epidote, and calcite; and potassium feldspar is dusted with kaolinite. Locally, the hydrothermal alteration of the dikes is phyllic in nature; biotite and plagioclase are pervasively sericitized; and small amounts of disseminated pyrite and chalcopyrite occur in the dike rock.

Cross-cutting relationships between the different types of porphyry dikes show that the granodiorite porphyry dikes are the oldest and the diorite porphyry dikes are the youngest. The dikes were not dated radiometrically and their minimum age is not known with certainty. It is possible that the granodiorite porphyry dikes are late-stage

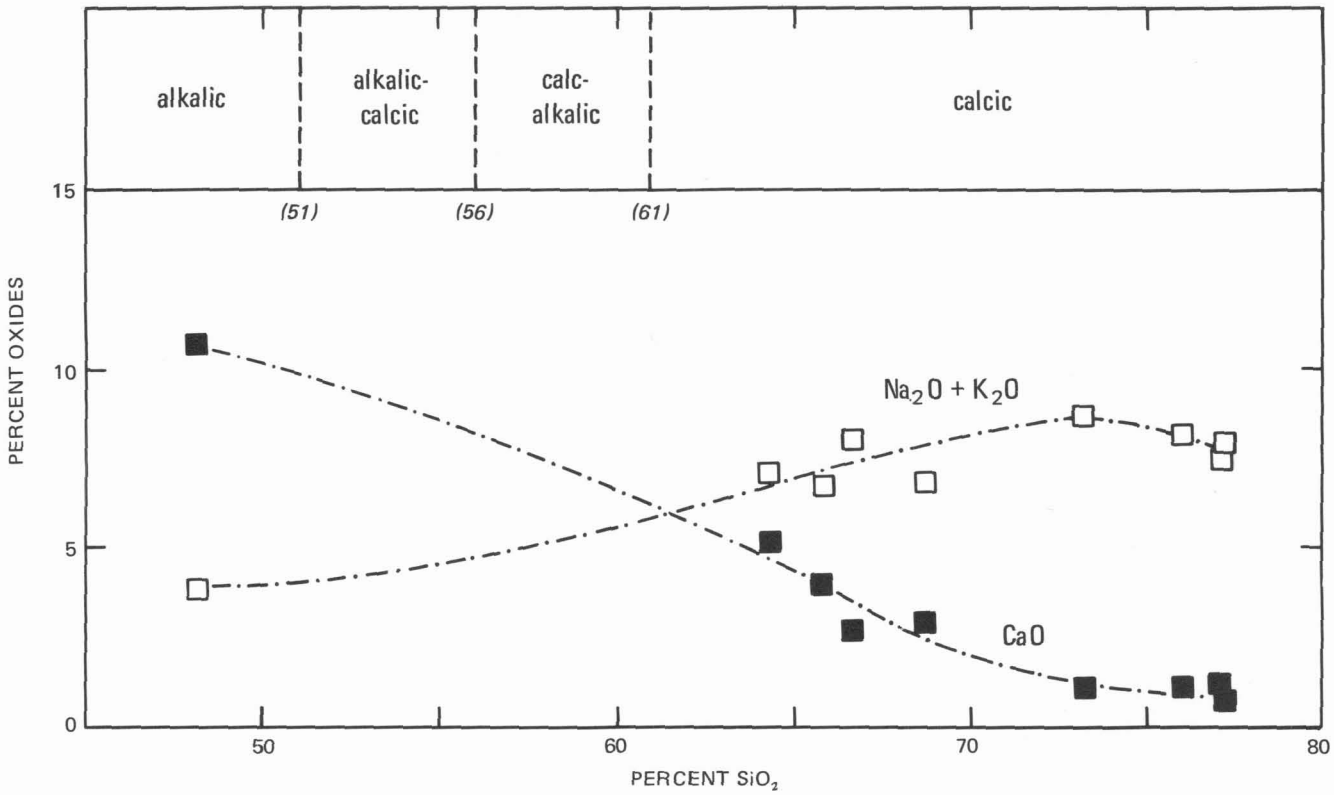


FIGURE 16. Peacock variation diagram of Mesozoic plutonic rocks in Tonopah, Lone Mountain, and Mud Lake Quadrangles.

differentiates of the same magma that formed the Fraziers Well pluton since they are chemically quite similar to the quartz monzodiorite (table 6). The diorite porphyry dikes are similar lithologically to intrusive porphyries of the Mizpah Formation that cut rocks of the Tonopah Formation near Red Mountain just south of the southern boundary of the Fraziers Well pluton (pl. 1), and may very well be genetically related to them. The rhyolite porphyry dikes are lithologically similar to intrusive rhyolite of the Tonopah Formation and could quite possibly be correlative with it. The known age relationships between the porphyry dikes would fit these speculative correlations.

Cenozoic Rocks

TERTIARY SYSTEM

Tertiary rocks in the map area are mostly of volcanic origin. The volcanic rocks consist of lava flows and breccias, mud-flow breccias, domes, shallow intrusive bodies, and pyroclastic rocks of both ash-flow and ash-fall origin, which range in composition from trachyandesite to rhyolite. Sedimentary rocks of Tertiary age are composed predominantly of water-reworked ash-fall tuff and epiclastic volcanic siltstone, sandstone, and conglomerate.

The oldest known volcanic rocks of Tertiary age are part of a sequence of silicic ash-flow sheets that were emplaced between 34 and 24 m.y. ago. The source areas for these ash-flow sheets is unknown. Approximately 26 m.y. ago volcanic rocks of intermediate composition were erupted from centers located in the southern Monitor Range. Flows and breccias derived from these centers extend into the eastern part of the map area. About 24 m.y. ago vulcanism commenced in the San Antonio Mountains with the emplacement of rhyolite domes and flows. Episodic vulcanism continued in the San Antonio Mountains for another 10 m.y. During this period, volcanic rocks of intermediate composition were erupted from several central volcanoes and formed thick sequences of flows and breccias; three ash-flow sheets, apparently erupted from a caldera source within the San Antonio Mountains, were emplaced, and rhyolitic lavas and pyroclastics were erupted from numerous centers in the range. Vulcanism ceased about 10 m.y. ago when high-silica rhyolites were emplaced as dikes and plugs in the Klondyke Hills.

Only small amounts of sedimentary rocks of Tertiary age were deposited until about 17 m.y. ago when the beginning of major crustal extension resulted in the inception of basin and range faulting in this part of Nevada. Sedimentary rocks of the Siebert Formation accumulated in the initial fault-block basins formed as a result of basin and range faulting. The intermittent normal faulting, which has occurred in the map area subsequent to the deposition of the Siebert Formation, resulted in the uplift of most of the Siebert depositional basins and in the formation of new fault-block basins, where sedimentation has continued into the present.

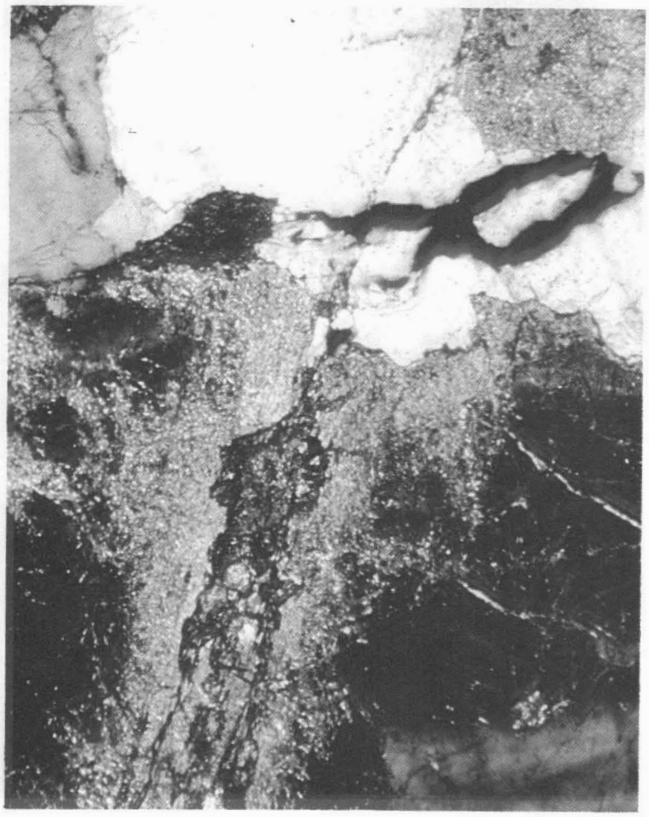
Older Welded Tuffs, Klondyke Hills

Erosional remnants of two silicic ash-flow sheets crop out on the southern and northern margins of the Klondyke Hills (pl. 1). The lower ash-flow tuff is the basal Tertiary unit in the Klondyke Hills and is provisionally correlated by us with the Monotony Tuff. The upper ash-flow tuff is herein tentatively correlated with one of the units in the Tuffs of Antelope Springs.

Nearly all exposures of the two ash-flow tuffs in the Klondyke Hills exhibit the effects of moderate to intense

0.2mm

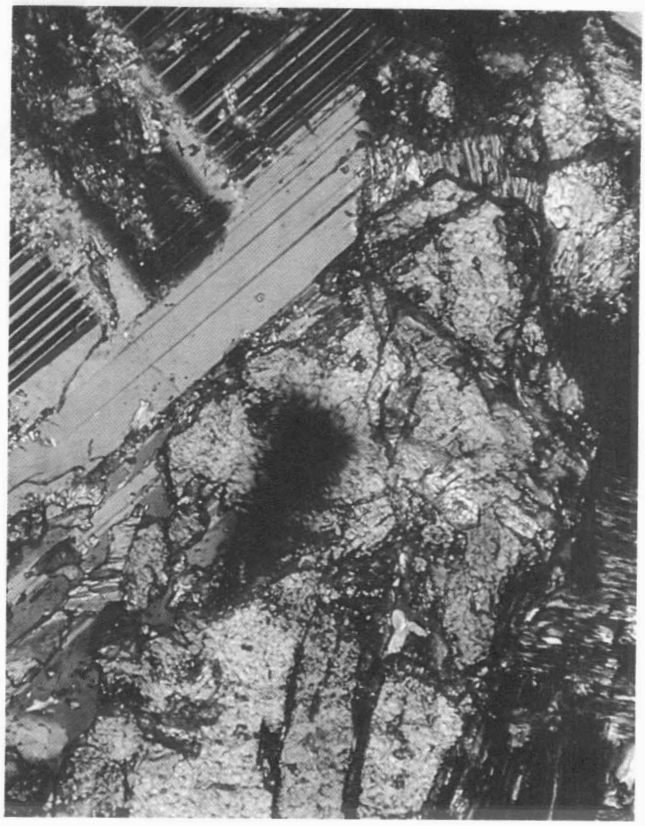
A. Plagioclase (An_{35-40}), microcline, quartz, biotite, hornblende, and sphene. Plagioclase dusted with sericite.



2mm

B. Epidote veinlet cutting plagioclase crystal. Note concentration of sericite adjacent to veinlet. Zircon from this sample gave a fission-time age date of 67.9 m.y.

FIGURE 17. Photomicrographs of Fraziers Well pluton.



0.1mm

C. Epidote replacing plagioclase.

hydrothermal alteration. Much of the tuff is propylitically altered, and some of the tuff is altered to an aggregate of quartz and sericite in which only the quartz phenocrysts of the original phenocryst assemblage remain unaltered.

Monotony(?) Tuff (Tmt?). The Monotony(?) Tuff is a yellowish-gray to light-gray or dusky-yellow, slabby-weathering, crystal to crystal-vitric biotite rhyodacite. The rock is densely welded, but does not have obvious eutaxitic structure in hand specimen. It is relatively easily eroded and commonly forms low, subdued outcrops.

The Monotony(?) Tuff contains 45 to 55 percent phenocrysts which consist of plagioclase (50 to 55%), quartz (20 to 25%), biotite (10 to 15%), and sparse alkali feldspar, hornblende, and pyroxene(?). The quartz phenocrysts are corroded and vermicular; a few are as large as 6 mm in diameter. Biotite phenocrysts average about 2 mm in diameter, but some are as much as 5 mm across. As a result of the pervasive hydrothermal alteration of the Monotony(?) Tuff in the Klondyke Hills, plagioclase is altered to albite, calcite, or sericite, biotite to an aggregate of Fe-Ti oxides, chlorite and/or sericite, alkali feldspar to calcite or sericite, and hornblende and pyroxene(?) to calcite, chlorite, and Fe-Ti oxides.

The Monotony(?) Tuff in the Klondyke Hills is lithologically very similar to the Montony Tuff in the Nellis Air Force Bombing and Gunnery Range as described by Ekren and others (1971, p. 25-27). Both tuffs are crystal rich, contain abundant large biotite and scattered large quartz phenocrysts, and have a high ratio of plagioclase to alkali feldspar. The exact age of the Monotony(?) Tuff in the Klondyke Hills is unknown, but it is overlain by an ash-flow tuff which is about 26 m.y. old. Because the Monotony Tuff is approximately 27 m.y. old (Ekren and others, 1971,

TABLE 6. Chemical analyses, Fraziers Well pluton.

Sample	T3 Quartz monzodiorite	T111B Quartz monzodiorite	T111A Granodiorite porphyry dike
Location number	1	2	3
	Normalized oxide values		
SiO_2	65.8	64.3	68.7
Al_2O_3	16.2	16.5	15.1
Fe_2O_3	2.5	1.8	1.7
FeO	2.5	2.8	2.2
MgO	1.5	1.8	1.7
CaO	4.1	5.2	3.0
Na_2O	3.2	3.1	2.7
K_2O	3.6	4.0	4.3
TiO_2	0.5	0.5	0.5
MnO	0.09	0.05	0.10
	Normative minerals		
Quartz	21.7	17.2	26.9
Corundum			0.7
Orthoclase	21.1	23.9	25.4
Albite	27.3	26.3	22.4
Anorthite	19.2	19.0	14.8
Diopside	1.0	5.4	
Hypersthene	5.2	4.6	6.3
Magnetite	3.7	2.7	2.5
Hematite			
Ilmenite	0.9	0.9	1.0
Wollastonite (diopside)	0.5	2.8	
Enstatite (diopside)	0.3	1.6	
Ferrosilite (diopside)	0.2	1.1	
Enstatite (hypersthene)	3.5	2.8	4.3
Ferrosilite (hypersthene)	1.7	1.8	2.0
	Petrologic indices		
Differentiation index	70.1	67.4	75.4
Felsic-mafic index	6.8	6.2	8.7

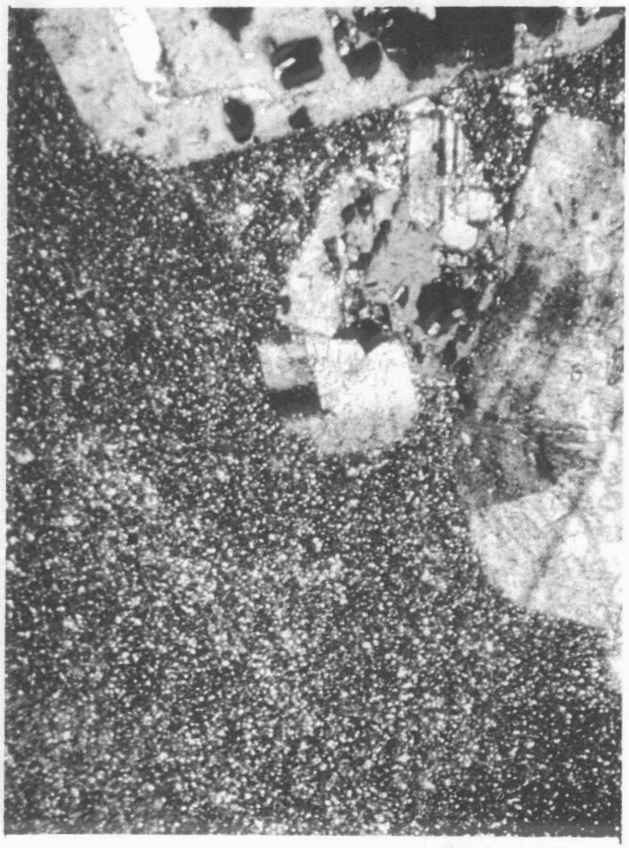
Locations: 1. SW/4 SW/4 S31,T4N,R43E
2. SW/4 SW/4 S36,T4N,R42E (unsurv.)
3. SW/4 SW/4 S36,T4N,R42E (unsurv.)

p. 28), the existing age data would permit the lower tuff unit in the Klondyke Hills to be correlative with the Monotony Tuff.

Tuffs of Antelope Springs(?) (Tas?). The upper ash-flow tuff unit in the Klondyke Hills, where least altered, is a densely welded, medium-light-gray to light-brownish-gray rock, which has prominent eutaxitic structure. It is a crystal-vitric to crystal tuff that contains about 50 percent phenocrysts, of which quartz forms 31 percent, sanidine 21 percent, plagioclase 40 percent, biotite 6 percent, and altered hornblende and opaques 2 percent. The rock contains 1 to 2 percent lithics, principally of intermediate volcanic rocks. The quartz phenocrysts range up to 5 mm in diameter and are somewhat corroded and vermicular (fig. 19). The rock contains abundant pumice and cognate blocks of tuff, which range up to 5 cm long. The tuff is either quartz latite or rhyolite. Much of the tuff is altered to an aggregate of quartz and sericite.

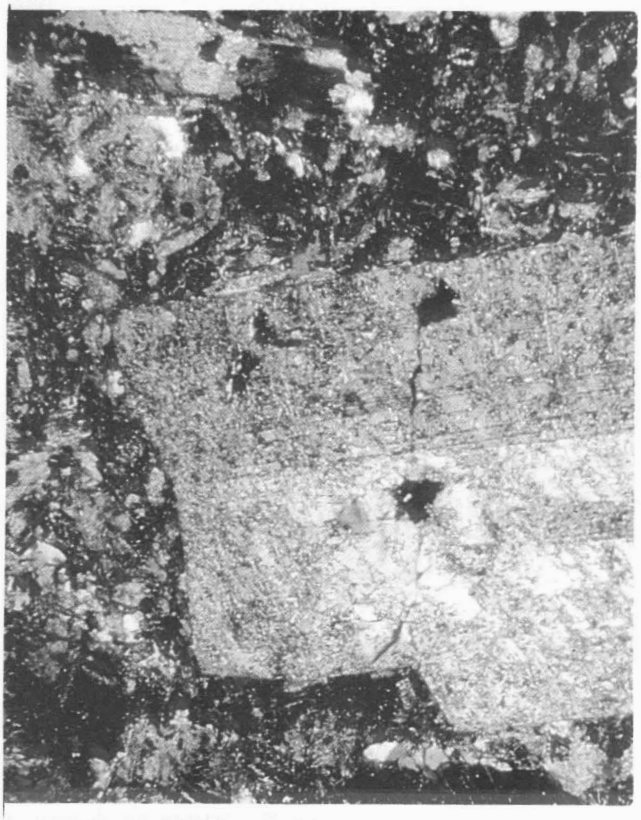
The upper ash-flow tuff disconformably overlies the Monotony(?) Tuff and is at least 100 m thick. It is overlain unconformably by volcanic sandstone and siltstone and by pyroxene and hornblende andesite of the northern Goldfield Hills.

In lithology and stratigraphic position, the upper ash-flow tuff seems to correlate best with one of the upper ash-flow tuff units in the tuffs of Antelope Springs (Ekren and others, 1971, p. 30). The tuffs of Antelope Springs form a thick (600 m) sequence in the Cactus Range about 30 km to the southeast of the Klondyke Hills. According to Ekren and others (1971, p. 28), the tuffs of Antelope Springs have K-Ar ages of 26.2±0.2 m.y. (biotite) and 27.7±0.8 m.y. (sanidine). Biotite from the upper ash-flow



0.2mm

A. Rhyolite porphyry dike. Phenocrysts of oligoclase and alkali feldspar in a fine-grained sugary matrix of quartz, alkali feldspar, calcite, sericite, and chlorite.



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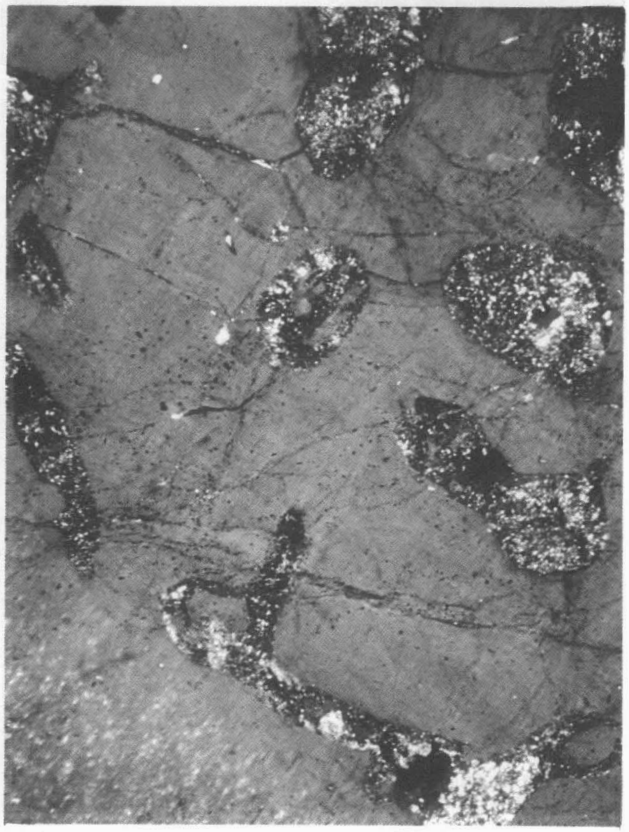
C. Granodiorite porphyry. Plagioclase phenocryst partially replaced by calcite and sericite; hornblende phenocryst altered to calcite; biotite phenocrysts replaced by chlorite and minor epidote. Phanerocrystalline matrix consists of plagioclase partially altered to calcite and sericite, quartz, and alkali feldspar.



2mm

B. Rhyolite porphyry. Vermicular quartz phenocryst.

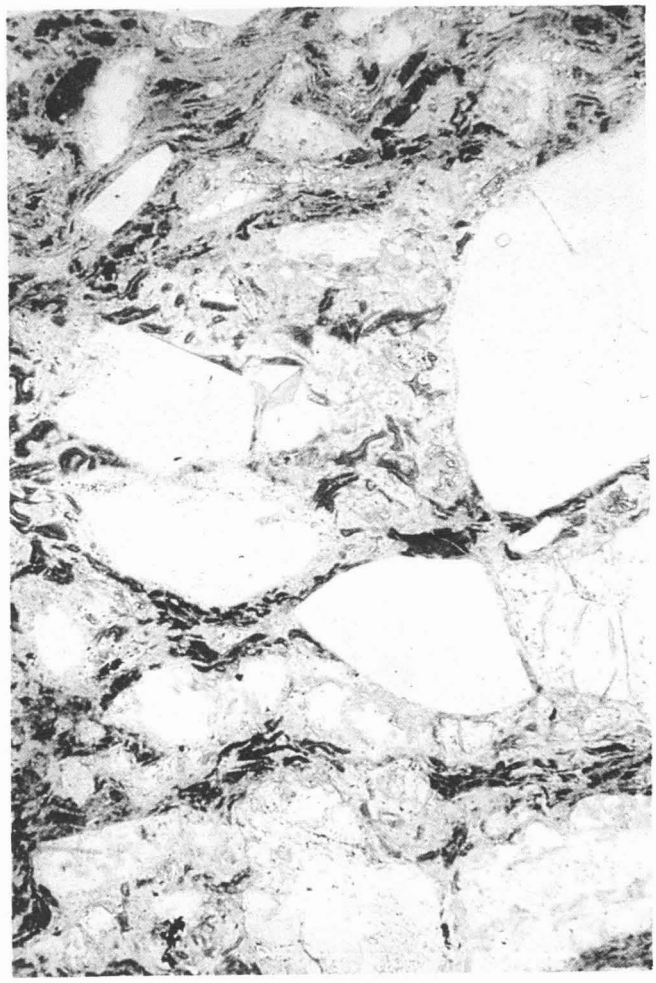
0.1mm

D. Granodiorite porphyry. Biotite phenocryst altered to chlorite and epidote.

FIGURE 18. Photomicrographs of porphyry dike rocks which intrude Fraziers Well pluton.

0.1mm

A. Quartz-sericite alteration in welded ash-flow tuff. Biotite completely replaced by sericite.



0.1m

B. Axiolitic structure in shards in densely welded tuff. Phenocrysts are quartz and alkali feldspar.

FIGURE 19. Photomicrographs of tuffs of Antelope Springs(?).

tuff in the Klondyke Hills (table 4) yielded a K-Ar age of 26.0±0.8 m.y. This date is well within the error limits of the ages for the tuffs of Antelope Springs.

Epiclastic sedimentary rocks (Tes). Volcanic sandstone and siltstone crop out in an area of a few hundred square meters on the eastern edge of the Klondyke Hills. The sandstone and siltstone occur in a channel cut in the tuffs of Antelope Springs(?). The sedimentary rocks are overlain and intruded by pyroxene andesite of the northern Goldfield Hills.

The volcanic siltstone and sandstone are composed almost entirely of quartz, alkali feldspar, and plagioclase. Hydrothermal alteration has converted them into an aggregate of quartz and sericite.

Tonopah Formation (Ttr, Tts)

Spurr (1905b, p. 41 and pl. 11; 1915, p. 745) applied the names Tonopah rhyolite-dacite and Tonopah rhyolite to rocks exposed in the underground workings at Tonopah and to surface exposures of rhyolitic pyroclastic rocks in the district, which are distinctly younger than the Tonopah Formation.

The name Tonopah Formation was proposed by Nolan (1930, p. 10) for a sequence of silicic tuffs, breccias, intrusives, and waterlain volcaniclastic rocks exposed in the underground mine workings in the Tonopah district. Broderick (1949, p. 18) correlated a sequence of rhyolitic ash-flow tuffs, intrusive rhyolite, ash-fall tuff, and volcaniclastic sedimentary rocks exposed immediately to the east of Red Mountain with the Tonopah Formation.

The Tonopah Formation, where its base is exposed, rests unconformably upon Paleozoic or Mesozoic rocks. Generally it is overlain by the Mizpah Formation, although in the surface exposures north and east of Red Mountain, it is overlain with angular unconformity by flows and minor gravels of the trachyandesite of Red Mountain.

Distribution and thickness. The Tonopah Formation is extensively exposed in the deeper mine workings in the Tonopah district (Nolan, 1935, p. 13-14). However, there are no surface exposures of the Tonopah Formation within the district. A number of isolated outcrops of the Tonopah Formation are present in the San Antonio Mountains several miles north of Tonopah near Red Mountain, Fraziers Well, Rhyolite Peak, and Rays Wells. These outcrop areas of the Tonopah Formation are distributed around the margins of the block of Paleozoic and Mesozoic rocks that extends from the vicinity of Red Mountain to just north of Rays Wells. No other outcrops of the Tonopah Formation were found within the mapped area. The total outcrop area of the Tonopah Formation in the San Antonio Mountains is approximately 3 km^2.

According to Nolan (1935, p. 13 and 16), the Tonopah Formation is more than 300 m thick in the underground workings in the Tonopah district. The total thickness of the Tonopah Formation is unknown, because all of the surface exposures of the unit are erosional remnants and because the base of the unit is not exposed in the underground workings.

Lithology. The Tonopah Formation on the geologic map (pl. 1) is divided into two informal units: a lower unit that is mainly welded, silicic ash-flow tuffs and epiclastic, volcanic siltstone and sandstone, and an upper unit made up of rhyolite domes and flows.

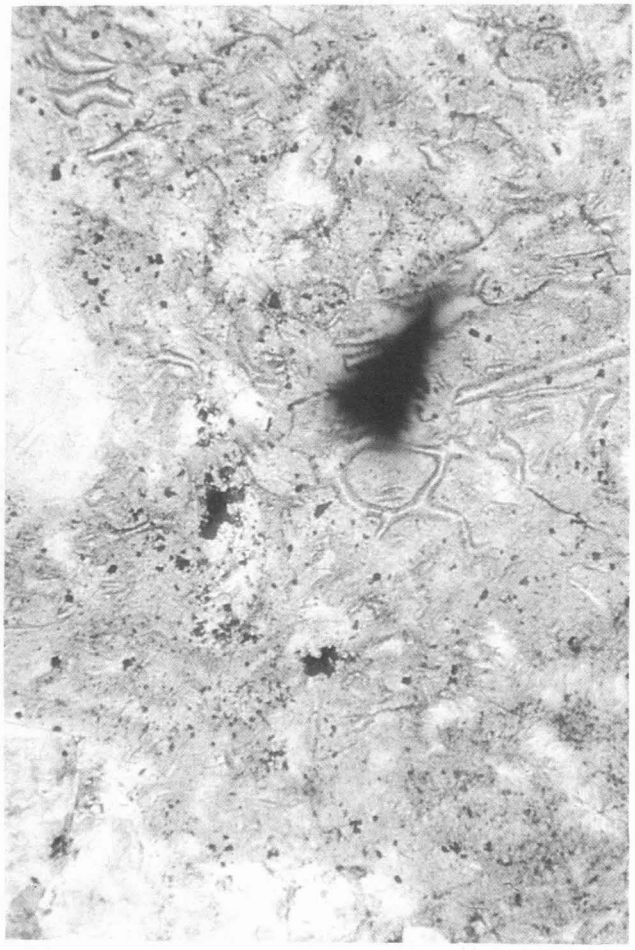
The lower unit is mostly vitric and vitric-lithic, welded ash-flow tuff that weathers to shades of very pale orange, grayish orange pink, grayish yellow, light gray, or white. Potassium feldspar, 1 to 2 mm, and plagioclase (An_{25-40}), 1 to 2 mm, are the most abundant phenocryst minerals followed by quartz, 1 to 2 mm, and biotite, 1 mm. A few of the ash flows have little to no phenocrystic quartz (fig. 20). Zircon, apatite, and Fe-Ti oxides occur as accessory minerals. Pumice, usually less than 5 cm long, is abundant, and most exposures of the tuffs contain 10 to 15 percent lithic fragments, 1 to 5 cm, of Paleozoic metasedimentary rocks and Tertiary volcanic rocks. The phenocryst mineralogy of the tuffs suggests that they are quartz latites, but chemical data are not available.

All of the surface exposures of the Tonopah Formation are hydrothermally altered. Propylitic and phyllic alteration phases are present in the lower unit in subequal amounts. As a result of this pervasive hydrothermal alteration, plagioclase is partially to completely replaced by albite, calcite, sericite, or adularia; biotite is replaced by chlorite or sericite; and potassium feldspar phenocrysts are commonly altered to sericite and adularia. In the phyllic zone, the shards and pumice are replaced by quartz, sericite, and adularia.

The hydrothermal alteration has also destroyed many of the textural and mineralogic features of the primary ash-flow zonation, and, consequently, it is difficult to recognize individual cooling units. However, the occurrence of air-fall tuff and epiclastic volcanic siltstone and sandstone intercalated within the ash-flow tuff unit and changes in the phenocryst mineralogy, such as the presence or absence of phenocrystic quartz, demonstrate that several cooling units are present in the lower map unit.

The upper unit of the Tonopah Formation is almost entirely flow-banded rhyolite, that is, at least in part, intrusive into the rocks of the lower unit. The rhyolite crops out in an area of approximately 1 km^2 immediately to the east of Red Mountain.

The rhyolite is a yellowish to white rock with well-developed flow banding, which contains sparse (less than 5



0.1 mm

A. Typical crystal-poor ash-flow tuff. Weakly welded, shards show excellent axiolitic structure.

0.1 mm

B. Spherulitic devitrification of shards in welded ash-flow tuff. Phenocryst is quartz.

FIGURE 20. Photomicrographs of ash-flow tuffs of the Tonopah Formation.

percent) phenocrysts of plagioclase (1 to 2 mm) and biotite (1 mm) in a fine-grained matrix of quartz and alkali feldspar. Zircon and Fe-Ti oxides occur as accessory minerals. The rhyolite is pervasively hydrothermally altered and it is now an aggregate of quartz, potassium feldspar, albite, sericite, and pyrite; hematite and goethite derived from the surficial oxidation of pyrite coat fracture and joint surfaces.

The underground exposures of the Tonopah Formation were not examined in the course of the present study. However, Nolan's (1935, p. 14–15) description of the lithology of the Tonopah Formation coincides closely with the lithology of the surface outcrops of the units that we have assigned to the Tonopah Formation.

No samples of the Tonopah Formation were found suitable for K-Ar dating because of the pervasive hydrothermal alteration present in the unit. Consequently, two zircon concentrates were prepared, one from the lower unit and one from the upper, and utilized for fission-track dating. The lower unit yielded a fission track age of 34.8± 4.2 m.y. and the upper unit a fission-track age of 24.3±2.8 m.y. (table 4).

The apparent 10-million-year difference in age, which could be reduced to 3.5 million years when error limits are considered, may be real. However, if the flow-banded rhyolite of the upper unit of the Tonopah Formation is the same age as the rhyolite flows that Nolan (1935, p. 14) described as interbedded with tuffs in the underground exposures of the Tonopah Formation at Tonopah, then an age discrepancy of several million years between the upper and lower units seems unlikely.

Tuff of Ralston Valley (Trv)

A distinctive ash-flow tuff, here informally called the tuff of Ralston Valley, crops out over an area of approximately 6 km^2 on the east side of Ralston Valley in T4N, R44E. Outcrops of the tuff form much of the western slope of Thunder Mountain. The tuff of Ralston Valley is overlain unconformably by the tuffs of Rye Patch and the trachyandesite of Thunder Mountain. The tuff of Ralston Valley is at least 180 m thick. However, its total thickness is unknown because the base of the tuff is not exposed.

The tuff of Ralston Valley is a light-gray, very densely welded, vitric ash-flow tuff. It has a platy jointing subparallel to the compaction foliation. Phenocrysts compose less than 10 percent of the tuff and consist of subequal amounts of plagioclase and alkali feldspar, minor biotite, and rare quartz. Most of the phenocrysts are less than 1 mm in diameter, but some plagioclase phenocrysts are as large as 3 mm in diameter. Lithic fragments, chiefly of volcanic rocks and Paleozoic quartzite and argillite, comprise between 5 to 10 percent of the rock (fig. 21) and commonly are less than 5 cm in longest dimension. The matrix of the tuff is composed of highly welded pumice, flattened shards and dust. In many places, the pumice is so flattened and elongated that it imparts a streaky lamination, similar to flow banding, to the tuff. Highly compressed petrified wood is present in the tuff at several localities.

The phenocryst mineralogy of the tuff of Ralston Valley indicates that it is either quartz latite or rhyolite. The altered nature of the rock, however, makes determination of the original rock composition impossible within the map area.

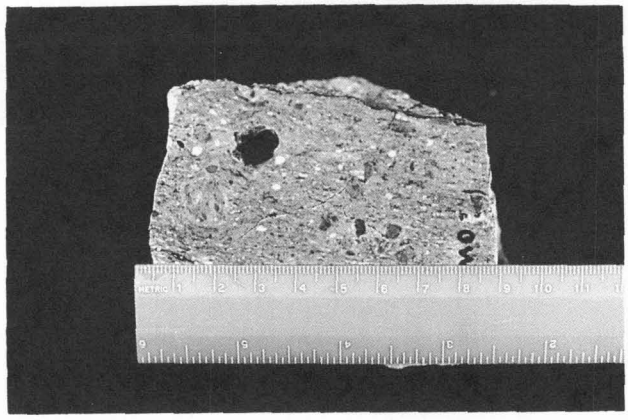


FIGURE 21. Tuff of Ralston Valley. Densely welded, moderately abundant lithic fragments. Prominent light-colored phenocrysts of altered plagioclase.

The tuff is pervasively hydrothermally altered. Plagioclase is albitized and partially replaced by sericite, calcite, and clay minerals. Alkali feldspar is dusted with sericite. Biotite is completely replaced by sericite, chlorite, and Fe-Ti oxides. The sparse phenocrystic quartz is unaffected by the hydrothermal alteration. The pumice and shards in the matrix are altered to a fine-grained aggregate of quartz, alkali feldspar, sericite, chlorite, and dusty hematite. Some of the shards still show relict axiolitic texture (fig. 22), but

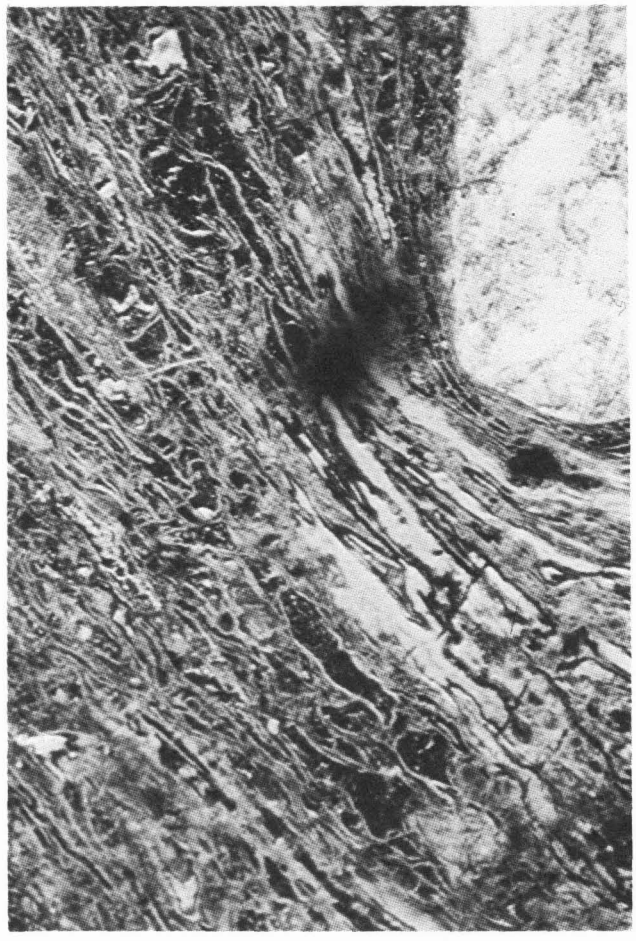


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FIGURE 22. Photomicrograph of tuff of Ralston Valley. Highly deformed shards in densely welded tuff. Shards altered to quartz, sericite, alkali feldspar, and dusty hematite.

in most thin sections the recrystallization related to hydrothermal alteration has destroyed the primary devitrification features of the tuff. The tuff of Ralston Valley contains sparse disseminated pyrite and is cut by numerous small quartz veinlets.

The tuff of Ralston Valley yielded a K-Ar age of 18.0± 0.4 m.y. and a fission-track age on zircon of 31.4±3.8 m.y. (table 4). We believe that the fission-track age is approximately correct because the tuff of Ralston Valley is older than the tuffs of Rye Patch, which are at least 25 m.y. old. The K-Ar age undoubtedly dates the age of the hydrothermal alteration of the rock.

The source area of the tuff of Ralston Valley is unknown. The tuff is quite similar in lithology and age to some of the tuffs of the Tonopah Formation and it is possible that they were erupted from the same center.

Dacite, Silver Ace Area (Tds)

Flows and breccias of porphyritic dacite crop out in S2, 11,14,T4N,R44E in the Silver Ace area (pl. 1). The dacite is overlain unconformably by the tuff of Rye Patch, but the base is not exposed.

The porphyritic dacite is at least 100 m thick in the Silver Ace area and may be substantially thicker. Flows and mudflow breccia are present in about equal amounts in the unit. All of the exposed dacite in the Silver Ace area is hydrothermally altered. Where least altered, the dacite is pale red purple to pale olive. Where the dacite is intensely altered, it is bleached to white or pale gray. The dacite contains 20 to 30 percent phenocrysts of plagioclase (An_{40-45}), hornblende, and biotite in a fine-grained, felsitic matrix. Plagioclase, up to 5 mm in length is the principal phenocryst mineral. Hornblende and biotite form euhedral crystals up to 2 mm long. Pleochroic apatite up to 0.2 mm long and Fe-Ti oxides are present as accessory minerals.

As a result of the hydrothermal alteration of the dacite, plagioclase is replaced by albite, calcite, and sericite, or by quartz and adularia, and hornblende and biotite are altered to chlorite, calcite, and sericite. Alkali feldspar, mostly of hydrothermal origin forms a major constituent of the felsitic matrix. Disseminated pyrite is present in the more highly altered dacite. A chemical analysis of hydrothermally altered dacite from the potassic zone of alteration is shown in table 7. The high K_2O content and low MgO and CaO contents of the altered dacite are quite evident in the analysis.

The porphyritic dacite is older than the tuffs of Rye Patch which are at least 25 m.y. old. We believe that the dacite is younger than the tuff of Ralston Valley (31 m.y. old), but we have no firm stratigraphic evidence for this assumption.

Tuffs of Rye Patch (Trpu, Trps, Trpb)

An assemblage of two ash-flow tuffs and intercalated sediments exposed adjacent to an area called the Rye Patch in Ralston Valley, is here informally named the tuffs of Rye Patch. The tuffs in this unit form moderately extensive outcrops in the northeastern part of the mapped area and are a major stratigraphic unit in the southern Monitor Range to the north and east.

The tuffs of Rye Patch are divided into three informal units on the geologic map; a lower, lithic-rich ash-flow tuff, a middle unit composed of several thin lenses of tuffaceous sediments, and an upper crystal-vitric ash-flow tuff. The tuffs have a combined thickness of approximately 90 m in the map area, but exceed 1,000 m to a few km to the northeast.

TABLE 7. Chemical analyses, dacite, Silver Ace area.

Sample	T197 (SE/4 S14,T4N,R44E) Hydrothermally altered dacite
Normalized oxide values	
SiO_2	64.4
Al_2O_3	20.8
Fe_2O_3	2.6
FeO	0.6
MgO	0.6
CaO	0.7
Na_2O	3.1
K_2O	6.4
TiO_2	0.8
MnO	0.04
Normative minerals	
Quartz	19.8
Corundum	7.6
Orthoclase	37.7
Albite	25.8
Anorthite	3.4
Wollastonite	
Diopside	
Hypersthene	1.5
Magnetite	0.0
Hematite	2.6
Ilmenite	1.4
Wollastonite (diopside)	
Enstatite (diopside)	
Ferrosilite (diopside)	
Enstatite (hypersthene)	1.5
Petrologic indices	
Differentiation index	83.4
Felsic-mafic index	16.4

Most of the rocks in the tuffs of Rye Patch are moderately to intensely hydrothermally altered and primary pyroclastic textures are modified or destroyed in many outcrop areas. Primary rock minerals, with the exception of quartz, apatite, and zircon are partially to completely replaced by secondary minerals in the hydrothermally altered areas. The altered rocks have drab, greenish-gray, grayish-orange, yellowish-gray or very pale-orange casts and form low rounded outcrops. Secondary minerals, principally epidote, chlorite, kaolinite, illite, calcite, quartz, albite, potassium feldspar, sericite, and montmorillonite, partially to completely replace both phenocrysts and the rock matrix. In the Silver Ace area the tuffs are partially to completely altered to aggregates of quartz, adularia, and sericite or to quartz and sericite. Phyllic and potassic alteration zones in the Silver Ace area grade outward into

propylitized tuff. Pyrite, oxidized in the surface outcrops, is disseminated throughout the zones of phyllic and potassic alteration.

Lower ash-flow tuff (Trpl). The lower ash-flow tuff has a maximum thickness of about 50 m in the mapped area. It is characterized by abundant lithic fragments, some of which reach dimensions of 15 by 10 by 5 m. The large lithic blocks are distributed rather uniformly throughout the ash flow and are only slightly concentrated at its base. These large lithics consist predominantly of blocks of older highly welded ash-flow tuff and Paleozoic quartzite and form prominent "outcrops" because of the soft, clayey alteration of the ash-flow tuff matrix between the blocks. Nearly all of the boulder-size lithics show varying degrees of brecciation. The brecciated areas of the lithic blocks are cemented by fine-grained quartz and hematite.

The lower ash-flow tuff is, in general, poorly welded to nonwelded. In a few areas the tuff is moderately welded and in these areas moderately to densely welded tuff forms rims around many of the lithic blocks. The densely welded rims commonly exhibit relic perlitic fractures. Phenocryst content of the tuff ranges from 10 to 15 percent and the lithic content is about 20 percent, excluding the cobble and boulder-size lithics. Plagioclase (An_{25-35}) composes approximately 50 percent of the phenocrysts; quartz, 20 percent; sanidine, 20 percent; and biotite, 8 to 10 percent. Hornblende, Fe-Ti oxides, zircon, and apatite are accessory minerals. Small lithic fragments are predominantly welded tuff and intermediate flow rocks, but include a variety of metasedimentary and granitic rocks. Pumice is abundant in the tuff, and shards are clearly visible in thin sections from the less altered samples of the tuff. All of the matrix, dust, shards, and pumice are devitrified.

Some of the devitrification is primary, and in the least altered specimens of the tuff shards and pumice are devitrified to aggregates of K-feldspar, tridymite, and cristobalite. In a few samples the shards exhibit axiolitic structure. Some of the pumice and shards were still glassy prior to hydrothermal alteration and devitrified during hydrothermal alteration to clay minerals, or quartz, sericite, K-feldspar, and chlorite.

The lower unit of the tuffs of Rye Patch unconformably overlies Paleozoic and Mesozoic rocks and dacitic lava flows and mudflow breccias of the Silver Ace area. It is overlain with minor disconformity by tuffaceous sediments and the upper unit of the tuffs of Rye Patch. It is intruded by the rhyolite of Silver Ace and overlain unconformably by trachyandesite flows of Red and Thunder Mountains.

Upper ash-flow tuff. The upper ash-flow tuff of the tuffs of Rye Patch reaches a maximum thickness of about 30 m in the mapped area. It is a simple(?) cooling unit of grayish-orange to grayish-orange-pink, devitrified, crystal-vitric to vitric-crystal tuff. The tuff is weakly welded at its base, but grades upward into densely welded tuff within a few meters. The average phenocryst content of the tuff ranges from 20 to 30 percent and the average lithic content is about 5 percent. The average phenocryst percentages are quartz, 21; alkali feldspar, 30; plagioclase, 43; biotite, 2; opaques, 2; and hornblende, trace. Plagioclase ranges in composition from An_{25-35} and shows oscillatory zoning. Apatite and zircon occur as accessories. Zircon occurs in distinctive stubby brown crystals up to 0.3 mm in length. Quartz phenocrysts are vermicular and moderately corroded (fig. 23). None of the phenocrysts observed in thin section exceeds 3 mm in maximum dimension.

Although much of the rock is too highly altered to show primary devitrification features, spherulitic devitrification of shards and pumice is common in the least altered portions of the tuff. Axiolitic structure is also present in some of the tuff.

Source and age. The tuffs of Rye Patch were erupted from the Big Ten Peak caldera in the southern Monitor Range located approximately 10 km northeast of the northeastern corner of the mapped area. The Big Ten Peak caldera is approximately 25 km in diameter and was a major eruptive center. Its location and approximate boundaries are shown on the map of Cenozoic rocks of Nevada by Stewart and Carlson (1976), map sheet 2.

Both the upper and lower units of the tuffs of Rye Patch, particularly the lower unit, thicken somewhat to the northeast toward the Big Ten Peak caldera. The intracaldera tuffs which correlate with the tuffs of Rye Patch, have a minimum exposed thickness of 500 m and they are probably substantially thicker. Within the caldera large landslide blocks, principally of lower Paleozoic quartzite and limestone occur floating in the intracaldera tuff (fig. 24). One of these blocks exceeds 2 km in long dimension and several are over 500 m long. Kleinhampl and Ziony (1967) show these blocks, which occur just west of Big Ten Peak, as outcrops surrounded by tuff. We interpret them as major landslide blocks emplaced during caldera collapse and concomitant with major ash-flow eruption from the caldera.

McKee (1974, p. 35–41; 1976, p. 29–32) has recently described very similar Paleozoic landslide blocks in the Northumberland caldera located approximately 60 km due north of the Big Ten Peak caldera. Some of the landslide blocks in the Northumberland caldera are as large as 1.6 km across. A similar origin for intracaldera megabreccias in the calderas of the San Juan volcanic field in Colorado has been proposed by Lipman (1976, p. 1397–1409). He interprets coherent masses of volcanic rocks over 500 m across as part of megabreccia resulting from landsliding during caldera collapse. The megabreccia is interlayered with intracaldera tuff (Lipman, 1976, p. 1403).

While most of the larger blocks in the outflow tuff of the lower unit of the tuffs of Rye Patch are pervasively brecciated, most of the large intracaldera landslide blocks are not pervasively brecciated and are commonly internally coherent. Lipman (1976, p. 1408) has suggested for the San Juan megabreccias that the lack of extensive shattering of the large blocks when they slid into the caldera was due to the cushioning effect of the erupting pyroclastic material and associated volcanic gases.

The majority of the large blocks in the caldera collapse breccias within the Big Ten Peak caldera consist of a distinctive white quartzite which Kleinhampl and Ziony (1967) have correlated with the Gold Hill quartzite. Identical white quartzite blocks, although considerably smaller in dimension, occur in the outflow sheet of the lower unit of the tuffs of Rye Patch within the mapped area. In fact, as previously described, the outflow sheet of the lower unit of the tuffs of Rye Patch contains enough lithic blocks—in places they constitute over 50 percent of the volume of the unit—that it resembles Lipman's (1976) description of some of the intracaldera breccias in the San Juan calderas. The presence of a distinctive suite of Paleo-

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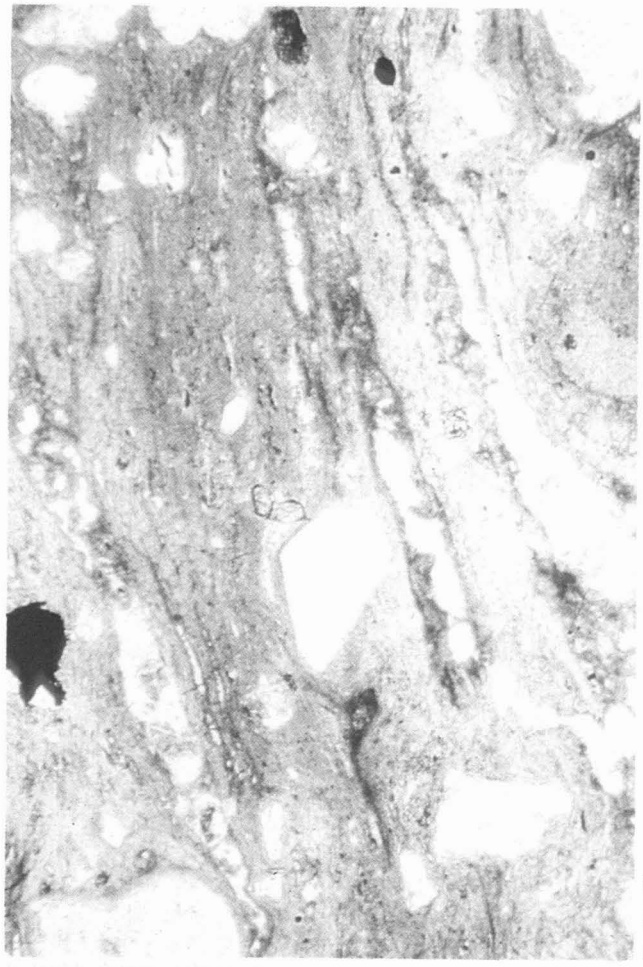
A. Phenocrysts of vermicular quartz, alkali feldspar, and sericitized plagioclase in a densely welded matrix.



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B. Highly flattened shards and pumice in densely welded tuff. Phenocrysts of quartz, alkali feldspar, and sericitized plagioclase. Two crystals of zircon in center of photomicrograph.

FIGURE 23. Photomicrographs of the upper unit of tuffs of Rye Patch.

zoic rocks in the lithic blocks within the outflow sheet of the lower tuff, which are lithologically identical to the caldera collapse breccias in the Big Ten Peak caldera, strongly suggests that the majority of the lithic blocks in the lower unit were incorporated during eruption and concomitant caldera collapse.

The upper unit, which is lithologically very similar to the lower unit, except that it has a much lower content of lithics and more phenocrysts, is also believed to have been derived from the Big Ten Peak caldera, but following major collapse. Its outcrop pattern is approximately coextensive with that of the lower unit.

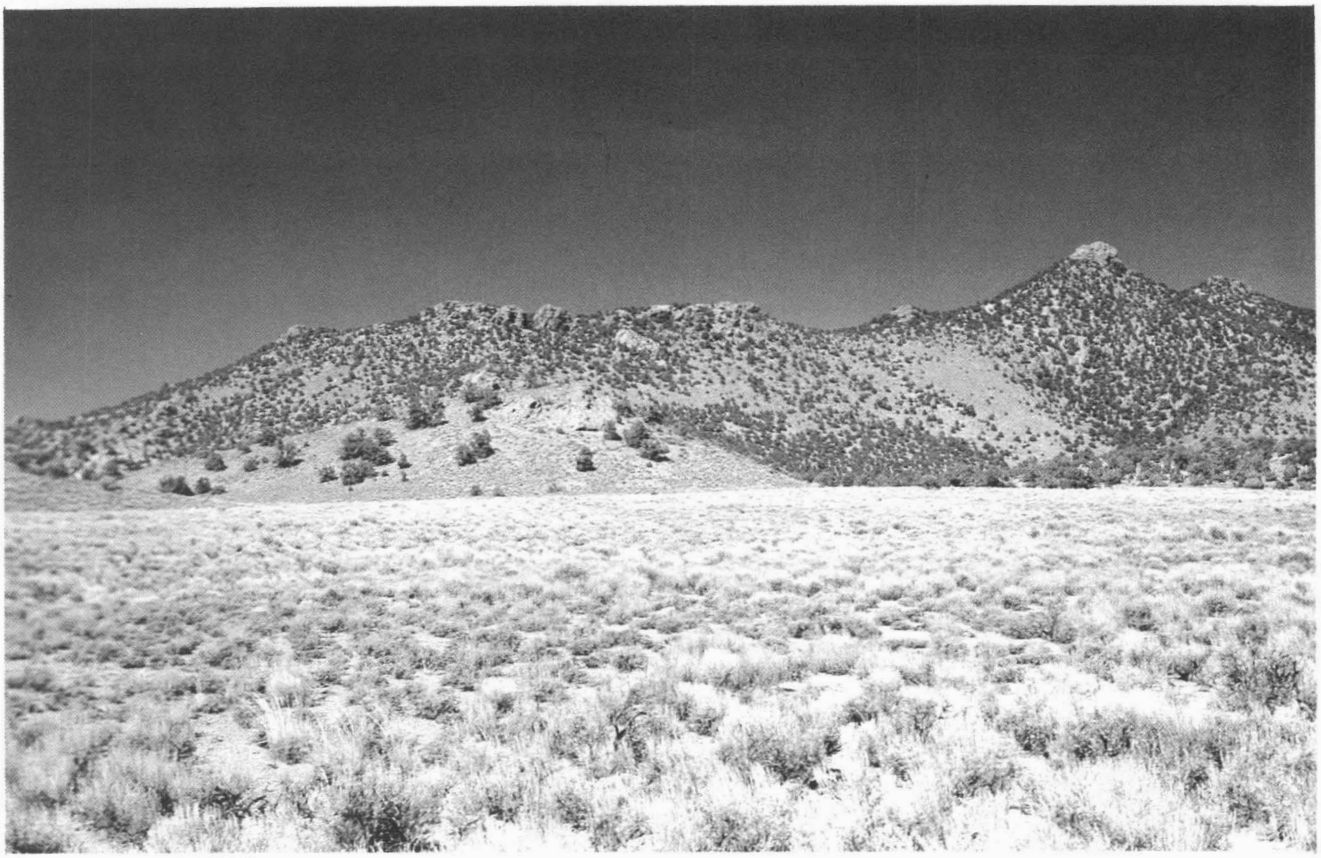
Kleinhampl and Ziony's (1967) Tf and Th map units and their Twa map unit in the southern Monitor Range include the ash-flow sheets mapped here as the tuffs of Rye Patch, as well as a variety of other Tertiary volcanic rocks.

Due to the pervasive hydrothermal alteration and moderate to high lithic content of the tuffs of Rye Patch within the mapped area and within the Big Ten Peak caldera, no samples were considered suitable for K-Ar dating. However, the intracaldera tuffs of the Big Ten Peak caldera, are unconformably overlain by several ash-flow sheets along the southern and eastern margins of the caldera and they are intruded and overlain by rhyolites in McCann Canyon (fig. 24), which are herein interpreted to be ring rhyolites of the caldera. The rhyolite of McCann Canyon has a K-Ar date of 24.8±1.5 m.y. (Marvin and others, 1973, p. 5). K-Ar dates of 25.2±0.7 m.y. on biotite and 24.0±0.7 m.y. on plagioclase (table 4) were obtained on a sample collected by us from an ash-flow tuff exposed near Murphy's Camp that unconformably overlies the intracaldera tuffs along the southern margin of the caldera in T5N,R46E at the northern limit of Saulsbury Wash. The Shingle Pass Tuff, which overlies the intracaldera tuffs unconformably along the east side of the Monitor Range in the vicinity of Piñon Peak, has K-Ar ages of 25.3±0.68 and 25.4±0.8 m.y. (Ekren and others, 1971, p. 28).

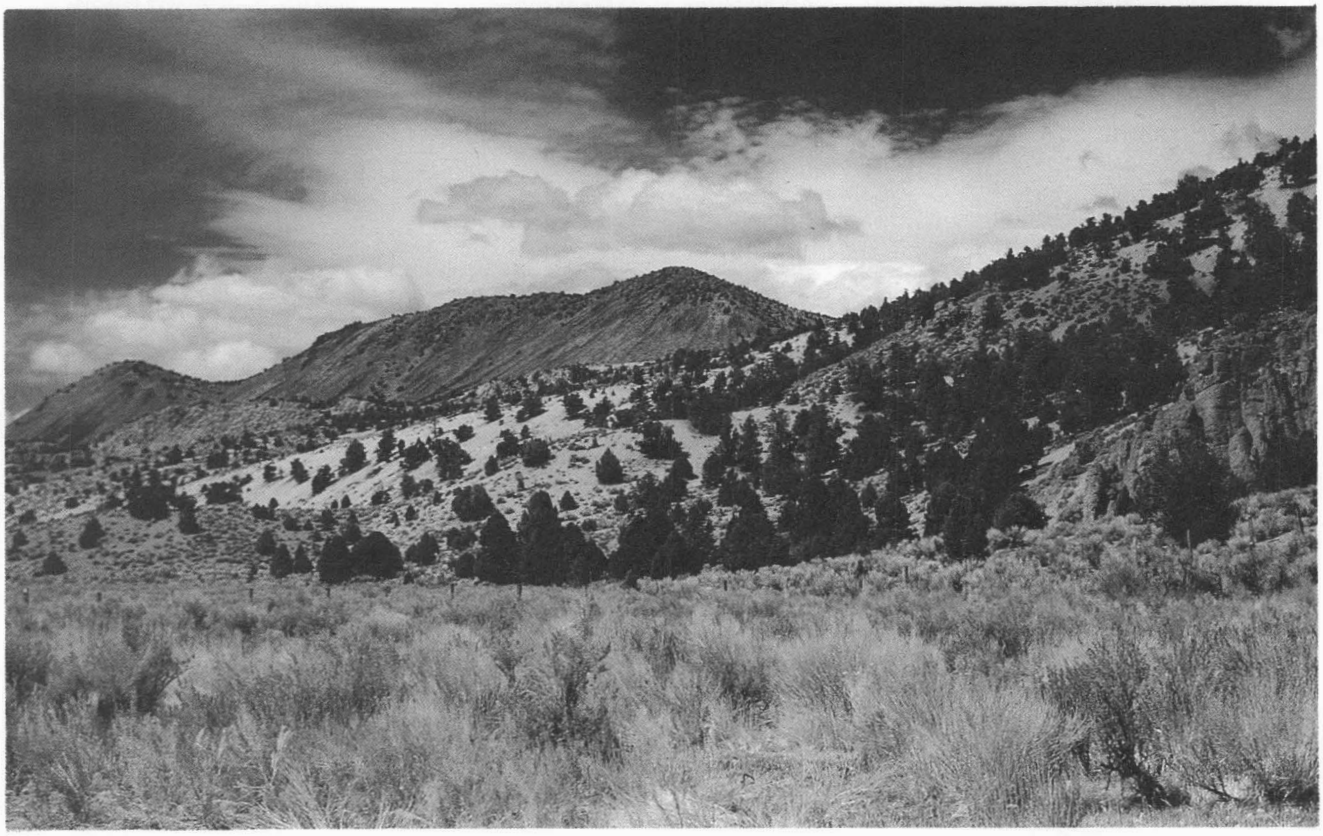
The above dates make it evident that the intracaldera tuffs and, therefore, the outflow facies tuffs of Rye Patch are older than 25 m.y. However, since we believe that the 24.8-m.y. date for the rhyolites of McCann Canyon reflects the age of ring fracture volcanism, Smith and Bailey's (1968, p. 641) Stage VI, the intracaldera tuffs are probably not more than a million years older or about 26 m.y.

Tuff of White Blotch Spring(?) (Twb?)

Erosional remnants of crystal-vitric densely welded ash-flow tuff crop out in isolated exposures at several localities north of Tonopah, including the north side of Booker Mountain and near Rhyolite Peak. The tuff overlies rocks



A. Large quartzite blocks (craggy outcrops) floating in intracaldera tuffs of the Big Ten Peak caldera.



B. Ring rhyolites intruding intracaldera tuffs in Hunts Canyon, Monitor Range. Intrusive rhyolites are dark-colored rocks which form ridge in background.

FIGURE 24. Big Ten Peak caldera.

of the Tonopah Formation disconformably in the area north of Red Mountain and is unconformably overlain by various younger Tertiary volcanic rocks including flows of the Mizpah Formation.

The rock is typically pale red and contains conspicuous white pumice and blocks of cognate tuff. The light-gray to white 2- to 3-cm blocks of cognate tuff are a prominent feature of the tuff. Phenocrysts compose about 33 percent of the rock, of which 35 percent are quartz, 25 percent are alkali feldspar, 35 percent are plagioclase, and 5 percent are biotite. Zircon, apatite, and Fe-Ti oxides are minor accessories. The quartz phenocrysts are conspicuous in hand specimen and reach maximum dimensions of 4 mm; the average diameter is 2 mm. The quartz phenocrysts are corroded and moderately vermicular. Plagioclase and alkali feldspar phenocrysts are also somewhat corroded and vermicular. The rock contains less than 1 percent lithics.

The tuff is entirely devitrified and densely welded throughout. The highly welded pumice and shards in the matrix have been partially obliterated by the growth of spherulitic aggregates during primary devitrification. No cooling breaks were noted in any of the outcrops of this tuff.

Ekren and others (1971, p. 32–35) designated a group of quartz-rich ash-flow tuffs erupted from centers in the Kawich Range and the Cactus Range as the tuff of White Blotch Spring. These tuffs are very similar in phenocryst mineralogy and content to those of the tuff north of Tonopah. Another striking similarity is the presence of cognate blocks of tuff in both units. Thus, it seems quite likely that the tuff from the isolated outcrops north of Tonopah is correlative with one of the ash-flow tuffs included by Ekren and others (1971) in the tuff of White Blotch Spring.

The tuff of White Blotch Spring(?) in the Tonopah area is older than the Mizpah Formation (20.5 m.y.) and younger than rocks of the Tonopah Formation (24 to 34 m.y.). Ekren and others (1971, p. 28) list K-Ar ages for the tuff of White Blotch Spring from several different localities, which range from 21.5 m.y. to 25.2 m.y. The radiometric ages are therefore compatible with the correlation of the quartz-rich tuff north of Tonopah with the tuff of White Blotch Spring.

Rhyolite of Silver Ace (Trs)

Spherulitic rhyolite, here informally named the rhyolite of Silver Ace, crops out in the area north and east of Thunder Mountain in T4N,R44E. The rhyolite occurs as dikes and plugs which intrude the tuffs of Rye Patch.

The least altered rhyolite is pinkish gray, flow banded, abundantly spherulitic, and contains less than 10 percent phenocrysts of plagioclase, quartz, alkali feldspar, and biotite set in a fine-grained matrix of quartz and alkali feldspar. All of the rhyolite has been affected by weak to intense hydrothermal alteration. In the less altered rocks, plagioclase is speckled with sericite and calcite, and biotite is partially altered to sericite. In the more intensely altered rocks primary plagioclase and biotite are sericitized, the rock is cut by quartz veinlets, and secondary biotite forms rosettes. Alkali feldspar is stable in all of the alteration phases.

The rhyolite of Silver Ace is younger than the tuffs of Rye Patch, which are at least 26 m.y. old, and older than the trachyandesite of Thunder Mountain (16 m.y.). The rhyolite is probably about the same age as the 25-m.y.-old rhyolite of McCann Canyon (Marvin and others, 1973, p. 5).

Silicic Porphyry Dikes (Tsp, Tspb)

A swarm of quartz monzonite, granite, and rhyolite porphyry dikes is present over a wide area on the northeast and east sides of Lone Mountain. The dikes occur in a northwest-trending zone up to 5 km wide and over 12 km long. The dikes intrude Precambrian and early Paleozoic metasedimentary rocks and Mesozoic plutonic rocks and are unconformably overlain by the Tonopah Summit Member of the Fraction Tuff and by arkose and conglomerate of the Siebert Formation. North of Willow Spring and south of Millers the dikes locally constitute over 50 percent of the bedrock outcrops, and the country rock occurs as elongate screens between the dikes. Where the dikes intrude metasedimentary rocks, they were emplaced approximately parallel to the strike of the bedding in the metasedimentary rocks, but are discordant to the dip. The dikes usually dip within 10 degrees of vertical.

In the central portion of S36,T3N,R40E, an elliptical intrusive breccia pipe cuts Mesozoic granitic rocks. The matrix of the intrusive breccia is rhyolite porphyry, and the breccia fragments are predominantly Mesozoic granitic rocks.

The dikes are divided into three main types: granodiorite and quartz monzonite porphyry, granite porphyry, and rhyolite porphyry. The granodiorite and quartz monzonite porphyry dikes are light gray to yellowish gray and contain prominent phenocrysts of plagioclase up to 3 cm long, plus smaller phenocrysts of quartz, orthoclase, and biotite in a felsitic matrix of quartz, orthoclase, and plagioclase. The granite porphyry is pale red, pinkish gray, or grayish orange pink and has phenocrysts of orthoclase (up to 2 cm), quartz, plagioclase, and biotite in a micrographic or aplitic matrix of quartz and alkali feldspar. The rhyolite porphyry is light gray, pinkish gray, grayish orange pink, pale red or very pale orange and contains sparse, 1- to 2-mm phenocrysts of quartz, orthoclase, plagioclase, and biotite in a spherulitic matrix of quartz and alkali feldspar (fig. 25).

The plagioclase in the dikes ranges from albite to oligoclase. Quartz phenocrysts are corroded and usually vermicular. Zircon and apatite plus Fe-Ti oxides are the common accessory minerals, but tourmaline is present in some of the dikes.

Chemical anlayses of three samples from the dike swarm are shown in table 8. They show a compositional range from granodiorite porphyry to alkali granite porphyry.

All of the dikes are hydrothermally altered. The alteration ranges from propylitic to argillic and phyllic. Most of the dikes also contain sparse disseminated pyrite. Hydrothermal alkali feldspar occurs in quartz veinlets in rocks exhibiting phyllic alteration.

It seems quite probable that a subjacent pluton was the magmatic source of the dike swarm and that the emplacement of this pluton caused doming and extensional fracturing of its roof. The dike swarm was emplaced in fractures developed as a result of the extension of the roof of the pluton.

A fission-track age of 22.1 m.y. was obtained on zircon from a granite porphyry dike (table 4). The 22-m.y. age of

0.1 mm

FIGURE 25. Photomicrograph of silicic porphyry dike, Lone Mountain area, showing spherulites in rhyolite porphyry.

the dike swarm suggests that it is related to the same period of silicic magmatism that produced the extensive ash-flow vulcanism in this part of Nevada.

Lamprophyre Dikes (Tl)

The Lone Mountain Pluton, Wyman Formation, Reed Dolomite, and Deep Spring Formation are intruded by lamprophyre dikes. The dikes are particularly abundant in the Lone Mountain Pluton where they were emplaced along joints in the granite. The dikes range in width from a few centimeters to over 100 meters. Many of the dikes in the pluton are too narrow to show on the geologic map.

Lamprophyre dikes are dark greenish gray and contain prominent hornblende phenocrysts up to 2 mm long in a fine-grained pilotaxitic matrix of plagioclase, augite, and alkali feldspar. Magnetite and apatite occur as accessory minerals. The dikes are deuterically altered and contain abundant calcite, chlorite, and epidote replacing the primary minerals. A few of the dikes are very coarse grained and contain crystals of hornblende and plagioclase up to 5 cm in length. These coarse-grained dikes have a pegmatitic texture and contain quartz, biotite, and alkali feldspar in micrographic intergrowths between the plagioclase and hornblende crystals. Most of the dikes are spessartite; some are close to vogesite.

The lamprophyre dikes intrude the silicic porphyry dikes (Tsp) at several localities and are therefore younger than 22 m.y. Albers and Stewart (1972, p. 31) report a K-Ar age on hornblende of 367 m.y. from one of the lamprophyre dikes (hornblende diorite of Albers and Stewart). This age is clearly much too old since the dikes are younger than both the Lone Mountain Pluton and the silicic porphyry dikes.

Intrusive Rhyodacite and Dacite Porphyry, Rye Patch Area (Trd)

Irregularly shaped bodies of rhyodacite and dacite porphyry intrude the tuffs of Rye Patch in T4N,R43E and are overlain unconformably by the trachyandesite of Red Mountain. The rhyodacite is a porphyritic, light-brownish-gray rock which contains phenocrysts of plagioclase (1 to 2 mm), alkali feldspar (0.5 to 1 mm), biotite (0.5 mm), and

TABLE 8. Chemical analyses, silicic porphyry dikes, Lone Mountain area.

Sample	T180 Alkali granite porphyry	T213 Granite porphyry
Location number	1	2
Normalized oxide values		
SiO_2	74.4	70.2
Al_2O_3	14.1	16.3
Fe_2O_3	0.5	1.5
FeO	0.5	0.3
MgO	0.3	0.6
CaO	1.7	2.4
Na_2O	2.9	2.1
K_2O	5.2	6.1
TiO_2	0.2	0.3
Mno	4.10	4.12
Normative minerals		
Quartz	33.2	28.7
Corundum	0.6	1.7
Orthoclase	0.6	36.3
Albite	30.7	18
Anorthite	24.9	12.1
Diopside		
Hypersthene	0.9	1.5
Magnetite	0.8	0.7
Hematite		0.8
Ilmenite	0.4	0.6
Wollastonite (diopside)		
Enstatite (diopside)		
Enstatite (hypersthene)	0.2	1.5
Ferrosilite (diopside)		
Ferrosilite (hypersthene)	0.2	
Petrologic indices		
Differentiation index	88.8	82.1
Felsic-mafic index	26.9	16.9

Locations: 1. SW/4 S36,T3N,R40E
2. SW/4 S19,T2N,R41E

sparse hornblende set in a fine-grained felsitic matrix of quartz and alkali feldspar. The plagioclase is almost entirely altered to calcite and sericite; hornblende is altered to calcite, sericite, and Fe-Ti oxides. Biotite is slightly oxidized, but not otherwise altered. The dacite is a porphyritic, light-brownish-gray rock with prominent phenocrysts of plagioclase (1 to 3 mm), hornblende (1 to 2 mm), and biotite (1 mm) set in a trachytic matrix of plagioclase microlites, mafic granules, and brown glass. The plagioclase exhibits oscillatory zoning and ranges in composition from An_{35} to An_{45}.

The rhyodacite and dacite are younger than the tuffs of Rye Patch (25 m.y.) and older than the trachyandesite of Red Mountain (15 m.y.).

Dacite, Millers Area (Tdm)

Several small outcrops of porphyritic dacite are exposed in the low hills that form the north end of the Lone Mountain block. The porphyritic dacite presumably overlies Mesozoic granodiorite, Tertiary granite, and rhyolite porphyry dikes unconformably, although the base of the dacite is not exposed. It is overlain unconformably by the Tonopah Summit Member of the Fraction Tuff, and it is intruded by rhyolite and quartz latite plugs.

The porphyritic dacite is lithologically virtually identical to dacites of the Mizpah Formation. It contains phenocrysts of plagioclase up to 5 mm long, biotite, and hornblende in a pale-red, fine-grained felsitic matrix containing abundant alkali feldspar. Propylitic alteration of the dacite in the Millers area converted plagioclase to calcite, sericite, and adularia; hornblende to calcite; and Fe-Ti oxides to weakly chloritized biotite.

The porphyritic dacite is probably younger than the 22-m.y.-old silicic porphyry dikes and older than the Tonopah Summit Member of the Fraction Tuff. It is essentially equivalent in age to rocks of the Mizpah Formation (20.5 m.y.).

Dacite, Rhyodacite, Pyroxene Andesite, and Hornblende-Biotite Andesite, of Northern Goldfield Hills (Tid, Tpa, Tag, Trdg)

Rhyodacite flows, andesite flows and dikes, and dacite dikes crop out over an area of about 2 km^2 in the Klondyke Hills. Outcrops of the rhyodacite and andesite are much more extensive in the northern Goldfield Hills than they are within the map area.

The andesite flows and dikes unconformably overlie and intrude the Monotony(?) Tuff and the tuffs of Antelope Springs(?). They are intruded by the rhyolite of Klondyke and by dacite dikes and are unconformably overlain by rocks of the Siebert Formation and the volcanics of Donovan Peak.

The rhyodacite flows are conformably overlain by flows of pyroxene andesite in the Klondyke Hills. In the northern Goldfield Hills, flows of the rhyodacite interfinger with flows of both pyroxene and hornblende-biotite andesite (Roger Ashley, personal commun., 1976). The dacite occurs as nearly vertical dikes intruding flows of hornblende-biotite andesite and the tuffs of Antelope Springs(?).

The dacite dikes are light- to medium-gray porphyritic rocks containing phenocrysts of oscillatory-zoned plagioclase (4 to 5 mm), diopsidic augite (1 to 2 mm), biotite (1 to 3 mm), and sparse corroded vermicular quartz in a felsitic matrix of quartz and alkali feldspar. The plagioclase phenocrysts range in composition from An_{40} to An_{55}, and are fractured and locally veined by alkali feldspar. Stilbite fills vesicles.

The andesite flows and dikes are mostly brownish-gray pyroxene andesite, but include some hornblende-biotite andesite. The pyroxene andesites have an intergranular texture and contain phenocrysts of plagioclase, (An_{50-60}), euhedral diopsidic augite and phlogopite, in a matrix of plagioclase, Fe-Ti oxides, augite, and apatite. Some of the augite crystals show glomeroporphyritic texture. Minor amounts of alkali-feldspar occur in the interstices of the plagioclase crystals. The phlogopite is pleochroic in light-yellow-brown tones (fig. 26). The hornblende-biotite andesites contain phenocrysts of zoned plagioclase (4 mm) (An_{50-60}) hornblende (2 to 4 mm), and biotite (1 to 2 mm) in a fine-grained matrix of plagioclase, Fe-Ti oxides, apatite, and alkali feldspar. The biotite is oxidized to Fe-Ti oxides and the hornblende is altered to aggregates of calcite, chlorite, and Fe-Ti oxides. Plagioclase is partially replaced by epidote, calcite, sericite, and quartz.

The flows of light to dark gray, porphyritic rhyodacite contain 50 to 60 percent phenocrysts of plagioclase (An_{40-45}) (5 to 10 mm), biotite (1 to 2 mm), pyroxene

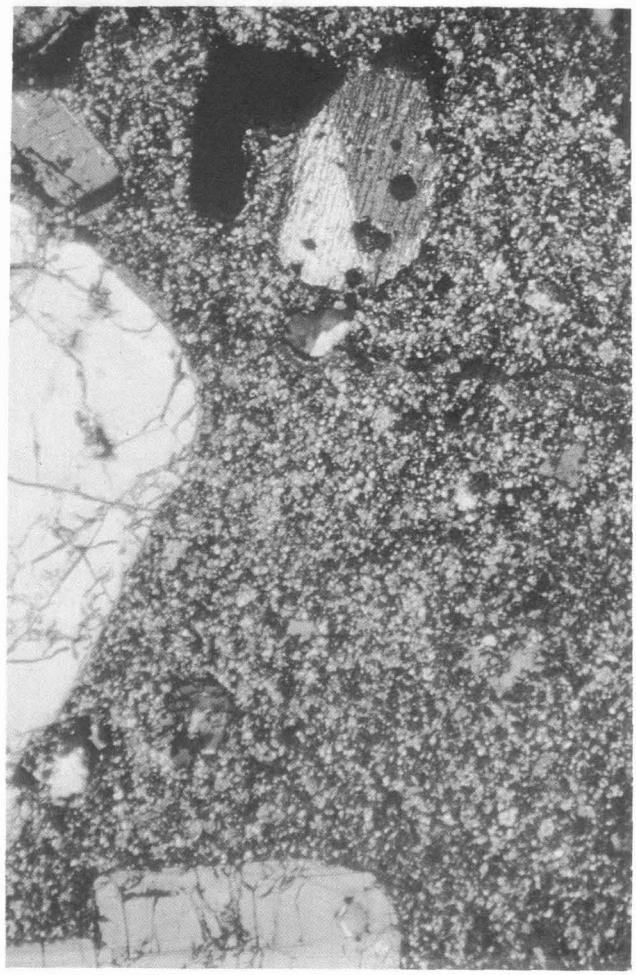


FIGURE 26. Photomicrograph of pyroxene andesite of northern Goldfield Hills. Phenocrysts of plagioclase (An_{50-60}) and augite in an intergranular matrix of plagioclase, augite, Fe-Ti oxides, phlogopite, apatite, and minor alkali feldspar.

(1 to 2 mm), sparse quartz, and alkali feldspar. The groundmass is medium-dark-gray perlitic glass in the marginal portions of the flows. The glass is devitrified to a fine-grained aggregate of quartz and alkali feldspar in the interiors of the flows.

The andesite and rhyodacite were not dated in the map area. Correlative rocks of the same sequence were dated a few kilometers to the south in the northern Goldfield Hills by Armstrong and others (1972, p. 27) who obtained a K-Ar age of 21.6 m.y. on feldspar (plagioclase?) and 21.8 m.y. on biotite from a "dacite vitrophyre". The dacite dikes were not dated, but they are lithologically similar to both the hornblende-biotite andesite and the rhyodacite and are quite probably of about the same age.

Mizpah Formation (Tm, Tml, Tmi)

The name Mizpah Trachyte was first applied to highly altered volcanic rocks of intermediate composition present in the Tonopah district by Spurr (1915, p. 720). Spurr (1905b) had originally called these rocks the "earlier andesite". He also named (1915, p. 743) propylitically altered volcanic rocks of intermediate composition in the Tonopah district the Midway Andesite (the "later andesite" of his earlier reports). He described the "later" or Midway Andesite as overlying the Mizpah Trachyte unconformably and forming a "cap rock" to the veins. Nolan (1935, p. 19–20) and Campbell (1931, p. 73–88) concluded that the "later" or Midway Andesite is simply the propylitically altered part of the Mizpah Trachyte and not a separate formation. They also stated that there was no evidence in the underground workings at Tonopah for any later andesite "cap rock" overlying the productive veins. Our study corroborates Nolan's conclusions in that all the rocks mapped by Spurr (1905b), Burgess (1909), and others as "later" or Midway Andesite are part of the Mizpah Trachyte.

Nolan (1935, p. 19) pointed out that the andesitic-appearing rocks of the Mizpah Trachyte within the Tonopah district are albitized andesite rather than trachyte, but he preferred to retain the name Mizpah Trachyte because of its long established usage in the district. Both Spurr and Nolan were describing hydrothermally altered rocks. Three chemical analyses of fresh rock from the Mizpah (table 9) show that the unaltered rock ranges in composition from trachyandesite to dacite. Inasmuch as the unit is not compositionally trachyte, and because it includes lava flows, intrusive phases, and volcaniclastic rocks, it seems desirable to change the lithologic designation applied to the unit. Because no simple lithologic designation such as andesite or dacite would be accurate if applied to the rocks of this formation, we hereby propose that the Mizpah Trachyte be renamed the Mizpah Formation.

The volcanic rocks of the Mizpah Formation in the Tonopah area are part of a suite of volcanic rocks of intermediate composition that are of widespread occurrence in west-central Nevada. This suite of rocks ranges in age from about 25 m.y. to 17 m.y. and was erupted from numerous stratovolcanoes. Some of the occurrences of these volcanic rocks in areas adjacent to Tonopah are described (Ekren, 1971, p. 37–48) in the Nellis Bombing and Gunnery Range, at Goldfield by Ashley (1974a) and Ashley and Silberman (1976, p. 907–910) and are shown on maps by Stewart and Carlson (1976).

The intermediate volcanic rocks range in composition from andesite and trachyandesite to rhyodacite and typically are porphyritic. Plagioclase is the principal phenocryst mineral in these intermediate volcanic rocks. Biotite and hornblende occur in nearly all of the rocks, and pyroxene is present in many of them. Quartz and alkali feldspar occur as phenocryst minerals, chiefly in dacite and rhyodacite. Chemically, the intermediate volcanic rocks have higher K_2O contents at the same SiO_2 percentage than similar rocks in the volcanic suites of such areas as the southern Andes or the Cascades.

A number of hydrothermally altered and mineralized areas occur in this group of volcanic rocks and they are the chief host rocks for the gold mineralization at Goldfield and the silver-gold mineralization at Tonopah. However, at Tonopah significant amounts of silver-gold ore were also mined from the rhyolitic rocks of the Tonopah Formation, the West End Rhyolite and the Extension Breccia.

Distribution and thickness. Lava flows, volcaniclastic rocks, and minor intrusive rocks of the Mizpah Formation crop out over an area of approximately 13 km^2 as intermittent exposures that extend from Tonopah north to Fraziers Well. Rocks of the Mizpah Formation are also present in the underground workings in the Tonopah district.

According to Nolan (1935, p. 23) the Mizpah Formation (his Mizpah Trachyte) is at least 610 m thick at Tonopah. The Mizpah Formation, as mapped in this study, is not that thick; however, its base is not exposed in several of the outcrop areas. The base of the Mizpah Formation is exposed at the surface only in the area just southeast of Red Mountain. Here the Mizpah unconformably overlies rhyolite tuffs and flows of the Tonopah Formation. The principal units which unconformably overlie the Mizpah Formation are the Tonopah Summit and King Tonopah members of the Fraction Tuff, the Siebert Formation, and the trachyandesite of Red Mountain.

Lithology. The Mizpah Formation is divided into three informal map units: a vent facies consisting largely of lava flows and flow breccia; a volcaniclastic facies, consisting predominantly of mudflow breccias; and intrusive dikes readily distinguishable only where they intrude rock types other than those of the Mizpah.

Vent Facies

The vent facies is composed of intermediate composition, porphyritic lava flows, and flow breccias. Where fresh, these rocks are dark gray to grayish brown and distinctly porphyritic, with conspicuous plagioclase phenocrysts up to 5 mm in length, and phenocrysts of hornblende and biotite set in a fine-grained matrix (fig. 27); some of the flows also contain clinopyroxene as a phenocryst mineral. The basal portions of some of the flows have a dark-gray groundmass of perlitic glass. The groundmass of most of the flows has a pilotaxitic texture. Plagioclase exhibits oscillatory zoning and ranges in composition from An_{30} to An_{35}. The biotite and hornblende are typically oxidized and are commonly rimmed by Fe-Ti oxides (fig. 28). The quartz phenocrysts are corroded and vermicular. The apatite is pleochroic in shades of brown and occurs in crystals up to 1 mm in long dimension. The clinopyroxene, when present, is very pale green and is diopsidic augite. Modal analyses of a typical clinopyroxene-bearing dacite lava flow and a typical hornblende-biotite dacite are shown in table 10.

TABLE 9. Chemical analyses, Mizpah Formation.

Sample	T5G Dacite-latite boundary	T5 Dacite-latite boundary	T67 Trachyandesite
Location number	1	2	3
	Normalized oxide values		
SiO_2	60.3	62.1	60.1
Al_2O_3	17.5	16.6	17.2
Fe_2O_3	4.8	5.7	5.1
FeO	1.2	0.8	0.9
MgO	1.9	2.4	3.1
CaO	5.5	4.9	6.6
Na_2O	3.5	4.3	2.6
K_2O	4.3	2.3	2.8
TiO_2	0.9	1.0	0.8
MnO	0.05	0.14	0.08
	Normative minerals		
Quartz	10.5	15.4	16.4
Orthoclase	25.4	13.8	16.7
Albite	29.8	35.9	21.8
Anorthite	19.3	19.2	28.7
Diopside	6.1	4.0	3.3
Hypersthene	1.9	4.1	6.2
Magnetite	1.5	0.1	0.9
Hematite	3.8	5.6	
Ilmenite	1.7	1.8	
Wollastonite (diopside)	3.3	2.2	1.8
Enstatite (diopside)	2.8	1.9	1.6
Enstatite (hypersthene)	1.9	4.1	6.2
	Petrologic indices		
Differentiation index	65.7	65.9	54.9
Felsic-mafic index	5.1	5.0	4.2

Locations: 1. SE/4 S31,T3N,R43E
2. NE/4 S35,T2N,R42E
3. SW/4 NW/4 S13,T3N,R42E

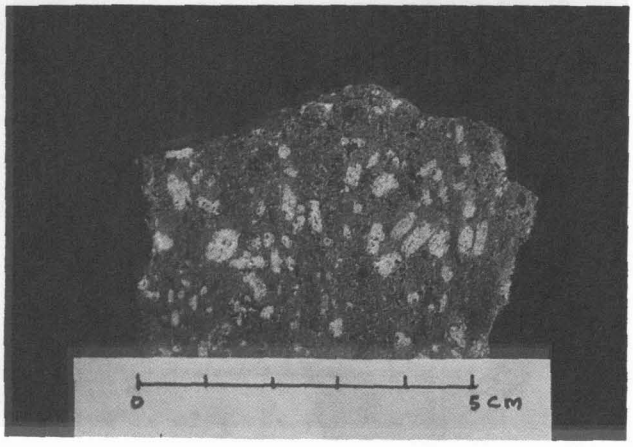
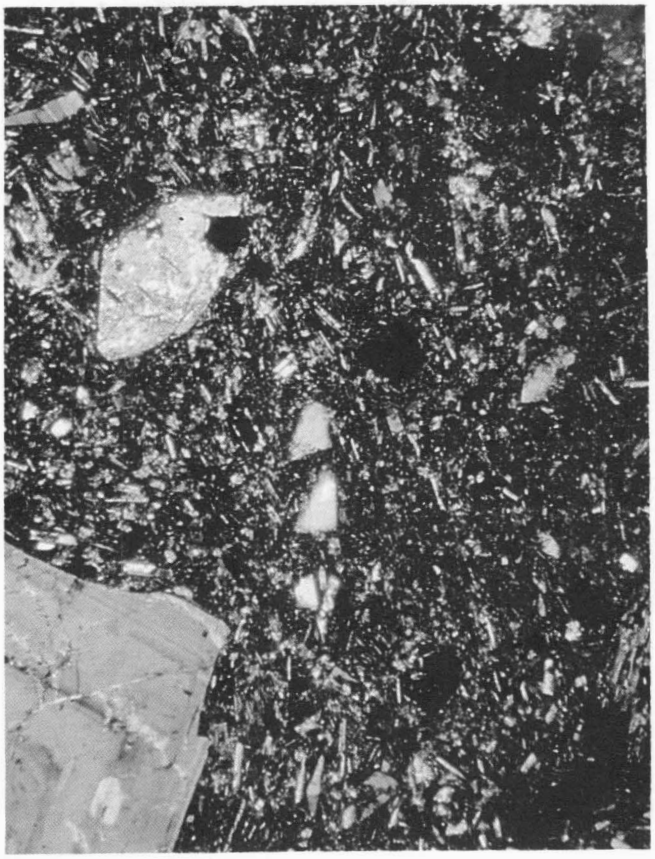


FIGURE 27. Porphyritic dacite, Mizpah Formation. Phenocrysts of plagioclase, hornblende, biotite, and pyroxene.

Specific details of the alteration in the Tonopah district are discussed in the Mineral Deposits section of this report.

Volcaniclastic Facies

The volcaniclastic facies of the Mizpah Formation is composed mainly of mudflow breccias, associated with minor amounts of lava flows. The mudflow breccias contain angular to subangular clasts of porphyritic flow rock, lithologically identical to typical lava flows of the Mizpah, in a fine-grained matrix of silt and sand-size material. The clasts range in size from a few millimeters to about 1 m and average about 30 cm in maximum dimension. The breccia fragments exhibit some degree of heterogeneity, principally in color, phenocryst size, and total amount of phenocrysts. The mudflow breccias are poorly sorted and crudely bedded. They occur principally in the area north of Booker Mountain and northeast of Tonopah in the vicinity of Ice Plant and Slaughterhouse Springs.

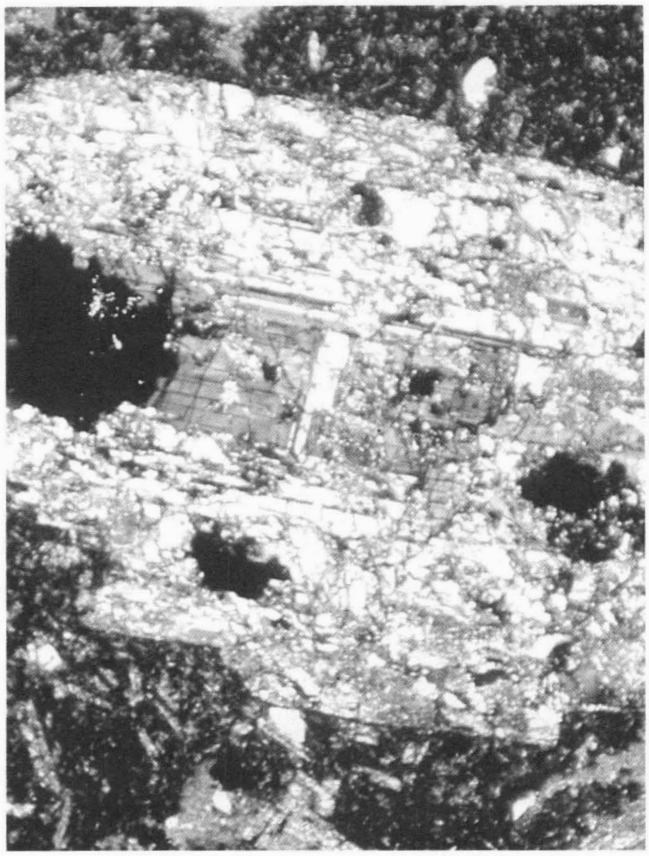


0.2mm

A. Plagioclase, hornblende, and biotite phenocrysts in a pilotaxitic matrix of plagioclase, alkali feldspar, apatite, and Fe-Ti oxides.

0.2mm

B. Radiating crystals of mordenite occurring as a replacement of the original groundmass in a dacite.



0.1mm

C. Plagioclase phenocryst in dacite, partially replaced by albite and calcite.

FIGURE 28. Photomicrographs of dacite of the Mizpah Formation.

The volcaniclastic facies rocks of the Mizpah Formation are, in most outcrops, fresh. Locally, they are weakly propylitically altered along fractures.

Intrusive Rocks

Several dikes and irregularly shaped bodies of porphyritic dacite, here included in the Mizpah Formation, intrude rocks of the Tonopah Formation in the area immediately to the east of Red Mountain.

The intrusive rocks consist of porphyritic dacite lithologically identical to similar-appearing dacite flow rock in the Mizpah Formation. The intrusives are moderately to intensely altered. The alteration phases present are quartz-sericite-adularia, argillic, and propylitic.

The dikes strike N. 50°–60° W., essentially parallel to the strike of the Mesozoic or Tertiary porphyry dikes in the Fraziers Well area located just to the north of the outcrop area of intrusive dikes of the Mizpah Formation.

Source vents. Geologic evidence for the eruptive sources for the lava flows and flow breccias of the Mizpah Formation is largely indirect. One possible source vent for the Mizpah lava flows is represented by the intrusive dike complex located just east of Red Mountain. This possible vent area is also the locus of an area of intense hydrothermal alteration in the Mizpah and Tonopah Formations. A second source vent, possibly the major one, appears to be located within the Tonopah district. This interpretation is based upon several factors. The areal distribution of the lava flows (vent facies) of the Mizpah versus the volcaniclastic facies suggests that the source vent lies to the west

TABLE 10. Phenocryst[1] mineralogy, fresh[2] Mizpah dacite.

[Phenocrysts and accessory minerals as percentage of total rocks. Numbers in parentheses show phenocrysts recalculated to 100 percent.]

	T219	T290
Groundmass	71.3	74.4
Plagioclase	18.4 (64.0)	17.5 (68)
Quartz	0.1 (0.3)	
Clinopyroxene	3.3 (11.4)	
Hornblende	3.9 (13.6)	1.7 (7)
Biotite	2.3 (7.9)	1.9 (7)
Fe-Ti oxides	0.7 (2.5)	0.5 (2)
Apatite	0.1 (0.3)	Tr
Mordenite[3]		4.0 (16)

[1] Phenocrysts and microphenocrysts >.1mm in diameter.
[2] Sample T290 shows weak propylitic alteration.
[3] Mordenite occurs as crystals up to 0.5 mm as patchy replacement of groundmass.

or southwest of the outcrops of the mudflow breccias of the volcaniclastic facies (pl. 1) within or near the Tonopah district. The Mizpah Formation is also thicker (>600 m) in the Tonopah district than elsewhere.

The Tonopah district is also the major locus of hydrothermal alteration and metallization in the rocks of the Mizpah Formation. Both Nolan (1935, p. 40 and p. 46) and Taylor (1973, p. 760) have postulated that an intrusive magmatic body underlies the district. Nolan concluded, on the basis of the structural geology and the distribution of the hydrothermal alteration and metallization, that the district was underlain by an intrusive body, while Taylor reached the same conclusion based upon stable isotope data. It seems probable that this postulated igneous body occupies the magma chamber from which the lavas of the Mizpah Formation were derived. The K-Ar ages of the lavas of the Mizpah Formation, approximately 20.5 m.y., and of the hydrothermal alteration in the Tonopah district, 18 to 19 m.y., are compatible with the theory that the same magmatic source that produced the lava flows of the Mizpah was also responsible for the hydrothermal alteration and metallization in the Tonopah district.

Extension Breccia and West End Rhyolite

The Extension Breccia and West End Rhyolite are extensively exposed in underground workings in the western portion of the Tonopah district, but do not crop out within the mapped area. Because neither of these units was studied during this investigation, the reader is referred to the Nolan (1930; 1935) reports, which give comprehensive descriptions of each.

Fraction Tuff

Previous usage. Spurr (1905b, p. 39–40) applied the name Fraction Dacite Breccia to what he considered to be a unit of flows, volcanic mudflows, and pyroclastic deposits in the Tonopah district. Spurr designated no type area, but stated that the Fraction Dacite Breccia covered "a considerable part of the southern half of the area mapped". Knopf (1921, p. 150–154) renamed the unit the Fraction Rhyolite Breccia and concluded that it was a member of the Siebert Formation and could be traced continuously from the Divide district into the Tonopah district. Nolan (1930, p. 21) renamed the unit the Fraction Breccia, "because at Tonopah the basal portion of the member contains locally very large amounts of andesitic-appearing debris, with the result that there has at times been a considerable confusion as to the proper correlation of the beds." Nolan (1935) included the Fraction Breccia in the Esmeralda Formation.

Ekren and others (1967) correlated a compound cooling unit of ash-flow tuff in the Belted Range (110 km southeast of Tonopah) with the Fraction Breccia at Tonopah and, at the same time, changed the name there to Fraction Tuff. Ekren and others (1971, p. 50) later extended the name Fraction Tuff to the Tonopah area and correlated a sequence of ash-flow tuffs in the Kawich Range over 2,100 m thick with the Fraction Tuff.

Davis and others (1971, p. 1) used the name Fraction Breccia to describe lithic-rich, rhyolitic ash-flow tuffs in and around Tonopah that overlie rocks of the Mizpah Formation and are overlain by sedimentary rocks of the Siebert Formation. They were aware that their Fraction Breccia contained more than one ash-flow sheet.

Albers and Stewart (1972, p. 36) recognized that much of the rock previously mapped as Fraction Breccia in the Tonopah area is rhyolitic ash-flow tuff that overlies the Mizpah "Trachyte" and underlies the Siebert "Tuff." They restricted the use of the name Esmeralda Formation to exposures of sedimentary rocks in the Weepah Hills.

Bonham and others (1972, p. 5) followed the usage of Ekren and others (1971) and called the ash-flow tuffs in the Tonopah district that overlie the Mizpah Formation the Fraction Tuff. Bonham and Garside (1974b, p. 43–45) continued the use of the name Fraction Tuff for this group of ash-flows in the Tonopah district and subdivided the Fraction into several informal members.

Present study. As the previous section illustrates, there have been a number of revisions of the stratigraphic rank and nomenclature of the Fraction Tuff. It is also obvious that there has been no real unanimity as to the stratigraphic boundaries of the Fraction.

As a result of our detailed geologic mapping in the Tonopah area, and for the reasons cited above, we propose the following revisons in the stratigraphic terminology and stratigraphic boundaries of the Fraction Tuff: (1) that the name "Fraction Breccia" be changed to "Fraction Tuff" in the Tonopah area; (2) that the Fraction Tuff be divided into two formal members, the Tonopah Summit Member (new name) and the King Tonopah Member (new name); (3) that the Heller Tuff (Heller Dacite of Spurr, 1905b) be excluded from the Fraction Tuff as it was in Spurr's (1905b, p. 37–39) original definition; and (4) that sedimentary breccias between Heller Butte and Brougher Mountain and between Golden Mountain and Heller Butte be excluded from the Fraction Tuff and placed in the Siebert Formation. These sedimentary breccias unconformably overlie the Fraction Tuff and form a continuous stratigraphic sequence with the other sedimentary and pyroclastic rocks of the Siebert. Similar sedimentary breccias occur elsewhere in the map area in the basal part of the Siebert Formation.

Lenses of epiclastic volcanic breccia, sandstone, conglomerate, and siltstone occur at the base of the Tonopah Summit Member and are here included in it. Lenses of epiclastic volcanic breccia, sandstone and siltstone also

occur at the base and locally between the upper and lower parts of the King Tonopah Member, and are herein considered a part of the member.

Tonopah Summit Member (Tft, Tftb). The Tonopah Summit Member of the Fraction Tuff is here named for exposures of vitric-lithic quartz latite to rhyolite ash-flow tuff near Tonopah Summit (pl. 1) 1.6 km southeast of the town of Tonopah. The type locality of the member is in S11,12,T2N,R42E on the low slopes to the south and southeast of Mount Butler and Brock Mountain.

Distribution

The distribution of the Tonopah Summit Member within the map area is shown on plate 1. The most extensive exposures of the member and its greatest thickness occur in the area between the Tonopah district and the Klondyke Hills. The Tonopah Summit Member is over 400 m thick in the main shaft of the Tonopah Divide Mine. The member is not present south of the Klondyke Hills nor is it known to occur east of Ralston Valley. Exposures of a welded tuff, which is probably part of the Tonopah Summit Member, are present at the south end of Clayton Ridge in T3,4S, R40E (K. G. Papke, personal commun., 1976). To the north, the Tonopah Summit Member is not present in the San Antonio Mountains north of Rays, nor does it occur in the Monitor Range. The Tonopah Summit Member is about 60 m thick in the low hills just to the south of Millers. The unit is not known to occur with certainty west of Millers, but similar-appearing lithic-rich ash-flow tuff, possibly correlative with the Tonopah Summit Member, is present near the Blanco Clay Mine south of Coaldale Junction.

Stratigraphic Relationships

In the Tonopah district, the Tonopah Summit Member overlies lava flows and breccias of the Mizpah Formation with angular unconformity. The base of the member is not exposed in the main part of the Divide district. Near the Gold Seam Mine, between the Divide district and the Klondyke Hills, the base of the member is apparently exposed in one isolated outcrop where it appears unconformably to overlie pyroxene andesite similar to that exposed in the Klondyke Hills. The pyroxene andesite may be a large landslide block incorporated in the tuff. In the northern part of the Klondyke Hills, basal sedimentary breccia of the Tonopah Summit Member unconformably overlies tuff of White Blotch Spring(?). In the exposures south of Millers, the Tonopah Summit Member unconformably overlies dacitic lava flows and breccias.

In the Tonopah district the Tonopah Summit Member is unconformably overlain by sedimentary breccias and tuffaceous sedimentary rocks of the Siebert Formation, by ash-flow tuff of the Heller Tuff, by rocks of the King Tonopah Member, and by flows of the trachyandesite of Red Mountain. It is intruded by the Oddie Rhyolite and is intruded and overlain by flow-dome complexes of the Brougher Rhyolite.

In the Divide district, the Tonopah Summit Member is unconformably overlain by epiclastic sedimentary rocks of the Siebert Formation. It is intruded by plugs of Oddie Rhyolite and protrusive domes of Brougher Rhyolite as well as a stock of Divide Andesite and the rocks of the Donovan Peak vent complex.

Lithology

The Tonopah Summit Member consists predominantly of nonwelded to weakly welded vitric-lithic quartz latite to rhyolite tuff. Most of the unit is hydrothermally altered in the Tonopah and Divide districts and in the vicinity of Millers. Where the tuff is not obviously hydrothermally altered, the pumice and shards have been secondarily devitrified to mordenite (fig. 29), cristobalite, montmorillonite and alkali feldspar. Much of the tuff was apparently glassy prior to hydrothermal alteration. The tuff shows little welding zonation and the only evidence of primary devitrification remaining is local vapor-phase alteration of pumice lapilli.

The ash-flow sheet that forms nearly all of the Tonopah Summit Member is probably a compound cooling unit, but the combination of extensive areas of hydrothermal alteration present in the tuff plus the lack of obvious welding or crystallization zonation in the tuff makes the recognition of such features as partial cooling breaks very difficult. No partial or complete cooling breaks were observed in the Tonopah Summit Member. Several partings between individual ash flows were recognized, however (fig. 30).

Chemical analysis of a sample from the type locality of the member (table 11) shows that at least part of the tuff is rhyolite.

Table 12 shows the modal data for five samples from the Tonopah Summit Member. Much of the unit exposed within the map area is too altered for accurate modal data to be obtained, but the samples listed in the tables are believed to be representative of the member.

Quartz phenocrysts range up to 3 mm in diameter and most are corroded (fig. 29). Some of the quartz phenocrysts are somewhat "wormy." Plagioclase and alkali feldspar phenocrysts (1 to 2.5 mm) are usually somewhat smaller than the quartz phenocrysts. Plagioclase (An_{35-45}) normally exhibits oscillatory zoning. Biotite phenocrysts rarely exceed 1.5 mm in maximum dimension.

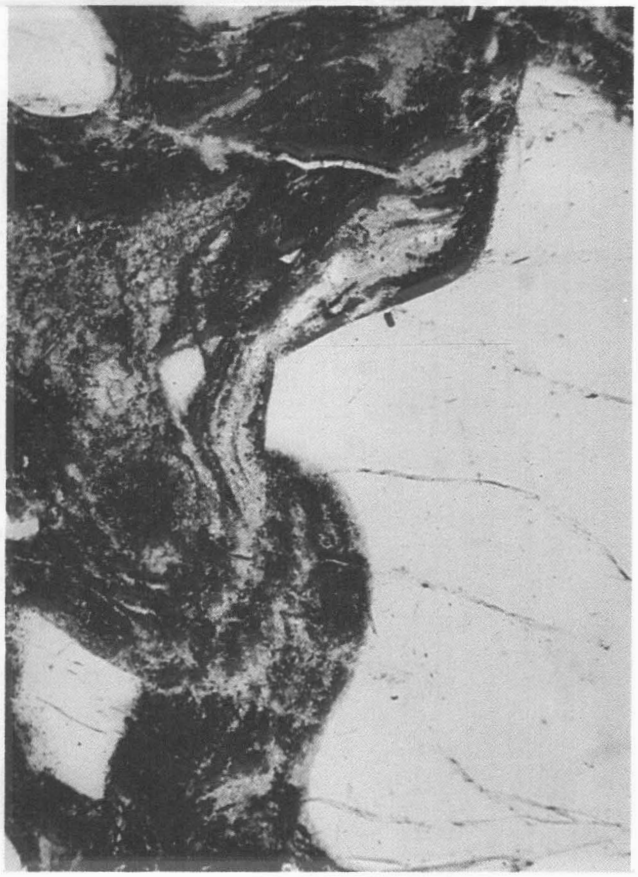
Pumice is abundant and typically constitutes 50 percent or more of the rock. In general, the larger pumice fragments in the ash flows reach maximum dimensions of 2 to 3 cm, but near the base of one ash-flow pumice blocks as large as 25 cm in length (fig. 31) occur.

A characteristic feature of the Tonopah Summit Member is the presence of moderately abundant lithic fragments ranging in size from 1 mm or less to large boulders several meters in diameter; fragments larger than 20 cm in size are uncommon. The lithic fragments are composed of a variety of Tertiary volcanic rocks, including volcanic rocks of the Mizpah Formation, welded tuffs, Mesozoic granitic rocks, and Paleozoic sedimentary and metamorphic rocks (fig. 31).

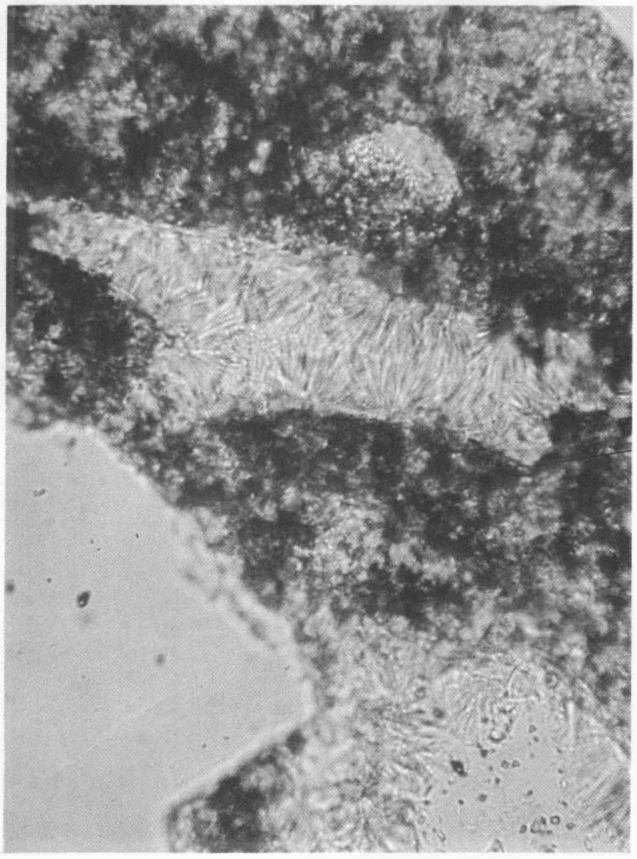
In areas where the tuff is zeolitized, it is typically light gray or pinkish gray. Hydrothermally altered phases of the tuff range from greenish gray in propylitized areas to orangish gray, very light gray and white in quartz-sericite alteration zones.

Coarse sedimentary breccia (Tftb) makes up the basal part of the Tonopah Summit Member at the northern edge of the Klondyke Hills. It is in fault contact with lower Paleozoic rocks, intruded by a rhyolite dome complex, and unconformably overlain by rhyolite flows and pyroclastic breccias.

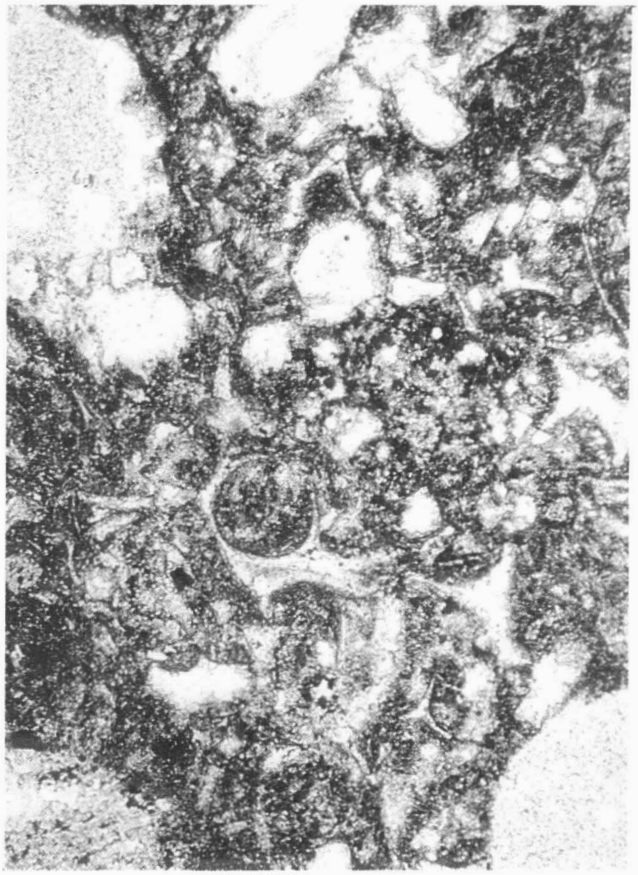
The breccia is composed of blocks up to 30 m in length, which consist predominantly of welded tuff of the tuffs of



A. Deformed shards adjacent to embayed margin of quartz phenocryst.



B. Shards replaced by mordenite.



C. Undeformed shards in nonwelded tuff.

FIGURE 29. Photomicrographs of the Tonopah Summit Member, Fraction Tuff.

Antelope Springs, and chert, argillite, and limestone of the Palmetto Formation, in a matrix of argillized tuff. We believe that the breccia probably originated as debris flows generated by caldera collapse associated with the eruption of the Tonopah Summit Member of the Fraction Tuff. We believe also that the fault contact between the breccia and the Paleozoic rocks in the Southern Klondyke Hills probably represents a remnant of the original caldera wall. Outcrops of the breccia are confined to the inner margin of the presumed caldera wall.

Hydrothermal Alteration

Within the mapped area, much of the Tonopah Summit Member has been hydrothermally altered. The unit is the chief host rock for the silver-gold deposits of the Divide district. The alteration in the tuff is zoned around mineralized fractures and fault zones, which range in width from a few centimeters to 30 m. The tuff in and immediately adjacent to the mineralized fractures and faults has been altered to quartz-sericite or quartz-sericite-adularia and contains small amounts of disseminated sulfides, chiefly pyrite. Phyllic and potassic alteration grades outward into a widespread propylitic alteration halo. Within the propylitic halo, biotite is chloritized; plagioclase is partially to completely altered to albite; and the groundmass is altered to illite, montmorillonite, quartz, and calcite.

King Tonopah Member (Tfku, Tfkub, Tfkl, Tfklb, Tfk, Tfbx). The King Tonopah Member of the Fraction Tuff is here named for exposures at the King Tonopah Mine 1.6

A. Concentration of pebbles and cobbles along contact between two ash flows.

B. Typical outcrop of poorly welded lithic-rich ash flow.

FIGURE 30. Tonopah Summit Member, Fraction Tuff.

km north of the town of Tonopah. The type locality of the member is in S24,25,T3N,R42E, and extends from the King Tonopah Mine 1.6 km in a northeasterly direction to the top of "TV Tower Hill" (pl. 1). The King Tonopah Member is composed of two simple cooling units of moderately to densely welded, vitric-lithic rhyolite tuff separated by a complete cooling break at the type locality. Thin lenses of epiclastic volcanic siltstone, sandstone, conglomerate, and breccia are present at the base of both cooling units and are included in the member. Excellent exposures of the lower ash-flow tuff of the King Tonopah Member also occur in S15,22,T3N,R42E, where the basal vitrophyre of the lower tuff rests on dacite flows of the Mizpah Formation. At the type locality, the lower ash-flow tuff of the member is in fault contact along the Halifax Fault with hydrothermally altered rocks of the Mizpah Formation.

Although the King Tonopah Member can be readily separated into two ash-flow tuff cooling units at the type locality (pl. 1), the two ash-flow tuffs are virtually identical in phenocryst mineralogy, lithic content, welding zonation, and in hand-specimen appearance. Because of this, it is extremely difficult to determine which ash-flow tuff is which in isolated outcrops or in fault blocks, where only one of the ash-flow tuff cooling units is present. Due to this practical difficulty of identification of the two cooling units in the field and the fact that their nearly identical petrographic characteristics and chemistry suggest a common eruptive source, both ash-flow cooling units have been included in the King Tonopah Member. It is quite probable that the two ash-flow tuffs of the King Tonopah Member could be separated by measurement of their remnant paleomagnetism in areas where the tuffs are not hydrothermally altered.

Distribution and Thickness

Neither of the ash-flow tuff cooling units of the King Tonopah Member are known to occur outside of the map area. The present areal distribution of the tuffs of the King Tonopah Member is centered around the Tonopah district (pl. 1). The tuffs of the King Tonopah Member are approximately 200 m thick in the area just south of the Tonopah district. They do not extend as far south as the Klondyke Hills, nor are they present in the San Antonio Mountains north of Red Mountain.

Lithology

Table 13 tabulates the results of thin-section modes of the lower and upper ash-flow tuffs of the King Tonopah Member. As can be seen in the table, the two ash-flow tuffs are nearly indistinguishable, although the upper tuff may have a slightly higher phenocryst content than the lower tuff. Sphene is a characterizing accessory mineral in both tuffs. Plagioclase (An_{20-30}) in both tuffs is usually oscillatory-zoned.

Phenocrysts rarely exceed 2 mm in dimension and are usually broken. Both plagioclase and alkali feldspar phenocrysts are corroded. Quartz is rare in most specimens; usually not more than 2 or 3 quartz phenocrysts are present in a thin section. The quartz phenocrysts contain vermicular inclusions of glass and are corroded slightly. Both hornblende and pyroxene are more abundant in vitrophyre than in devitrified tuff. Pyroxene is commonly nearly completely oxidized in devitrified tuff. The pyroxene is an apple-green diopsidic augite.

Both tuffs, where not hydrothermally altered, show excellent welding and devitrification zonation. Nonwelded to poorly welded tuff (fig. 32) at the base of the ash-flows grades upward within 2 m into hydrated vitrophyre, usually several meters thick which in turn grades upward into primarily devitrified, densely welded tuff (fig. 32) which is gradational into partially welded tuff of the vapor-phase zone. Where fresh, the densely welded and devitrified tuff is usually brownish gray. The vitrophyres are composed of black hydrated glass.

Lithic fragments are moderately abundant throughout the ash-flows, but large boulder-sized lithics up to 25 m long occur in the basal 20 m of the tuffs, and lithic fragments 2 to 3 m long are relatively common in the tuffs up to 40 m from the base. The lithic fragments include flow-banded rhyolite, Mizpah-like dacitic flow rock, granitics, welded tuffs, and a variety of Paleozoic sedimentary rocks including argillite, chert, limestone, and quartzite (fig. 33).

Large blocks of dacite of the Mizpah Formation occur in ash-flow tuff of the King Tonopah Member in S13,24,T2N, R42E about 4 km south of Tonopah. The blocks are as large as 400 m long and occur in brecciated, hematite-stained tuff. They are interpreted herein as large landslide blocks that slid into the tuff while it was still hot since densely welded tuff occurs above and below the blocks and

TABLE 11. Chemical analyses.

Sample	Fraction Tuff, Tonopah Summit Member			Fraction Tuff, King Tonopah Member		Heller Tuff
	T173 Propylitized rhyodacite	T148 Sericitic alteration rhyolite (hydrothermally altered)	T3G Zeolitized rhyolite	TONO IV* Rhyolite	SS25 Alkali rhyolite	T87 Quartz latite
Location	1	2	3	4	5	6
			Normalized oxide values			
SiO_2	64.2	71.6	75.1	75.7	75.4	68.0
Al_2O_3	18.9	17.4	13.2	12.7	13.4	16.4
Fe_2O_3	2.4	1.5	1.2	1.1	0.1	1.4
FeO	1.5	0.9	0.5	0.5	1.2	1.5
MgO	1.0	0.9	0.3	0.3	0.6	0.8
CaO	4.6	1.0	2.2	1.5	0.7	3.6
Na_2O	2.4	0.7	2.5	3.3	3.1	4.0
K_2O	4.4	5.5	4.8	4.7	5.3	3.7
TiO_2	0.5	0.4	0.3	0.2	0.2	0.6
MnO	0.05	0.06	0.01	0.03	0.03	0.03
			Normative minerals			
Quartz	21.7	42.9	37.4	35.2	33.6	21.8
Corundum	1.7	8.5	0.1		1.2	
Orthoclase	26.0	32.6	28.2	27.8	31.5	21.9
Albite	20.7	5.8	20.9	27.7	26.5	33.7
Anorthite	22.9	5.0	10.8	6.0	3.5	16.1
Diopside				1.2		1.3
Hypersthene	2.6	2.3	0.8	0.1	3.4	2.2
Magnetite	3.4	1.9	0.7	1.1	0.2	2.1
Hematite	0.1	0.2	0.7	0.4		
Ilmenite	1.0	0.8	0.6	0.4	0.3	1.1
Wollastonite (diopside)				0.7		0.7
Enstatite (diopside)				0.6		0.5
Ferrosilite (diopside)						0.2
Enstatite (hypersthene)	2.6	2.3	0.8	0.1	1.6	1.6
Ferrosilite (hypersthene)					1.9	0.6
			Petrologic indices			
Differentiation index	68.4	81.3	86.5	90.8	91.4	77.4
Felsic-mafic index	7.4	18.0	20.0	24.4	32.1	10.4

Locations: 1. C S11,T1N,R42E
2. SE/4 S3,T1N,R42E
3. SE/4 S12,T2N,R42E
4. S24,T3N,R42E
5. SW/4 S22,T3N,R42E
6. C S17,T2N,R42E

*Analyses by U. S. Geological Survey Rapid Rock Analysis Laboratory; L. Shapiro, project leader. Analysts, M. Smith and J. Glenn.

because some of the blocks are surrounded by a thin rind of vitrophyre.

Much of the tuff in the King Tonopah Member in the area south and east of Tonopah is weakly to pervasively brecciated (fig. 32). The brecciation is confined to the tuffs of the King Tonopah Member and does not affect underlying or overlying rocks. Brecciated portions of the tuffs are shown on plate 1. The breccia fragments commonly show little to no rotation and the degree of brecciation of the tuff is highly variable within a single outcrop. The interstices between the breccia fragments contain altered comminuted fragments of tuff surrounded and partially re-

TABLE 12. Modal data, Tonopah Summit Member, Fraction Tuff.

Phenocryst and lithic fragments as percentage of total rock. Tonopah Summit Member, Fraction Tuff.

	T42	T88	T149	T89	T3G
Groundmass	65.0	77	72.2	82.4	68
Lithics	15.4	11	10.1	9.7	17
Phenocrysts	19.6	12	17.7	8.0	15

Phenocryst mineralogy, Tonopah Summit Member, Fraction Tuff. [Phenocrysts as volume percent of total crystals.]

	T42	T88	T149	T89	T3G
Quartz	14.1	35	20.2	32.5	29
Alkali feldspar	29.5	27	26.7	33.8	27
Plagioclase	45.5	33	34.0	26.3	40
Biotite	8.6	5	6.7	6.3	4
Hornblende	1.4	Tr	Tr	Tr	Tr
Opaque	0.5	Tr	2.4	1.3	Tr

Locality Data

T42: NW/4 S11,T2N,R42E. T88: SE/4 S17,T2N,R42E. T149: S/2 S3,T1N,R42E. T89: SW/4 S1,T2N,R42E. T3G: SE/4 S12, T2N,R42E.

Accessory minerals include zircon, apatite, Fe-Ti oxides, and rare allanite.

All data were compiled from thin-section modes. Between 1,200–2,000 points were counted in each thin section.

placed by hematite. The brecciation occurred after the tuff was consolidated, but apparently while it was still hot. The abundant hematite in the breccia matrix appears to be the result of vapor phase transport of iron late in the cooling history of the tuff.

The cause of the widespread brecciation of the tuff is unclear, but since it does not appear to be tectonic and the brecciated tuff locally rests upon undisturbed sedimentary rocks, the brecciation is apparently related to the cooling history of the tuff. It is possible, in the areas where the brecciated tuff occurs, that the tuff was emplaced on water-saturated sediments and rocks. This would have produced substantial amounts of water vapor which would have streamed through the still hot tuff resulting in its brecciation. Iron and other elements extracted from the tuff by the water vapor would have been deposited in the interstices of the breccia.

The tuff of the King Tonopah Member is hydrothermally altered in both the Tonopah and Divide districts. Alteration of the tuffs ranges from propylitic to phyllic. The main area of relatively unaltered tuff in the King Tonopah Member occurs in the outcrops of the member located north and northwest of the Tonopah district. In this area the hydrothermal alteration of the tuff is confined to the Halifax Fault zone and its immediate vicinity.

Age of the Fraction Tuff. Reliable K-Ar ages on the two ash-flow tuffs of the King Tonopah Member are readily obtainable since fairly extensive areas of unaltered rock are present in the member. However, virtually all of the

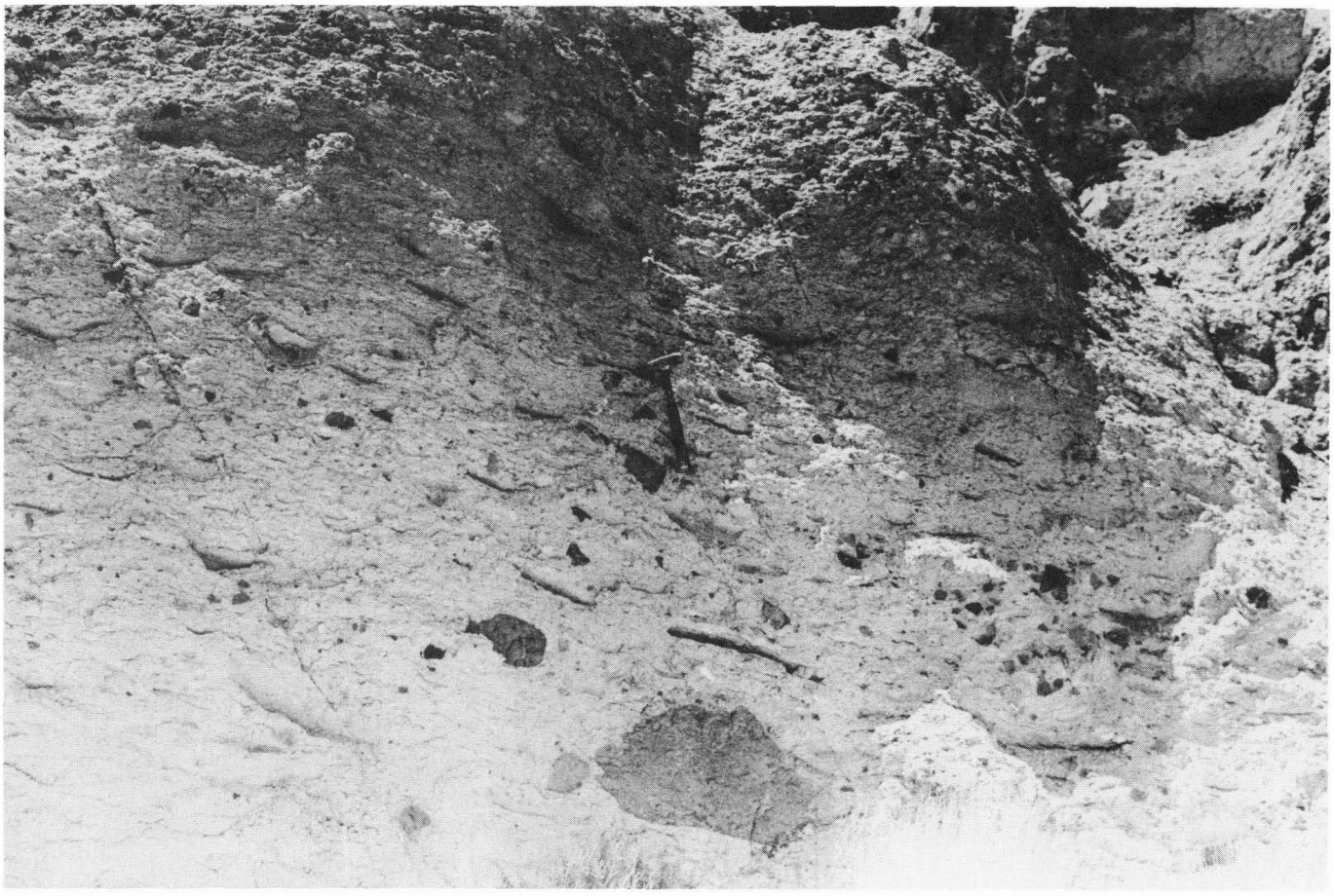


FIGURE 31. Tonopah Summit Member, Fraction Tuff. Large lithic and pumice blocks within 10 m of base.

TABLE 13. Modal data, King Tonopah Member, Fraction Tuff.

Phenocryst and lithic fragments as percentage of total rock. King Tonopah Member, Fraction Tuff, lower ash-flow tuff.

	TV2	SS25	T218B	T218A	T243B
Groundmass	87	68	83.3	87.3	79.7
Lithics	8	28	8.6	10.5	15.4
Phenocrysts	5	4	8.1	2.2	4.9

Phenocryst and lithic fragments as percentage of total rock. King Tonopah Member, Fraction Tuff, upper ash-flow tuff.

				Correlation uncertain	
	TV1	T244A	SS152	SS151	T243A
Groundmass	86	83	73.8	68	80.5
Lithics	6	11	18.1	27	14.5
Phenocrysts	9	6	8.1	5	5.0

Phenocryst mineralogy, King Tonopah Member, Fraction Tuff, lower ash-flow tuff.
[Phenocrysts as volume percent of total crystals.]

	TV2	SS25	T218B	T218A	T243B
Quartz	4	Tr	Tr	Tr	Tr
Alkali feldspar	19	9	16.0	31.8	30
Plagioclase	72	73	80.2	40.9	68
Biotite	1	7	Tr	9.1	2
Hornblende	3	11	1.2	4.5	Tr
Pyroxene	Tr	Tr	Tr	13.6	Tr
Opaque	Tr	Tr	2.5	Tr	Tr

Phenocryst mineralogy, King Tonopah Member, Fraction Tuff, upper ash-flow tuff.
[Phenocrysts as volume percent of total crystals.]

				Correlation uncertain	
	TV1	T244A	SS152	SS151	T243A
Quartz	1	Tr	6.2	Tr	14.5
Alkali feldspar	20	32.0	28.4	22.4	21.8
Plagioclase	70	56.5	63.0	73.5	58.2
Biotite	2	3.2	1.2	Tr	1.8
Hornblende	7	1.6	1.2	4.1	1.8
Pyroxene	Tr	6.5	Tr	Tr	Tr
Opaque	1	Tr	Tr	Tr	1.8

Locality Data

TV2 (vitrophyre): SE/4 S15,T3N,R42E. SS25 (vitrophyre): SW/4 S22,T3N,R42E. T218B: SE/4 S15,T3N,R42E. T218A: SE/4 S15,T3N,R42E. T243B: SE/4 S23,T3N,R42E. TV1 (vitrophyre): NW/4 SW/4 S24,T3N,R42E. T244A (vitrophyre): SW/4 S24,T3N,R42E. SS152: C S24,T3N,R42E. SS151: NE/4 S29,T3N,R43E. T243A: SE/4 S23,T3N,R42E.

Accessory minerals: sphene, zircon, apatite, Fe-Ti oxides, and rare allanite.

tuff of the Tonopah Summit Member has been either hydrothermally altered or subjected to secondary devitrification, and unaltered rock from this unit in the map area is not available.

The Tonopah Summit Member rests unconformably on 20.5-m.y.-old (table 4) volcanic flows and breccias of the Mizpah Formation, and is overlain unconformably by the upper cooling unit of the King Tonopah Member (18.7 m.y., table 4), the rocks of the Siebert Formation, and the Heller Tuff; it is intruded by the Oddie and Brougher Rhyolites. The Heller Tuff is approximately 17 m.y. old, and the Oddie and Brougher Rhyolites range in age from 16 to 17 m.y. (table 4).

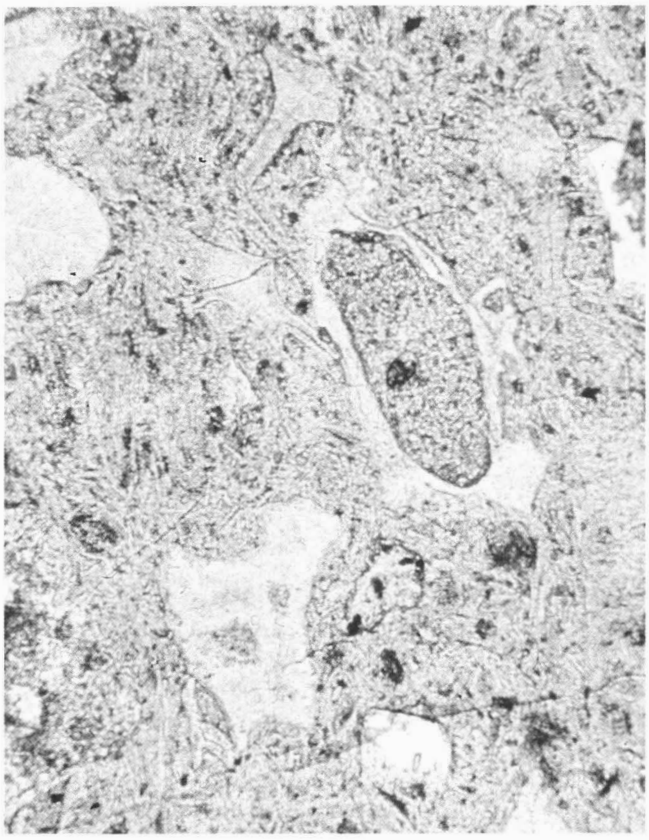
K-Ar ages of 17.3 and 16.8 m.y. on biotite and 16.2 m.y. on alkali feldspar and fission-track ages of 17.0 m.y. on zircon and 18.4 m.y. on apatite were obtained from tuff of the Tonopah Summit Member. The stratigraphic evidence cited above indicates that the Tonopah Summit Member is younger than 20.5 m.y., is almost certainly older than 17.0 m.y., and is probably older than 18.0 m.y. The K-Ar ages and the zircon fission track age are inconsistent with the age limits imposed by the known stratigraphic relationships. Although the tuffs of the Tonopah Summit Member selected for dating were the least altered obtainable, two of the samples were propylitically altered and the third was zeolitized. The younger radiometric ages reflect the age of hydrothermal alteration in the Divide district, approximately 16.5 m.y., rather than the age of emplacement of the ash-flow tuff of the Tonopah Summit Member.

The fission-track age of 18.4±3.1 m.y. on apatite is slightly younger than the 18.7 m.y. age of the upper cooling unit of the King Tonopah Member, which overlies the Tonopah Summit Member, but the error limits for the fission-track ages are sufficiently broad to fit the stratigraphic relationships. The available evidence indicates that the age of the Tonopah Summit Member is between 18 and 19 m.y.

The lower cooling unit of the King Tonopah Member yielded K-Ar ages of 19.6 m.y. on hydrated glass, 20.4 m.y., and 19.9 m.y. on alkali feldspar and 21.5 m.y. on biotite. The average age of the four samples is 20.45 m.y. Because the lower tuff of the King Tonopah Member unconformably overlies the Mizpah Formation (20.5 m.y.) an age of about 20 m.y. for the lower tuff is geologically reasonable.

A single K-Ar age of 18.7 m.y. on alkali feldspar (table 4) was obtained from the upper ash-flow tuff of the King Tonopah Member. This age is probably accurate because the upper ash-flow tuff overlies rocks approximately 20 m.y. old and is overlain by rocks approximately 17 m.y. old (Heller Tuff).

The problem of the stratigraphic relationship between the lower ash-flow tuff of the King Tonopah Member and the tuff of the Tonopah Summit Member was not fully resolved in this study. It is clear that at least the upper ash-flow tuff of the King Tonopah Member is younger than the tuff of the Tonopah Summit Member since ash-flow tuff, which is clearly part of the King Tonopah Member, unconformably overlies the Tonopah Summit Member in a number of localities in the Tonopah and Divide districts. However, since there is an approximate hiatus of 1 m.y. between the emplacement of the lower and upper ash-flow tuffs of the King Tonopah Member, it is possible that the ash-flow tuff of the Tonopah Summit Member was emplaced in that interval. The lower tuff of the King Tonopah Member and the tuff of the Tonopah Summit Member are in contact at several localities north and northwest of the Tonopah district, but the contact relationships between the two ash-flow tuffs are equivocal in every out-



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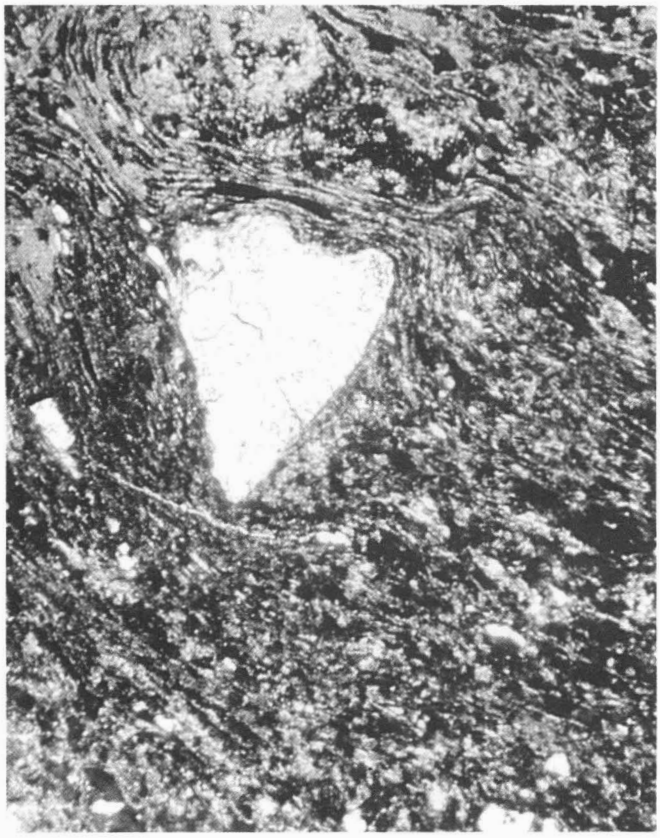
A. Shards in slightly welded tuff.



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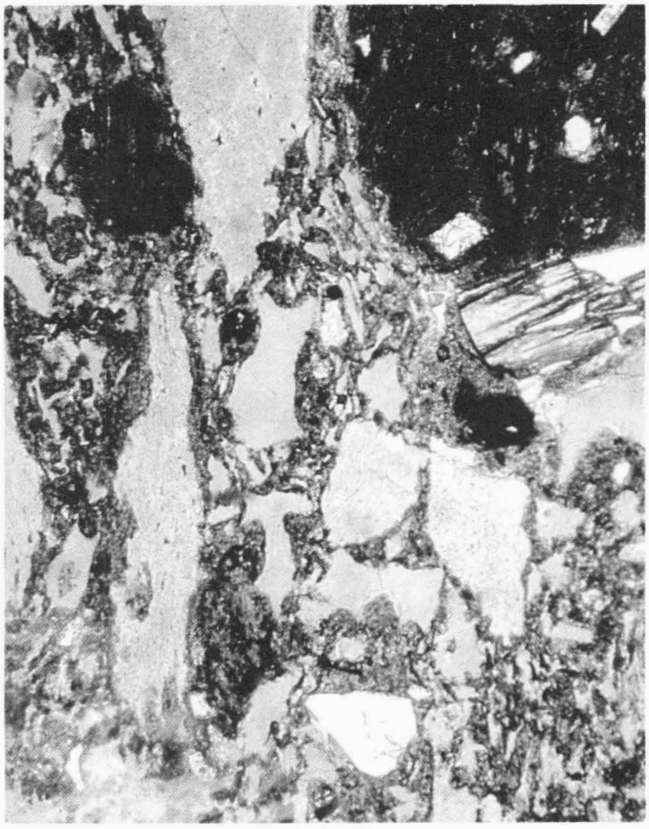
C. Highly welded shards in zone of devitrification. Note molding of shards around phenocryst and lithic fragment.



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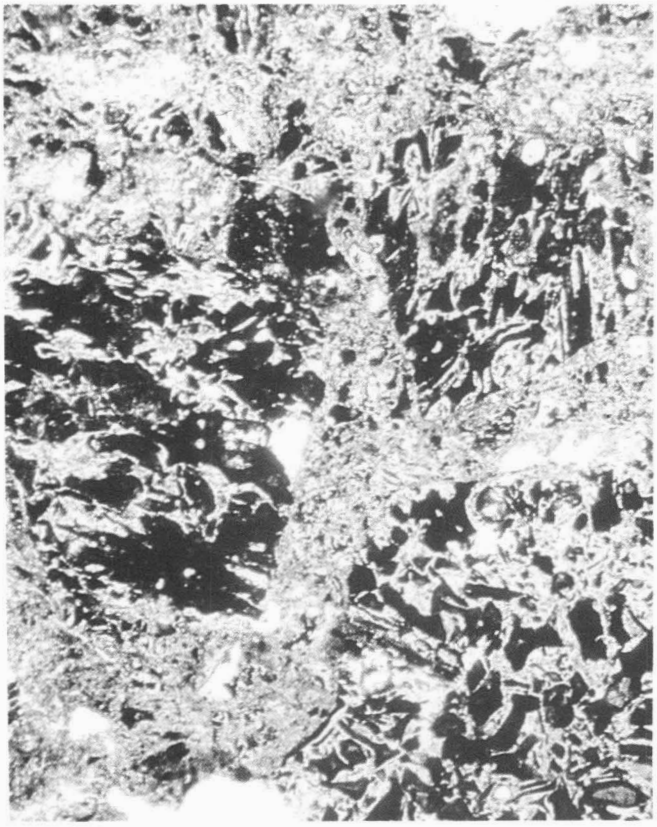
B. Highly welded shards and pumice in vitrophyre. Two lithic fragments, plagioclase and pyroxene phenocrysts.



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D. Brecciated tuff. Note shards in breccia fragments.

FIGURE 32. Photomicrographs of the King Tonopah Member, Fraction Tuff.

A. Upper cooling unit, King Tonopah Member. Low rounded hills in foreground are ash-flow tuff of upper cooling unit. Tonopah in distance. Rugged hills in distance are composed of Oddie Rhyolite and Brougher Rhyolite.

B. Boulders in lower 10 m of lower unit, King Tonopah Member.

C. Boulder of Mizpah dacite in densely welded tuff near base of lower cooling unit of King Tonopah Member.

FIGURE 33. King Tonopah Member, Fraction Tuff.

crop examined. The available radiometric evidence indicates that the Tonopah Summit Member is younger than the lower cooling unit of the King Tonopah Member and was emplaced during the hiatus between the eruption of the two cooling units of the King Tonopah Member.

Source area of the Fraction Tuff. Ekren and others (1971, p. 72) have correlated over 2,100 m of ash-flow tuff in the Kawich Range with the Fraction Tuff of the Tonopah area, and have identified the source of this thick section of tuff in the Kawich Range as the Cathedral Ridge caldera, also in the Kawich Range. We do not believe, however, that any of the Fraction Tuff at Tonopah (as herein redefined), is correlative with the Fraction Tuff of Ekren and others (1971) in the Kawich Range. A comparison of their modal data (Ekren and others, 1971, p. 53) on the Kawich Range Tuffs with the modal data on the Fraction Tuff from the Tonopah area shown in this report strongly suggests that the two sequences of tuffs are not correlative. Secondly, Ekren and others (1971, p. 28) report K-Ar ages of 15.0, 17.8, 15.7, and 16.4 m.y. from the tuffs in the Belted, Kawich, and Cactus Ranges that they correlate with the Fraction Tuff of the Tonopah area, but it is now known that the Fraction Tuff at Tonopah is between 20.5 and 18.0 m.y. old. Both the lack of correlation between the modal data and the differences in age clearly indicate that the tuffs Ekren and others (1971) called Fraction Tuff are not equivalent to the Fraction Tuff in the type area. It also means that the source of the Fraction Tuff in the Tonopah area is not the Cathedral Ridge caldera.

The eruptive source for the Fraction Tuff has not been positively identified. The outcrop pattern of the Fraction Tuff (pl. 1) suggests that the source of the ash flows was somewhere in the area of the Tonopah and Divide districts. The abundant and large lithic fragments in the tuffs of the Fraction also suggest that the tuffs are near their eruptive source. The large blocks of dacite of the Mizpah Formation in the tuff of the King Tonopah Member could well represent landslide blocks from a caldera margin. The fact that the ash-flow tuffs of the Tonopah Summit Member are over 420 m thick in the Divide district and thin markedly away from this area also suggests that the source for the ash flows of this member was located in the vicinity of the Divide district.

We believe that a remnant of caldera wall related to the eruption of the Tonopah Summit Member of the Fraction Tuff may be preserved at the southern margin of the Southern Klondyke Hills, where coarse breccias, which we interpret as debris flows related to caldera collapse, occur in the basal portion of the Tonopah Summit Member and are in fault contact with Paleozoic rocks and the tuffs of Antelope Springs. The northern margin of the proposed caldera would be located along the southern edge of the Tonopah district in the vicinity of Mount Butler and Brougher Mountain. The eastern and western margins of the presumed caldera are concealed beneath the Quaternary alluvium of Ralston and Montezuma Valleys.

The intrusive rocks of the Oddie Rhyolite and the Divide Andesite, the domes and flows of the Brougher Rhyolite, and the intrusive rocks of the Donovan Peak vent complex define a crude arcuate pattern (pl. 1) in the Tonopah and Divide districts, and it is possible that they were emplaced in part along ring fractures related to the extrusion of the Fraction Tuff. Since the intrusive rocks of the Oddie Rhyolite, Divide Andesite, and Donovan Peak vent complex and the domes and flows of the Brougher range in age from about 15 m.y. to 17 m.y., they would seem to be too young to be related to the magma which produced the eruptions of the Fraction Tuff.

These intrusives and domes could have been emplaced along the same crustal structures which guided the emplacement of the magma responsible for the Fraction Tuff

eruptions. Recurrent magmatic activity over a period of millions of years in a particular area or zone characterizes many areas of vulcanism and has certainly occurred in the Tonopah area. Lipman (1975, p. 109–110) has recently documented a sequence of postcollapse vulcanism spanning 10 million years around the margins of the Summitville caldera in the San Juan Mountains of Colorado. It is reasonable to assume that similar posteruptive volcanic activity occurred around the margins of the eruptive center for the Fraction Tuff. The lack of any deep dissection of the Tertiary section in the Tonopah and Divide areas, however, effectively conceals most of the internal and marginal structures that could be definitely related to the caldera source for the Fraction Tuff.

Relationship of Fraction Tuff to age of mineralization, Tonopah district. The Fraction Breccia was long assumed to be of postmineralization age in the Tonopah district. Bastin and Laney (1918, p. 31–32) describe one locality in the West End Mine where Fraction "Dacite Breccia" apparently unconformably overlies the West End vein. Nolan (1935, p. 27) also stated that Fraction Breccia unconformably overlies the Tonopah veins.

However, the Fraction Tuff, as herein redefined, is largely, if not entirely, preore in age in the Tonopah district. This is indicated by the ages of the various units of the Fraction Tuff as compared to the age of mineralization in the Tonopah district. The mineralization at Tonopah, according to K-Ar dates on vein adularia, and a whole rock sample of quartz-sericite-adularia-altered Mizpah dacite (table 4) occurred between 18.1 and 19.1 m.y. ago. The Fraction Tuff was deposited between 18.0 and 20.5 m.y. ago.

The youngest ash-flow tuff in the Fraction Tuff, the upper ash flow of the King Tonopah Member, has a K-Ar age of 18.7 m.y., which is virtually identical to the age of the Tonopah mineralization.

The obvious question that arises as a result of the conclusion that most of the Fraction Tuff is preore in the Tonopah district is how to explain the observations of Bastin and Laney (1918) and Nolan (1935) that indicate that the Fraction is postore. Much of the problem can be resolved by realizing that until now, there has never been any rigorous definition as to which rock units were included in the term Fraction. Various workers have included such rock units as the Heller Tuff (Heller Dacite of Spurr, 1905b) and the basal sedimentary breccias of the Siebert Formation in the Fraction. Both of these rock units are, in fact, post-main-stage, vein-silver mineralization in the Tonopah district. Thus, most, if not all, of the examples cited of Fractionlike rocks unconformably overlying mineralized veins in the Tonopah district can be ascribed to either the basal breccias of the Siebert or the Heller Tuff.

The present distribution of the Fraction Tuff in the Tonopah district is such that there are no outcrops of the Fraction in the area where the productive portions of veins in the Tonopah district crop out. In the areas where the Fraction Tuff overlies rocks of Mizpah Formation in which productive veins are present, the productive portion of the veins apparently did not extend up to the contact between the Mizpah Formation and the Fraction Tuff.

The Fraction Tuff is hydrothermally altered in the Tonopah district, as pointed out by Campbell (*in* Nolan, 1935, p. 27). However, rocks as young as the Oddie Rhyolite are hydrothermally altered and contain gold-silver mineralization at Tonopah, so hydrothermal alteration cannot be used as a simplistic guide at Tonopah to determine whether the rocks are pre- or post-main-stage silver mineralization in the district.

Rhyolite of the Cleft (Trc, Trct)

The rhyolite domes and associated pyroclastic deposits present in T4,5N,R42,43E in the north-central portion of the map area are named the rhyolite of the Cleft after a prominent vertical walled canyon (fig. 34) cut through one of the domes (pl. 1). The rhyolite of the Cleft is unconformably overlain by lava flows and volcaniclastic rocks of the volcanics of Lime Mountain and by sedimentary rocks of the Siebert Formation. The base of the unit is not exposed within the map area.

The rhyolite of the Cleft consists of two map units: massive rhyolite ash-fall tuff and rhyolite domes. The rhyolite domes were emplaced in the vents from which the pyroclastic rocks were erupted. The pyroclastic rocks crop out around the margins of the domes and form tuff rings (fig. 34). The rhyolite tuff is light gray, usually massive, and contains sparse phenocrysts of quartz, plagioclase, alkali feldspar, and minor biotite in a matrix of ash and pumice lapilli which is often altered to clinoptilolite. Pyroclastic

A. Vent-dome complex of the rhyolite of the Cleft. Vertical walled canyon cut in the rhyolite. Light-colored rocks are massive ash-fall tuffs which form a tuff ring around the rhyolite dome.

B. Massive rhyolite ash-fall tuff forming a tuff ring peripheral to a dome in the rhyolite of the Cleft.

FIGURE 34. Rhyolite of the Cleft.

breccias and surge deposits occur interlayered with the rhyolite ash-fall tuff.

The rhyolite domes consist of partially devitrified, perlitic glass containing 5 percent or less phenocrysts. The rhyolite is flow banded on a scale of 1 mm or less up to several centimeters. It is brownish gray where devitrified and light gray where still glassy. The devitrified rhyolite contains abundant spherulite trains parallel to flow banding. The spherulites consist of fibrous cristobalite and alkali feldspar. Spherulites up to several centimeters in diameter, usually nucleated around a phenocryst, also occur as devitrification products in perlitic glass.

The rhyolite, which forms most of the domes, contains phenocrysts of quartz, alkali feldspar, plagioclase, and minor biotite; in two domes plagioclase and biotite are the only phenocrysts present in the rhyolite. Oscillatory-zoned plagioclase (An_{25-30}) commonly occurs in glomeroporphyritic clusters and is corroded. Phenocrysts are corroded and are frequently "wormy." Devitrified rhyolite is microvesicular and contains vapor phase tridymite and hematite in gas cavities. Fine-grained calcite is also present in the matrix of devitrified rhyolite.

A chemical analysis of the rhyolite of the Cleft (table 14) shows that it is an alkali rhyolite. Alkali feldspar from the rhyolite of the Cleft has been dated (table 4) by the potassium-argon method at 18.9 m.y.

TABLE 14. Chemical analyses, rhyolite of the Cleft.

Sample	T90 Alkali rhyolite	T100A Alkali rhyolite
Location	1	2
	Normalized oxide values	
SiO_2	76.8	73.8
Al_2O_3	12.1	14.6
Fe_2O_3	0.2	0.5
FeO	0.4	0.5
MgO	0.2	0.3
CaO	1.9	0.9
Na_2O	3.3	3.8
K_2O	5.1	5.3
TiO_2	0.1	0.3
MnO	0.01	0.05
	Normative minerals	
Quartz	35.0	29.3
Corundum		1.0
Orthoclase	30.1	31.3
Albite	28.0	31.7
Anorthite	3.0	4.5
Wollastonite	1.8	
Diopside	1.8	
Hypersthene		1.0
Magnetite	0.3	0.7
Hematite		
Ilmenite	0.2	0.5
Wollastonite (diopside)	0.9	
Enstatite (diopside)	0.5	
Ferrosilite (diopside)	0.4	
Enstatite (hypersthene)		0.8
Ferrosilite (hypersthene)	0.2	0.2
	Petrologic indices	
Differentiation index	93.1	92.3
Felsic-mafic index	32.5	37.2

Locations: 1. Hill 6276, T4N,R42E
2. NE/4 T4N,R42E (outcrop in canyon)

Heller Tuff (Tht)

This rock unit was originally named the Heller Dacite by Spurr (1905b, p. 37–38) for rocks present at the type locality on Heller Butte (NE/4 S2,T2N,R42E). Spurr thought that the rock was a dacite lava flow. Subsequent workers in the Tonopah district have included this rock unit in the Fraction Tuff. The name, Heller Dacite, is here modified to Heller Tuff because our mapping of the rock at its type locality reveals that it is entirely quartz latite ash-flow tuff.

Distribution and thickness. The Heller Tuff has a total outcrop area of about 1 km^2 within the map area. The principal outcrop areas are Heller Butte in the Tonopah district and the north and east flanks of Mount Butte in the western part of the Divide district. The Heller Tuff has a maximum exposed thickness of about 90 m at Heller Butte. It rests unconformably upon the Tonopah Summit and King Tonopah Members of the Fraction Tuff and is unconformably overlain by rocks of the Siebert Formation at Heller Butte and Mount Butte.

Lithology. The Heller Tuff is a simple ash-flow cooling unit of quartz latite crystal-vitric tuff. The Heller Tuff is typically pale red and moderately to densely welded and contains abundant flattened pumice up to 2 cm in length and prominent black shiny biotite, which is parallel to the compaction foliation.

Typically the base of the Heller Tuff is marked by 1 m or less of poorly welded gray tuff which grades upward into 3 to 4 m of densely welded black vitrophyre, which in turn changes abruptly upward into moderately to densely welded primarily devitrified tuff. The Heller Tuff is nearly always fresh and unaltered. Phenocrysts compose about 40 percent of the rock where densely welded and lithic fragments 8 to 10 percent. The phenocrysts consist of 20 percent quartz, 10 to 11 percent alkali feldspar, 53 percent plagioclase (An_{30}), 12 percent biotite, 2 percent Fe-Ti oxides, and 2 percent hornblende. Apatite and zircon are minor accessory minerals. Both the quartz and plagioclase phenocrysts are as much as 2.5 mm in diameter. Alkali feldspar reaches 3 mm in diameter and biotite as much as 1.5 mm.

Lithic fragments make up about 8 percent of the tuff and normally do not exceed a few centimeters in diameter. They consist of granitic rocks, spherulitic rhyolite, and intermediate volcanic rocks.

The Heller Tuff is readily distinguished from either member of the Fraction Tuff by its significantly higher phenocryst content and by the abundant biotite, which is characteristic of this unit (fig. 35).

0.2mm

FIGURE 35. Photomicrographs of the Heller Tuff. Phenocrysts of vermicular quartz, alkali feldspar, plagioclase, biotite, and hornblende.

Chemical analyses of the Heller Tuff (table 11) indicate that the rock is a quartz latite.

Alkali feldspar from the Heller Tuff yielded a potassium-argon age of 16.9 m.y. and biotite from the tuff a potassium-argon age of 17.1 m.y. These ages are in accordance with the stratigraphic position of the Heller Tuff, which unconformably overlies the Fraction Tuff and is unconformably overlain by the Siebert Formation.

Source and correlation. The source of the Heller Tuff is unknown. The Heller Tuff is similar in phenocryst percentage and composition to some of the ash-flow tuffs in the Cactus and Kawich Ranges mapped as Fraction Tuff by Ekren and others (1971, p. 53).

Volcanics of Lime Mountain (Tlmi, Tlma, Tlms, Tlm)

A sequence of intermediate composition flows and intercalated sedimentary lenses, vent agglomerate and breccia, and an associated intrusive plug, located just north of the old townsite of Rays in T4N,R42E, is herein informally named the volcanics of Lime Mountain. These rocks represent the eroded remnants of a stratovolcano that originally covered an area of at least 65 km^2. The intrusive core of the volcano and its associated vent agglomerate and breccia are well exposed along the northwest boundary of the mapped area (pl. 1). The Lime Mountain volcano was constructed upon an eroded dome complex of the rhyolite of the Cleft.

The volcanics of Lime Mountain unconformably overlie rocks of the Tonopah Formation and the rhyolite of the Cleft. They are in fault contact with Paleozoic rocks in the vicinity of Rays and are overlain unconformably by fluvatile and lacustrine sedimentary rocks of the Siebert Formation, which lap up on an erosion surface cut on the volcanics of Lime Mountain. The volcanics of Lime Mountain are intruded by domes of Brougher Rhyolite. The trachyandesite of Red Mountain unconformably overlies the volcanics of Lime Mountain along their eastern margin.

Lithology and Chemistry. Eight chemical analyses of the Lime Mountain rocks (table 15) show that they are dominantly trachyandesite in composition. Dacite, rhyodacite, and latite flows also occur in the sequence, but are distinctly subordinate volumetrically to the trachyandesite lavas. Figure 61B (p. 90) is a differentiation index diagram on which the chemical analyses of the volcanics of Lime Mountain are plotted as well as several of Nockolds' (1954) average extrusive rocks. Three of the analyses are close to Nockolds' average trachyandesite, while five of the analyses are about halfway between average dacite and the average trachyandesite. These five rocks have approximately the same differentiation index as Nockolds' average dacite (61–62), but all five have lower silica contents than his average dacite.

The vent agglomerate and breccia consist of subangular to rounded blocks and bombs of scoriaceous medium-dark-gray to grayish-red pyroxene trachyandesite in a matrix of ash. The bombs and breccia fragments are predominantly aphyric and contain 0.1 to 0.3 mm crystals of plagioclase and pyroxene in a matrix of pale-brown glass. Fe-Ti oxides and apatite are accessory minerals.

The vent agglomerate and breccia unit is intruded by a subequant plug about 2 km across of porphyritic hornblende-biotite trachyandesite. The plug contains phenocrysts of hornblende and oscillatory zoned plagioclase (An_{50-60}) (up to 3 mm in long dimension) in a fine-grained matrix of plagioclase, hornblende, sparse biotite, potassium feldspar, and cristobalite. The hornblende is surrounded by reaction rims of pyroxene and magnetite. The potassium feldspar occurs associated with cristobalite, interstitial to plagioclase and hornblende. Apatite and Fe-Ti oxides are accessory minerals.

The lava flow unit in the volcanics of Lime Mountain can be subdivided megascopically into three types: (1) a fine-grained nonporphyritic group of flows, commonly exhibiting platy flow jointing; (2) porphyritic lava flows which contain 1 to 3 mm phenocrysts of plagioclase and pyroxene; (3) porphyritic lava flows that contain phenocrysts of oxyhornblende up to 5 cm long.

Many of the flows that do not contain megascopic phenocrysts are microporphyritic with abundant microphenocrysts 0.1 to 0.5 mm in diameter in a fine-grained (<0.1 mm) groundmass. Table 16 shows the typical phenocryst mineralogy of representative lava flows in the volcanics of Lime Mountain. The phenocrysts are set in a groundmass of plagioclase and pyroxene microlites, anhedral potassium feldspar, Fe-Ti oxides, and tridymite or cristobalite. Some samples also contain granules of olivine and/or hornblende in the matrix. Apatite crystals up to 1 mm long are present in all of the flows, and sphene is present in a few flows. Plagioclase phenocrysts are oscillatory-zoned and have an average composition of

TABLE 15. Chemical analyses, volcanics of Lime Mountain.

Sample	T95A Trachyandesite	T91 Trachyandesite	T94C Trachyandesite	Vent agglomerate T101A Trachyandesite	Intrusive plug R101B Trachyandesite	T132 Latite	T125 Latite	T118 Rhyodacite	T117 Dacite
Location number	1	2	3	4	5	6	7	8	9
Normalized oxide values									
SiO_2	55.8	59.2	56.3	57.3	60.2	58.8	56.4	62.4	59.8
Al_2O_3	18.1	17.9	16.9	16.3	16.7	19.3	18.1	19.3	19.7
Fe_2O_3	5.7	5.3	6.6	7.7	4.7	5.7	7.5	2.6	1.1
FeO	1.2	1.1	1.1	1.1	1.6	0.9	0.5	1.5	5.4
MgO	3.1	2.2	3.7	3.0	3.2	1.2	2.1	0.4	0.5
CaO	9.8	6.5	8.3	7.1	6.1	6.5	5.1	5.0	5.4
Na_2O	3.5	4.7	3.5	3.4	3.9	4.1	4.2	4.0	4.2
K_2O	1.6	2.8	2.5	2.9	2.7	2.5	4.6	3.5	3.8
TiO_2	1.0	0.9	1.0	1.3	0.9	1.0	1.3	1.2	1.2
MnO	0.17	0.10	0.14	0.10	0.06	0.05	0.09	0.01	0.03
Normative minerals									
Quartz	7.8	9.5	6.8	10.5	11.2	10.6	2.0	14.3	5.7
Orthoclase	9.5	16.4	14.8	15.9	16.2	14.7	27.4	20.9	22.4
Albite	29.9	35.2	29.9	28.7	33.2	34.9	35.5	34.0	35.1
Anorthite	28.8	21.9	23.0	21.4	19.8	26.6	17.0	24.2	24.0
Diopside	15.4	8.0	14.1	10.7	8.3	4.5	5.0	0.4	2.6
Hypersthene	0.6	1.8	2.8	2.6	4.2	1.0	3.9	0.9	8.0
Magnetite	1.6	1.3	1.1		2.7	0.2		1.4	
Hematite	4.6	4.4	5.8	7.7	2.8	5.5	7.5	1.6	
Ilmenite	1.9	1.7	1.8	2.4	1.7	1.9	1.3	2.2	2.3
Wollastonite (diopside)	8.3	4.3	7.6	5.7	4.4	2.4	2.7	0.2	1.2
Enstatite (diopside)	7.1	3.7	6.5	5.0	3.8	2.1	2.3	0.2	0.9
Derrosilite (diopside)	1.2								1.2
Enstatite (hypersthene)	1.1	1.8	2.8	2.6	4.2	1.0	2.9	0.9	1.1
Ferrosilite (hypersthene)	6.9								6.9
Petrologic indices									
Differentiation index	47.2	61.0	51.5	55.1	60.6	60.3	64.9	63.2	63.2
Felsic-mafic index	3.1	4.4	3.2	3.4	4.3	4.6	4.3	6.1	6.1

Locations:
1. 1 km south of the Cleft
2. Hill 6276, T4N,R42E
3. In canyon 2 km SW of the Cleft
4. T5N,R42E, 2.5 km ENE of the Cleft
5. T5N,R42E, 2 km ENE of the Cleft
6. T4N,R42E, 1.5 km NE of the Cleft
7. T4N,R42E, in canyon 2 km W of Rays Wells
8. T4N,R42E, 2 km W of Rhyolite Peak
9. In canyon 2 km W of Rhyolite Peak

TABLE 16. Phenocryst mineralogy, volcanics of Lime Mountain.

[Phenocrysts as percentage of total rock. Numbers in parentheses refer to phenocrysts recalculated to 100 percent. Phenocrysts and microphenocrysts > .1 mm in diameter.]

	T94A		T94B	
Groundmass	63.0		60.0	
Plagioclase	21.7	(58.8)	24.7	(62.6)
Hornblende	7.1	(19.3)	6.9	(17.5)
Pyroxene	5.4	(14.7)	6.2	(15.7)
Olivine	1.0	(2.7)	1.5	(3.7)
Opaques	1.7	(4.5)	0.2	(0.5)
	T95A		**T96**	
Groundmass	55.5		53.1	
Plagioclase	23.5	(52.9)	31.4	(66.8)
Hornblende	17.1	(38.4)		
Pyroxene	2.4	(5.3)	7.3	(15.6)
Olivine			6.0	(12.9)
Opaques	1.5	(3.3)	2.2	(4.8)

An_{60-70}. The matrix plagioclase has an average composition of An_{50-60}. The oxyhornblende is commonly rimmed by Fe-Ti oxides and in many samples is completely replaced by Fe-Ti oxides. Typical textures are pilotaxitic to intergranular (fig. 36).

Olivine is invariably partially to completely altered to serpentine minerals. Chlorite, celadonite and more rarely montmorillonite and calcite occur as replacement minerals in the devitrified groundmass of the flows. Some flows display alteration of pyroxene to chlorite. Plagioclase is usually unaltered; in some flows plagioclase is partially replaced by calcite. The alteration minerals appear to be the result of deuteric alteration coupled with alteration produced by ground-water migration through the flows. None of the flows exhibits any obvious alteration related to hydrothermal fluids.

The volcanics of Lime Mountain are younger than the rhyolite of the Cleft (18.9 m.y.) and older than the Siebert Formation. A Barstovian (17 to 12-m.y.) fauna (Henshaw, 1942) occurs in fluvial sedimentary rocks of the Siebert Formation approximately 25 m above the unconformity between the Siebert and the volcanics of Lime Mountain. The trachyandesite of Red Mountain dated at 14.7 m.y. also overlies the volcanics of Lime Mountain unconformably. Table 4 lists six K-Ar dates from lava flows of the Lime Mountain sequence. Three of these dates, 9.7. 10.0, and 13.5 m.y., are believed to be too young on the basis of the preceding discussion. The remaining three dates, 15.8, 15.7, and 16.8 m.y., are clearly in accord with the ages of the overlying and underlying rocks and are believed to indicate the true age of the volcanics of Lime Mountain, which would be approximately 16 m.y.

Siebert Formation (Tsti, Tst, Ts, Tsb)

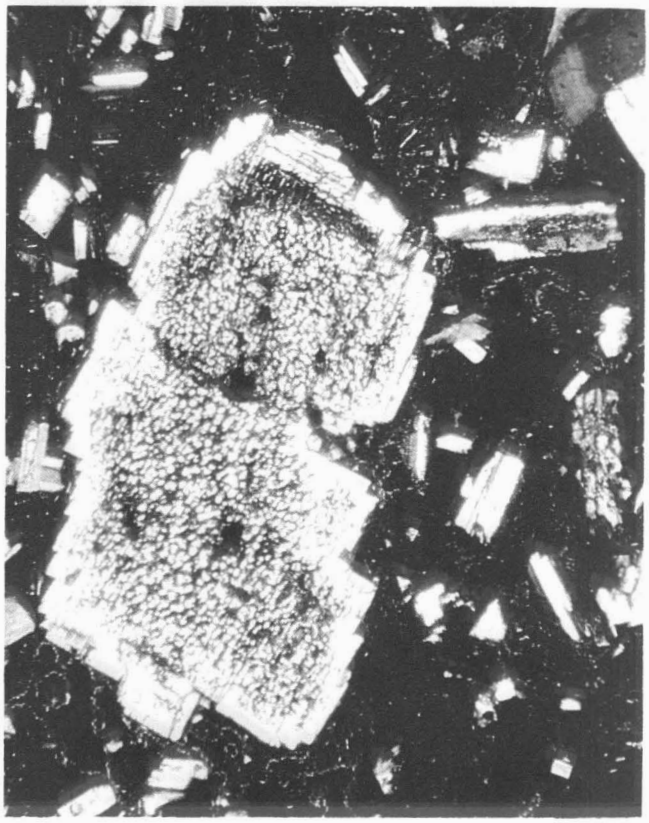
The Siebert Tuff was named by Spurr (1905b) for over 180 m of well-bedded white tuffs exposed on the east side of Siebert Mountain, just southwest of Tonopah. Ball (1907) applied the name to a variety of volcanic rocks and lacustrine deposits in west-central Nevada and eastern California. Ransome (1907, 1909) extended the usage of the name Siebert to sedimentary rocks at Goldfield, and Knopf (1921) correlated sedimentary rocks at Divide with the Siebert, which he believed to be intercalated with the Fraction Breccia (Fraction Tuff of this report). Ransome (1909 was the first to correlate the Siebert with the Esmeralda Formation (Turner, 1900a, b). Spurr (1905b) noted the similarity of sedimentary units exposed in the San Antonio Range near Rays (east of Crescent Dunes) to the Esmeralda, but he believed the Siebert to be the older of the two on the basis of fossil evidence. Ferguson (1924) included both the Fraction Breccia and the Siebert Tuff in the Esmeralda Formation and Nolan (1935) and Broderick (1949) followed this usage. Robinson and others (1968) have designated the type area of the Esmeralda Formation in the southwestern Weepah Hills about 30 km west of Tonopah, and Albers and Stewart (1972) restrict its use to that area. The restricted Esmeralda Formation in the Silver Peak area is probably not correlative with the Siebert Formation, as Robinson and others (1968) report that the oldest reliably dated rocks in the Esmeralda Formation are 13.1 m.y.; our work at Tonopah indicates that the Siebert is 13 to 17 m.y. (see the following section on the age of the Siebert). Ransome (1909) was the first to apply the more general term "formation" to the Siebert at Goldfield, and we follow that usage here. The varied lithology of the unit almost requires the use of a nonlithologic designation; therefore, we herein recommend that the name Siebert Formation be applied to the rocks called the Siebert Tuff by Spurr (1905b) and to related rocks described in this report.

The Siebert Formation is exposed throughout the San Antonio Mountains at the northeast end of Lone Mountain (pl. 1), and in the Goldfield Hills just to the south of the mapped area. The Siebert usually forms low, rounded hills or occurs as inliers on pediment surfaces. Where exposed in an area of more rugged topography, the hilltops are most often covered by protective flows of trachyandesite or rhyolite. Prominent cuestas of Siebert are present southeast of Crescent Dunes, at the northern edge of the mapped area.

Lithology and stratigraphy. The Siebert Formation contains a wide variety of sedimentary and pyroclastic rocks, plus a few interbedded trachyandesite flows and dikes. The bulk of the formation includes fluvatile and lacustrine epiclastic volcanic conglomerate, sandstone, siltstone, and lesser amounts of subaerially and subaqueously deposited tuff. Algal limestone is an important part of the section in the vicinity of the Crescent Dunes, and arkosic sandstone and conglomerate (derived from granitic rock) are present at the northeast margin of Lone Mountain. The formation lies unconformably on several different rock units, especially the various units of the Fraction Tuff, the Mizpah Formation, and the volcanics of Lime Mountain. The basal sedimentary beds of the Siebert in some areas were derived from the erosion of the underlying rock units, although in other areas tuffaceous shales often lie directly on older volcanic rocks with no basal conglomerate or indication that any portion of the Siebert was derived from the underlying rocks. Compaction of shales over buried hills has sometimes resulted in supratenuous folds. Onlap deposition around the hills, plus the deposition of thicker units away from the hills may accentuate the dips on the flanks of these folds.

.2mm

A. Phenocrysts of hornblende with oxidized rims. Smaller phenocryst of plagioclase and augite in an intergranular matrix of plagioclase, augite, Fe-Ti oxides, and apatite.

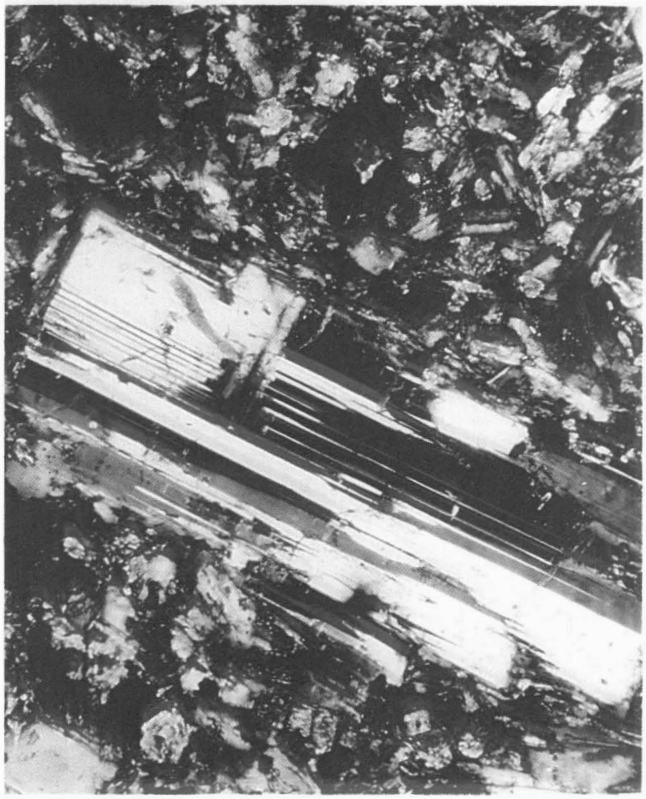


0.2mm

C. Plagioclase phenocryst. Glass-charged, partially resorbed core of calcic plagioclase, and a rim of clear andesine. Smaller phenocrysts of pyroxene and andesine.

1mm

B. Pyroxene, plagioclase, and pleochroic apatite phenocrysts in pyroxene trachyandesite.



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D. Labradorite phenocryst in intergranular matrix of plagioclase, pyroxene, Fe-Ti oxides, and apatite.

FIGURE 36. Photomicrographs of typical pyroxene and hornblende trachyandesites of the volcanics of Lime Mountain.

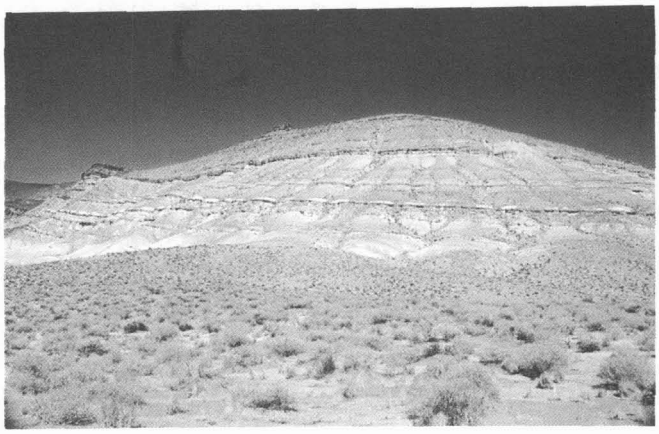


FIGURE 37. Exposures of clastic rocks in the Siebert Formation 16 km north of Tonopah.

The thickness of the Siebert is quite variable. It is over 180 m thick on Siebert Mountain southeast of Tonopah, approximately 300 to 450 m thick just east of Crescent Dunes (fig. 37), and it seems likely that an even thicker section is present beneath Quaternary alluvium in the central part of Montezuma Valley between Tonopah and Lone Mountain as gravity data indicate a maximum of 900 m of Cenozoic material in this valley (Erwin, 1968), including an unknown amount of pre-Siebert volcanic rocks. This indicates that the area of maximum Siebert deposition probably coincides with the center of Montezuma Valley. Most of the Siebert exposed in the central part of the San Antonio Range is fluvial sandstone and slope accumulations of pyroclastic rocks, whereas lacustrine rocks crop out to the west (basinward). The limited outcrops of Siebert Formation in the Lone Mountain area, indicate a similar relation there; fluvial rocks are exposed near the mountainous area and lacustrine units further east (basinward).

The Siebert Formation was derived predominantly from local sources in the San Antonio Mountains and at Lone Mountain; the pyroclastic portion came from rhyolitic volcanic vents located in the San Antonio Mountains between Divide and Rays. These vents are the sites of later intrusions and flows of Brougher Rhyolite. For that reason, coarse pyroclastic breccias (tuff breccias) and lapilli tuffs are usually found in the vicinity of Brougher cumulo domes. Blocks of rhyolitic pumice up to 0.5 m in diameter are common in tuff breccias in S14,36,T3N,R42E and in S17,T2N,R43E. Bedded to massive lapillistones of similar composition are present at a number of localities (fig. 38), including the type area of the Siebert on Siebert Mountain, 0.6 km southwest of Tonopah. Some bedding features in the bedded lapillistones are indicative of base surge deposition, and it is probable that some of the tephra from the Brougher vents was erupted under water. At Mt. Butte, however, both tuff breccias and waterlaid lapillistones are present, and pebbles of Brougher Rhyolite in the Siebert lapillistones (fig. 39) indicate the synchronous age of the two formations. Fine-grained tuff and tuffaceous sandstone are also present in the Siebert (fig. 40); in some cases the shard structure in these tuff beds is beautifully preserved. The shale in the Siebert also probably has had a considerable portion of its clay-size fraction contributed by volcanic activity. Some of these shales exhibit very shallow water features such as raindrop impressions?, bird tracks (fig. 41), and mud cracks and associated ripple marks.

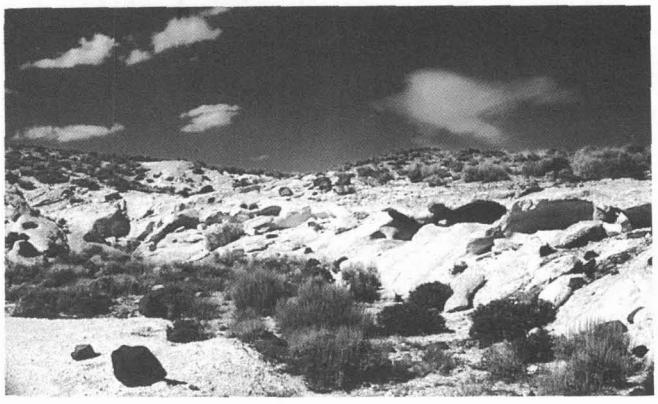


FIGURE 38. Massive lapillistone and tuff breccia in the Siebert Formation about 2.5 km east of Tonopah.

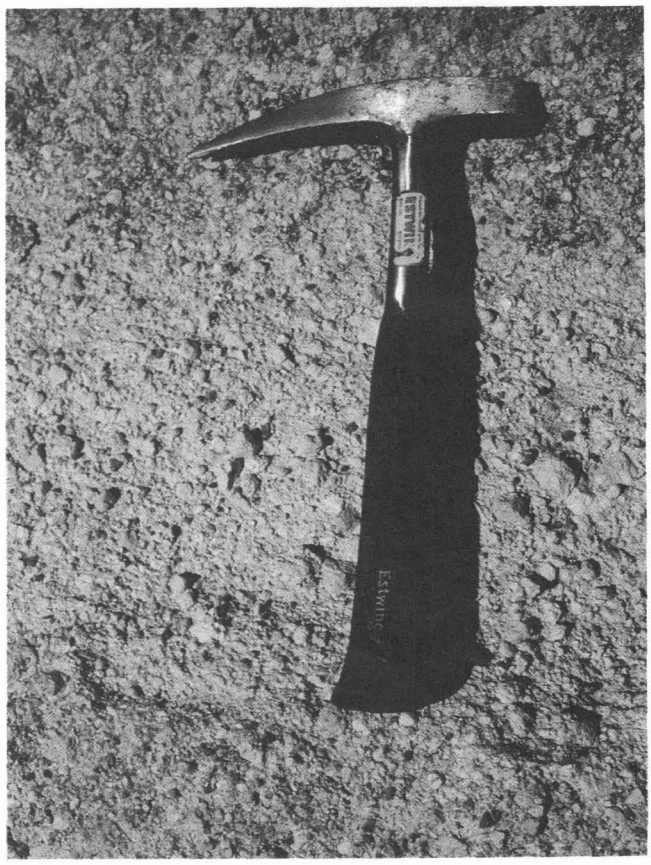


FIGURE 39. Brougher Rhyolite pebbles in lapillistone of the Siebert Formation.

In many areas these Siebert shales contain soft sediment deformation features including slump folds (fig. 42). Single folds range in size from 0.3 to 3 m in length. A good exposure of such a fold can be seen in the wall of the adit of the Tonopah Hasbrouck Mine about 131 m from the portal. Some of these slump folds are recumbent or may exhibit even more contorted shapes, including hook-shaped structures (slump overfolds), and are overlain by normally laminated shales, indicating their penecontemporaneous nature. In a few areas load casts are seen in sandstone or tuff beds which overlie finer grained beds. The slump features and load casts may indicate a rapid supply of sediment to the depositional area. In many cases this sediment was originally pyroclastic material which may

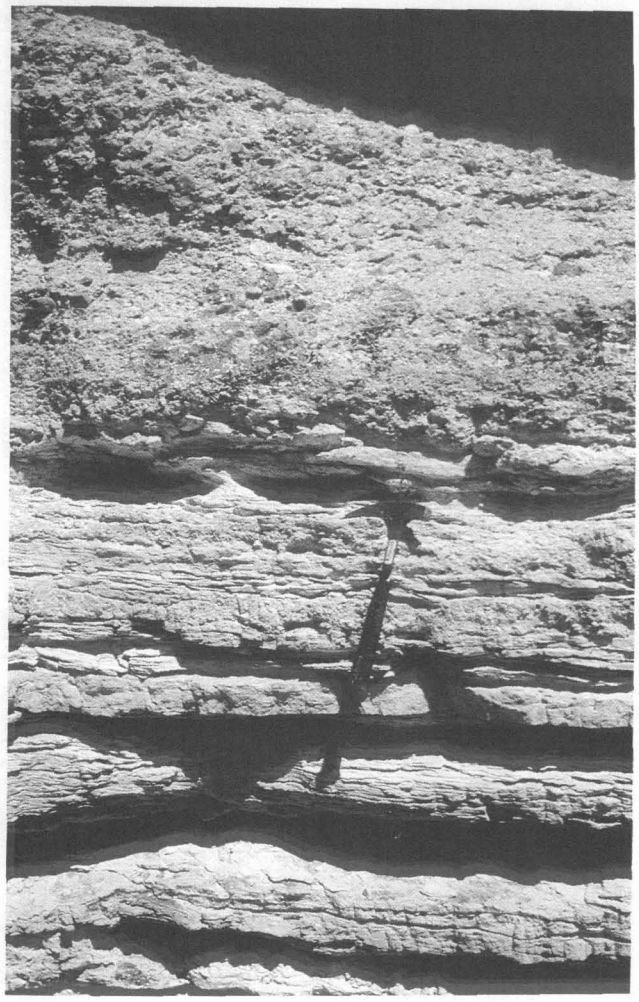


FIGURE 40. Tuff and tuffaceous sandstone in the Siebert, overlain by caliche-cemented gravel. Approximately 6 km southwest of Tonopah.

have been supplied sporadically from several vents. Accretionary lapilli (pisolites) have been recognized in fine shales and probably result from the accretion of fine volcanic ash around raindrops. These pisolites then fell into fine muds in shallow water, deforming the underlying muds.

The basal part of the Siebert Formation at Tonopah and the Divide mining district consists of poorly exposed sandstone and bouldery conglomerate derived from ash-flow tuff units of the underlying Fraction Tuff. This basal epiclastic unit is often nearly indistinguishable from this underlying Fraction Tuff, although rounded sand grains and the absence of pumice in the basal Siebert are useful in distinguishing it from the Fraction. These clastic beds were originally included by Spurr (1905b) in the Fraction Breccia (see also the section on the Fraction Tuff).

In the Divide district and to the southeast of Donovan Peak the lower part of the Siebert consists of a strongly silicified, pale-yellowish-green, rhyolitic pyroclastic breccia (fig. 43). It was not mapped separately.

Conglomerate beds are locally common within the Siebert as well as at its base, and often seem to be the result of fluvatile channel deposition. Good exposures of conglomerates and pebbly sandstones can be seen at the top of Hasbrouck Mountain in the Divide mining district and in S/2 S32,T3NR42E southwest of Tonopah. The pebbles and cobbles usually consist of various volcanic rock types, including fragments of Mizpah(?) dacite, Brougher Rhyolite, and trachyandesite.

Approximately 6 km north of Tonopah the Siebert Formation overlies the volcanics of Lime Mountain and is well exposed in several cuestas just to the southeast of Crescent Dunes. The exposures there consist of over 300 m of tuffaceous siltstone and epiclastic volcanic sandstone overlain by a distinctive, cliff-forming limestone. These rocks are predominantly lacustrine near shore and beach deposits, based on the sedimentary structures present. The base of the Siebert at one locality consists of a gastropod-bearing sandstone; shale beds in the section are often very finely laminated (paper shale) and contain rare fish scales and poorly preserved fish remains (see the following section on fossils). Oscillation ripple marks, mud cracks, and clay galls present in the sandstones indicate shallow water deposition. The limestone unit in the area southeast of Crescent Dunes contains algal structures which vary from fine, crinkly laminated beds to cabbagelike "algal heads" 25 to 50 cm in diameter. Some laminae are replaced by chalcedonic silica. These features indicate an algal mat (stromatolitic) origin and are apparently formed by the entrapment of carbonate detritus in mats of blue-green algae (Pettijohn, 1957, p. 220, 399). The crinkling shown by the algal laminations has been attributed to drying, indicating that the water may have been quite shallow. At some localities, very thin-bedded (2 to 5 cm) micritic

FIGURE 41. Fossil bird tracks in the Siebert Formation 5 km west of Tonopah. Hammer is about 35 cm long.

FIGURE 42. Soft-sediment deformation features in the Siebert Formation approximately 5 km west of Tonopah.

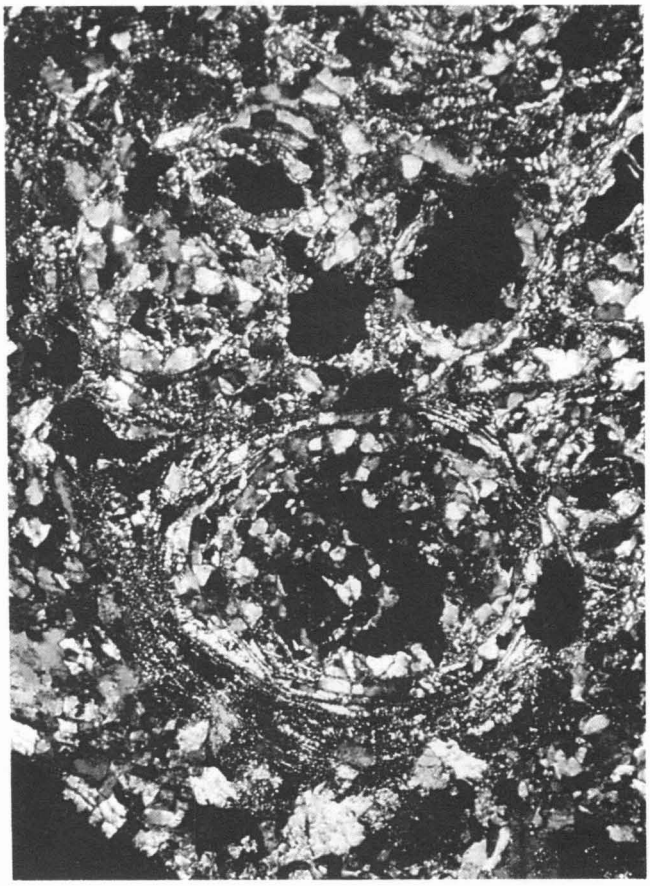
(lithographic) limestone and mud-cracked shale are interbedded. Possible ice-crystal casts were seen in these rocks and are also indicative of a very shallow lacustrine or playa environment. One sample of finely crystalline limestone is banded (varved?) in alternating dark and light bands, 1/2 to 1/3 mm thick. The limestone beds contain ostracod valves (carapaces), several species of gastropods, and rarely oolites? or pellets?. The above features indicate a lacustrine environment with periods of dessication. The lake may have been alkaline at times, as analcime found in tuffaceous sedimentary rocks in this section may be indicative of more saline conditions (Hay, 1966, p. 92).

Fluvatile, beach, and delta sediments in the Siebert Formation are well exposed in the northern San Antonio Mountains 2 to 10 km south of Crescent Dunes. They consist of poorly sorted, feldspathic, and epiclastic volcanic sandstones and conglomerates which are believed to be time-equivalent to lacustrine rocks exposed 5 km west of Tonopah. Crossbedding and cut and fill features are common, limestone beds are absent, and individual sandstone beds cannot be traced for great distances. Fluvatile beds in this area contain mammal remains (Henshaw, 1942). Immature sandstones exposed in the northern San Antonio Mountains were derived predominantly from a volcanic terrane and contain grains of subangular quartz, potash feldspar, plagioclase, and volcanic rock fragments. Lesser amounts of biotite, pyroxene, and other mafic minerals are present Volcanic ash is common in the rocks, and is, in part, altered to zeolites such as erionite and clinoptilolite (fig. 43).

The Siebert Formation contains a thin trachyandesite flow near its top at Siebert Mountain (fig. 44). Dike rocks which cut the lower part of the Siebert near Mt. Butte are correlated with this unit. The flow rocks are augite- or olivine-and-augite-bearing (crystals up to .3 mm) and contain plagioclase laths (0.1 mm in length) as well as magnetite, apatite, and cristobalite. The texture is pilotaxitic-trachytic, and the rock is somewhat vesicular. The dike

0.1 mm

A. Erionite and clinoptilolite replacing shards in sandy tuff of the Siebert Formation.



0.2mm

B. Relict perlitic cracks in rhyolitic pyroclastic breccia at base of Siebert, Divide district.

FIGURE 43. Photomicrographs of rocks of the Siebert Formation.

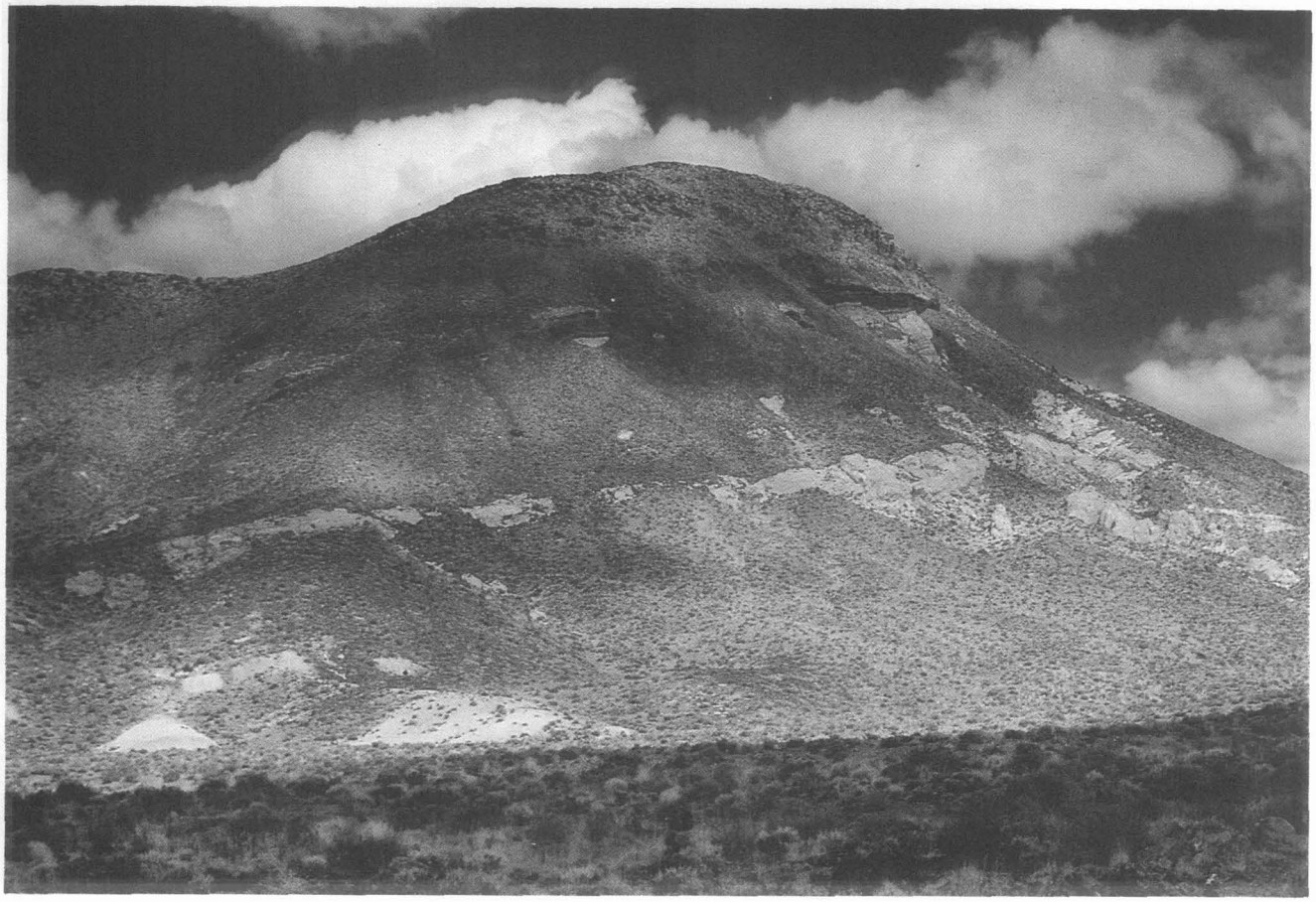


FIGURE 44. Siebert Formation at Siebert Mountain, 2 km southwest of Tonopah. White tuffs and lapillistones overlain by a thin trachyandesite flow (dark band). A flow of Brougher Rhyolite forms the top of the mountain.

rocks are augite or augite-hornblende trachyandesites with pilotaxitic fluidal textures. Iddingsite present in some samples indicates the original presence of olivine. Two analyses of trachyandesite flows in the Siebert are given in table 17.

Environment of deposition. The majority of the rocks of the Siebert Formation were deposited under alternating fluvatile and lacustrine conditions. The margins of the lake were shallow, and detris was supplied from the erosion of older volcanic rocks plus added pyroclastic material, most of which came from vents that were later filled by Brougher Rhyolite. The lake may have been somewhat alkaline, but was occupied by gastropods, ostracods and fish. Periods of partial dessication occurred, and temperatures occasionally may have fallen below freezing. Algal mats were present along the shore in places and lake tufa was deposited locally.

The late Tertiary was a period of increasing aridity in the Great Basin (Axelrod, 1940). The climate may be comparable to that described by Axelrod (*in* Barrows, 1971) in the Eastgate area, 150 km to the northwest. At that locality, the Eastgate flora indicates a rainfall of about 102 cm per year, with a mean annual temperature of 10°C and a mean annual range of 12°C. The precipitation was probably seasonal, with more moisture in the winter months. The Tonopah area was probably a lake, surrounded by grassy, shrub-covered plains (Henshaw, 1942).

Following deposition of the sediments, a number of authigenic minerals were formed, especially in the lacustrine deposits. Zeolites (erionite, clinoptilolite, and analcime) are found as alteration products of tuffaceous material in the sediments. Also, authigenic potassium feldspar is present locally as overgrowth rims on detrital potassium feldspar grains.

Fossils. A number of vertebrate and invertebrate fossils are present in the Siebert Formation in the mapped area, and they are useful in assigning an age to the formation (see the following section on age). Henshaw (1942) has described in some detail fossil mammals from a locality on the western flank of the San Antonio Mountains, approximately 14 km north of Tonopah in SW/4 SW/4 S15(projected),T4N,R42E. This locality, originally described as California Institute of Technology Vertebrate Paleontology locality 172, was found by H. G. Ferguson during reconnaissance mapping in the summer of 1922. In 1931 and 1932 field parties of the California Institute of Technology collected a large amount of fossil material from a pit at the site. This material consisted almost entirely of teeth and limb bones of 225 individual mammals, mainly adults. Of these, there are 195 herbivores, 29 carnivores, 1 insectivore, and a number of uncounted rodents and lagomorphs. Table 18 includes a census of the genera found and a complete faunal list, both adapted from Henshaw (1942). Henshaw's paper also includes a good historical review of flora and fauna descriptions from other nearby late Tertiary localities. These mammalian remains are believed to be Barstovian in age, and compare favorably with the type Barstow fauna.

Henshaw (1942) also tentatively identified four species

TABLE 17. Chemical analyses for two samples of trachyandesite flows from the Siebert Formation.

Sample	T40A	T41
Location number	1	2
Normalized oxide values		
SiO_2	56.9	55.7
Al_2O_3	17.6	16.5
Fe_2O_3	6.7	4.2
FeO	2.0	4.3
MgO	1.5	4.1
CaO	6.9	7.2
Na_2O	4.0	3.7
K_2O	2.8	2.7
TiO_2	1.6	1.4
MnO	0.24	0.10
Normative minerals		
Quartz	8.5	4.7
Orthoclase	16.4	15.7
Albite	34.1	31.3
Anorthite	21.8	20.7
Wollastonite	0.9	
Diopside	7.9	12.1
Hypersthene		6.6
Magnetite	1.8	6.9
Hematite	5.5	
Ilmenite	3.1	2.9
Wollastonite (diopside)	4.2	6.4
Enstatite (diopside)	3.7	4.8
Ferrosilite (diopside)		1.0
Enstatite (hypersthene)		5.5
Ferrosilite (hypersthene)		1.1
Petrologic indices		
Differentiation index	59.1	51.7
Felsic-mafic index	3.7	3.1

Locations: 1. SE/4 SW/4 S3,T2N,R42E; south side, Siebert Mountains
2. NW/4 S10,T2N,R42E

of Mollusca from the mammal locality. These represent the same species which Spurr (1905b, p. 67) mentions. These are: *Pisidium? meeki* Hannibal, *Planorbis* cf. *cordillerana* (Hannibal), *Lanx* cf. *undulatus* (Meek), and *Viviparus turneri* Hannibal. Additionally, fossil collections were made by the authors from a nearby locality. J. R. Firby (oral commun., 1970) identified two species from this collection, *Viviparus turneri* Hannibal, and *Planorbis utahensis* Meek.

Gastropods collected from Siebert exposures in NE/4 NE/4 SE/4 S13,T4N,R41E were also identified by Firby, and include *Promenetus* species, *Viviparus turneri* Hannibal, and *Valvata* sp. The molluscan fauna from these various localities is Barstovian in age.

Poorly preserved fish remains and abundant scales were found at a locality in SW/4 SW/4 S15(projected),T4N, R42E in a sequence of pinkish-gray "paper" shales. A single fossil fish collected at the nearby California Institute of Technology Vertebrate locality 172 and described by Henshaw (1942), was referred to as *Leuciscus turneri* Lucas. However, the caudal and anal fins were missing and the remaining skeletal parts were poorly preserved. *Leuciscus turneri* Lucas is a top-dwelling, fresh-water minnow (a type of carp), and is apparently not known elsewhere except in the Silver Peak area, where Lucas (1900) first described it. However, pharygeal teeth of cyprinoid fishes (carp) have been reported from the Tertiary beds of the Cedar Mountain region (Merriam, 1916). The original *Leuciscus turneri* Lucas was associated with beds containing plant remains that Axelrod (1940) describes as being of probable lower Pliocene age (this age probably corresponds to the Clarendonian).

Spurr (1905b, p. 69) reports that a bed in the tuffs exposed at the east base of Siebert Mountain is made up entirely of diatoms. These diatoms were identified as *Melosira granulata* Bailey and *Melosira varians* Agardh, the latter being considerably less abundant. A few *Coscinodiscus radiatus* Ehrenberg were also found. *Melosira granulata* was also identified by Keith Papke (personal commun., 1975) in a sample of impure diatomite from the Siebert of the Klondyke region in the southern part of the mapped area.

In addition, *Candona* sp., an ostracod, was identified in a sample collected from exposures in the NE/4 NE/4 SE/4 S13,T4N,R41E, which also contained several species of Barstovian gastropods (J. R. Firby, personal commun., 1970). Two different sets of fossil bird tracks (fig. 41) were noted at a locality about 5 km west of Tonopah (C SE/4 NW/4 S32,T3N,R42E). These tracks probably represent a large and a medium-size shore bird. *Chara* oogonia (algal remains) were also found at this locality.

The Siebert Formation lies with angular unconformity on Miocene pyroclastic and flow rocks. At Tonopah, the Siebert overlies the Heller Tuff (17 m.y.) and the Mizpah Formation (20.5 m.y.), and it overlies volcanics of Lime Mountain (probably about 16 m.y.) in the northern San Antonio Mountains. At numerous localities in the mapped area, rocks of the Siebert Formation are intruded by Oddie Rhyolite (16.4 to 16.9 m.y.), and intruded and overlain by flows of Brougher Rhyolite (13.2 to 16.2 m.y.). K-Ar age dates in the Siebert Formation include a 16.2±0.6-m.y. whole rock date on a trachyandesite flow unit in the upper part of the formation at Siebert Mountain and a 15.5±1.6-m.y. date on biotite in pumice from Mt. Butte (see table 4 for detailed location data). The Siebert Formation at Goldfield overlies the 17.8-m.y.-old Meda Rhyolite (Ashley, 1974a); biotite from a pumiceous rhyolite air fall tuff in the Siebert there has been dated at 14.2±0.3 m.y. (Silberman and McKee, 1972). Thus, the Siebert is 13 to 17 m.y. old, according to K-Ar data. This is in general agreement with a Barstovian age based on fossil determinations discussed in the previous section.

Oddie Rhyolite (To)

The Oddie Rhyolite was named by Spurr (1905b, p. 49) for exposures of intrusive rhyolite on Mount Oddie in the Tonopah district (fig. 45). Later workers, including Ferguson and Cathcart (1954) and Vitaliano (1963a, b), extended the name Oddie Rhyolite to rhyolitic flows, intrusives, and ash-flow tuffs as distant as 100 km from the Tonopah district. Since the Oddie Rhyolite in the type area consists solely of intrusive rhyolite, the extension of the

TABLE 18. Faunal list, Tonopah fauna.

Perissodactyla

Hypohippus near *affinis* (Leidy)
Merychippus calamarius (Cope)
Aphelops? cristalatus, n. sp.

Articactyla

Camelidae

Alticamelus? stocki, n. sp.

Antilocapridae

Merycodus Ioxocerus Furlong
Merycodus hookwayi Furlong

Insectivora

Metechinus fergusoni, n. sp.

Rodentia

"Mylagaulus" sp.
Cf. *Eutamias ateles* Hall
Cf. *Peromyscus longidens* Hall or possibly n. sp.

Lagomorpha

Hypolagus sp.

Carnivora

Tomarctus paulus, n. sp.
Tomarctus? kelloggi (Merriam)
Tomarctus brevirostris Cope
Leptocyon vafer (Leidy)
Aelurodon wheelerianus asthenostylus, n. var.
Amphicyon? sp.
Brachypsalis pachycephalus Cope
Pseudaelurus intrepidus Leidy

Census of Tonopah mammalian fauna

Metechinus (hedgehog)	1
Tomarctus ("dog")	9
Leptocyon (fox)	6
Aelurodon (wolf)	4
Amphicyon? ("bear-dog")	2
Brachypsalis (badgerlike mustelid)	3
Pseudaelurus (cat)	5
Hypohippus (horse)	12
Merychippus (horse)	110
Aphelops? (rhinoceros)	3
Alticamelus? ("giraffe"-camel)	8
Mercodus (deer-antelope)	62
"Mylagaulus" (squirrellike rodent)	1
Cf. *Eutamias* (chipmunk)	1
Cf. *Peromyscus* (mouse)	1
Hypolagus (rabbit)	1

name to a variety of rhyolitic rocks many kilometers distant is unwarranted and can only lead to confusion and misuse of a valid stratigraphic unit.

Distribution. The Oddie Rhyolite forms plugs and dikes in the Tonopah and Divide districts. The principal exposures in the Tonopah district are on Mount Oddie, Rushton Hill, and Ararat Mountain (fig. 45). Gold Mountain and Hill 6708 in the Divide district also consist partially of intrusive Oddie Rhyolite. Small irregular dikes and plugs of Oddie Rhyolite occur at several other localities in both districts and are shown on plate 1.

The Oddie Rhyolite intrudes rocks as young as the Siebert Formation and is slightly older than the domes and flows of the Brougher Rhyolite.

Lithology. The Oddie Rhyolite is a pinkish-gray to very pale-orange, sparsely porphyritic rock. Virtually all of the Oddie Rhyolite is at least weakly hydrothermally altered. Where least altered, the rock contains phenocrysts of quartz, alkali feldspar, sodic plagioclase, and sparse biotite in a matrix of quartz and alkali feldspar. Phenocrysts rarely exceed 1 mm in diameter and constitute less than 20 percent of the rock. Quartz shows varying degrees of corrosion and some phenocrysts are vermicular.

In areas where the Oddie Rhyolite is weakly altered, plagioclase is partially to completely albitized and speckled with sericite; biotite is sericitized; and alkali feldspar appears to be relatively unaltered. Where the Oddie is strongly altered, it consists of an aggregate of quartz and sericite. Much of the Oddie is weakly to strongly silicified and contains sparse, disseminated pyrite.

The rocks of the Oddie Rhyolite contain low-grade gold-silver mineralization in the Tonopah district and some narrow, relatively high-grade gold-bearing veins in the Divide district (fig. 46). In both districts, sedimentary rocks of the Siebert Formation at Hasbrouck Mountain and "Three Hills" (NW/4 S4,T2N,R42E) have been strongly

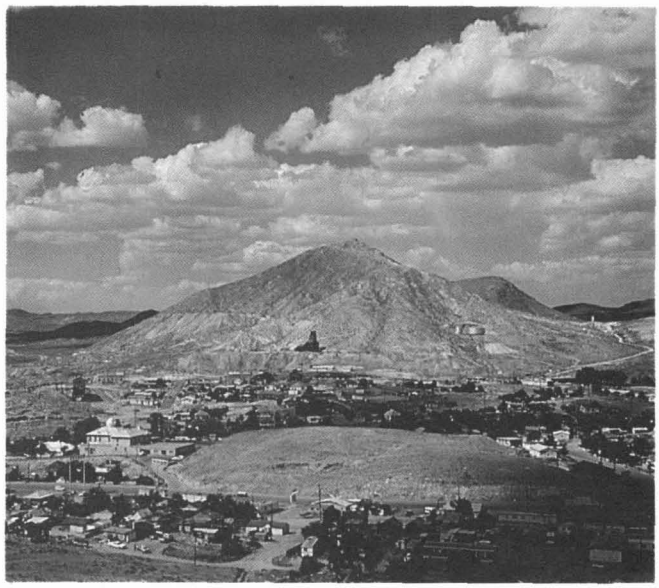


FIGURE 45. Intrusive plug of Oddie Rhyolite which forms Mount Oddie (center of picture).

silicified adjacent to small intrusions of Oddie Rhyolite. The silicified rocks contain low-grade, disseminated, gold-silver mineralization.

Chemical analyses of two samples of Oddie Rhyolite listed in table 19 indicate that the Oddie is high-silica rhyolite. The high-silica contents of both samples may reflect the addition of at least some silica to the rhyolite during hydrothermal alteration. The low Na_2O content may also be due to hydrothermal alteration. The relatively high CaO content of sample 11550-1 is due to the presence of calcite in this sample. Both samples are from Mount Oddie and are the least altered obtainable from this locality.

Biotite from two samples of Oddie Rhyolite yielded potassium-argon ages of 16.4 and 16.9 m.y. (table 4).

Divide Andesite (Td)

The Divide Andesite was originally named by Knopf (1921, p. 155–156). The type locality for the unit is The Divide on the old Goldfield-Tonopah road from which the Divide district was named (fig. 47). Chemical analyses of the Divide indicate that its dominant lithology is quartz latite rather than andesite, however the name Divide Andesite is retained in this report because of its long usage

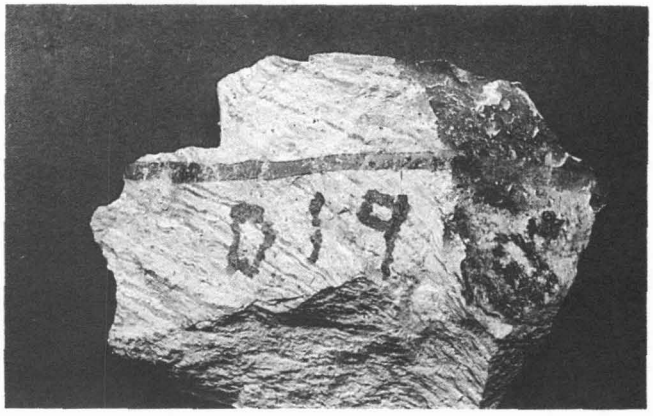


FIGURE 46. Flow-banded Oddie Rhyolite from Gold Mountain, Divide district. Small quartz vein cuts across the flow banding. 0.7 X

TABLE 19. Chemical analyses, Oddie Rhyolite.

[Analyses by U. S. Geological Survey Rapid Rock Analysis Laboratory; L. Shapiro, project leader. Analysts, M. Smith, J. Glenn, J. Kelsey, G. Chloe, P. Elmore]

Sample	11550-1 Rhyolite	T6 Extreme alkali rhyolite
Location number	1	2
Normalized oxide values		
SiO_2	76.8	79.2
Al_2O_3	13.1	12.7
Fe_2O_3	0.4	0.2
FeO	0.6	0.4
MgO	0.3	0.3
CaO	2.6	0.7
Na_2O	0.8	1.1
K_2O	5.2	5.3
TiO_2	0.1	0.2
MnO	0.09	0.10
Normative minerals		
Quartz	46.3	50.5
Corundum	1.5	3.9
Orthoclase	30.4	31.4
Albite	6.4	8.9
Anorthite	13.0	3.6
Diopside		
Hypersthene	1.5	1.2
Magnetite	0.5	0.2
Hematite		
Ilmenite	0.3	0.3
Wollastonite (diopside)		
Enstatite (diopside)		
Enstatite (hypersthene)	0.8	0.7
Ferrosilite (hypersthene)	0.7	0.4
Petrologic indices		
Differentiation index	83.1	90.8
Felsic-mafic index	21.2	52.5

Locations: 1. Mount Oddie
2. Mount Oddie

in the district and because its phenocryst mineralogy (table 20) is typical of many rocks that are called hornblende or biotite andesites.

Table 21 lists two chemical analyses of the Divide Andesite. The SiO_2 content varies from 67–70 percent and the K_2O/Na_2O ratio is approximately 0.9 percent.

At the present level of erosion the contacts of the Divide Andesite with the Fraction Tuff and Siebert Formation are all intrusive. The intrusive is exposed near its original roof since there are several large and many small pendants of Fraction Tuff or Siebert Formation "floating" in the Divide Andesite.

The contact of the Divide Andesite with its wall rocks is intricate in detail, with many re-entrants of the wall rocks extending into the intrusion and apophyses of the intrusion

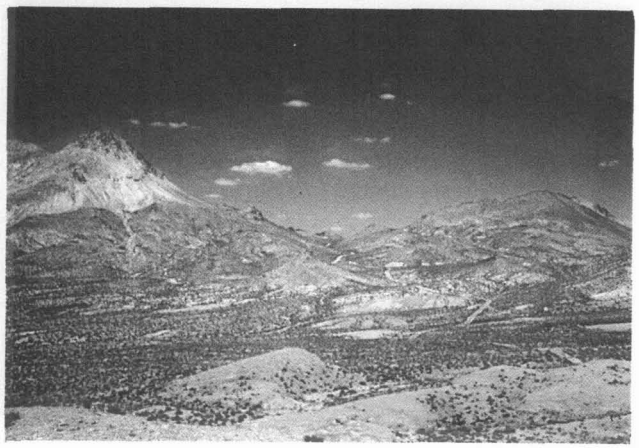


FIGURE 47A. The Divide, Divide district. Low hills in middleground are Divide Andesite. Light-colored peak in left background is Gold Mountain, an intrusive plug of Oddie Rhyolite. Outcrops in foreground are ash-flow tuff of the Tonopah Summit Member, Fraction Tuff.

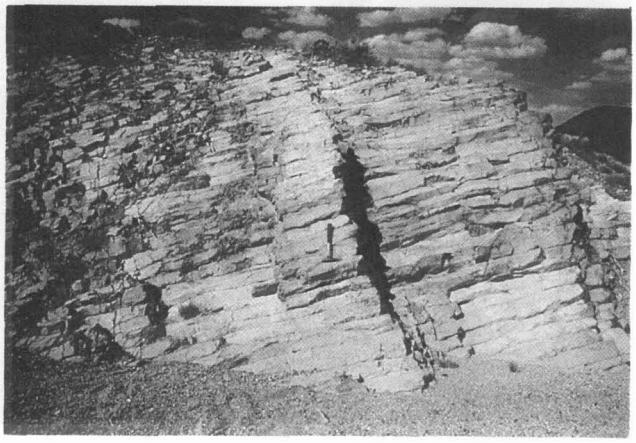


FIGURE 47B. Unusually well-developed columnar jointing in Divide Andesite.

extending out into the walls. In general, the contact of the Divide Andesite with its enclosing wall rocks is quite steep, but locally, in exposures of the contact along the west and southwest margins of the intrusion, the contact dips inward at angles of 15–20 degrees.

The Divide Andesite is flow-banded and exhibits crude layering. Locally, well-developed columnar jointing is present (fig. 47).

Extensive areas of the Divide Andesite are hydrothermally altered particularly in the western and southern parts of the intrusion. The alteration ranges from weak propylitization to complete alteration of the rock to an aggregate of quartz, sericite and adularia. Although the hydrothermal alteration in the Divide Andesite is extensive, no economic mineralization has yet been found. Significant amounts of precious metal mineralization do occur in the Fraction Tuff, Oddie Rhyolite, and Siebert Formation adjacent to the Divide Andesite.

Distribution. The Divide Andesite is the oldest in a cogenetic sequence of shallow intrusive rocks centered around Donovan Peak. Outcrops of the Divide Andesite form an east-west belt that extends from Gold Mountain in the Divide district to Ralston Valley. The outcrop area of the Divide Andesite is approximately 14 km^2.

TABLE 20. Phenocryst mineralogy, Divide Andesite.

[Phenocrysts and accessory minerals as volume percent of total crystals.]

	T215
Plagioclase	76.3
Hornblende	10.4
Biotite	8.2
Opaque	2.9
Apatite	2.2

Locality Data
T215: NW/4 S33,T2N,R43E.

Zircon and rare sphene also occur as accessory minerals.

TABLE 21. Chemical analyses, Divide Andesite.

Sample	T38 Quartz latite	T125 Quartz latite
Location number	1	2
Normalized oxide values		
SiO_2	70.0	67.1
Al_2O_3	15.2	17.0
Fe_2O_3	1.3	1.9
FeO	1.3	1.5
MgO	0.5	0.8
CaO	2.8	3.1
Na_2O	4.4	4.3
K_2O	4.1	3.8
TiO_2	0.4	0.5
MnO	0.06	0.06
Normative minerals		
Quartz	22.8	19.3
Corundum		0.1
Orthoclase	24.2	22.7
Albite	36.9	36.4
Anorthite	9.8	15.3
Diopside	3.2	
Hypersthene	0.5	2.5
Magnetite	1.9	2.7
Hematite		
Ilmenite	0.8	1.0
Wollastonite (diopside)	1.6	
Enstatite (diopside)	1.0	
Ferrosilite (diopside)	0.6	
Enstatite (hypersthene)	0.3	2.0
Ferrosilite (hypersthene)	0.2	0.5
Petrologic indices		
Differentiation index	83.8	78.4
Felsic-mafic index	13.3	10.3

Locations: 1. NW/4 NW/4 S34,T2N,R43E
2. NW/4 S33,T2N,R43E

The Divide Andesite intrudes the Fraction Tuff and the Siebert Formation. It is intruded by the volcanics of Donovan Peak and by the Brougher Rhyolite. Its age relationship to the Oddie Rhyolite is uncertain.

Lithology. The Divide Andesite, where fresh, is a porphyritic, medium-dark-gray to light-brownish-gray rock containing phenocrysts of plagioclase, hornblende, biotite, and Fe-Ti oxides in a fine-grained felsitic matrix. Plagioclase is oscillatory-zoned, euhedral, and much of it is "spongy" with abundant groundmass inclusions. The plagioclase ranges in composition from An_{30-50} and reaches maximum dimensions of 5 mm. Hornblende is pleochroic in shades of green and brown and is commonly rimmed by Fe-Ti oxides. A few phenocrysts of hornblende reach 3 mm in length, but most are 1 to 2 mm long. Biotite averages 1 mm in diameter and is pleochroic in shades of light to dark brown.

The groundmass texture is trachytic to pilotaxitic, it consists of plagioclase microlites, anhedral alkali feldspar, mafic granules, fine-grained Fe-Ti oxides and cristobalite. Tridymite, stilbite, and calcite are present in some specimens in vugs. The matrix constitutes approximately 80 percent of the rock.

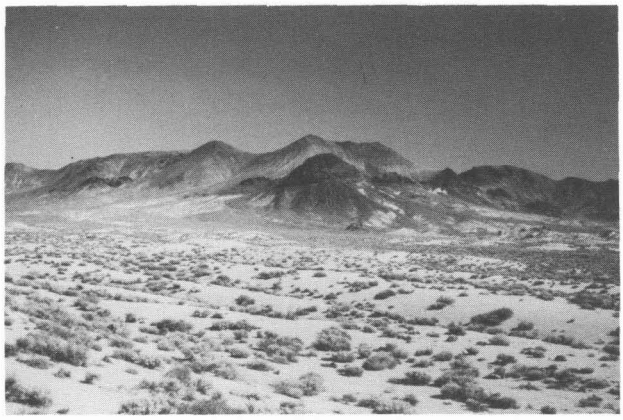
Concordant potassium-argon ages of 16.8 m.y. (biotite) and 16.9 m.y. (hornblende) were obtained from a sample of Divide Andesite. Discordant potassium-argon ages of 15.6 m.y. (hornblende) and 14.9 m.y. (plagioclase) from the Divide Andesite are also listed in table 4. We believe that the concordant potassium-argon ages of 16.8 to 16.9 m.y. reflect the actual age of the Divide Andesite since it is older than the hydrothermal alteration in the Divide district (about 16.4 m.y.), and it is older than rhyolite of the volcanics of Donovan Peak which has been dated at 16.3 m.y. We have no ready explanation for the discordant young potassium-argon ages since they came from a sample of fresh Divide Andesite. The anomalously young plagioclase age (14.9 m.y.) may be caused by the presence of numerous groundmass inclusions in much of the plagioclase from the Divide Andesite. Silberman (personal commun., 1976) has noted that "spongy," inclusion-filled plagioclase usually gives poor results in potassium-argon dating.

Volcanics of Donovan Peak

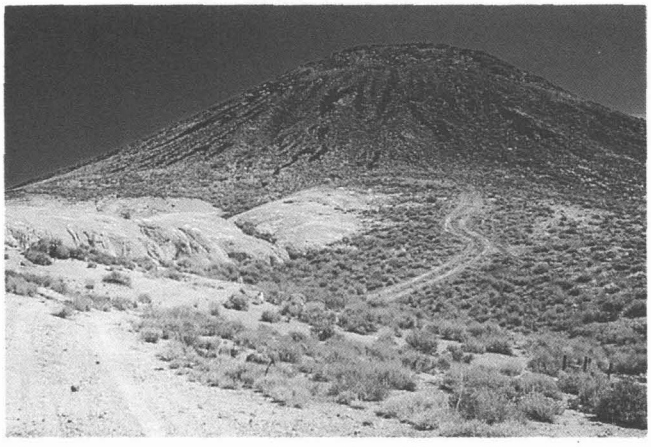
The volcanics of Donovan Peak are a group of intrusive and extrusive volcanic rocks ranging in composition from dacite to rhyolite. The name is derived from the occurrence of the three main lithologic units that comprise the volcanics in a vent complex centered on Donovan Peak. The volcanics of Donovan Peak occur principally on the east side of the San Antonio Mountains in an area extending from Golden Mountain in the Tonopah district on the north, to the northeastern edge of the southern Klondyke Hills on the south (fig. 48).

The volcanics of Donovan Peak occur as dikes, plugs, domes, cinder cones and associated flows. They are subdivided on the geologic map into three informal units, which are, in order of decreasing age: flow-banded rhyolite, rhyodacite to rhyolite, and dacite.

Flow-banded rhyolite (Tvr). The flow-banded rhyolite comprises a group of rhyolite domes and dikes which intrude the Brougher Rhyolite, the Divide Andesite, the Siebert Formation, and the Fraction Tuff and are intruded



A. Donovan Peak vent complex. View looking northwest. Dark-colored rocks are fused pyroclastics of the rhyodacite to rhyolite unit. Light-colored rocks in foreground are hydrothermally altered ash-flow tuff of the Tonopah Summit Member, Fraction Tuff.



B. Dike of rhyodacite to rhyolite unit cutting ash-flow tuff of the Tonopah Summit Member, Fraction Tuff.

FIGURE 48. Volcanics of Donovan Peak.

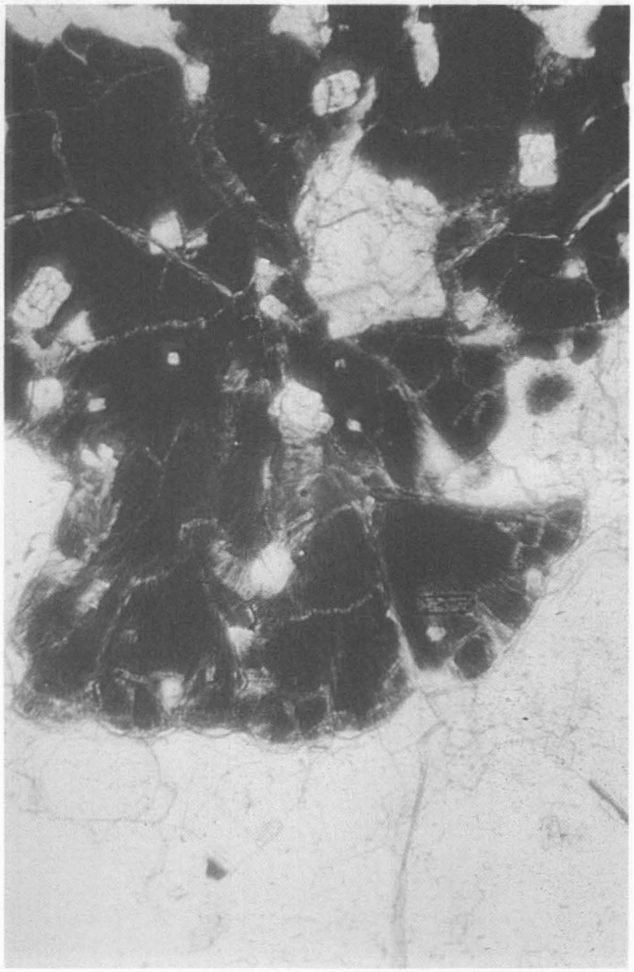
by the rhyodacite to rhyolite unit and the dacite unit of the volcanics of Donovan Peak. The rhyolite is unconformably overlain by the trachyandesite of Mud Lake. The rhyolite domes are clustered around the Donovan Peak vent.

The rhyolite is a light-brownish-gray to light gray porphyritic rock with phenocrysts of alkali feldspar, plagioclase, and biotite in a felsophyric to vitrophyric matrix. Phenocrystic quartz is sparse to absent. The rhyolite is prominently flow-banded on both a megascopic and microscopic scale and it is commonly microvesicular.

In the marginal portions of the domes the matrix of the rhyolite consists of perlitic, light-gray glass which contains numerous trichites (fig. 49). In the interior of the domes the glassy matrix has devitrified to alkali feldspar and cristobalite. Cristobalite is also abundant in vesicles and mordenite occurs as vesicle filling and as veinlets (fig. 49).

Phenocrysts compose about 12 percent of the rhyolite. Table 22 lists the phenocryst mineralogy of the rhyolite computed from thin-section modes.

Plagioclase ranges in composition from An_{25-35}. It is oscillatory-zoned and much of it is jacketed by alkali feldspar. Some plagioclase phenocrysts are as long as 3 mm, but most are 0.5 mm or less in maximum dimension. Biotite is the only mafic mineral present in the rhyolite.



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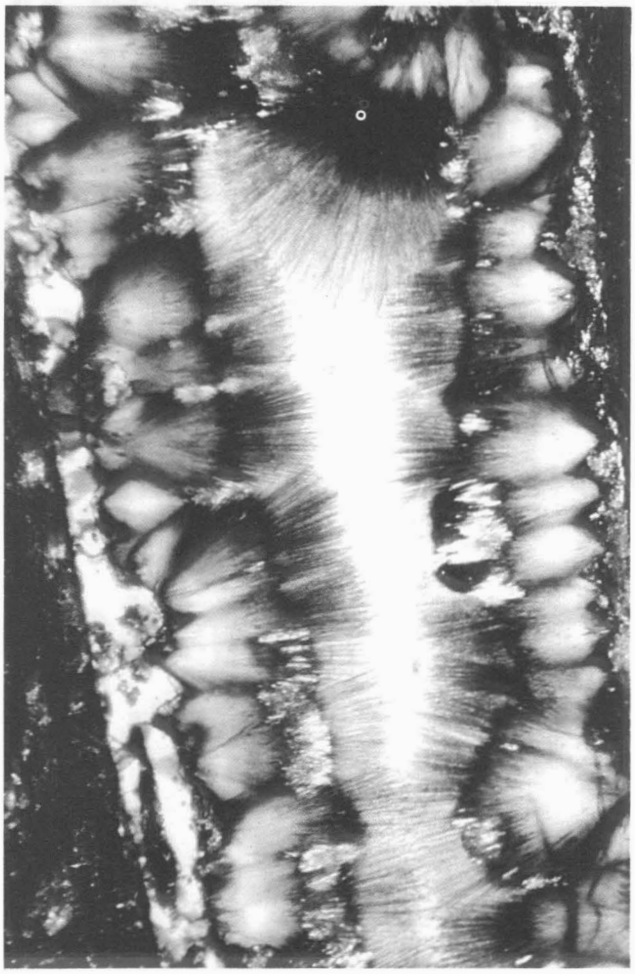
A. Spherulitic devitrification of perlite glass. Phenocrysts are plagioclase and alkali feldspar.



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B. Veinlet of mordenite in devitrified, flow-banded rhyolite.

FIGURE 49. Photomicrographs, flow-banded rhyolite unit, volcanics of Donovan Peak.

Accessory minerals are zircon, apatite, and Fe-Ti oxides.

Chemical analyses of the flow-banded rhyolite unit show that it is rhyolite to alkali rhyolite in composition (table 23).

Rhyodacite to rhyolite (Tvrd, Tva). The rhyodacite to rhyolite unit is the most widespread of the three units which comprise the volcanics of Donovan Peak. Most of the unit consists of intrusive plugs, dikes, and domes (fig. 48), which occur in a north-south belt extending from Donovan Peak to Golden Mountain.

The intrusive rocks and domes were emplaced in volcanic vents that were the sites of pyroclastic eruptions. Some of the smaller plugs and dikes consist entirely of glassy, fused pyroclastic breccia, and fused pyroclastic breccia occurs as a border phase in several of the larger intrusive masses and domes. Fused pyroclastic breccia is particularly well exposed in the marginal portion of the vent complex centered on Donovan Peak.

The fused pyroclastic breccia consists of abundant, highly welded pumice lapilli and shards, xenoliths of volcanic rocks and 15 to 20 percent phenocrysts of plagioclase, hornblende, augite, hypersthene, and rare biotite (fig. 50). The xenolithic rocks are usually either Brougher Rhyolite or Divide Andesite depending upon which unit constitutes the wall rock of the vent.

The rhyodacite is typically a microporphyritic, light-brownish-gray to medium-dark-gray rock with sparse (10 to 15 percent) phenocrysts (0.5 to 1 mm) of plagioclase, hornblende, augite, hypersthene and biotite in a very fine-grained trachytic to pilotaxitic matrix of alkali feldspar, plagioclase microlites, mafic granules, and Fe-Ti oxides (fig. 50). Plagioclase ranges in composition from An_{35-40} in rims to An_{60} in cores. Biotite and hornblende are commonly rimmed by Fe-Ti oxides. Apatite occurs as an accessory mineral. Tridymite is common in microvesicles in the rock.

The quartz latites and rhyolites are grayish red, pale red purple, or light brownish gray, microvesicular and microporphyritic rocks containing 10 to 15 percent phenocrysts

TABLE 22. Phenocryst mineralogy, flow-banded rhyolite, volcanics of Donovan Peak.

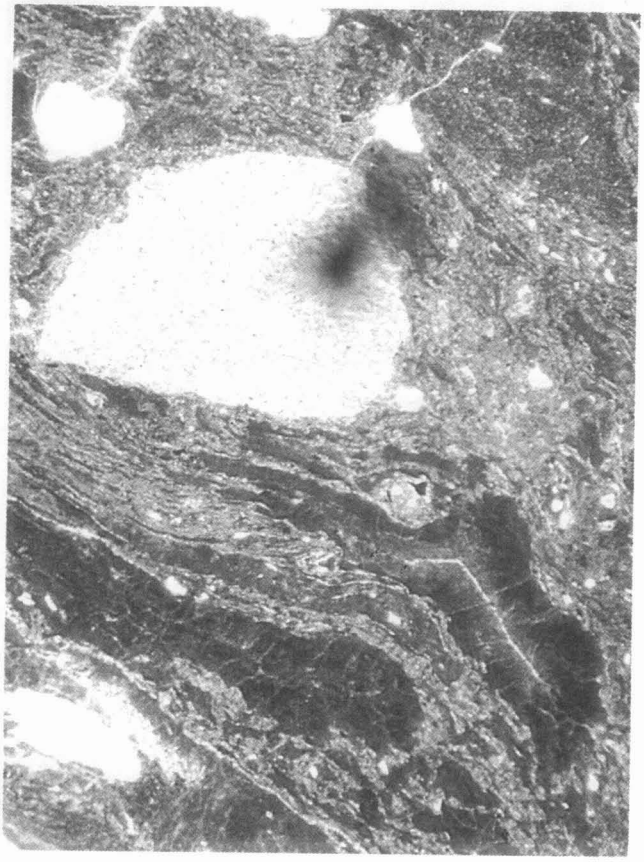
[Phenocrysts as volume percent of total crystals.]

	T142
Alkali feldspar	45.6
Plagioclase	44.0
Biotite	9.6
Opaques	0.8

TABLE 23. Chemical analyses, volcanics of Donovan Peak.

Sample	T19 Rhyodacite	T28A Quartz latite	T30 Quartz latite	T39 Rhyolite	T53 Rhyodacite	T145 Rhyolite	T143 Rhyodacite	T137B Rhyolite	T162B Rhyolite	T142 Alkali rhyolite	T138A Dacite
Location	1	2	3	4	5	6	7	8	9	10	11
Normalized oxide values											
SiO_2	65.3	66.5	69.7	71.3	65.7	71.6	65.5	70.7	72.2	76.0	60.9
Al_2O_3	16.4	16.4	14.9	15.5	15.9	14.3	16.0	15.9	14.7	12.8	17.5
Fe_2O_3	2.2	2.7	1.9	0.7	3.8	1.8	3.7	0.9	1.4	0.8	2.5
FeO	2.2	1.0	1.2	1.0	0.8	0.5	0.6	0.7	0.6	0.6	3.0
MgO	1.1	0.7	0.5	0.3	1.0	0.4	0.5	0.2	0.2	0.2	2.0
CaO	3.2	2.9	2.5	2.1	3.4	2.0	4.0	1.6	2.4	1.1	5.0
Na_2O	4.7	4.7	4.5	4.1	4.4	4.5	4.5	4.9	3.9	3.4	4.8
K_2O	3.9	4.2	4.3	4.7	4.0	4.4	4.1	4.7	4.1	4.9	3.1
TiO_2	1.0	0.8	0.6	0.5	0.9	0.4	0.9	0.5	0.3	0.2	1.1
MnO	0.06	0.05	0.03	0.01	0.08	0.08	0.25	0.01	0.04	0.01	0.05
Normative minerals											
Quartz	14.9	16.6	22.2	24.4	17.3	24.4	16.2	20.6	28.5	35.0	8.0
Orthoclase	23.3	24.8	25.4	27.6	23.5	26.1	24.0	27.8	24.3	28.7	18.6
Albite	39.9	39.6	37.6	34.9	37.0	38.3	38.1	41.3	32.6	28.9	40.8
Anorthite	12.0	11.3	7.9	9.9	12.0	5.7	11.4	7.6	10.8	5.2	16.8
Wollastonite			0.4			0.6	2.1				
Diopside	3.1	2.3	2.8	0.3	3.8	2.2	2.8	0.2	0.8	0.2	6.5
Hypersthene	2.0	0.7		1.1	0.8			0.4	0.7	0.5	3.6
Magnetite	3.1	1.0	2.1	1.0	0.3	0.6	0.1	0.9	1.1	1.2	3.7
Hematite		2.0	0.5		3.6	1.4	3.7	0.2	0.6		
Ilmenite	1.8	1.6	1.2	0.9	1.7	0.8	1.7	0.9	0.6	0.4	2.1
Wollastonite (diopside)	1.6	1.3	1.5	0.1	2.0	1.2	1.5	0.1	0.4	0.1	3.4
Enstatite (diopside)	1.1	1.1	1.3	0.1	1.8	1.0	1.3	0.1	0.4	0.1	2.8
Ferrosilite (diopside)	0.4			0.4							0.8
Enstatite (hypersthene)	1.5			0.7	0.8			0.4	0.7	0.4	2.7
Ferrosilite (hypersthene)	0.5			0.4						0.0	1.0
Petrologic indices											
Differentiation index	78.0	81.1	85.3	86.9	77.8	88.7	78.3	89.8	89.5	92.5	67.4
Felsic-mafic index	8.6	10.3	13.0	19.9	8.2	17.8	8.4	24.3	17.8	30.9	5.5

Locations:
1. SW/4 S5,T2N,R43E
2. NW/4 NW/4 S17,T2N,R3E
3. SW/4 S18,T2N,R43E
4. NE/4 S35,T2N,R42E
5. SW/4 S30,T2N,R43E
6. NW/4 S5,T1N,R43E
7. SW/4 S30,T2N,R43E
8. C S36,T2N,R42E
9. SW/4 S16,T1N,R43E
10. SW/4 S30,T2N,R43E
11. C S36,T2N,R42E



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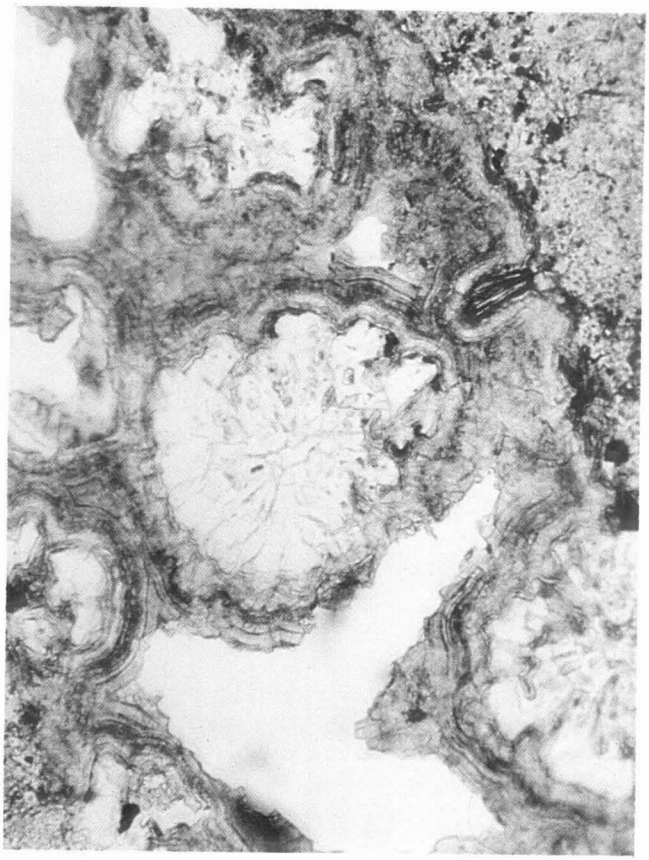
A. Fused tuff (note collapsed pumice and highly appressed shards). Large lithic fragment in center of picture.



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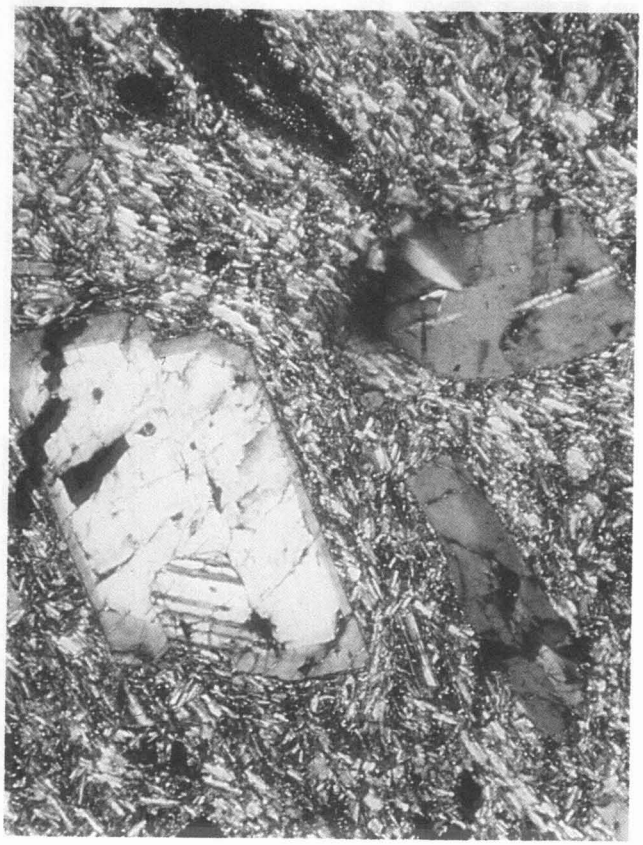
C. Cristobalite filling a vesicle.

FIGURE 50. Photomicrographs, rhyodacite to rhyolite unit, volcanics of Donovan Peak.



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B. Plagioclase and oxidized hornblende phenocryst in a trachytic matrix of plagioclase, alkali feldspar, cristobalite, and Fe-Ti oxides.

of plagioclase, hornblende, and biotite in a pilotaxitic or vitrophyric matrix. Where devitrified, the matrix consists of alkali feldspar, plagioclase, cristobalite, Fe-Ti oxides, biotite, and apatite. Alkali feldspar does not occur as a phenocryst mineral, and quartz rarely does. Tridymite or cristobalite occur lining vesicles (fig. 50). Scattered spherulites composed of alkali feldspar and cristobalite occur as a devitrification product in rhyolite or quartz latite where the matrix is still glass. The glass is hydrated and shows perlitic structure.

Chemical analyses of rock from this map unit show a compositional range from rhyolite through quartz latite into the rhyodacite field (table 23).

Rhyodacite flows and an eroded cinder cone which marks the vent for the flows, are present in the eastern part of the southern Klondyke Hills. The flows are up to 50 m thick and contain sparse phenocrysts and microphenocrysts of plagioclase, hornblende, biotite and augite in a very fine-grained pilotaxitic or vitrophyric matrix.

Knopf (1921, p. 156–157) called the rhyodacite to rhyolite unit "latite," although a partial chemical analysis from this unit showed a SiO_2 content of 69.97 percent, which, he (Knopf, 1921, p. 157) states, "it fully confirms the inference as to the latitic character of the rock but it shows an unexpectedly high percentage of silica."

Dacite unit (Tvd). Porphyritic dacite occurs as plugs in the center of the Donovan Peak vent complex. The dacite is greenish gray with phenocrysts of plagioclase, hornblende, augite, and biotite in a trachytic matrix of plagioclase microlites, mafic granules, Fe-Ti oxides, and alkali feldspar.

The plagioclase is corroded and has cores which are commonly spongy. Plagioclase rims average An_{40}, cores An_{60}. Plagioclase phenocrysts are as long as 3 mm, hornblende 2 mm, and augite about 1 mm. Apatite and Fe-Ti oxides are the main accessory minerals.

The dacite is the youngest phase of the volcanics of Donovan Peak. It intrudes the flow-banded rhyolite and the rhyodacite to rhyolite unit.

A chemical analysis of a sample from the core of one of the plugs is shown in table 23.

The age of the flow-banded rhyolite unit is about 16.3 m.y. based on K-Ar determinations on biotite (table 4). A whole rock K-Ar age of 15.9 m.y. was obtained from quartz latite; hornblende from rhyodacite yielded a 14.8 m.y. K-Ar age (table 4). The dacite unit was not dated, but it seems highly unlikely that it is significantly younger than the 14.8-m.y. age of the rhyodacite.

The volcanics of Donovan Peak thus range in age from about 14.8 to 16.3 m.y. The K-Ar ages match the known stratigraphic sequence, since the oldest unit in the volcanics of Donovan Peak, the flow-banded rhyolite, has the oldest K-Ar age, and the volcanics of Donovan Peak are all somewhat younger than the Divide Andesite, which is the oldest volcanic unit in the cogenetic sequence which includes the volcanics of Donovan Peak.

Hydrothermal alteration and mineralization. In general the volcanics of Donovan Peak, unlike the Divide Andesite, are not hydrothermally altered or mineralized. Intrusive plugs, in the NE/4, S7,T1N,R43E, here correlated with the flow-banded rhyolite unit, are hydrothermally altered and contain gold-silver mineralization. No hydrothermal alteration or mineralization is known to occur in either the rhyolite to rhyodacite unit or the dacite unit.

Rhyolite Domes and Pyroclastic Breccias (Tr); Rhyolite Dikes and Intrusive Breccias (Tri)

Rhyolite domes and associated marginal and pyroclastic breccias crop out in the northern part of the Southern Klondyke Hills. They cut through and overlie the Tonopah Summit Member of the Fraction Tuff, the volcanics of Donovan Peak, porphyritic rhyodacite, and the tuffs of Antelope Springs(?).

The domes are composed of pumiceous, pinkish-gray porphyritic rhyolite containing phenocrysts of quartz, alkali feldspar, plagioclase, and sparse biotite in a spherulitic matrix of quartz and alkali feldspar. Plagioclase (An_{20-25}) is distinctly subordinate in amount to quartz and alkali feldspar. The quartz and alkali feldspar phenocrysts range up to a maximum diameter of 4 mm. Quartz phenocrysts are corroded and vermicular.

The rhyolite in the domes is flow banded and commonly brecciated. The brecciated margins of the domes, in places, grade into pyroclastic breccias composed of pumice blocks and lapilli. The rhyolite is locally silicified and cut by numerous quartz veinlets. Plagioclase is commonly altered to calcite and is locally albitized.

A number of rhyolite dikes, plugs, and intrusive breccias are present in the area between the Southern Klondyke Hills and Donovan Peak. The rhyolite intrudes rocks of the Siebert Formation, the Tonopah Summit Member of the Fraction Tuff, and the Divide Andesite.

The intrusive rhyolite is commonly flow banded and has sparse phenocrysts of alkali feldspar, quartz, biotite, and plagioclase in a fine-grained felsitic to spherulitic matrix of quartz, alkali feldspar, and Fe-Ti oxides. Phenocrysts range from 0.5 to 1 mm in diameter, and normally constitute less than 5 percent of the rock. Much of the rhyolite has been hydrothermally altered; biotite is sericitized and plagioclase is altered to sericite and calcite, and there is abundant fine-grained sericite and calcite in the matrix. The original igneous alkali feldspar has been altered to hydrothermal potassium feldspar. Veinlets of quartz and calcite are present in much of the intrusive rhyolite.

A number of the rhyolite dikes and plugs are pervasively brecciated with breccia fragments ranging from a few millimeters to more than a meter in diameter. The intrusive breccias appear to have originated in several ways; some originated by the brecciation of partially congealed highly viscous rhyolite magma in conduits, others are of pyroclastic origin and occur in pipes formed by explosive vulcanism, and some appear to have originated by the injection of rhyolite magma into water-saturated sediments.

The rhyolite domes and intrusives have not been radiometrically dated. They are at least in part younger than the Divide Andesite and part of the Siebert Formation. They may be essentially contemporaneous with the Oddie Rhyolite and the flow-banded rhyolite of the volcanics of Donovan Peak.

Brougher Rhyolite (Tb, Tbd)

This rock unit was named the Brougher Dacite by Spurr (1905b, p. 44) for exposures of a rhyolite dome on Brougher Mountain in the Tonopah district. Albers and Stewart (1972, p. 37) noted that quartz latite was a more accurate petrographic name for the rock based on thin-section studies. Eleven chemical analyses (table 24) made in the course of the present study, indicate that the Brougher ranges from rhyolite to extreme alkali rhyolite in composition. We therefore rename the Brougher Dacite the Brougher Rhyolite to reflect more accurately the composition of the rock that composes this stratigraphic unit.

Distribution. The Brougher Rhyolite consists of a large number of protrusive (cumulo) domes (fig. 51) and associated flows that extend from the Southern Klondyke Hills on the south to the vicinity of Rays on the north. The major dome complexes of the Brougher occur in the area extending from the Divide district on the south to the Tonopah district on the north. Most of the higher hills in the Tonopah and Divide districts and in the intervening area are formed by domes of Brougher Rhyolite.

The Brougher Rhyolite intrudes and overlies rocks of the Siebert Formation, the volcanics of Lime Mountain, the Divide Andesite, and the Oddie Rhyolite. It is unconformably overlain by the trachyandesites of Red Mountain and Mud Lake, and the volcanics of Donovan Peak.

Lithology. The Brougher Rhyolite domes occupy the sites of volcanic vents that produced most of the pyroclastic rocks that occur in the Siebert Formation. The domes are surrounded by pyroclastic breccias, lapillistones, and tuffs in part deposited in a subaqueous environment. The coarser pyroclastic deposits occur in the immediate vicinity of the domes (fig. 51). It is apparent that the Brougher Rhyolite represents devolatilized magma emplaced as domes in explosion craters. The emplacement of the domes was preceded by extensive pyroclastic eruptions.

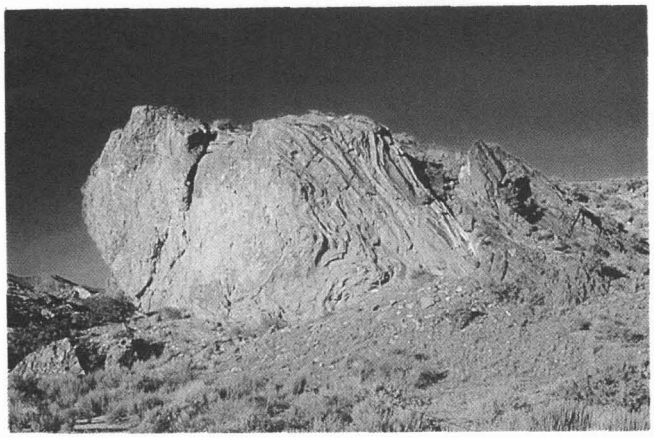
The margins of the domes usually consist of several

TABLE 24. Chemical analyses, Brougher Rhyolite.

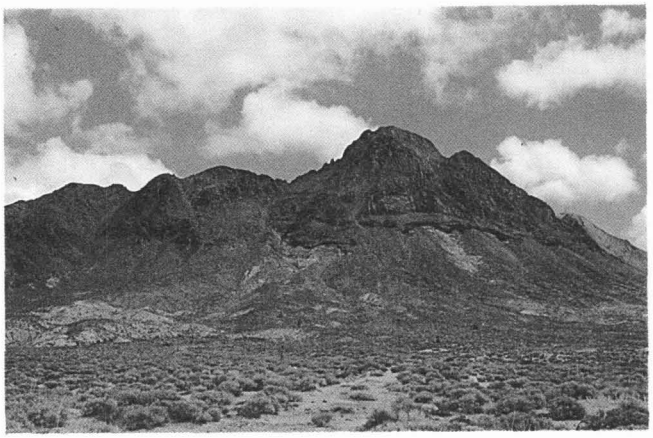
Sample	T165 Rhyolite	T171 Extreme alkali rhyolite	SS7 Alkali rhyolite	SS100 Rhyolite	SS103 Rhyolite	T109A Rhyolite	T106 Rhyolite	T10 Alkali rhyolite	T17A Alkali rhyolite	T17B Alkali rhyolite	T17C Extreme alkali rhyolite
Location number	1	2	3	4	5	6	7	8	9	10	11
Normalized oxide values											
SiO_2	74.0	78.0	77.0	73.7	73.8	72.8	73.7	74.8	78.2	78.2	77.3
Al_2O_3	13.0	12.2	12.2	13.4	13.7	14.1	14.2	13.8	10.8	10.9	12.0
Fe_2O_3	0.6	0.4	0.2	1.1	0.1	0.4	0.1	0.7	0.1	0.1	10.0
FeO	0.6	0.2	0.7	0.4	1.4	0.7	0.1	0.6	1.0	0.6	0.5
MgO	0.4	0.1	0.3	0.3	0.5	0.7	0.4	0.3	0.2	0.2	0.1
CaO	3.1	0.7	1.0	2.4	2.2	2.4	1.7	1.4	0.8	0.9	0.9
Na_2O	3.4	3.8	3.7	3.5	3.1	2.9	3.1	3.5	3.6	3.4	3.9
K_2O	4.8	4.4	4.7	4.9	5.0	5.7	5.4	4.6	5.1	5.2	4.6
TiO_2	0.2	0.1	0.2	0.3	0.3	0.3	0.3	0.3	0.1	0.5	0.5
MnO	0.01	0.01	0.04	0.03	0.03	0.01	0.01	0.03	0.03	0.05	0.02
Normative minerals											
Quartz	30.3	37.5	35.2	30.4	31.1	28.4	29.9	33.4	37.4	37.9	35.4
Corundum							0.1	0.6			
Orthoclase	28.4	26.3	28.0	28.8	29.5	33.8	31.8	27.3	30.7	30.7	27.1
Albite	29.1	31.8	31.0	29.5	25.8	24.5	26.5	29.3	27.4	27.2	33.3
Anorthite	5.8	3.4	2.7	6.6	9.1	8.5	8.5	7.0			1.7
Wollastonite	2.6			1.2							0.8
Acmite									0.3	0.3	
Sodium metasilicate									0.6	0.4	
Diopside	2.5	0.1	1.7	1.6	1.4	2.5			3.6	1.8	0.7
Hypersthene		0.2	0.7		2.6	1.1	2.5	0.9	0.4		
Magnetite	0.8	0.3	0.3	0.6	0.2	0.6	0.2	1.0			0.1
Hematite		0.2		0.7							
Ilmenite	0.4	0.3	0.4	0.5	0.5	0.6	0.6	0.5	0.2	1.0	1.0
Wollastonite (diopside)	1.3	0.1	0.9	0.9	0.7	1.3			1.7	0.9	0.4
Enstatite (diopside)	1.0	0.1	0.4	0.8	0.3	1.0			0.4	0.5	0.3
Ferrosilite (diopside)	0.2		0.5		0.4	0.3			1.4	0.3	0.1
Enstatite (hypersthene)		0.2	0.3		0.9	0.8	1.0	0.8	0.1		
Ferrosilite (hypersthene)			0.4		1.7	0.2	1.5	0.2	0.3		
Petrologic indices											
Differentiation index	87.8	95.6	94.2	88.7	86.3	86.7	88.2	90.0	94.9	95.8	95.8
Felsic-mafic index	17.9	61.6	39.6	19.5	19.9	19.4	24.7	27.5	40.0	49.6	53.6

Locations:
1. NW/4 S11,T1N,R43E
2. NE/4 S14,T1N,R42E
3. SW/4 S14,T2N,R42E
4. SE/ NE/4 S17,T1N,R43E
5. SW/4 SW/4 S8,T1N,R43E
6. Rhyolite Peak, T4N,R42E
7. Hill 5364, T4N,R42E
8. Brougher Mountain
9. N/2 S7,T2N,R43E
10. N/2 S7,T2N,R43E
11. N/2 S7,T2N,R43E

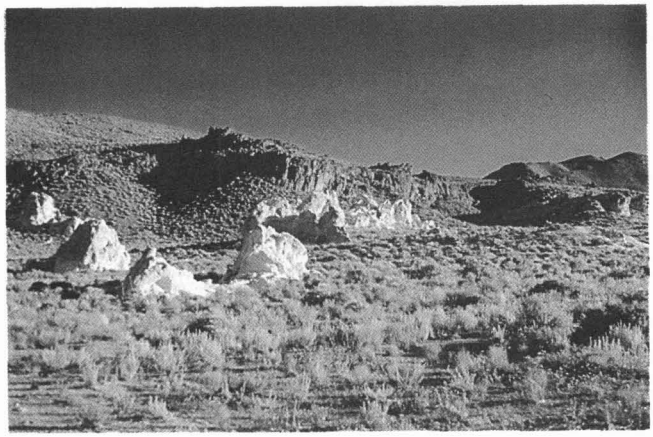
A. Rhyolite Peak, a protrusive dome of Brougher Rhyolite.



C. Flow banding in a Brougher Rhyolite dome.



B. Brougher Rhyolite flow dome complex. Mount Butler, Tonopah district.



D. Brougher Rhyolite dome (dark-colored rocks) surrounded by subaqueously deposited pyroclastic breccias and tuffs.

FIGURE 51. Brougher Rhyolite.

meters of glassy, highly brecciated rhyolite, which grades inward to a several-meter-thick zone of flow-banded, glassy, unbrecciated to slightly brecciated rock which in turn grades into devitrified flow-banded rhyolite that forms the main part of the dome. Flow banding in the domes is usually high-angle and dips inward from the margin of the domes. The flow banding is usually concentrically layered and the domes are therefore endogenous.

The Brougher domes are only slightly to moderately eroded and are remarkably well preserved. The marginal features of many of the domes are well exposed since the domes are more resistant to erosion than the surrounding rocks (fig. 51). It is obvious from the excellent state of preservation of the domes that the present cycle of erosion has not extended very far below the original level of emplacement of the domes.

Thick, stubby rhyolite flows are associated with several of the Brougher Rhyolite domes. Perhaps the best exposed of the Brougher flow-dome complexes is that of Mount Butler. At this locality a steeply dipping mass of intrusive rhyolite is traceable upwards into a subhorizontal flow of rhyolite more than 100 m thick, which caps the west side of the mountain. An erosional remnant of the same flow caps Siebert Mountain.

The Brougher Rhyolite is a light-gray, grayish-orange-pink, very pale-orange to yellowish-gray rock containing 15 to 20 percent phenocrysts of quartz, sodic plagioclase, alkali feldspar, and biotite in a fine-grained to glassy matrix (fig. 52). Thin-section modes of four samples of the Brougher Rhyolite are given in table 25.

Rhyolite in some of the Brougher domes contains trace amounts of clinopyroxene and/or hornblende. Allanite is present as an accessory mineral in rhyolite from Brougher domes in the Divide area.

Phenocrysts in the Brougher Rhyolite seldom exceed 2 to 5 mm in maximum diameter. Quartz phenocrysts are corroded and are frequently vermicular (fig. 52). Plagioclase is commonly oscillatory-zoned and ranges in composition from An_{35-40} in cores to An_{20} in rims. Some plagioclase phenocrysts have spongy, glass-charged cores.

Lithophysae and large gas cavities are abundant in the marginal parts of the domes. In the interior of the domes the devitrified rhyolite is microvesicular and usually spherulitic. The devitrification products of the glassy groundmass are principally cristobalite and alkali feldspar.

Chemical analyses of 11 samples of Brougher Rhyolite are shown in table 24. The chemical analyses show that the Brougher ranges from rhyolite to alkali rhyolite.

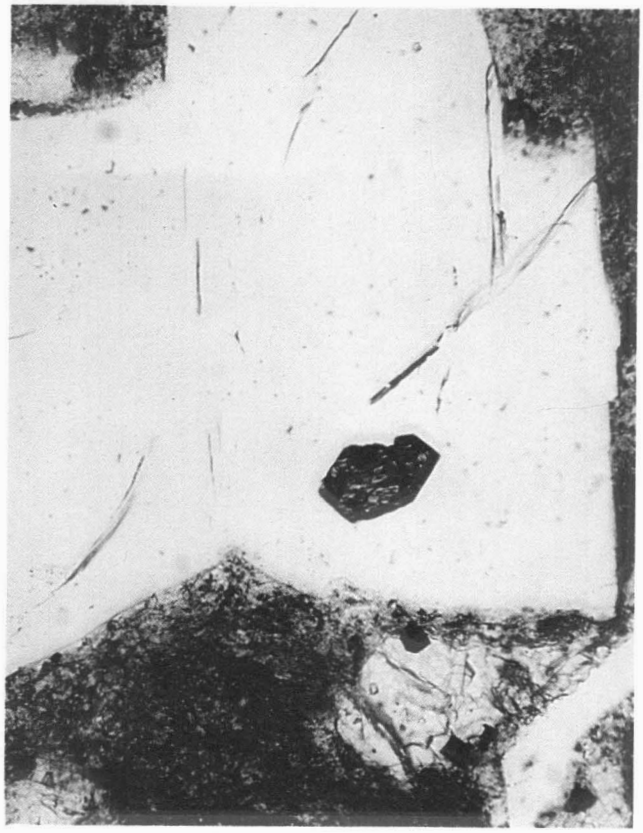
The Brougher Rhyolite is part of a distinct phase of intermediate to silicic vulcanism that commenced approximately 17 m.y. ago with the intrusion of the Oddie Rhyolite and Divide Andesite, continued with the emplacement of the Brougher domes, and ended with emplacement of the intrusive vent complex of the volcanics of Donovan

).2mm

A. Phenocrysts of oscillatory-zoned plagioclase, alkali feldspar, and corroded quartz in a matrix of perlitic glass.

2mm

B. Phenocrysts of plagioclase, alkali feldspar, corroded quartz, and biotite in a devitrified, spherulitic matrix of alkali feldspar and cristobalite.



0.1 mm

C. Zircon in a corroded quartz phenocryst.

FIGURE 52. Photomicrographs of Brougher Rhyolite.

Peak. The dominantly trachyandesitic volcanic rocks of the volcanics of Lime Mountain may also be related to this magmatic episode. The widespread occurrence of intermediate to silicic volcanic rocks ranging in age from about 17 to 15 m.y. old in the San Antonio Mountains in a belt 55 km long and up to 10 km wide indicates the presence of a subjacent magma chamber of batholithic dimensions beneath the San Antonio Mountains. The intermediate volcanic rocks, trachyandesite, dacite, and rhyodacite may represent the bulk composition of the batholith, probably granodioritic, while the quartz latite and rhyolite represent differentiates from the cupola portions of the magma chamber.

Olivine Trachyandesite (Tot)

A dike of olivine trachyandesite crops out in the NE/4 S11,T3N,R44E. The dike intrudes rhyodacite and is overlain unconformably by Quaternary alluvium.

TABLE 25. Phenocryst mineralogy, Brougher Rhyolite.

[Phenocrysts as volume percent of total crystals.]

	T109A	T171	T17A	T12
Quartz	18	41.2	32.6	36.3
Alkali feldspar	37	34.1	19.2	17.8
Plagioclase	33	23.2	43.6	43.3
Biotite	12	10.4	4.7	2.5

Locality Data

T17A: N/2 S7,T2N,R43E. T12: N/2 S24,T2N,R42E. T109A: Rhyolite Peak, T4N,R24E. T171: SE/4 S14,T1N,R42E.

Sphene, apatite, Fe-Ti oxides, and zircon occur as accessory minerals.

The dike rock is porphyritic, dark gray to black, and contains phenocrysts of plagioclase, olivine, augite, Fe-Ti oxides, and phlogopite in a fine-grained matrix of the same minerals, plus anhedral alkali feldspar. The plagioclase phenocrysts are euhedral to subhedral, average An_{60} in composition and are as long as 1 cm. Some have "spongy" cores with numerous matrix inclusions. The olivine phenocrysts are as much as 2 mm in diameter and are relatively little altered. A few olivine phenocrysts are rimmed by iddingsite. The augite is unaltered and occurs in phenocrysts up to 2 mm in diameter. Phlogopite constitutes 1 to 2 percent of the phenocrysts and has ragged, resorbed margins. Apatite occurs as an accessory mineral.

The dike is probably genetically related to the trachyandesites of Thunder Mountain and is assumed to be of the same age, or about 16 m.y.

Trachyandesite of Thunder Mountain (Tti, Tta, Tt)

Thunder Mountain in T4N,R44E is the vent area for a series of trachyandesite flows approximately 160 m thick that compose the bulk of the mountain. The actual vent area, which forms the central portion of Thunder Mountain, consists of an intrusive trachyandesite plug and associated scoria. The trachyandesite flows do not extend further than 3 km from Thunder Mountain (fig. 53).

The trachyandesite flows are composed of porphyritic to microporphyritic dark gray, basaltic-appearing rock containing phenocrysts of plagioclase (An_{55-60}), olivine, augite, and rare hornblende in a fine-grained matrix of plagioclase microlites, olivine and pyroxene granules, Fe-Ti oxides, and interstitial potassium feldspar. Plagioclase phenocrysts in some flows are as much as 2 mm long, but are usually no more than 0.5 to 1 mm long. They are oscillatory-zoned. Olivine is commonly partially to completely altered to iddingsite and is usually less than 1 mm in diameter. Hornblende is altered to Fe-Ti oxides and augite, and usually only pseudomorphs remain. The plagioclase microlites are somewhat more sodic (An_{45-50}) than most of the plagioclase phenocrysts.

Armstrong and others (1972, p. 27) give the following petrographic description of one of the Thunder Mountain flows:

> "Under the microscope it is seen to be microporphyritic with small (<1 mm) microphenocrysts of zoned plagioclase (An_{45-51}) constituting 20 percent of the rock, iddingsitized olivine (10%), augite (10%), hornblende rimmed with iron oxide (about 5%) and magnetite (about 3%). The groundmass (50%) consists of microlites of the above minerals with a small amount (about 3% of the groundmass) of brown glass."

They classify the rock as an olivine trachyandesite.

A chemical analysis of one of the flows is given in table 26. According to the classification system used in this report the rock is a trachyandesite. The trachyandesite is essentially unaltered and the only secondary minerals seen were minor amounts of carbonate and opal lining vesicles.

Armstrong and others (1972, p. 27) report a Sr^{87}/Sr^{86} initial ratio of .7052±.0007 for one of the trachyandesite flows of Thunder Mountain. This ratio is well within the range of Sr^{87}/Sr^{86} ratios (.7035–.706) typical of late Cenozoic basalts from the northwestern Great Basin (McKee and others, 1972, p. D101) and rules out any major degree of crustal contamination of the parent basaltic magma of the trachyandesite lavas.

A whole rock K-Ar age of 16.1±0.5 m.y. (table 4) was determined on one of the trachyandesite flows of Thunder Mountain. Armstrong and others (1972, p. 27) obtained a K-Ar whole age of 18.9±1.5 m.y. on another trachyandesite flow from Thunder Mountain. The trachyandesite of Thunder Mountain is not in contact with rocks younger than the tuffs of Rye Patch (>25 m.y.) so either K-Ar age, 18.9 m.y. or 16.1 m.y. could be correct. However, since

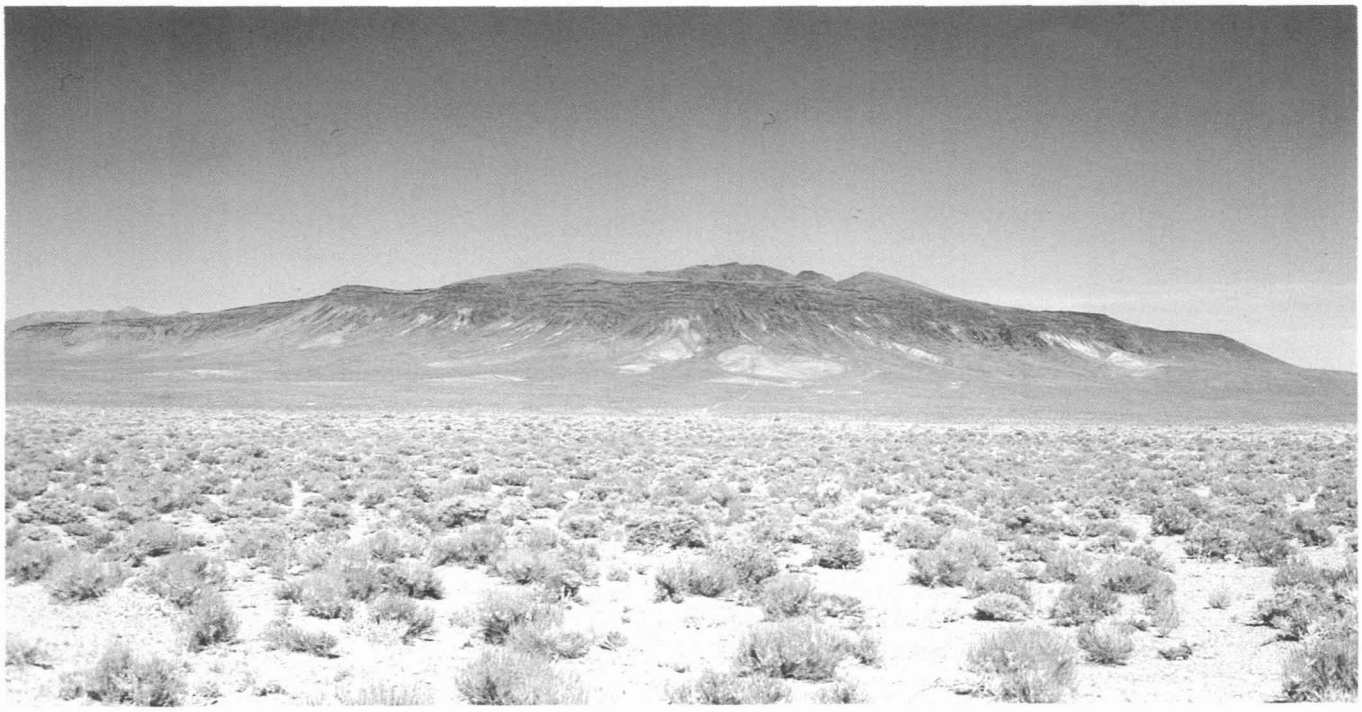


FIGURE 53. Thunder Mountain. Several trachyandesite flows overlying ash-flow tuff. Vent area in high, central part of mountain.

TABLE 26. Chemical analyses, trachyandesite of Thunder Mountain

Sample	T82 SE/4 S23,T4N,R44E Trachyandesite
Normalized oxide values	
SiO_2	54.6
Al_2O_3	18.7
Fe_2O_3	5.9
FeO	2.7
MgO	2.9
CaO	8.1
Na_2O	3.9
K_2O	1.9
TiO_2	1.2
MnO	0.14
Normative minerals	
Quartz	5.8
Orthoclase	11.2
Albite	33.0
Anorthite	27.9
Wollastonite	
Diopside	9.5
Hypersthene	2.7
Magnetite	5.7
Hematite	2.0
Ilmenite	2.3
Wollastonite (diopside)	5.1
Enstatite (diopside)	4.4
Ferrosilite (diopside)	
Enstatite (hypersthene)	2.7
Ferrosilite (hypersthene)	
Petrologic indices	
Differentiation index	50.0
Felsic-mafic index	3.1

very similar trachyandesite flows in the San Antonio Mountains have K-Ar ages of about 15 to 16 m.y. (Armstrong and others, 1972, p. 26, and table 4 this report), we believe that the 16.1 m.y. age reported herein is probably correct.

Gravel (Tg)

A unit of weakly lithified gravel and sandstone which overlies the Tonopah Formation and underlies the trachyandesite of Red Mountain is exposed in the northern part of the San Antonio Mountains. The outcrop area is approximately 2 km^2, located in two areas: 1 km west of Black Rock Wash (S16,21,28,33,T4N,R43E), and about 1.5 km northeast of Black Mountain (S19,30,T4N,R43E). The unit has a total thickness of 200 m or less, and is apparently lenticular, as it is absent below the trachyandesite of Red Mountain elsewhere in the map area. The gravel unit forms areas of low relief and poor exposure; commonly pebbles, cobbles, and boulders occur as a lag gravel on a soil-covered surface.

At the few good exposures of the unit, coarse, poorly sorted gravel beds are interlayered with light-brown, pebbly, epiclastic volcanic sandstone. Similar sand-size material also makes up the framework of the gravel beds. The pebble- to boulder-size clasts consist of Tertiary ash-flow tuffs and accidental lithic fragments from these tuffs, in addition to chert and quartzite of the Valmy(?) Formation and Tertiary trachyandesite. Sand-size grains also consist of lithic fragments of chert, trachyandesite, and rhyolite as well as quartz and feldspar. The cobbles and boulders are often subrounded and can be up to 15 cm in diameter at eastern exposures of the gravel near Black Rock Wash. The western exposures (northeast of Black Mountain) appear to contain more coarse gravel beds and larger boulders.

The gravel unit is locally derived, probably from erosion of the Valmy(?) and Tonopah Formations exposed in the central San Antonio Range to the west of the gravel outcrops. Exposures of the Tonopah Summit Member of the Fraction Tuff directly east of the gravel outcrops may also have supplied detritus. The gravel unit consists of fluvial deposits, probably from in and along stream channels. It is probably only slightly older than the trachyandesite of Red Mountain, as it appears conformable with the lower flows of that unit and contains cobbles of similar trachyandesite near its top.

Trachyandesite of Red Mountain (Ttri, Ttra, Ttrf, Ttrs)

The name "trachyandesite of Red Mountain" is here applied to an assemblage of dark, sparsely porphyritic lavas and minor associated sedimentary, intrusive, and pyroclastic rocks that crop out in the central and eastern parts of the San Antonio Mountains. The name is derived from Red Mountain, a prominent local landmark about 10 km due north of Tonopah. Red Mountain is one of the vent areas for the trachyandesite lavas (fig. 54).

The trachyandesite of Red Mountain is locally as much as 300 m thick and forms the bulk of the rock outcrops on the eastern side of the San Antonio Mountains north of Tonopah. The trachyandesite lavas were erupted from several vents in the central portion of the range (shown on pl. 1) and the erosional remnants of the flows now form a sequence of eastward-dipping cuestas (fig. 55). Vent areas for the trachyandesite lavas are distinguishable by locally thick accumulations of scoria cored by intrusive trachyandesite.

Lithology. The trachyandesite of Red Mountain is composed predominantly of lava flows which have an average thickness of 3 to 4 m. The flow rock is dark gray, brownish gray, or grayish red and has a basaltic appearance. The rocks are sparsely porphyritic or microporphyritic and typically contain scattered phenocrysts on microphenocrysts of plagioclase, olivine, pyroxene, Fe-Ti oxides, and, more rarely, hornblende, in a pilotaxitic to intergranular matrix of the same minerals. Glomeroporphyritic texture is common in some flows (fig. 56). Some flows contain sparse phenocrysts of pyroxene up to 3 mm, olivine up to 2 mm, and plagioclase up to 3 mm in diameter, but usually the phenocryst minerals do not exceed 1.5 mm in diameter. In one typical sample, 5 percent of the rock is phenocrysts, of olivine (3.6%) and augite (1.4%). The groundmass consists of microlites of plagioclase (An_{60-65}) olivine, pyroxene, Fe-Ti oxides, potassium feldspar, and apatite. The

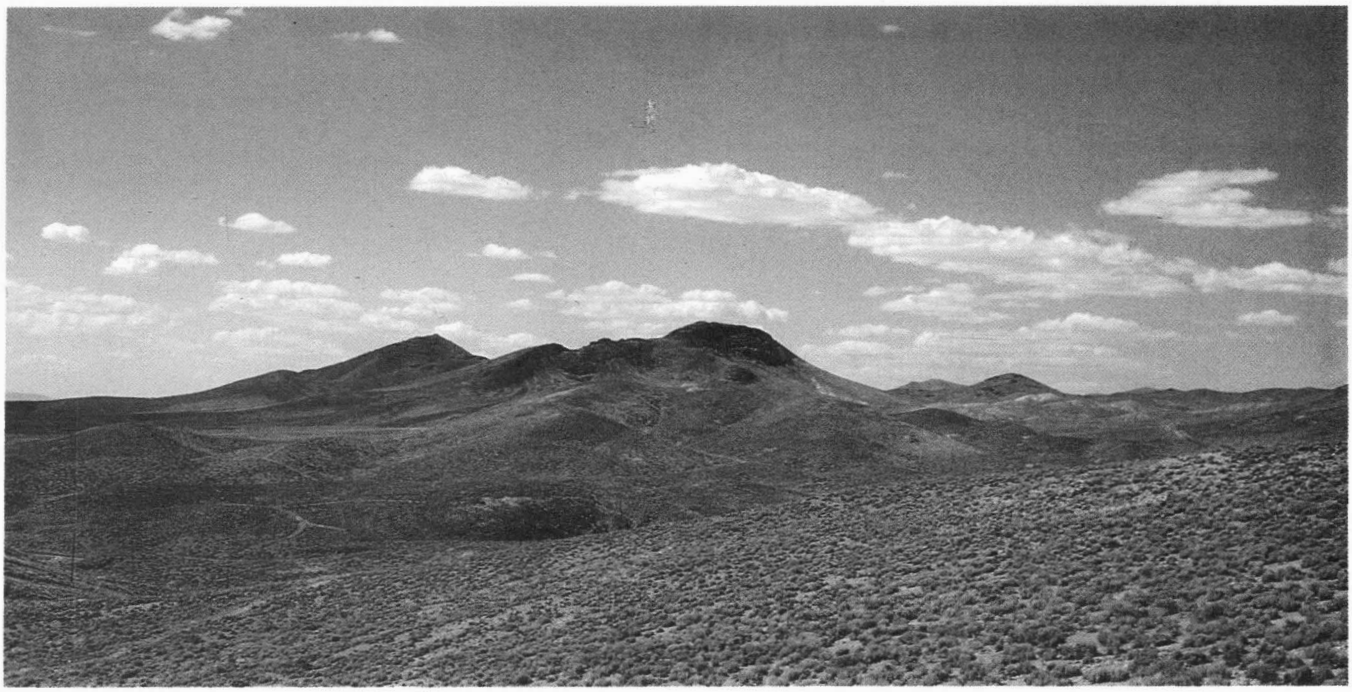
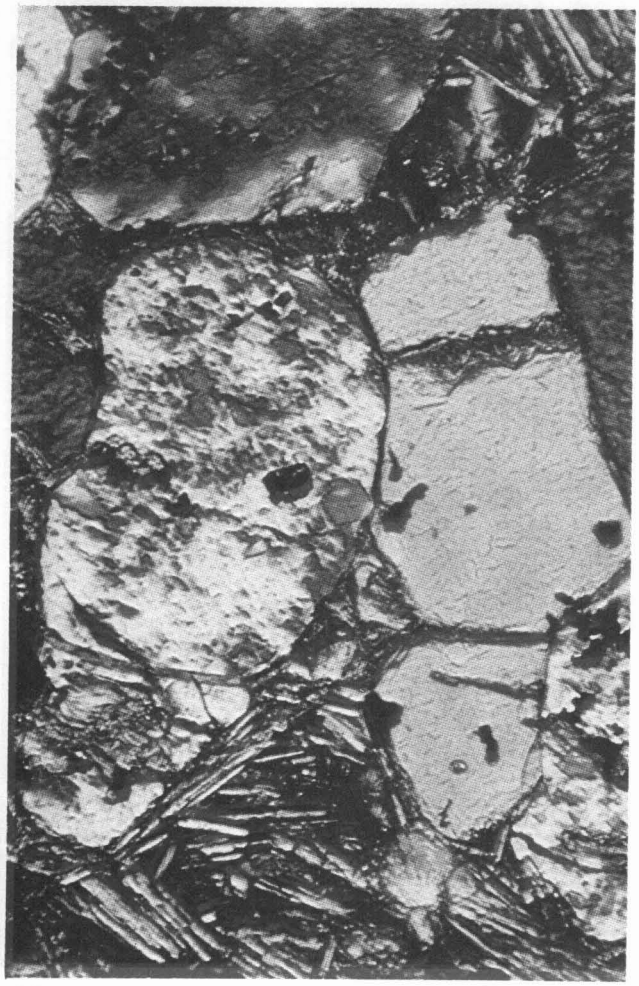


FIGURE 54. Red Mountain, a trachyandesite vent north of Tonopah. Rocks in foreground are Fraction Tuff and dacitic flows of the Mizpah Formation.

FIGURE 55. Flows of the trachyandesite of Red Mountain overlying tuffaceous lacustrine deposits of the Siebert Formation, Booker Mountain.



1 mm

FIGURE 56. Trachyandesite of Red Mountain. Photomicrograph shows olivine phenocrysts with glomeroporphyritic texture.

texture is pilotaxitic. In another sample the groundmass constitutes 63 percent of the rock, while phenocrysts of plagioclase (An_{60-65}) constitute 22.2 percent, augite 6.5 percent, olivine 5.7 percent, and Fe-Ti oxides 2.7 percent. The plagioclase phenocrysts average 0.5 mm in diameter, olivine phenocrysts 1 mm, and some augite phenocrysts are as large as 2.5 mm. The matrix contains microlites of plagioclase, olivine, augite, Fe-Ti oxides, potassium feldspar, and apatite. Many of the plagioclase phenocrysts in the trachyandesite flows have spongy, corroded cores charged with glass. The plagioclase ranges in composition from An_{45} to An_{65}.

Some of the flows contain phenocrysts of hornblende which is largely oxidized to Fe-Ti oxides. A few flows contain microphenocrysts of phlogopite. Hypersthene is also present in some flows, but is rare compared to diopsidic augite, which is the main pyroxene in the trachyandesite flows. Most of the flows in the lower part of the sequence in the area east of the block of Paleozoic rocks between Rays Wells and Red Mountain contain xenocrystic quartz which is surrounded by reaction coronas of pyroxene. Possibly the xenocrystic quartz was derived from Paleozoic quartzites.

Olivine in the trachyandesite flows is commonly altered partially or completely to iddingsite or, more rarely, serpentine minerals. Most of the flows, except for the olivine alteration, are fresh, but a few flows show deuteric alteration effects. The mild deuteric alteration has resulted in some marginal replacement of plagioclase by calcite and the partial replacement of mafic minerals by chloritic minerals. Chlorophaeite and calcite also occur as amygdaloidal minerals in these rocks.

Petrographic descriptions of two trachyandesite flows from the trachyandesite of Red Mountain are also given in an article by Armstrong and others (1972, p. 26).

Tuffaceous sedimentary rocks are found at a few localities at the base of the sequence of flows. These tuffs are water-reworked and predominantly andesitic.

Chemical analyses of eight samples of lava flows of the trachyandesite of Red Mountain are listed in table 27; six of the rocks are trachyandesites, one is on the latite-trachyandesite boundary, and one is andesite. Figure 57, a plot of the differentiation index versus silica content, shows that the chemically analyzed rocks plot primarily in the trachyandesite field.

Armstrong and others (1972, p. 26) report two whole rock K-Ar ages from trachyandesite flows that are here included in the trachyandesite of Red Mountain. Their sample Y-5780 yielded a K-Ar age of 15.8±2 m.y. and their sample Y-57233 a K-Ar age of 17.9±3 m.y. (The location given by them for sample Y-57233 is incorrect. The sample is probably from S6,T3N,R43E.)

A K-Ar age of 14.7±0.5 m.y. on hornblende from one of the trachyandesite flows of Red Mountain was obtained in this study (table 4). We believe it is more nearly correct than either of the whole rock ages listed above. The 17.9 m.y. whole rock age is certainly too old since the trachyandesite of Red Mountain overlies the volcanics of Lime Mountain which are no older than 16.8±0.5 m.y. In addition, the trachyandesite flows overlie rocks of the Siebert Formation which are approximately 16 to 16.5 m.y. old. Therefore, we believe that the trachyandesite flows of Red Mountain are approximately 15 m.y. old.

Rhyolite of Millers (Trmi, Trmf)

The name rhyolite of Millers is given to irregularly shaped masses of intrusive rhyolite and minor related flow rock that crop out just to the south of the site of Millers (pl. 1). The total outcrop area of the rhyolite is about 2.5 km^2. The rhyolite intrudes silicic porphyry dike (Tsp, Tspb), porphyritic dacite (Tdm), and the Tonopah Summit Member of the Fraction Tuff.

The rhyolite of Millers is pale orange, pale red or pinkish gray, porphyritic, flow banded, and spherulitic (fig. 58). Prominent gas cavities up to several centimeters in diameter are a common feature of the rhyolite. The rhyolite contains moderately abundant phenocrysts, averaging 1 mm in diameter, of quartz, alkali feldspar, plagioclase, and sparse biotite. The quartz is corroded and vermicular. Alkali feldspar phenocrysts are fresh and euhedral. Plagioclase is invariably altered to calcite or replaced by quartz and adularia; biotite is altered to aggregates of hematite and calcite. The outlines of hornblende phenocrysts (now Fe-Ti oxides) were seen in some samples.

The spherulitic matrix of the rhyolite consists of alkali feldspar, quartz, and irregular areas of secondary calcite. Numerous quartz veinlets are present in the rhyolite and both quartz and hematite occur as linings in gas cavities. Disseminated pyrite is present in much of the rhyolite.

TABLE 27. Chemical analyses, trachyandesite of Red Mountain.

Sample	T123B Trachyandesite	T133 Latite	T192 Andesite	T195A Trachyandesite	SS64A Trachyandesite	SS51 Trachyandesite	T77A Trachyandesite	SS65 Trachyandesite
Location number	1	2	3	4	5	6	7	8
				Normalized oxide values				
SiO_2	57.7	57.5	54.4	55.9	55.4	58.8	58.1	57.0
Al_2O_3	17.3	17.1	18.8	17.8	17.0	16.9	18.2	18.3
Fe_2O_3	2.7	6.9	5.8	4.6	5.0	2.7	5.3	6.1
FeO	4.8	1.1	1.9	3.9	3.1	4.0	2.1	1.0
MgO	3.5	1.9	4.1	2.9	4.1	3.1	2.4	1.8
CaO	6.4	6.4	8.7	7.4	7.5	6.8	6.7	7.6
Na_2O	3.6	3.7	3.4	3.8	3.7	3.7	3.6	4.0
K_2O	2.9	4.1	1.7	2.3	3.0	3.0	2.6	2.9
TiO_2	1.2	1.2	1.0	1.3	1.2	0.9	0.9	1.4
MnO	0.14	0.04	0.16	0.15	0.13	0.13	0.08	0.04
				Normative minerals				
Quartz	6.4	6.6	5.7	6.3	3.9	7.8	10.6	7.0
Orthoclase	17.3	24.4	10.3	13.8	17.6	17.8	15.6	17.1
Albite	30.7	31.4	29.1	32.3	31.1	31.2	30.8	33.6
Anorthite	22.2	17.9	30.6	24.7	21.2	20.1	25.4	23.6
Wollastonite		0.5						0.5
Diopside	7.9	10.0	9.8	9.7	12.4	10.5	6.0	9.5
Hypersthene	9.4		5.6	4.1	4.6	6.6	3.2	
Magnetite	3.9	0.1	3.6	6.6	6.8	3.9	4.3	
Hematite		6.9	3.4		0.3		2.4	
Ilmenite	2.2	2.3	1.9	2.4	2.3	1.8	1.8	2.2
Wollastonite (diopside)	4.1	5.4	5.3	5.1	6.6	5.4	3.2	5.1
Enstatite (diopside)	2.5	4.7	4.6	3.8	5.7	3.4	2.8	4.4
Ferrosilite (diopside)	1.3			0.9		1.7		
Enstatite (hypersthene)	6.2		5.6	3.4	4.6	4.4	3.2	
Ferrosilite (hypersthene)	3.2			0.8		2.1		
				Petrologic indices				
Differentiation index	54.4	62.3	45.1	52.5	52.6	56.7	57.0	57.7
Felsic-mafic index	3.7	4.0	2.9	3.3	3.2	4.0	3.9	3.9

Locations: 1. W2 S26,T4N,R43E
2. S34,T4N,R42E
3. SW/4 NW/4 S12,T4N,R43E
4. NW/4 S25,T4N,R44E
4. NW/4 S2,T3N,R42E
6. 600 m NNE of Rays Wells
7. NE/4 S31,T5N,R44E
8. NE/4 S3,T3N,R42E

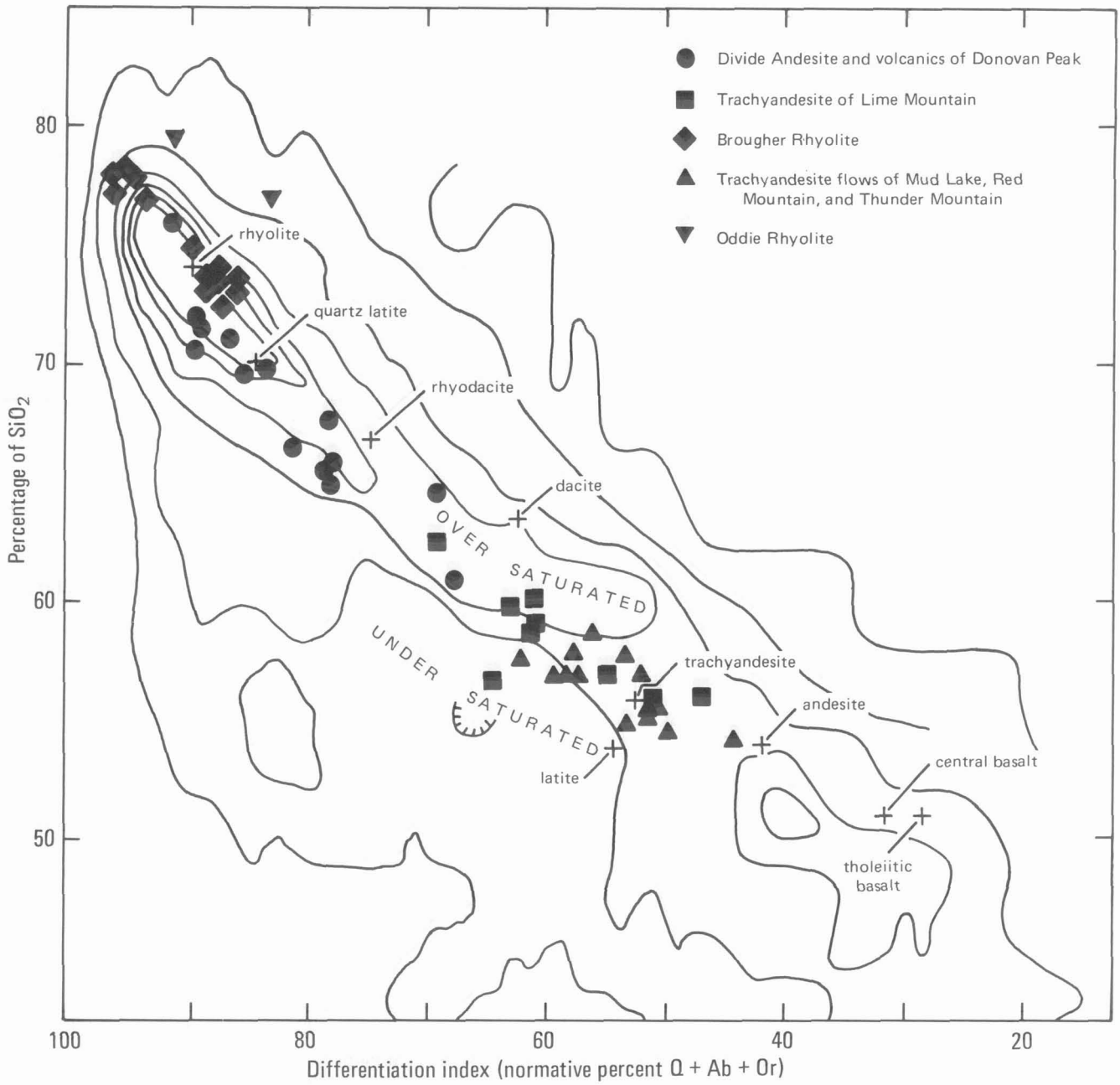


FIGURE 57. Differentiation index diagram. Named points in silica field are average extrusive rocks. *From Nockolds (1954).* Contours show the abundances of 5,000 igneous rocks plotted from Washington's tables. *From Thornton and Tuttle (1960, p. 674).*

Alkali feldspar from the rhyolite of Millers yielded a K-Ar age of 14.7 m.y. (table 4).

Rhyolite, northeastern Lone Mountain (Trl)

A rhyolite mass 3.5 km south of Millers intrudes silicic porphyry (Tsp, Tspb), dacite (Tclm), the Tonopah Summit Member of the Fraction Tuff, Harkless Formation, and quartz monzodiorite. The intrusive plug is 1.5 km by 0.4 to 0.5, and is elongate in a northwest direction. The rhyolite plug is located to the southeast of most of the outcrops of the rhyolite of Millers, but they are in contact along the southern margin of the plug. We believe that this rhyolite is closely related to the rhyolite of Millers, but the exact age relationship is unknown.

The rhyolite forms rugged, light-gray to light-purplish-gray outcrops. The rock is porphyritic and contains phenocrysts of alkali feldspar, quartz, plagioclase, and biotite. Most phenocrysts are 1 to 3 mm long, although some alkali feldspar phenocrysts are as long as 5 mm. Near its intrusive margins the rhyolite has somewhat smaller phenocrysts and is flow banded. Alkali feldspar and quartz phenocrysts are corroded. Accessory minerals are Fe-Ti oxides and zircon. The matrix, originally glassy, is now a pale-brown, finely devitrified mass of cristobalite, alkali feldspar, and finely disseminated opaque material. The matrix is quite commonly spherulitic, and curving microfractures from the originally perlitic matrix are visible in thin section. Biotite and alkali feldspar are usually quite fresh, although plagioclase may be partially altered to quartz, alkali feldspar, and calcite. Pyrite(?) was noted in a few samples.

This rhyolite is distinguished from the rhyolite of Millers by larger alkali feldspar phenocrysts and more abundant

0.1mm

FIGURE 58. Photomicrograph, rhyolite of Millers. Typical spherulitic texture. Alkali feldspar phenocryst in center of photo.

biotite. Also the rhyolite of Millers is considerably more altered and iron stained, and the mafic minerals are usually destroyed. No hornblende was noted in any thin sections of this rhyolite, while some samples of the rhyolite of Millers have the ghostlike outlines of original hornblende phenocrysts.

Trachyandesite of Mud Lake (Ttm, Ttmi)

Trachyandesite lavas and two intrusive plugs, here informally termed the trachyandesite of Mud Lake, crop out over an area of several km^2 on the west and southern edges of Mud Lake and extend out the map area to the south. The lava flows unconformably overlie rocks of the Siebert Formation, the volcanics of Donovan Peak, and the Brougher rhyolite; they are overlain by Quaternary alluvial deposits.

The trachyandesite lavas occur as subhorizontal erosional remnants that cap ridges and form mesalike topography in the area adjacent to Mud Lake. The lavas appear to have originally covered most of the southeastern part of the Mud Lake quadrangle. Individual flows are 3 to 10 m thick. The maximum exposed thickness of the unit is 110 m.

The trachyandesite is dark gray to medium dark gray on fresh surfaces and weathers to brownish gray. Most of the flow rock contains scattered small (<1 mm) phenocrysts of plagioclase (An_{65}) and olivine (altered to iddingsite) in a trachytic matrix (fig. 59) of plagioclase, augite, olivine, alkali feldspar, Fe-Ti oxides, and apatite. Sparse phenocrysts of phlogopite occur in a few of the flows; olivine is sparse to absent in others. Much of the phenocrystic plagioclase has "spongy" calcic cores surrounded by clear, more sodic rims. The groundmass of the trachyandesite in some of the flows consists of palagonite and nontronite; the texture is intersertal.

Two trachyandesite plugs, which may have served as feeders for some of the lavas, are present in the vicinity of Mud Lake. One of the plugs is located in the extreme southeastern part of the map area on the edge of Mud Lake; the other crops out in S21,22,T1N,R43E.

The trachyandesite that forms the plugs is a dense, fine-grained brownish-gray rock which contains sparse phenocrysts of plagioclase (An_{50-60}, 1 to 2 m), hornblende (1 mm), and augite (1 mm) in a groundmass of plagioclase, augite, Fe-Ti oxides, apatite, and brown glass. The hornblende is rimmed by Fe-Ti oxide (fig. 59). Chemical analyses of the trachyandesites are listed in table 28. None of the trachyandesite flows within the map area were dated, but very similar trachyandesite flows, 11 km to the south of the map area (basalt of Black Cap Mountain), have been dated by the whole rock K-Ar method at 12.0 m.y. (Armstrong and others, 1972, p. 26). It seems quite probable that the trachyandesite flows of the Mud Lake area are part of this same magmatic episode and are also about 12.0 m.y. old. The stratigraphic evidence indicates that the trachyandesite flows are younger than the volcanics of Donovan Peak (minimum age about 15 m.y.).

Rhyolite of Klondyke (Trk)

Rhyolite plugs and dikes that crop out in the Klondyke Hills are here named the rhyolite of Klondyke. They are the youngest known volcanic rocks in the map area. The rhyolite intrudes Paleozoic rocks, the Monotony(?) Tuff, the tuffs of Antelope Springs(?), the Fraction Tuff, and pyroxene andesite. The largest plug (fig. 60) is about 1.6 km by 0.5 km in dimension. The dikes are commonly 3 to 10 m thick and locally more than 100 m thick.

The plugs and dikes consist of very light-gray, flow-banded, sparsely porphyritic rhyolite that contains phenocrysts of quartz (1 to 2 m) alkali feldspar (1 mm), plagioclase (1 to 2 m), and rare biotite (1 mm) in a felsitic matrix of quartz and alkali feldspar. The quartz phenocrysts are corroded and vermicular.

Nearly all of the rhyolite of Klondyke is hydrothermally altered. Plagioclase and biotite are altered to sericite. Despite the extensive hydrothermal alteration no economic metallic mineralization was found in or associated with the rhyolite of Klondyke in the course of this study.

Alkali feldspar from the intrusive plug in the NW/4, S31,T1N,R43E yielded a potassium-argon age of 10.5 m.y. (table 4).

Travertine South of Klondyke (Tts)

There is a small circular outcrop of calcareous spring deposits about 250 m in diameter in C W/2 S5,T1S,R42E. The small size and circular outline indicate deposition by a spring, possibly a warm spring. The travertine lies on the Cambrian Emigrant Formation and Tertiary tuffs of Antelope Springs(?). It consists predominantly of calcite, although Chipp (1969) reports a few aragonite nodules.

0.2mm

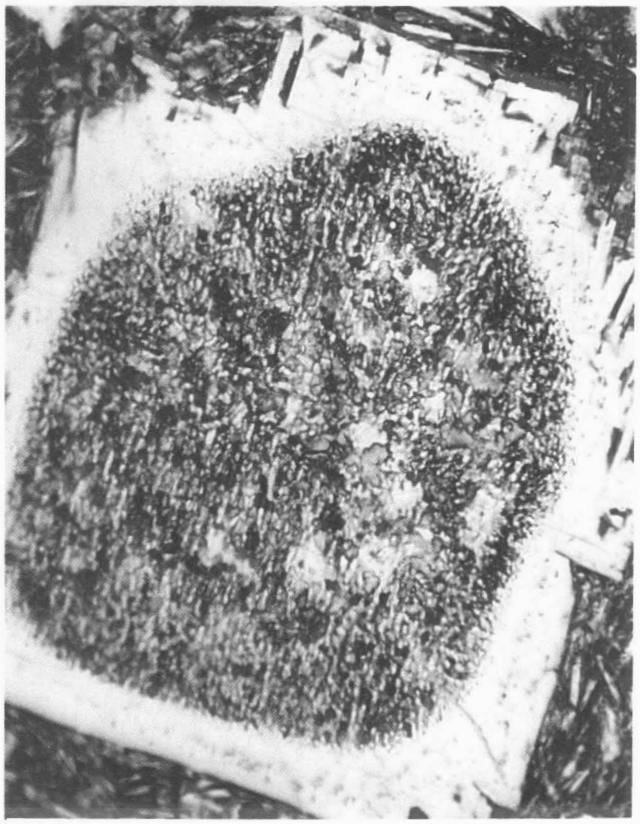
A. Trachytic texture formed by alignment of plagioclase laths.

0.2mm

C. Plagioclase and hornblende phenocrysts from intrusive plug of trachyandesite of Mud Lake.

1mm

B. Olivine phenocrysts altered to iddingsite and plagioclase.



0.1mm

D. Typical "spongy" core of plagioclase phenocryst (An_{70}) surrounded by rim of clear, more sodic plagioclase (An_{55}).

FIGURE 59. Photomicrographs, trachyandesite of Mud Lake.

TABLE 28. Chemical analyses, trachyandesite of Mud Lake.

Sample	T159 Trachyandesite	T160 Trachyandesite	T166 Trachyandesite
Location number	1	2	3
	Normalized oxide values		
SiO_2	57.1	54.7	57.2
Al_2O_3	18.3	18.2	17.7
Fe_2O_3	5.5	5.7	3.2
FeO	1.8	2.9	3.0
MgO	2.6	2.6	3.5
CaO	7.7	7.7	7.9
Na_2O	3.4	3.9	3.6
K_2O	2.5	2.9	2.6
TiO_2	1.1	1.3	1.1
MnO	0.05	0.57	0.10
	Normative minerals		
Quartz	10.0	3.9	6.6
Orthoclase	14.6	17.0	15.4
Albite	28.4	32.9	30.8
Anorthite	27.5	23.7	24.2
Wollastonite			
Diopside	4.4	11.4	11.7
Hypersthene	2.6	1.2	4.5
Magnetite	2.6	6.2	4.5
Hematite	3.7	1.4	
Ilmenite	2.2	2.4	2.1
Wollastonite (diopside)	4.5	6.1	6.2
Enstatite (diopside)	3.9	5.3	4.8
Ferrosilite (diopside)			0.7
Enstatite (hypersthene)	2.6	1.2	4.0
Ferrosilite (hypersthene)			0.5
	Petrologic indices		
Differentiation index	57.6	53.7	52.8
Felsic-mafic index	3.6	3.3	3.6

Locations: 1. NE/4 S15,T1N,R43E
2. SW/4 S15,T1N,R43E
3. SE/4 S15,T1N,R43E

It is younger than the tuffs of Antelope Springs(?), and seems, from its undissected appearance, to be late Tertiary or Quaternary in age.

Speculations and Conclusions on Petrologic Evolution and Tectonic Setting of Tertiary Vulcanism in the Tonopah Region

Volcanic rocks of Tertiary age erupted from sources within the San Antonio Mountains, the southern Monitor Range, the Klondyke Hills, and Lone Mountain (pl. 1) prior to 17 m.y. ago are part of a suite of intermediate to silicic composition that includes extensive ash-flow sheets. Between 17 and 10 m.y. ago voluminous flows of trachyandesite and large amounts of rhyolite were erupted from numerous vents in this same area, and a cogenetic sequence of dacite, rhyodacite, quartz latite, and rhyolite was emplaced as a large vent complex centered on Donovan Peak. No major ash-flow sheets were emplaced during this time interval in the Tonopah area.

Tertiary volcanic rocks in western Nevada (including the Tonopah area) older than about 17 m.y. are generally considered to be calc-alkaline (Ekren and others, 1971; Noble, 1972). Relatively few chemical analyses of fresh or slightly altered rock from the volcanics of this age group in the Tonopah area are available because of pervasive hydrothermal alteration. However, selected analyses of the least altered rocks, plotted on an alkali-lime index diagram (figs. 9; 61A, B), indicate that these volcanic rocks are also calc-alkaline. The overall chemistry and petrography of these intermediate to silicic rocks also indicate that they belong to a calc-alkaline suite (see criteria used by Noble, 1972; and Lipman and others, 1972).

FIGURE 60. Rhyolite of Klondyke. Rhyolite plug intruding Paleozoic metasedimentary rocks (dark-colored outcrops).

The thesis is presented in recent papers (Lipman and others, 1972; Noble, 1972; McKee, 1971) that mid-Tertiary calc-alkaline volcanic rocks in the western United States are genetically related to the subduction of oceanic lithosphere in a trench along the western continental margin of North America. The calc-alkaline volcanic rocks in the Tonopah area are included by Noble (1972) in this subduction-related suite.

The eruption of significant volumes of mafic trachyandesite in the Tonopah area commencing about 17 m.y. ago coincides with the initiation of crustal extension in the central Great Basin. Christiansen and Lipman (1972) conclude that the onset of crustal extension in the western United States was accompanied by a genetically related transition from calc-alkalic to "fundamentally basaltic" vulcanism characterized in many areas by a bimodal suite of basalt and high-silica alkaline rhyolite. In the Tonopah area, however, intermediate to silicic volcanic rocks of the Divide Andesite and the volcanics of Donovan Peak were erupted during the same interval as trachyandesite and high-silica rhyolite, and the question naturally arises whether the trachyandesite and high-silica rhyolite in the Tonopah area represent a bimodal basalt-rhyolite suite, or whether they are related to the same source magma that produced the cogenetic volcanic suite of the Divide Andesite and the volcanics of Donovan Peak. Because trace element and Sr isotope data for these rocks are largely lacking, the major-element chemistry of these rocks provides the only clues for an answer. Silica variation diagrams for the trachyandesites, Brougher Rhyolite, Divide Andesite, and the volcanics of Donovan Peak are shown in figures 62A-H.

On the Na_2O–SiO_2 diagram the trend line for the Divide and Donovan Peak rocks plot well above trend lines for the trachyandesites and the Brougher Rhyolite. The trend lines for the Divide and the Donovan Peak rocks on the K_2O/Na_2O and MgO–SiO_2 diagram plot below the trend lines for the trachyandesites and the Brougher Rhyolite. Although these trend lines might be expected to show some degree of curvilinearity in a simple differentiation sequence, we feel that the deviation of the trend lines, in particular that for Na_2O, of the Divide Andesite and the volcanics of Donovan Peak from those of the trachyandesites and the Brougher Rhyolite, is pronounced enough that it precludes the interpretation that these rocks were derived by differentiation from a common source magma. We believe, therefore, that more than one magma source was involved in the generation of these volcanic rocks. An examination of these diagrams, in particular those for Na_2O–SiO_2, K_2O/Na_2O–SiO_2, and MgO–SiO_2, has led us to the conclusion that it is highly unlikely that these volcanic rocks are related in any simple way to a common source magma, and that it is more probable that multiple magma sources were involved.

We believe that the trachyandesite flows are part of a "fundamentally basaltic" suite related to crustal extension. The Brougher Rhyolite is probably part of the Christiansen and Lipman (1972) basalt-rhyolite association, although its chemistry and petrography do not fit some of their criteria for rhyolite of this association (higher Na/K ratio than calc-alkaline rhyolite, Na-rich alkali feldspar, $SiO_2 > 72$ percent, may contain ferroaugite and fayalite). The Brougher has an SiO_2 content of 73 to 78 percent, but it contains both plagioclase and K-rich alkali feldspar and has a Na_2O/K_2O ratio of 0.69, which is similar to typical calc-alkaline rhyolite (fig. 63). Perhaps the Brougher Rhyolite was derived from a magma source transitional between calc-alkalic and basaltic (Noble, 1972).

The volcanics of Donovan Peak and the Divide Andesite were erupted from the same vent complex and form relatively linear differentiation trends on the variation diagrams (figs. 62A–H). On the alkali-lime index (fig. 61B) the projected intersection of the CaO trend and Na_2O+K_2O trend would plot in the alkalic-calcic field. We believe that the Divide Andesite and the volcanics of Donovan Peak are part of the last stages of the subduction related calc-alkalic vulcanism that commenced in this area over 30 m.y. ago and may, with the Brougher Rhyolite, represent a magma suite transitional between calc-alkalic and basaltic magmatism. These somewhat speculative conclusions are in harmony with Noble's (1972) concept that in the western and southern parts of the Great Basin the early stages of basalt-rhyolite bimodal vulcanism were superimposed on the latter stages of subduction-related calc-alkalic and transitional vulcanism.

Interpretative History of Tertiary Vulcanism in the San Antonio Mountains

1. 35 to 30 m.y.
   Eruption of ash-flow and ash-fall tuffs of the Tonopah Formation and the tuff of Ralston Valley, probably from a caldera source in or near the San Antonio Mountains.
2. 26 to 24 m.y.
   Emplacement of rhyolite flow-dome complex of the Tonopah Formation. Eruption of the tuffs of Rye Patch from the Big Ten Peak center with associated caldera collapse. Emplacement of the Monotony Tuff and the tuffs of Antelope Springs(?) and White Blotch Spring(?).
3. 24 to 23 m.y.
   Emplacement of a batholith of granodiorite to quartz monzonite magma of regional extent (250 km^2?) with development of major volcanic centers (Tonopah, Goldfield) over cupolas of the batholith. Eruption of intermediate lavas from stratavolcanoes, forming such units as the Mizpah Formation in the Tonopah area.
4. 21 to 18 m.y.
   Cooling and differentiation of the batholith with

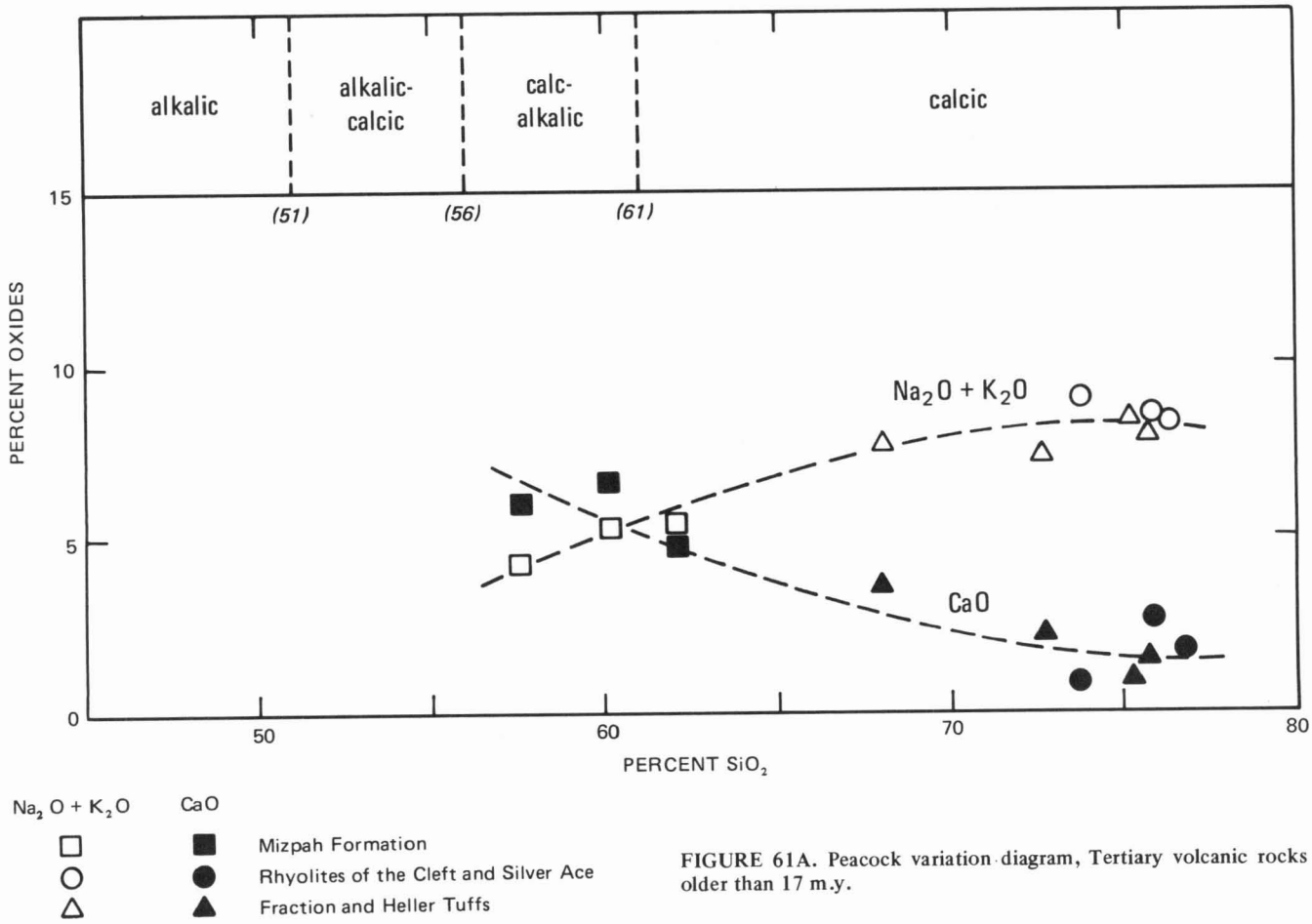


FIGURE 61A. Peacock variation diagram, Tertiary volcanic rocks older than 17 m.y.

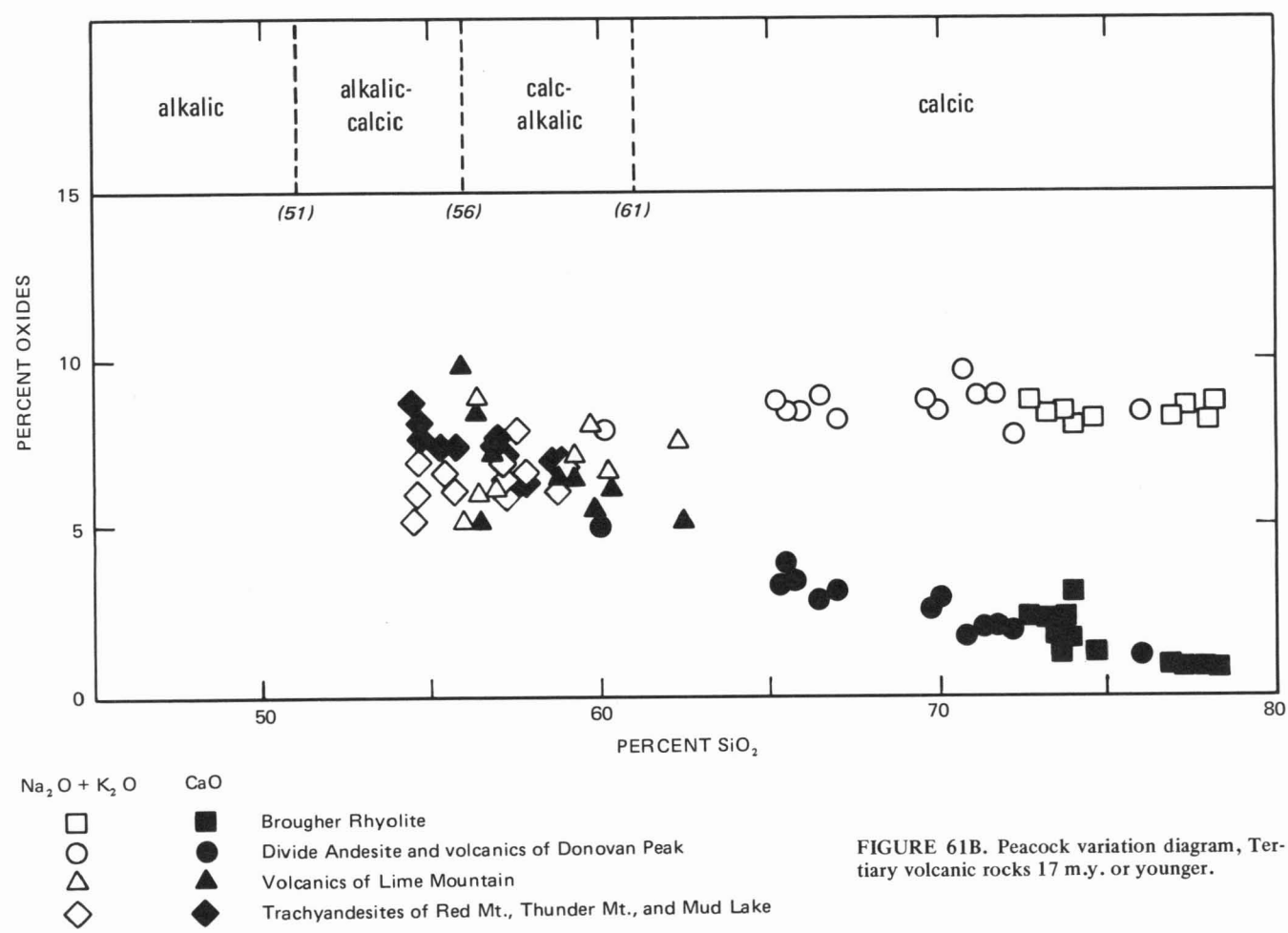


FIGURE 61B. Peacock variation diagram, Tertiary volcanic rocks 17 m.y. or younger.

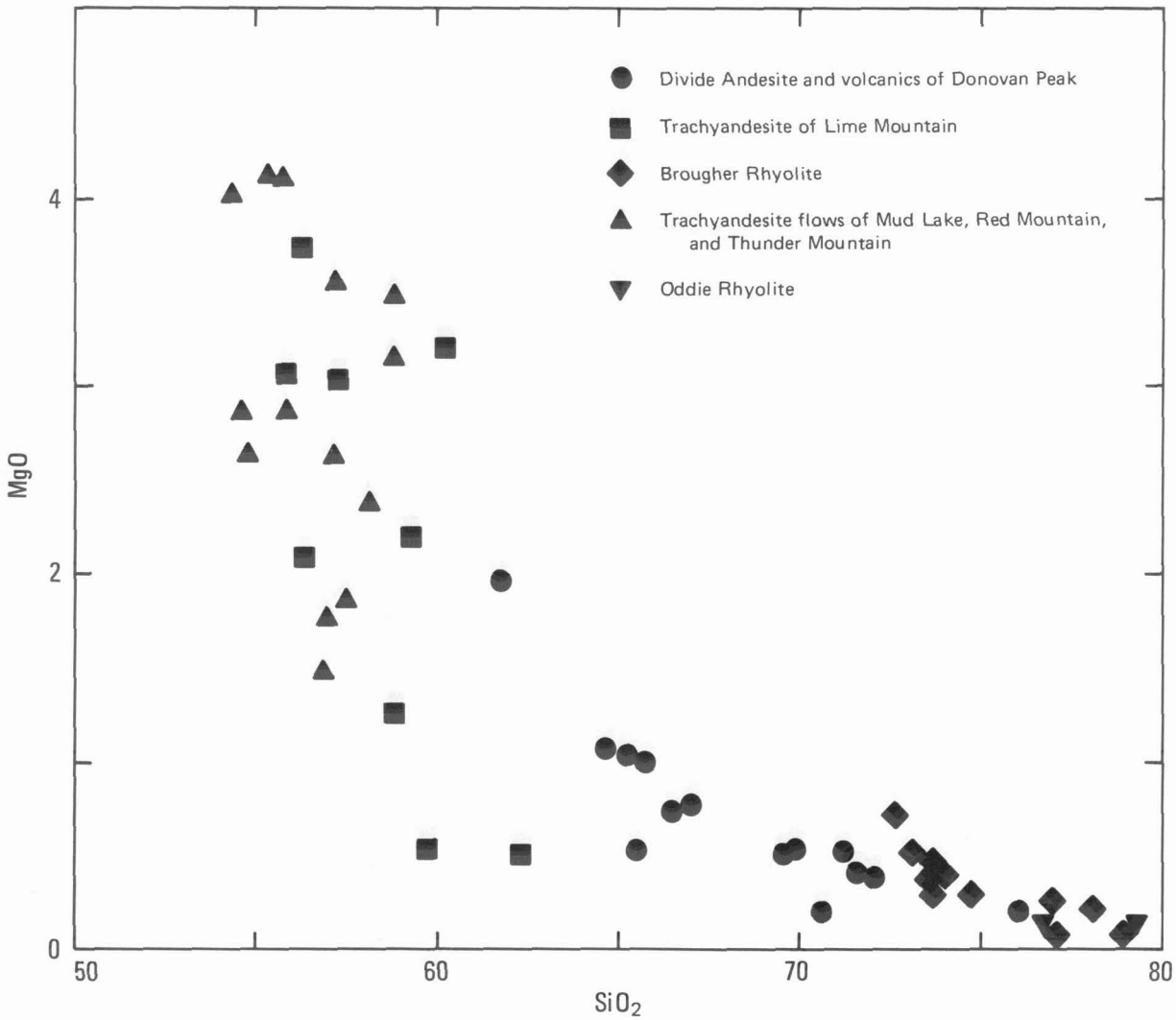


FIGURE 62A. MgO–SiO_2 variation diagram of Divide Andesite and volcanics of Donovan Peak; trachyandesite of Lime Mountain; Brougher Rhyolite; trachyandesite flows of Mud Lake, Red Mountain, and Thunder Mountain; Oddie Rhyolite.

silicic magma concentrated in cupolas. Intrusion of rhyolite plugs, dikes, and sills (West End Rhyolite, Extension Breccia). Eruption of the Tonopah Summit Member of the Fraction Tuff with associated caldera collapse in the area between the Tonopah district and the Southern Klondyke Hills. Emplacement of landslide debris from the caldera walls into the caldera during eruption. Eruption of the King Tonopah Member of the Fraction Tuff, additional caldera subsidence(?), large landslide blocks from caldera walls incorporated in ash-flow tuff of King Tonopah Member. Emplacement of rhyolite flow-dome complexes and associated pyroclastic rocks (rhyolite of the Cleft). Period of vein formation and silver-gold mineralization in Tonopah district.

5. 17 m.y.
   Emplacement of the Heller Tuff, probably from an eastern source. Beginning of major extensional faulting.
6. 17 to 16.5 m.y.
   Renewed emplacement of granodioritic magma beneath the San Antonio Mountains with major eruptions of dacite to rhyodacite lavas in the northern portion of the range (porphyritic dacite of Davis and others, 1971). Emplacement of a shallow granodioritic pluton beneath the Divide district centered in the area of caldera collapse associated with the Fraction Tuff. Intrusion of the Oddie Rhyolite and Divide Andesite. Hydrothermal alteration and gold-silver mineralization in the Divide district.
7. 16.5 to 14 m.y.
   Extensive pyroclastic eruptions from numerous vents concentrated in and adjacent to area of Fraction caldera collapse, pyroclastic debris from eruptions incorporated into rocks of the Siebert Formation. Emplacement of Brougher Rhyolite as domes and flows into pre-existing explosion centers and emplacement of vent complex of volcanics of Donovan Peak. Extrusion of trachyandesite flows in Siebert Formation. Eruption of trachyandesite and olivine trachyandesite flows from numerous vents (trachyandesite of Red Mountain and Thunder Mountain). Final phase of vulcanism in Tonopah district.
8. 12 to 10 m.y.
   Extrusion of trachyandesite of Mud Lake and intrusion of rhyolite of Klondyke. Cessation of vulcanism in San Antonio Mountains.

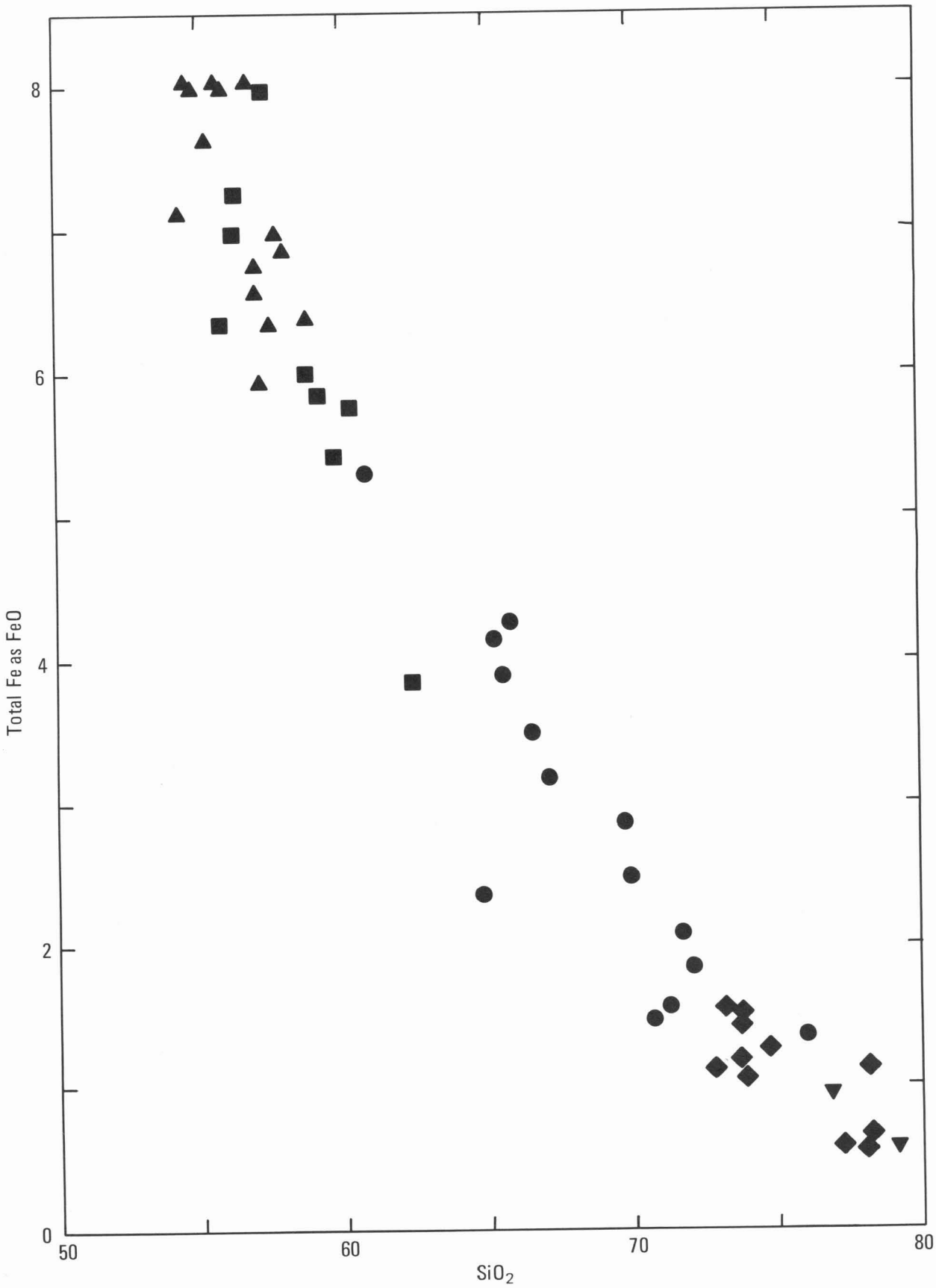


FIGURE 62B. $FeO-SiO_2$ variation diagram.

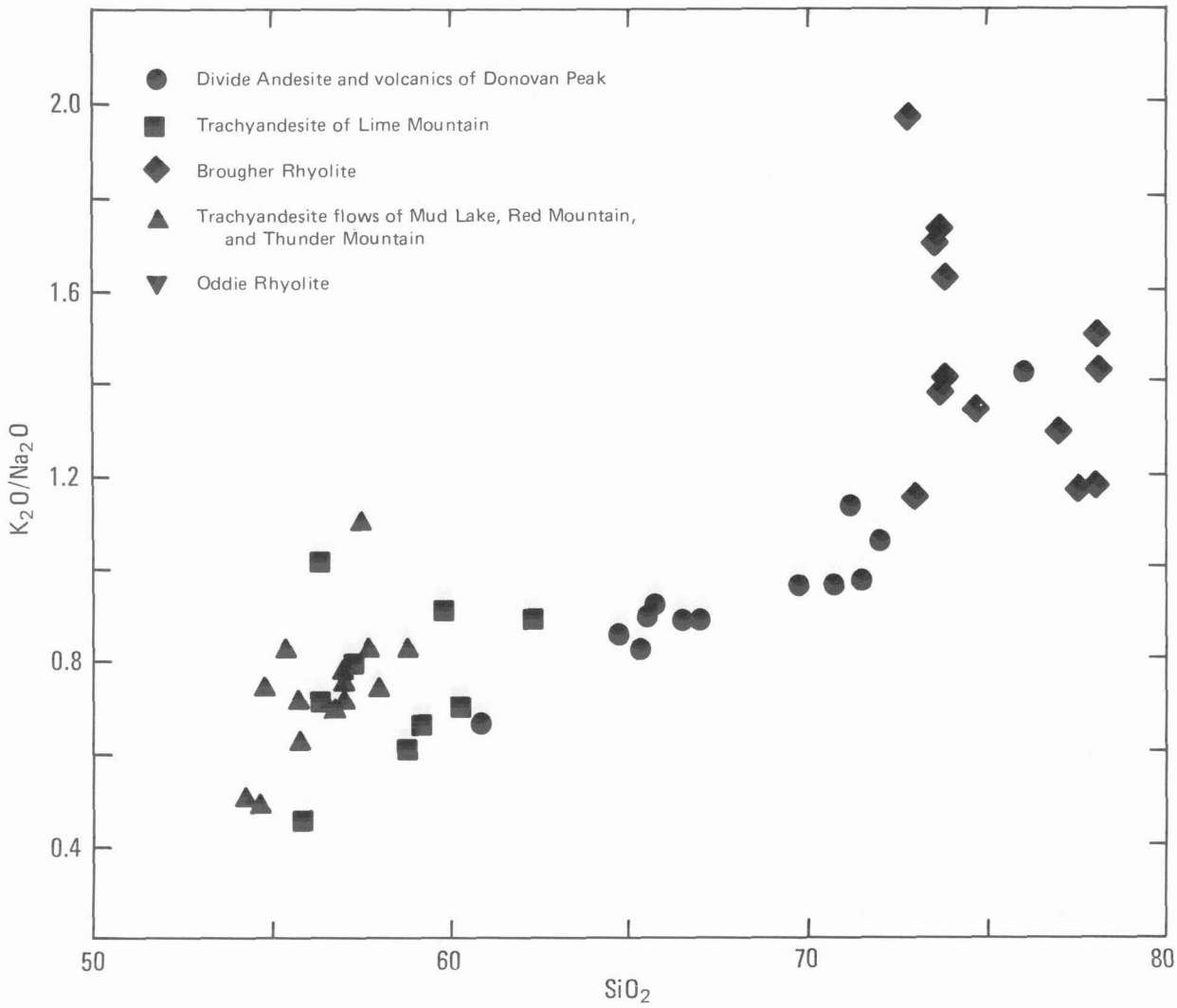


FIGURE 62C. K_2O/Na_2O-SiO_2 variation diagram of Divide Andesite and volcanics of Donovan Peak; trachyandesite of Lime Mountain; Brougher Rhyolite; trachyandesite flows of Mud Lake, Red Mountain, and Thunder Mountain; Oddie Rhyolite.

QUATERNARY DEPOSITS

The Quaternary deposits in the mapped area include a variety of alluvial, colluvial, eolian, and playa deposits as well as mine dumps and mill tailings. Approximately 55 percent of the area on plate 1 consists of Quaternary deposits, predominantly in areas of relatively lower elevation and relief. Good cross sections of the units are seldom encountered, and thickness information is very limited. Much of the subdivision of the Quaternary in the mapped area was based on the surface morphology and topographic position of the deposits as seen on aerial photographs. In general, geomorphic relations are used to establish the relative ages of the deposits, which are predominantly Pleistocene and Holocene. Pliocene deposits are probably present at depth in the valley areas.

Older Gravel Deposits (Qog)

A few, small, poorly exposed areas of older gravel deposits were mapped in the extreme southern part of the area, about 3.8 km southeast of the mining camp of Klondyke. They overlie Tertiary pyroxene andesite of the northern Goldfield Hills and appear to underlie older alluvial deposits, which are described in the following section of this report. They are poorly sorted, but contain many rounded pebbles of chert, pyroxene andesite and welded tuff; the pebbles represent many of the Paleozoic and Tertiary rock types exposed in the near by bedrock area. The thickness of the exposed older gravel deposits is not more than approximately 3 to 6 m. This unit is probably at least as old as Pleistocene and may be older. Because of the limited extent of the unit beneath other more extensive alluvial deposits, we believe it is probably a stream deposit.

Older Alluvial Deposits (Qoa)

Older alluvial deposits are exposed adjacent to and extending out from bedrock areas in Ralston, Big Smoky, and Montezuma Valleys, and consist mainly of fan and pediment deposits of poorly sorted material ranging in size from boulders to clay. However, the coarser size fractions predominate in many areas especially near the mountain-range bedrock outcrops. The surface of the older alluvium is more dissected by small to large intermittent streams than is the surface of the overlying younger fan and pediment deposits. In SE/4 S6,T2N,R42E caliche-cemented

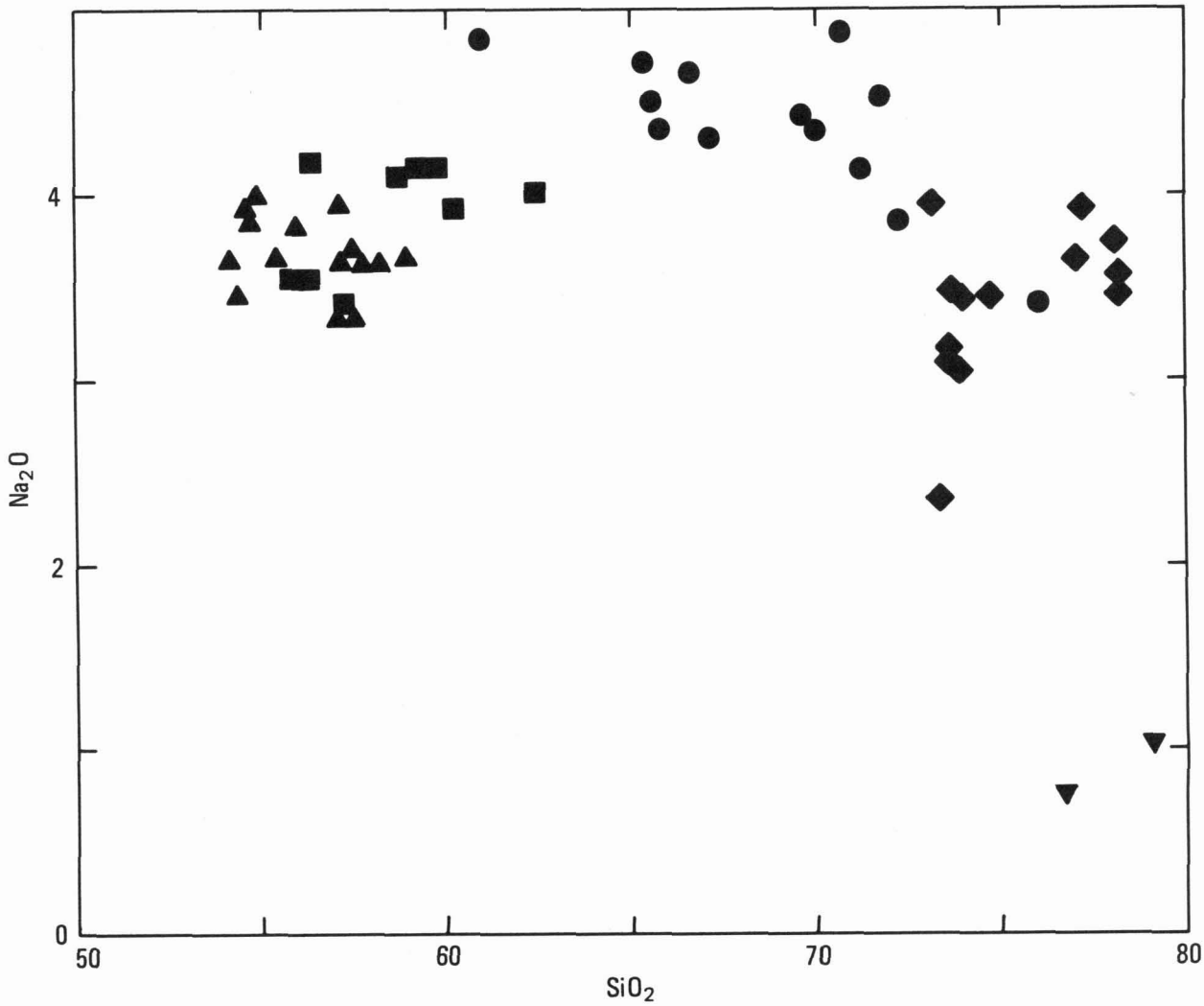


FIGURE 62D. Na_2O-SiO_2 variation diagram.

conglomerate in the older alluvial deposits is well exposed (fig. 64), and caliche zones are probably present elsewhere in the subsurface.

The rock fragments in the older alluvial deposits represent units in the mountain areas which have supplied the material. The deposits exposed along the east flank of Lone Mountain consist predominantly of poorly sorted alluvial fan material derived from the granitic Lone Mountain pluton. These deposits partially cover the Precambrian and Paleozoic metasedimentary rocks surrounding the Lone Mountain pluton. The older alluvial deposits on the west flank of the San Antonio Mountains contain a great variety of volcanic rock fragments and occur here as relatively thin pediment gravels.

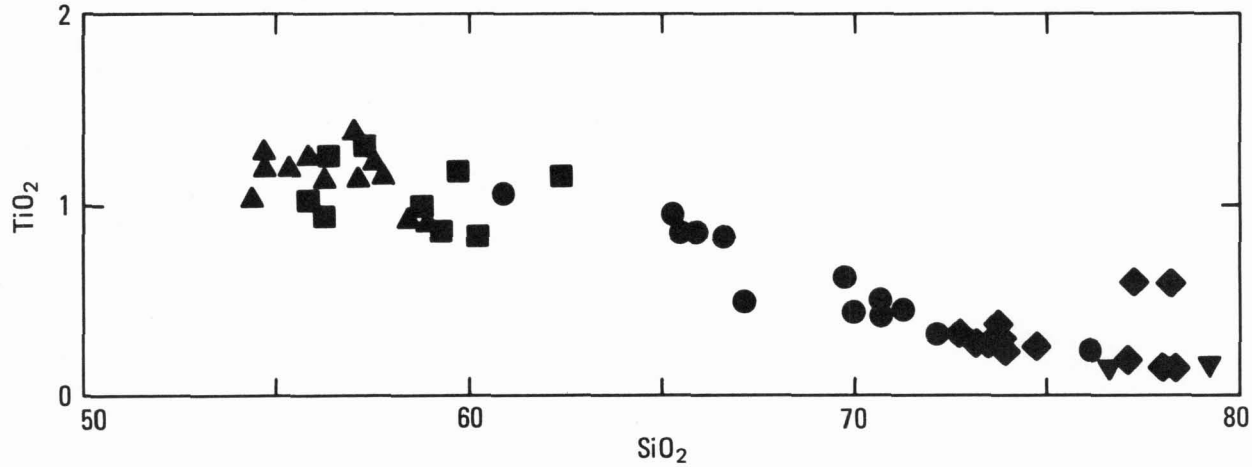


FIGURE 62E. TiO_2-SiO_2 variation diagram.

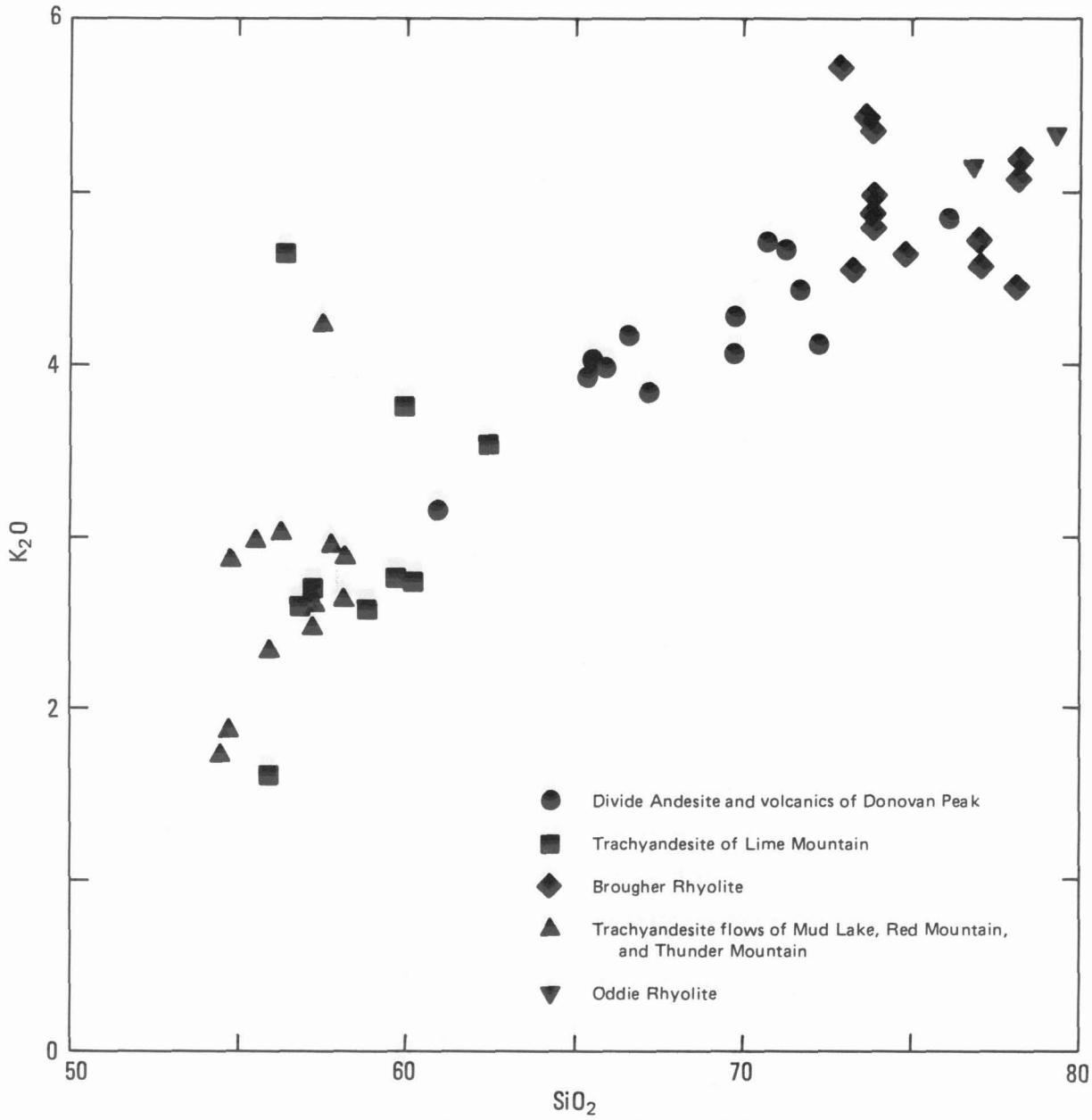


FIGURE 62F. K_2O-SiO_2 variation diagram of Divide Andesite and volcanics of Donovan Peak; trachyandesite of Lime Mountain; Brougher Rhyolite; trachyandesite flows of Mud Lake, Red Mountain, and Thunder Mountain; Oddie Rhyolite.

Fan and Pediment Deposits (Qfp)

The most areally extensive unit of Quaternary deposits in the mapped area consists of undissected or slightly dissected younger fan and pediment deposits. In general, these deposits are in the process of formation and often cover fans of older alluvial deposits. The separation of older alluvial deposits from these fan and pediment deposits is based mainly on photogrammetric interpretations and is often quite difficult. The unit is probably both Holocene and Pleistocene in age, and includes some gravel beaches and beach ridges northwest of Lone Mountain that were formed by Pleistocene Lake Tonopah (Meinzer, 1917), probably at its high stand in the Late Wisconsin Stage, approximately 12,000 years ago.

The fan deposits are primarily in alluvial and coalescing fans (bajadas) on the east flank of Lone Mountain and on part of the eastern flank of the San Antonio Mountains. Pediments are more commonly developed on the western flank of the San Antonio Mountains (fig. 64) and to the west of Thunder Mountain. The fan and pediment deposits are found in upland areas and are generally of low to moderate gradient. The contact with valley-bottom, ephemeral-stream deposits is often transitional, and is generalized on plate 1.

The fan and pediment deposits are a heterogeneous mixture of predominantly silt, sand, and gravel from local sources. Some colluvium is included in the unit in areas near bedrock outcrops or in small, upland alluvial basins within the mountain ranges themselves. The pediment surfaces are usually of lower gradient than the fans, and can be recognized by the common occurrence of inliers of older bedrock units up to several miles basinward from the main mountain range. Large bajada areas, on the other hand, are often developed adjacent to the mountain front faults, where more rapid changes in gradient occur. The direction of transport of most fan and pediment deposits

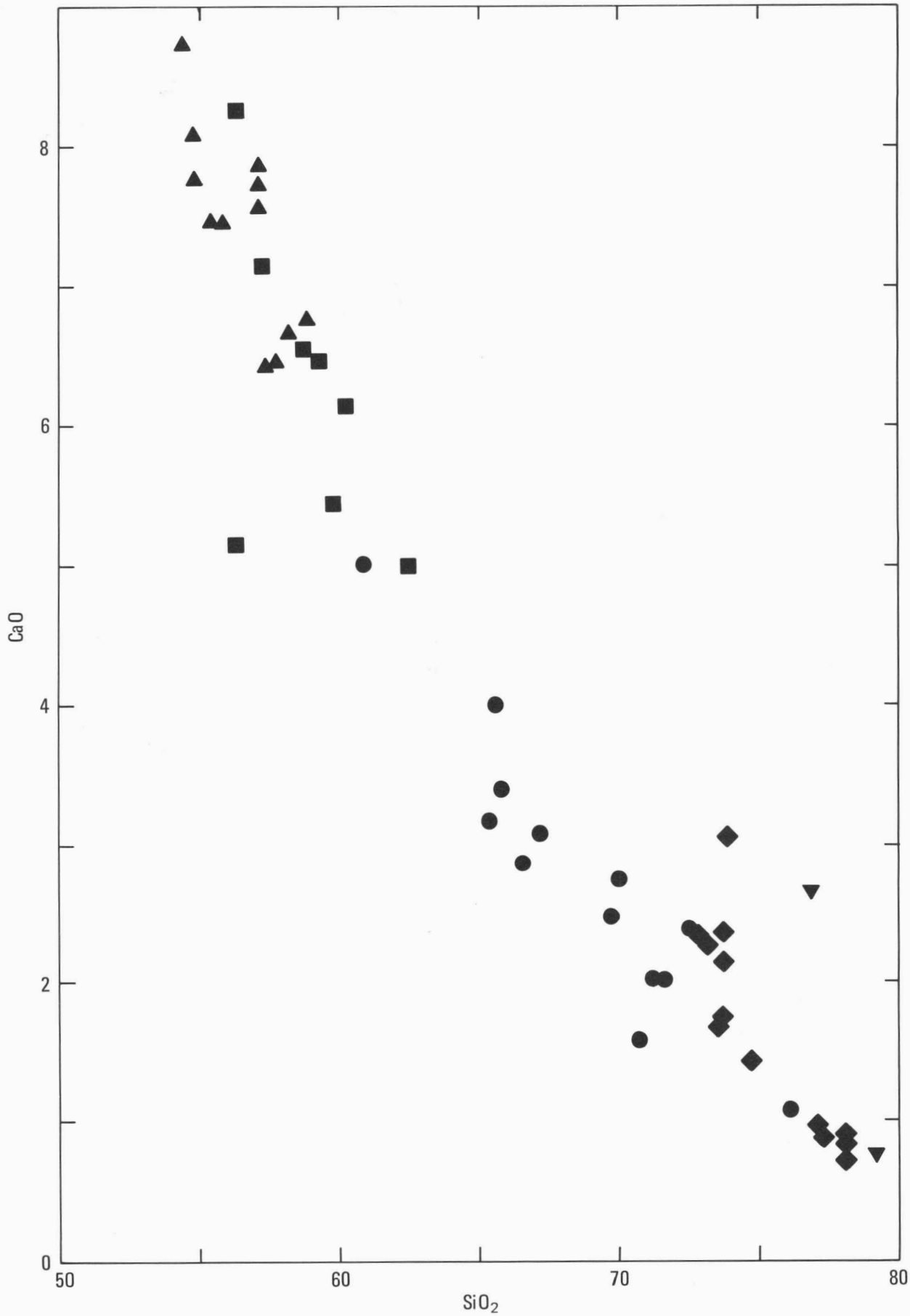


FIGURE 62G. $CaO-SiO_2$ variation diagram.

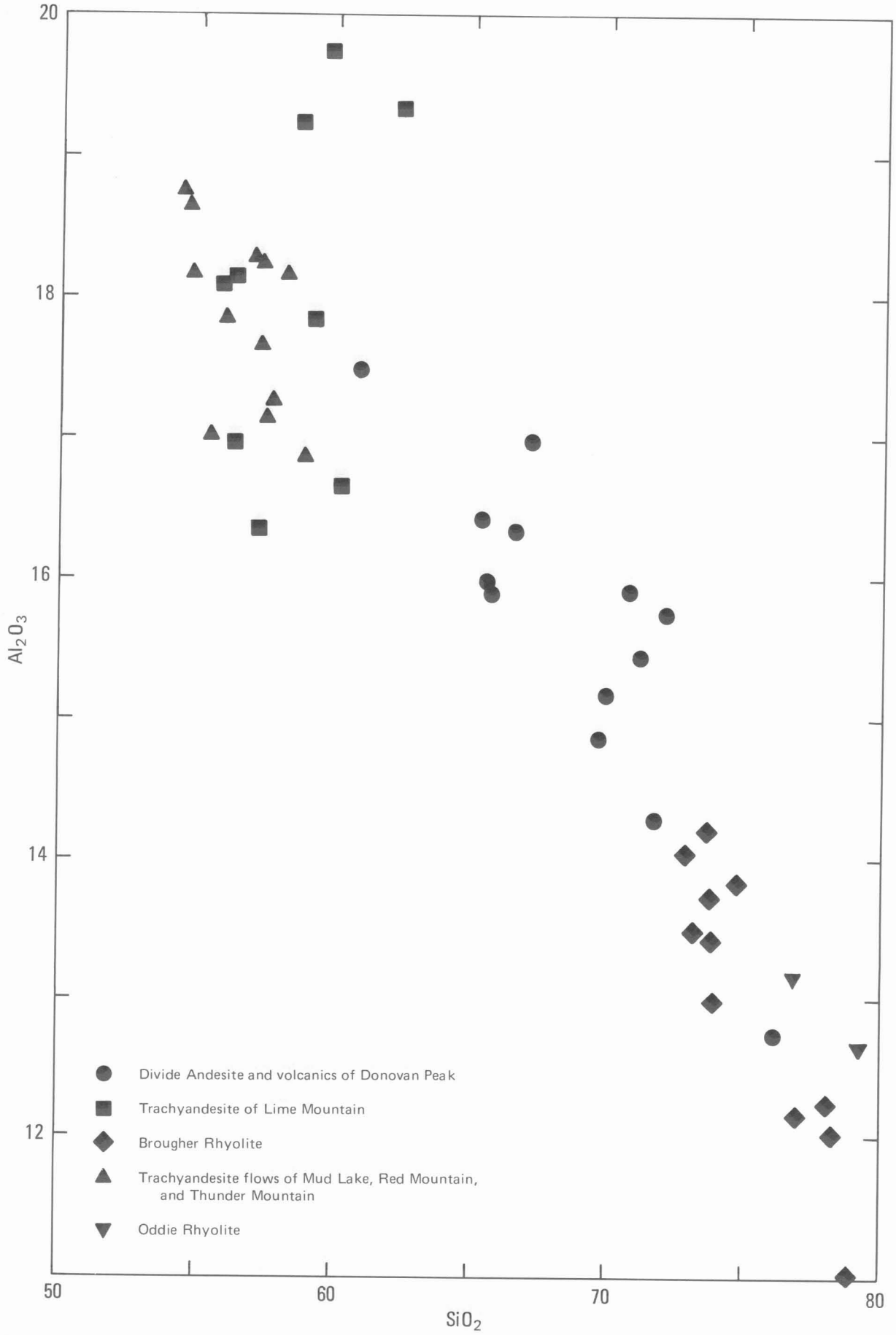


FIGURE 62H. Al_2O_3-SiO_2 variation diagram.

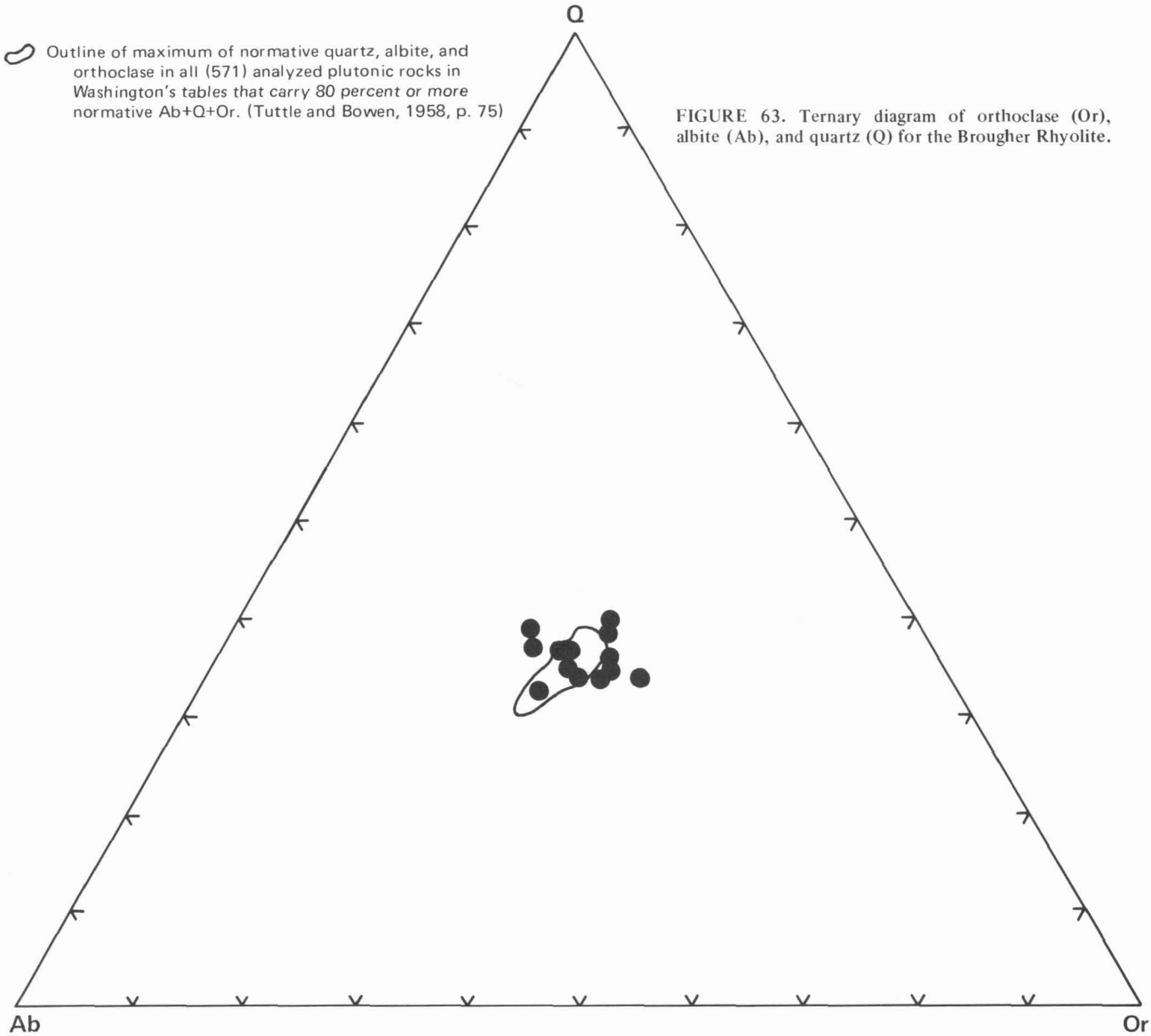


FIGURE 63. Ternary diagram of orthoclase (Or), albite (Ab), and quartz (Q) for the Brougher Rhyolite.

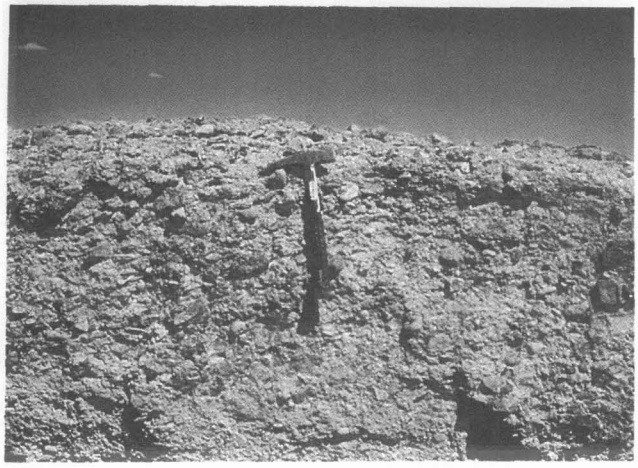
is outward from the mountain ranges. Fan deposits are thickest near the source area, whereas pediment deposits commonly grade into thicker units basinward.

Ephemeral-Stream Deposits (Qs)

The Quaternary unit that occupies a portion of many of the valley bottom areas in the Tonopah region we have called ephemeral-stream deposits. This unit is transitional between upland fans or pediments and the low relief areas consisting of stabilized sand dunes, small dry lakes, and playas. It is mainly made up of sands and silts; the coarser debris is left behind along the various washes in the fans and pediments, and the clay-size fraction is concentrated in the playa areas. The ephemeral-stream deposits are distinguished from other alluvial units by their position near valley floors and their texture and color on aerial photographs. Their lighter color on black-and-white aerial photos is due to the absence of larger, dark-colored rock fragments on the surface. In contrast to fan and pediment gravels, the ephemeral-stream deposits have fewer washes, and these washes are commonly wider, slightly more geomorphically subdued, of lower gradient, and oriented parallel to the valley axis. The contact between these two units is often drawn at the change in slope and geomorphic texture at the point where the radial drainage of the fans changes to the more widely separated ephemeral-stream valleys. Ephemeral-stream deposits along narrow upland washes were not mapped separately, and were included with the fan and pediment deposits where they are present in alluvial areas. The age of the ephemeral-stream deposits is probably both Holocene and Pleistocene, and is generally equivalent in age to the fan and pediment deposits.

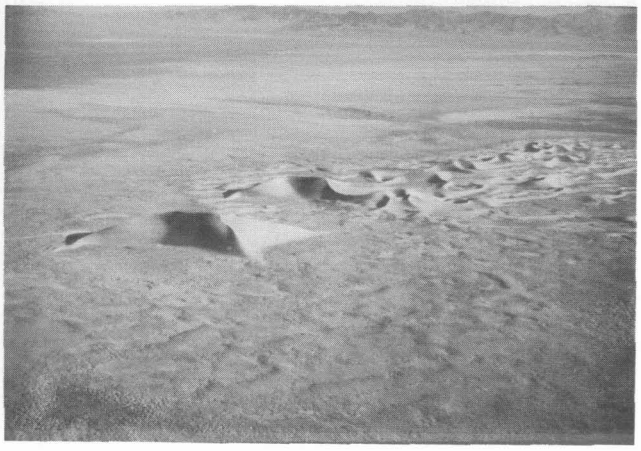
Mixed Dune-Playa Deposits (Qdp)

The mixed dune-playa deposits in Ralston, Big Smoky, and Montezuma (Alkali Spring) Valleys consist of sand, silt, and clay and occur in depositional environments that are a mixture of eolian and playa-lake. Usually these deposits are adjacent to the lowest areas of the valley floor (where the major playa deposits accumulate), and are transitional



A. Caliche-cemented stream conglomerate in the older alluvial deposits.

B. Dissected pediment surface cut on Fraction Tuff between Klondyke Hills and the Divide district.



C. Crescent Dunes north of Tonopah; looking north. *Photo by Dennis Trexler.*

FIGURE 64. Quaternary deposits.

with these playa deposits, although they may also be present in other areas where intermittent stream courses are absent or restricted.

The mixed dune-playa areas are easily recognized on aerial photographs as a lacey network of gray sand dunes and white playa deposits. The proportions of dunes and small playas (microplayas) can vary considerably. The small playalike areas are usually only a few hundred meters across, although they may be up to 1 km or more. In dry weather they have a hard, flat, dessicated surface, but are submerged in a few centimeters of water following heavy rainstorms. The sand dunes are usually small (several tens of meters long and as much as 3 to 4 m high); most of them are stabilized by vegetation (shrub coppice) such as big greasewood. Meinzer (1917, p. 48, 49, and pl. VIII) has described these wind-formed mounds in Big Smoky Valley to the northeast of Lone Mountain. He suggests that the shrub coppice dunes or mounds are the result of the collection of sand behind a well-established bush until more vegetation can grow on the dunes to stabilize them completely. These have been called "phreatophyte mounds" by Walker and Motts (1970). Some Pleistocene? lakeshore bars and ridges just north of Mud Lake are included in the mixed dune-playa deposits, and these ridges have concentrated several small playalike areas. The contact of the mixed dune-playa deposits with the main playa deposits is usually apparent because the large valley-bottom playas are essentially devoid of any dunes or vegetation. However, the contact of mixed dune-playa areas with ephemeral-stream deposits is often a matter of interpretation.

Playa Deposits (Qp)

Portions of two large playas are present in the mapped area at the lowest part of two closed basins, in Ralston and Montezuma (Alkali Spring) Valleys. These playas are nearly level, dry, relatively smooth, flat surfaces free of vegetation; they are underlain by fine-grained sediments that may contain saline minerals.

Mud Lake playa, at the southern end of Ralston Valley, is nearly circular in plan, approximately 8 km in diameter, and has an elevation of 1,584 m. It occupies an area of about 50 km^2, slightly less than half of which is in the mapped area. Ball (1907, p. 83) reports that the depth to water at Mud Lake is about 73 m below the playa. Because of the considerable depth to the water table, the playa surface is usually hard and firm, and has been used as an emergency landing site for an experimental U. S. Air Force airplane, the X-15. Water stands on the surface of the playa only a few times per year, following heavy runoff from the surrounding mountain ranges.

Alkali Spring playa is an elongate flat 9 km long by 2 to 4 km wide at the south end of Montezuma or Alkali Spring Valley. Its surface area is about 21 to 24 km^2, and the elevation is about 1,466 m. Meinzer (1917, p. 148) reports that the water table is 15.3 m below the playa surface, and water wells encountered alternating fine sand and clay beds to 118.6 m, where a hard formation (possibly bedrock) was encountered. A small amount of salt was produced by the evaporation of brines in pits dug on this playa in the 1880's (Williams, 1883).

Talus (Qt)

Mapped talus accumulations consist of coarse, angular rock fragments lying at the base of cliffs and steep slopes. This rubble is derived from the adjoining rock outcrops, mainly the trachyandesite of Red Mountain and the Brougher and Oddie Rhyolites. Although small accumulations of talus are present at many localities in the mapped area, we have mapped them separately only when they were so thick and

extensive as to obscure the bedrock. In some areas, small amounts of talus are included with other alluvial units, mainly the fan and pediment deposits. Exposures of talus are found around Rhyolite Peak and Red Mountain in the northern part of the area, near Booker Mountain 5 km northeast of Tonopah, and just north of the Divide mining district.

Dunes and Eolian Sand (Qes)

This map unit comprises the complex dune field called Crescent Dunes along the west side of the San Antonio Mountains. The area of outcrop is about 5 km^2. The dune complex contains a variety of active dunes and an extensive area of sheet or drift sand (fig. 64). These sand deposits are accumulating on a relatively flat, slightly sloping fan surface. Smaller dunes are predominantly sigmoidal (S-shaped) dunes; their long axes trend roughly northeast, the prevailing wind direction. One large dune appears to be a complex of sigmoidal dunes, and the most obvious dune near the south end of the field is a star or pyramidal dune. This dune, over 60 m high, is sharply crested and star shaped. This type of dune is reputed to remain in the same place for long periods. All of the dune features seem to suggest winds of varying direction. Sand from the star dune is medium sized and well sorted, and is acoustic or sound producing when walked upon (D. Trexler, personal commun., 1977). The source of the sand may be the fan deposits and Pleistocene beaches in the vicinity of Lone Mountain.

Mine Dumps and Mill Tailings (Qd)

The mining and milling of ores at Tonopah and near Millers at the northeast end of Lone Mountain produced a large amount of dump material and tailings. Generally these man-deposited materials were mapped only in areas where they obscured the bedrock units, or where they were extensive. Small dumps at individual mines and shafts were not mapped separately. Coarse broken rock in dumps from the main workings at Tonopah is mostly concentrated in the area between Mt. Oddie and Heller Butte. Areas of mill tailings are located northeast of Mt. Oddie, along Slime Wash west of Tonopah, and near Millers.

STRUCTURE

Regional Tectonics

The Tonopah area lies to the east of a zone of disrupted structure which separates the Sierra Nevada batholith from the Basin and Range province. This zone contains a number of parallel and subparallel right-lateral strike-slip faults and includes a zone of bending resulting from this right-lateral movement (Albers and Stewart, 1972). The Walker Lane is a prominent zone of disrupted topography 800 km long (Locke and others, 1940) which roughly corresponds to this disrupted zone. Figure 65, adapted partly from Albers and Stewart (1972), shows the location of some of the major strike-slip faults and bends in structural trend lines and facies boundaries. Albers (1967) recognized also that mountain ranges with arcuate trends, which he called oroflexes, are present along the Walker Lane, and he suggested that they resulted from tectonic bending of the crust. The structural pattern suggests gigantic dextral drag associated with strike-slip faulting.

Although it has often been suggested (for example, see Shaw, 1965; Nielson, 1965) that the Walker Lane continues to the southeast from the Hawthorne area and connects with the Las Vegas Shear, Albers and Stewart (1972) have proposed that the Walker Lane may be offset in a right-lateral sense along an east-west zone just north of Lone Mountain. This would suggest that the zone of strike-slip faults in the Gillis and Gabbs Valley Ranges 50 km east of Hawthorne (Anonymous, 1977) continues further to the south along the Fish Lake Valley-Furnace Creek and Inyo (Owens Valley) faults. This offset of the Walker Lane may result from east-west strike-slip faulting, oroflexural bending, or a combination of the two. Ekren and others (1976) believe that there is little indication of large-scale strike-slip displacement of Tertiary age along the Walker Lane at the latitude of Tonopah, and this is confirmed by our geologic mapping in the area. We do not believe that any major strike-slip faults pass through the area shown on plate 1, and it seems likely that the continuation of the Walker Lane fault zone is along the Furnace Creek–Death Valley fault zone and related strike-slip faults. The predominant north trend of the Basin and Range faults in the Tonopah area is parallel to the mountain ranges and fault trends to the east and north of Tonopah, which also suggests that Tonopah is to the east of the Walker Lane disrupted zone.

Ekren and others (1976) have proposed that several east-trending topographic and structural lineaments occur in central Nevada. Two of these appear to cross the Walker Lane with little or no displacement. These lineaments supposedly influence the location of volcanic centers and commonly exhibit left-lateral strike-slip movement. The Warm Springs lineament of Ekren and others (1976) purportedly extends from Warm Springs, 75 km east of Tonopah, to the California–Nevada border just north of Boundary Peak. The trace of this lineament is concealed by alluvium in most of the mapped area (pl. 1) except where it crosses the San Antonio Mountains. They suggest that it passes south of Thunder Mountain, crosses the San Antonio Mountains about 7 km north of Tonopah, and passes just to the north of Lone Mountain. No obvious east-trending faults are apparent along this zone in the mapped area, although the N. 30° W. contact between Mesozoic granodiorite and Tertiary volcanic rocks would probably be considered a related feature by Ekren and others (1976).

Thrust Faults

Thrust faults are mapped in Precambrian and Paleozoic rocks at Lone Mountain, the General Thomas Hills, Klondyke, and near Rays (fig. 66). In addition to the thrusts shown on plate 1, there are many small intraformational thrust faults which were not mapped because of scale limitations and difficulty of mapping. The thrusts are recognized on the basis of both structural and stratigraphic discontinuities, and all of them have younger rocks in the upper plate.

At Klondyke and in the General Thomas Hills to the west across Montezuma Valley, a thrust fault separates the Palmetto Formation from the underlying Emigrant. The Palmetto Formation directly overlies the Emigrant with apparent conformity in the Palmetto Mountains 50 km to the south (Albers and Stewart, 1972), and the depositional

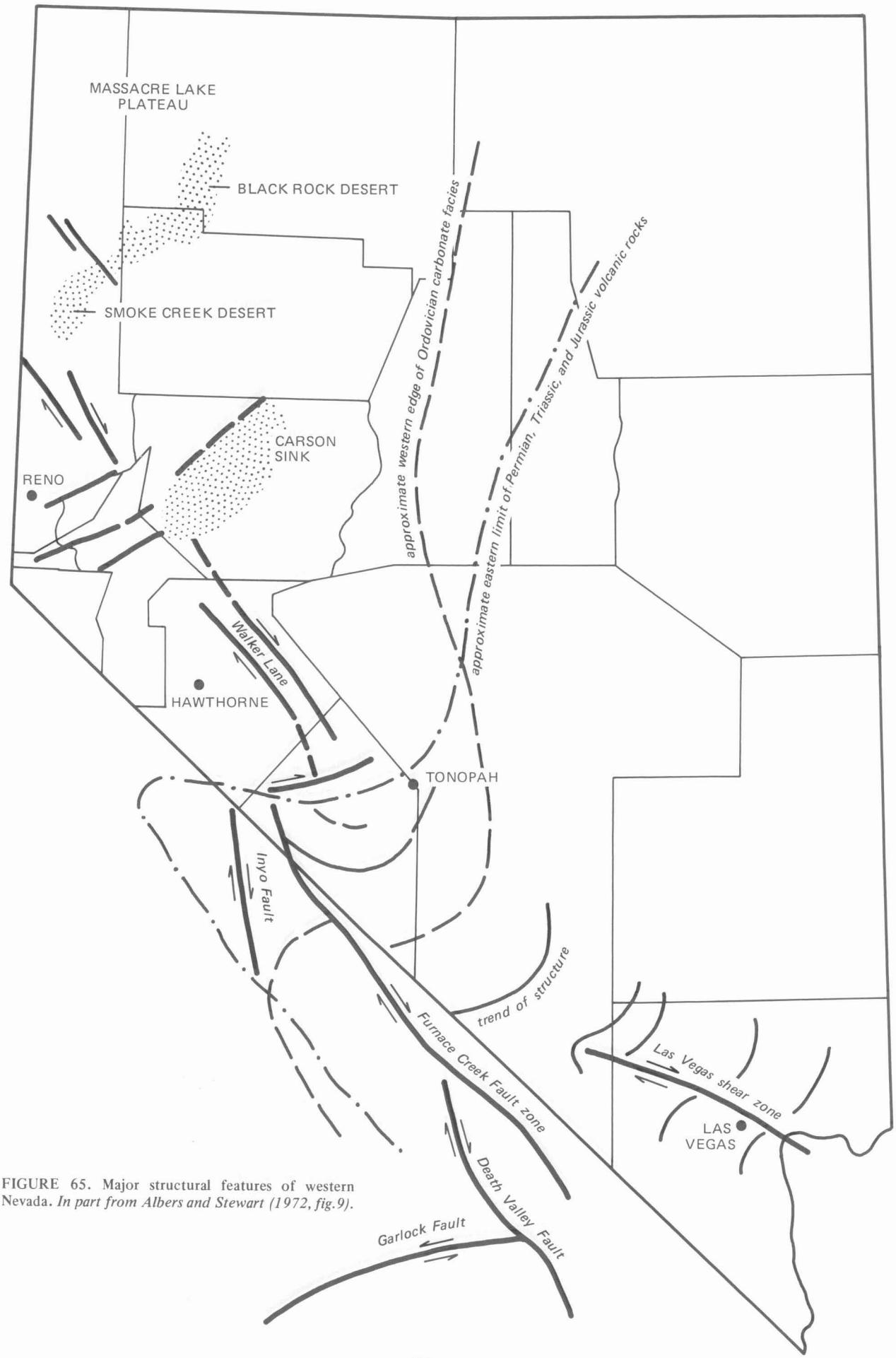


FIGURE 65. Major structural features of western Nevada. *In part from Albers and Stewart (1972, fig. 9).*

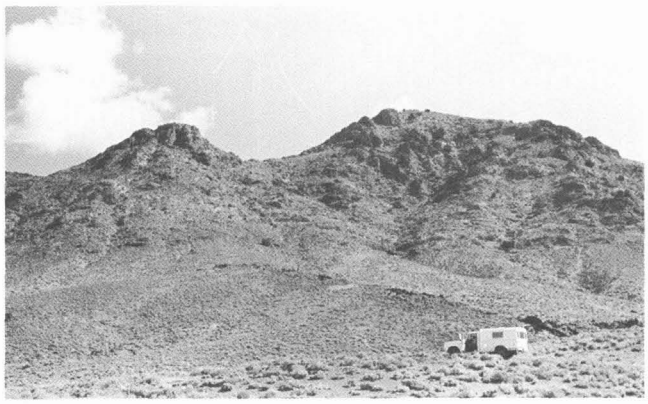


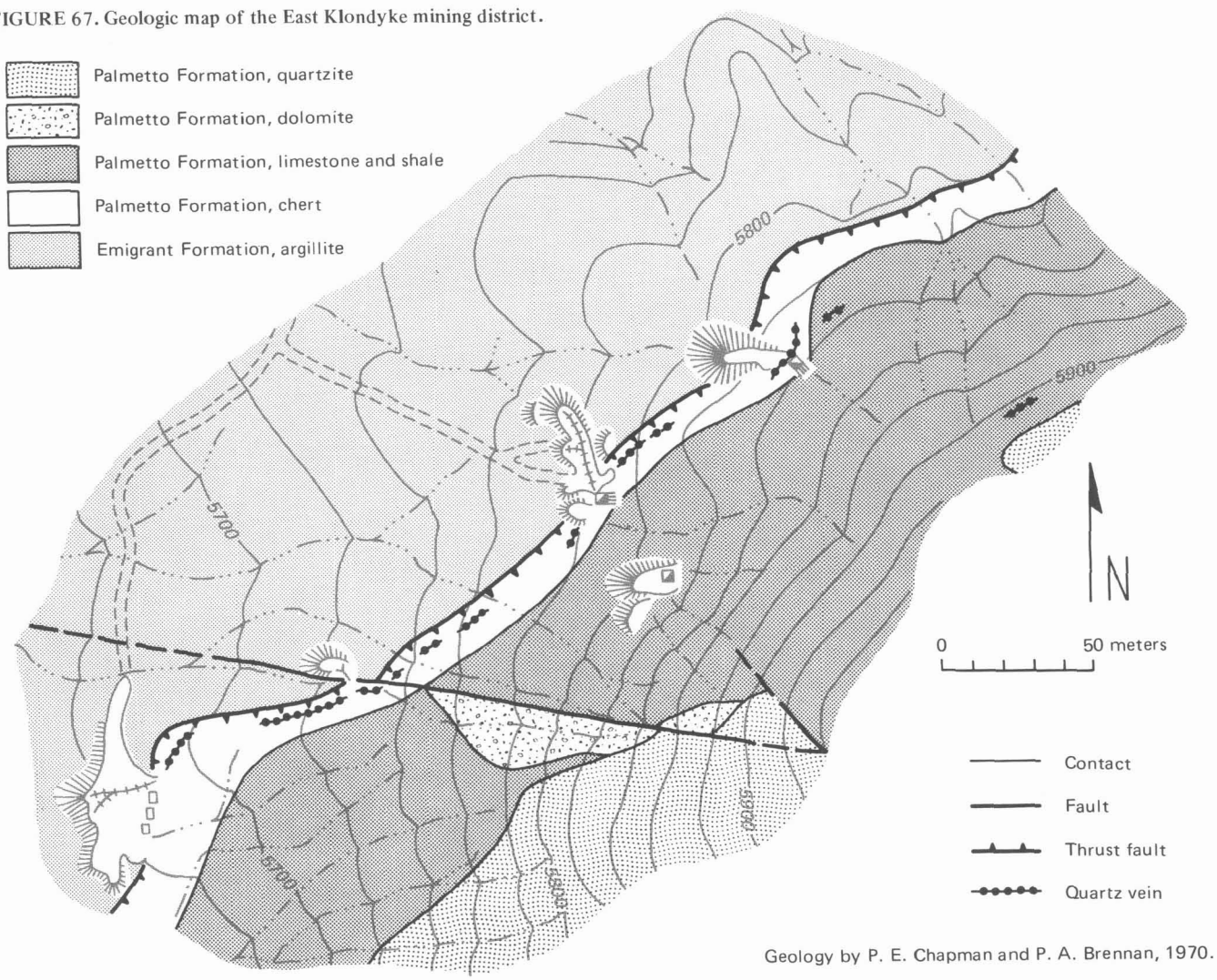
FIGURE 66. Mississippian limestone overlying Ordovician Valmy(?) Formation near Rays, about 15 km north of Tonopah. The contact is a thrust fault.

environment of the two formations was apparently similar. For these reasons, there is little reason to believe that the thrust fault between the Palmetto and Emigrant is of regional extent or had a large amount of movement. There are also thrusts at Klondyke that are mapped within the Emigrant and that separate the Emigrant from the Mule Springs. Chipp (1969) has mapped several smaller thrust faults in this district in more detail. The thrusts are commonly low angle, as seen in the map by Chapman and Brennan (fig. 67), and small-scale folding is present in the upper plate rocks.

The thrust faulting at Lone Mountain emplaced the Harkless(?) Formation over the Reed Dolomite and Deep Spring Formation, cutting out 1,000 to 2,000 m of section, including part of the Reed Dolomite and the Deep Spring, Campito, and Poleta Formations. The thrust fault plane is often obscured by talus and colluvium but seems nearly parallel to bedding in the upper and lower plates. In some places, this would result in a near vertical fault plane. The younger-over-older relations and progressive crosscutting of units indicate major offset along a plane which was originally low angle and subsequently has been tilted by high-angle faults of Tertiary age.

Near Rays in the northern part of the mapped area, a large block of Late Mississippian limestone and minor shale is thrust on the Ordovician Valmy? Formation. The thrust separating these units is nearly horizontal and is mineralized at several locations. It is highly visible, has a crushed zone several meters wide, and seems to have a crosscutting relationship to the surrounding rocks. Numerous small thrusts and folds are present in the Valmy? up to 300 m below the thrust (fig. 68), and they diminish in frequency downward. Silicification of the upper plate limestone has obscured most small scale features in that unit.

FIGURE 67. Geologic map of the East Klondyke mining district.



Geology by P. E. Chapman and P. A. Brennan, 1970.

FIGURE 68. Thrust fault in the Ordovician Valmy(?) Formation 1 km south of the site of Rays.

Albers and Stewart (1972, p. 44) report that low-angle or thrust faults having dips less than 45° and mostly less than 20° are extremely common in the pre-Tertiary rocks of Esmeralda County, but they do not affect Tertiary rocks. They report also that the age of thrusting is little known in this part of the State, but suggest that it is mid-Jurassic to early Tertiary and associated with the development of oroflexural structures and quartz monzonite intrusion. A thrust at Klondyke is cut by muscovite granite of 104 m.y., and Late Mississippian rocks are in the upper plate of the thrust fault at Rays. The Valmy(?) Formation near Rays is also probably allochthonous, although its base is not exposed. Thus, all that can be said concerning the age of the thrust faulting in the Tonopah area is that at least some of it is pre-Middle Cretaceous and elsewhere some of it is post-Late Mississippian.

Low-angle mineralized faults in the Tonopah mining district (the Tonopah fault and branches) cut the Tertiary volcanic rocks and are believed by Nolan (1935) to be related to the intrusion of a pluton below the district. The Tonopah fault is discussed further in the section on mineral deposits in the Tonopah district. Low-angle faults were not recognized in Tertiary rocks elsewhere in the mapped area.

Folds

All of the Paleozoic and Precambrian rocks in the mapped area are folded, and in several localities beds of the Tertiary Siebert Formation are folded as well. Folds were not observed elsewhere in the area in Tertiary rocks. Major folds in the Precambrian and Paleozoic rocks at Lone Mountain and Klondyke appear to be fairly broad and open, whereas minor folds are extremely tight and complex in the vicinity of thrust faults. Crenulation folds (2 to 3 mm in amplitude) and flexural-slip folds (10 to 30 cm in amplitude) are present in the Wyman Formation near the contact with the main Lone Mountain pluton (fig. 69). According to Albers and Stewart (1972), the overall structural setting at Lone Mountain is that of a mass of granite in the core of an anticline which plunges to the southeast under the General Thomas Hills and is cut off at the northwest end by a series of faults. The presence of the Wyman Formation both at the top of Lone Mountain and along its flanks, an elevation difference of about 900 m, is a result of this anticlinal form. Sandy (1965) has suggested that the Lone Mountain pluton was probably emplaced in a zone of weakness, such as a pre-existing anticline, and that some doming was due to intrusive forces. The main granite intrusive mass at Lone Mountain is approximately 70 m.y. old and may postdate most of the folding and thrust faulting in the pre-Tertiary of this area.

The lower Paleozoic rocks at Klondyke appear to be folded into a large northeast-trending syncline. Smaller folds which have the same trend are impressed upon the structure (Chipp, 1969).

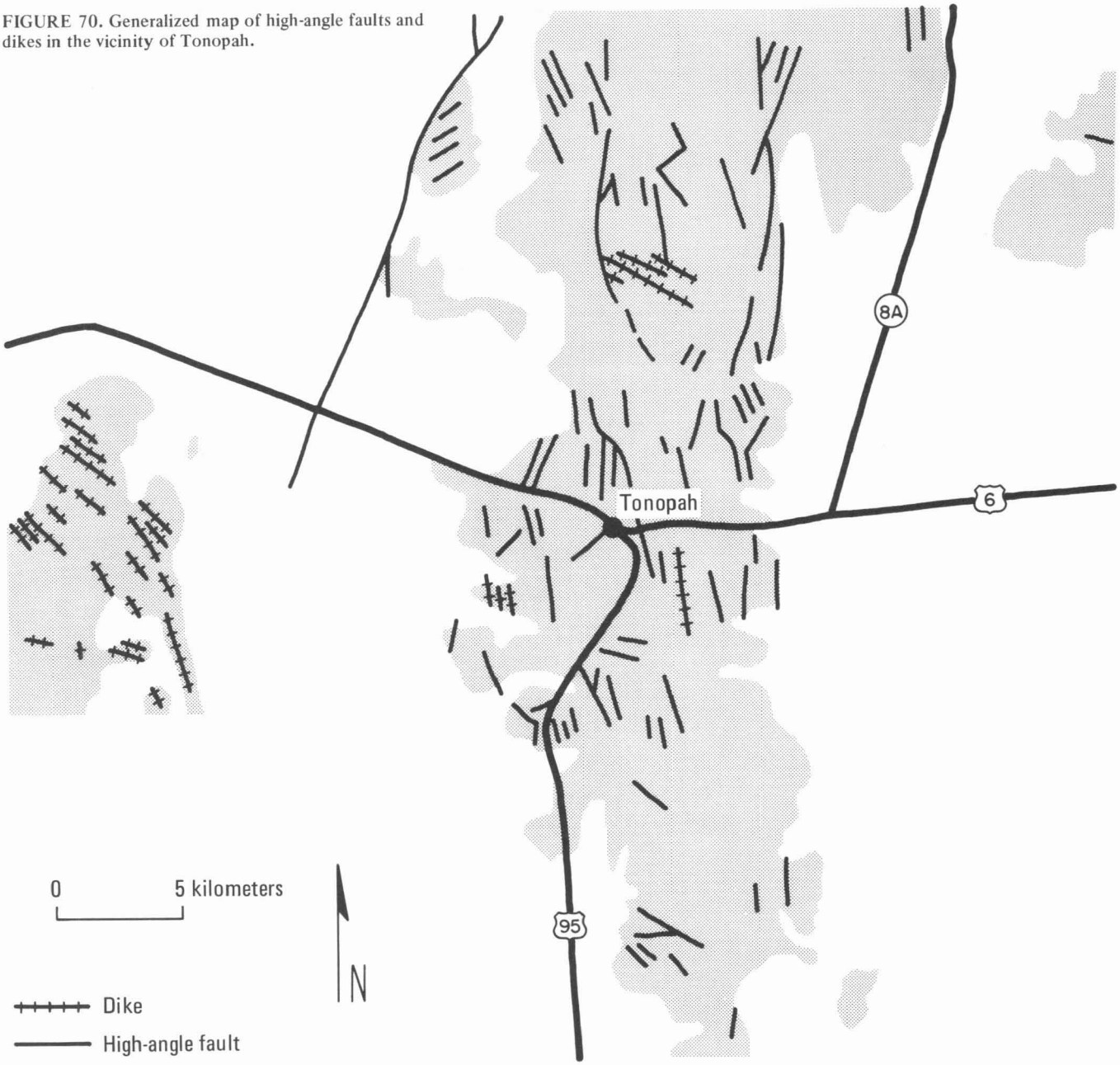
Small (1 to 10 m) isoclinal, or near-isoclinal, folds and minor thrust faults are present in the Valmy(?) Formation near Rays, and are concentrated below the major thrust fault that separates an unnamed Mississippian limestone from the Valmy(?) Formation.

Beds of the Siebert Formation are folded in the area along the west edge of the San Antonio Mountains from just west of Tonopah (S32,T3N,R42E) north to Crescent Dunes. Where the underlying volcanics of Lime Mountain form the core of anticlines, the folds are partly due to compaction of lakebeds over hills. It is not certain how many of the folds in the Siebert shown on the geologic map are related to pre-Siebert topography. However, in any one area, several folds are usually subparallel, and may be up to 1.6 km long. Dips on the limbs are usually 30° to 35°, and the folds die out into homoclinal sequences or terminate against faults. The faults may be perpendicular to the fold axes or at an angle of approximately 60°. These relations are best exhibited in the Siebert outcrops just to the southeast of Crescent Dunes and continuing to the south for about 8 km.

FIGURE 69. Flexural slip folds in the Wyman Formation on Lone Mountain near the intrusive contact with the main Lone Mountain pluton. Pocket knife is 10 cm long.

It seems likely that these folds in the Siebert do not involve the pre-Siebert rocks, and result from a combination of compaction over buried hills and the crumpling of the sedimentary beds over an uninvolved basement of older volcanic rocks, a thin-skinned interpretation. Some evidence for this interpretation is seen in the faults perpendicular to the folds near Crescent Dunes. A fault in S7, T4N,R42E (unsurveyed) slightly displaces an anticlinal axis, and slickensides at its western end indicate that the last fault movement, at least, was horizontal. Strike-slip motion along these faults could have resulted from differential movements as the thin skin of Siebert moved over the underlying volcanic rocks.

FIGURE 70. Generalized map of high-angle faults and dikes in the vicinity of Tonopah.



High-Angle Faults and Dike Trends

Most high-angle faults in the mapped area trend within 20° east or west of due north, and are vertical or steep normal faults (fig. 70; pl. 1). The majority of these faults are from 0.8 to 3 km long, but a few more persistent faults are up to 7 km long. These faults are parallel to the major faults in mountain ranges to the north and east of the Tonopah area and are probably related to Basin and Range structure.

A range-bounding Basin and Range fault cuts Quaternary deposits in Big Smoky Valley and forms the alluvium–bedrock contact in the vicinity of Crescent Dunes. This is the only fault in the mapped area that is really typical of the Basin and Range structure of mountain horsts and valley grabens. We have, however, suggested the presence of other concealed faults in the diagrammatic cross sections on plate 1, partly on the basis of the gravity map and interpretations of Erwin (1968). The northern San Antonio Mountains in the mapped area appear to be tilted slightly eastward, probably as a result of uplift of the west side of the range along the boundary fault exposed near Crescent Dunes. Further to the south in the range this effect is not apparent, as units dip predominantly toward the west.

The main outcrop of pre-Tertiary rocks in the San Antonio Mountains north of Tonopah is a north-trending horst block bounded in part on its east and west margins by normal faults. These faults appear to decrease in displacement and terminate near the south end of the horst block. The western fault which ends about 0.5 km south of Fraziers Well, may be a reactivated portion of a pre-Tertiary(?) fault which continued to the south through the trachyandesite volcanic center at Red Mountain and along the edge of a small Valmy? outcrop southwest of the military reservation. Other faults in the mapped area, such as the Halifax Fault in the Tonopah district, are also

probably older faults which have been re-activated during Basin and Range faulting.

The Halifax Fault, which bounds the Tonopah district on the east, is about 6 km long, generally north trending, and dips 35° to 40° to the east. The total amount of premineral (pre-19 m.y.) movement along the fault is unknown but was probably more than 600 m. The postmineral movement, probably during Basin and Range faulting, has been estimated at somewhat less than 460 m (Nolan, 1935). Other faults present in the underground workings at Tonopah are described in the section on the Tonopah mining district.

The Tonopah–Laundry Fault (Broderick, 1949, pl. 1) is parallel to the Halifax Fault about 1 km to the east. Movement on the fault preceded the deposition of the upper part of the King Tonopah Member of the Fraction Tuff (about 18.7 m.y. ago). The amount of displacement on this fault is unknown.

One of the few structural features which does not fit the north-south fault pattern is the Fraziers Well pluton 10 km north of Tonopah, which is elongate in a northeast direction, as are the porphyry dikes which cut it. The pluton is Late Cretaceous and the dikes may be the same age. The southern boundary of the pluton here is parallel with the trend of these dikes and coincides approximately with the proposed Warm Springs lineament of Ekren and others (1976) as discussed above.

Porphyry dikes in Precambrian and Cambrian rocks on the northeast side of Lone Mountain are 22 m.y. old and appear to parallel the contact of the Lone Mountain pluton (fig. 70). The curving trend of these dikes generally parallels that of the bedding in the surrounding rocks and thus is believed related to the anticlinal form of Lone Mountain.

The Basin and Range faulting in the Tonopah area probably began approximately 16 to 17 m.y. ago, as indicated by the age of basinal deposits (Siebert Formation) and the extrusion of olivine trachyandesite. Most of the north-trending faults are probably of this age or younger, although some older faults were re-activated at this time. Several north-trending faults are cut off or overlain by Brougher Rhyolite in the vicinity of Tonopah, indicating that no movement has taken place on those faults since approximately 16 m.y. ago. Other faults cut units as young as Quaternary.

Volcanic Centers and Calderas

Donovan Peak (S31,T2N,R43E) is an intrusive center which is centered in an east-west elongated intrusive body of Divide Andesite. This east-west-trending intrusion lies due east of a major east-west fault at the south end of Lone Mountain (see Albers and Stewart, 1972, pl. 1, inset) across Montezuma Valley to the west. The Donovan Peak center lies at the intersection of this east-west zone with a north-south lineament which is visible on high-altitude photography from northeast of Klondyke to U. S. Highway 6. This north-south lineament is visible in part due to the outcrop pattern of dikes of Brougher Rhyolite and several intrusive units of the volcanics of Donovan Peak.

As discussed in more detail in the section on the Fraction Tuff, intrusive rocks of the Oddie Rhyolite, Divide Andesite, Donovan Peak volcanics, and the domes and flows of the Brougher Rhyolite define a crude arcuate pattern (pl. 1) which encompasses the area between Tonopah and Donovan Peak. Although the rocks intruded along this possible ring fracture are too young to be related to the Fraction Tuff, the structural feature may have been a site for later vulcanism.

Ekren and others (1976, pl. 1) show an inferred buried cauldron fault just to the east of Thunder Mountain in the area mapped during this study. The tuffs of Rye Patch are exposed in this area overlying flow rocks of intermediate composition. The source of these tuffs is the Big Ten Peak caldera to the northeast. Dikes and plugs of the rhyolite of Silver Ace cut the tuffs of Rye Patch, and might possibly be related to a ring fracture for the postulated caldera of Ekren and others (1976). However, the rocks here exposed (tuffs of Rye Patch) are not intracaldera deposits, but outflow rocks from the Big Ten Peak caldera. Therefore, it seems likely that any caldera-margin fault would be to the east of the mapped area (pl. 1), east of Thunder Mountain.

MINERAL DEPOSITS

Tonopah Mining District

The Tonopah mining district is centered around the town of Tonopah (figs. 71, 72) in T2,3N,R42,43E, Nye and Esmeralda Counties, Nev. (fig. 73). The principal productive part of the district is located in S34,35,36,T3N,R42E. Production figures for the district are listed in table 29.

The Tonopah district is the second largest silver-producing district in the State of Nevada, exceeded only by the silver production from the Comstock Lode. It is also one of the major gold-producing districts in the State.

Since its discovery in 1900, numerous articles have been published on the geology and ore deposits of the Tonopah district. Nolan (1935) has given an excellent summary of the more significant papers published on the geology and ore deposits of the district between 1905 and 1935. Nolan's summary also details the evolution of various geologic interpretations of the structure, stratigraphy, and ore deposits in the district (Spurr, 1905a, b, c; Burgess, 1909; Locke, 1912; Spurr, 1915; Bastin and Laney, 1918; and Nolan, 1930, 1935).

Relatively little new geologic information on the Tonopah district has been published since 1935. The most significant new article concerning the district is that of Taylor (1973, p. 747–764), which includes a section on oxygen isotope analytical data on rocks and ores from the district. Short articles on the geology of the district have also been published by Bonham and others (1972) and Bonham and Garside (1974b). Other data sources include unpublished theses on various aspects of the geology of the district by Broderick (1949), and Core (1959).

No detailed examination of the underground geology or ore deposits in the district was made during the present study, as it was felt that the existing published and unpublished works were fairly comprehensive. New information on various aspects of the surface geology was gained in the course of our study.

STRUCTURE

Nolan's (1935) study of the underground geology and structural features of the Tonopah district remains the definitive work on these subjects. The reader is referred

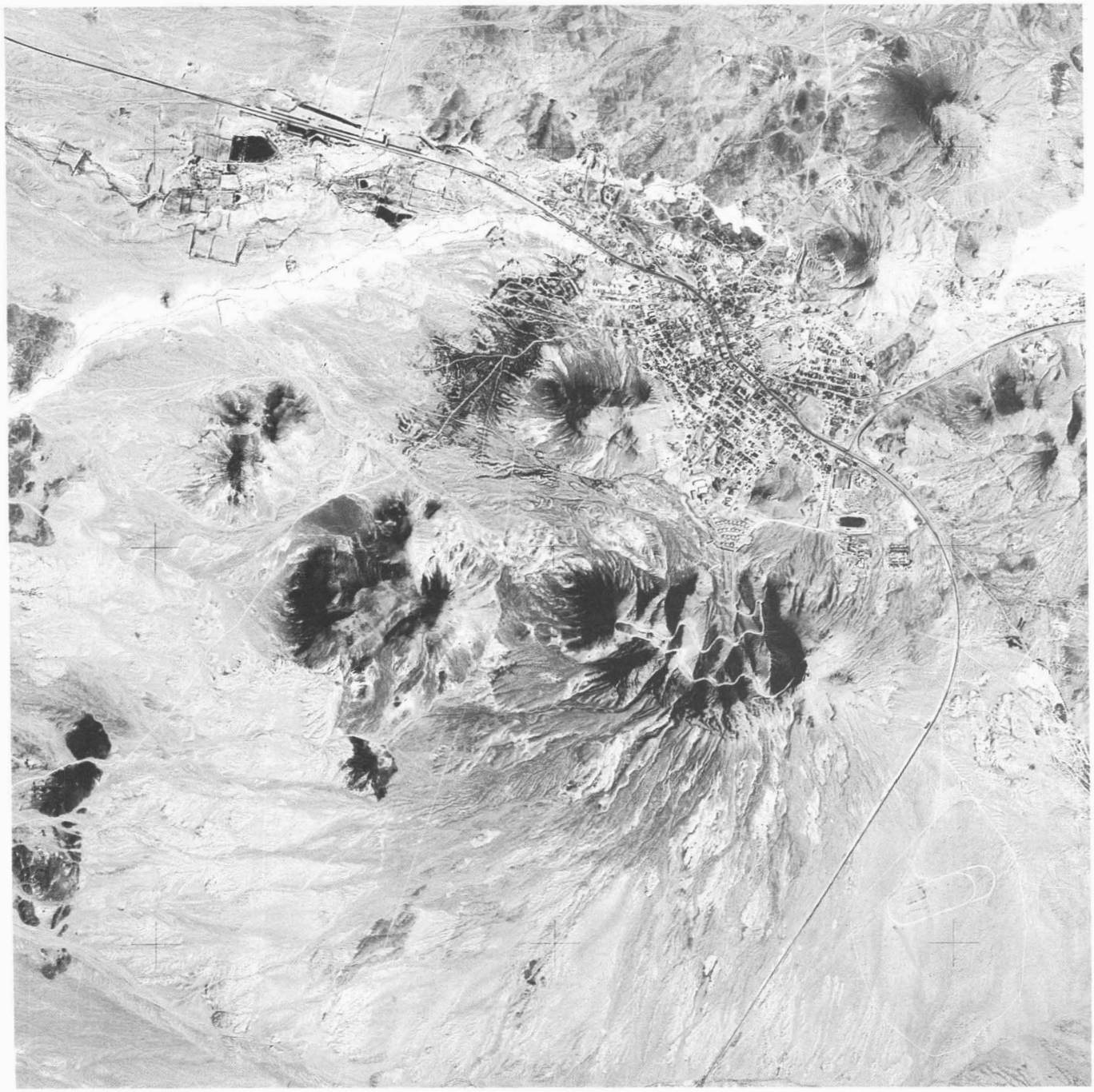


FIGURE 71. Aerial view of Tonopah. *From NASA RB-57 mission 249, photo 32–027, 29 Aug 73.*

especially to his discussion of the structural setting of the ore bodies, including his description of the origin and development of faulting in the district. (A cross section of the Tonopah fault before later faulting is shown on fig. 74.)

ORE DEPOSITS

Nolan (1935)* has also described the ore bodies in the Tonopah district in detail. In addition, an extensive list of other articles on the subject may be found in the bibliography.

*Reproduced copies of the Nolan work (49 p.) may be obtained by writing the Nevada Bureau of Mines and Geology, University of Nevada, Reno 89557.

Isotope Geology and Conditions of Ore Deposition

Taylor (1973, p. 753–760) has reported on his study of the oxygen and hydrogen isotope data from rocks and ores in the Tonopah district. The significant conclusions reached by Taylor from his isotope study are: (1) the ore fluid at Tonopah was dominantly, if not entirely, composed of meteoric water with very low salinities (1 percent NaCl or less); (2) the district is underlain by an intrusive magmatic body that raised the temperature of the meteoric water system to at least 250°C and possibly up to 400°C; (3) the hydrothermal fluids in the central part of the district had higher temperatures than those in the peripheral portions; and (4) the hydrothermal fluids thoroughly permeated a very large volume of rock in the district because there was

FIGURE 72. Tonopah, Nevada. View looking north toward Mount Oddie; productive area at base of mountain.

essentially complete isotopic exchange of hydrogen and oxygen between the ore fluid and large volumes of the country rock.

Taylor's data obviously lend strong support to Nolan's (1935) hypothesis of an intrusive pluton underlying the Tonopah district and are compatible with Nolan's conclusion that the zone or shell (fig. 75) in which most of the precious metals occur in the district represents the optimum temperature interval for the deposition of precious metals and that the increase in the silver/gold ratio from the center of the district to the periphery is related to a decrease in temperature of the ore fluids.

Dreier (1976, p. 100) in his study of the Pachuca-Real Del Monte district, Mexico, a major epithermal silver district with many similarities to Tonopah, concluded through fluid-inclusion studies that vein formation commenced at about 300° to 320°C and that the ore minerals in the veins were deposited in the range 250° to 200°C. In view of Taylor's (1973) stable isotope data from the Tonopah, Comstock, and Goldfield districts it seems quite likely that the vein matter and ore minerals in the Tonopah district were also deposited in the temperature range between about 350°C and 200°C.

Dreier (1976, p. 100) also concluded that ore minerals and vein matter at Pachuca-Real Del Monte were probably deposited from dilute fluids, with Ag concentrations in the 10^{-4} to 10^{-2} ppm range, coincident with low concentrations of sulfide and chloride ions. Taylor's (1973) conclusion that the ore fluids at Tonopah were dilute meteoric waters is compatible with Dreier's assumptions as to the nature of the ore fluids at Pachuca-Real Del Monte. Therefore, we believe that the ore fluid that accomplished the hydrothermal alteration, vein formation, and ore deposition at Tonopah was dilute meteoric water with an Ag concentration in the ppb range, a NaCl content of 1 percent or less, and temperatures in the 350° to 200°C range. The heat source that produced the convective circulation of the meteoric water was a shallow igneous stock.

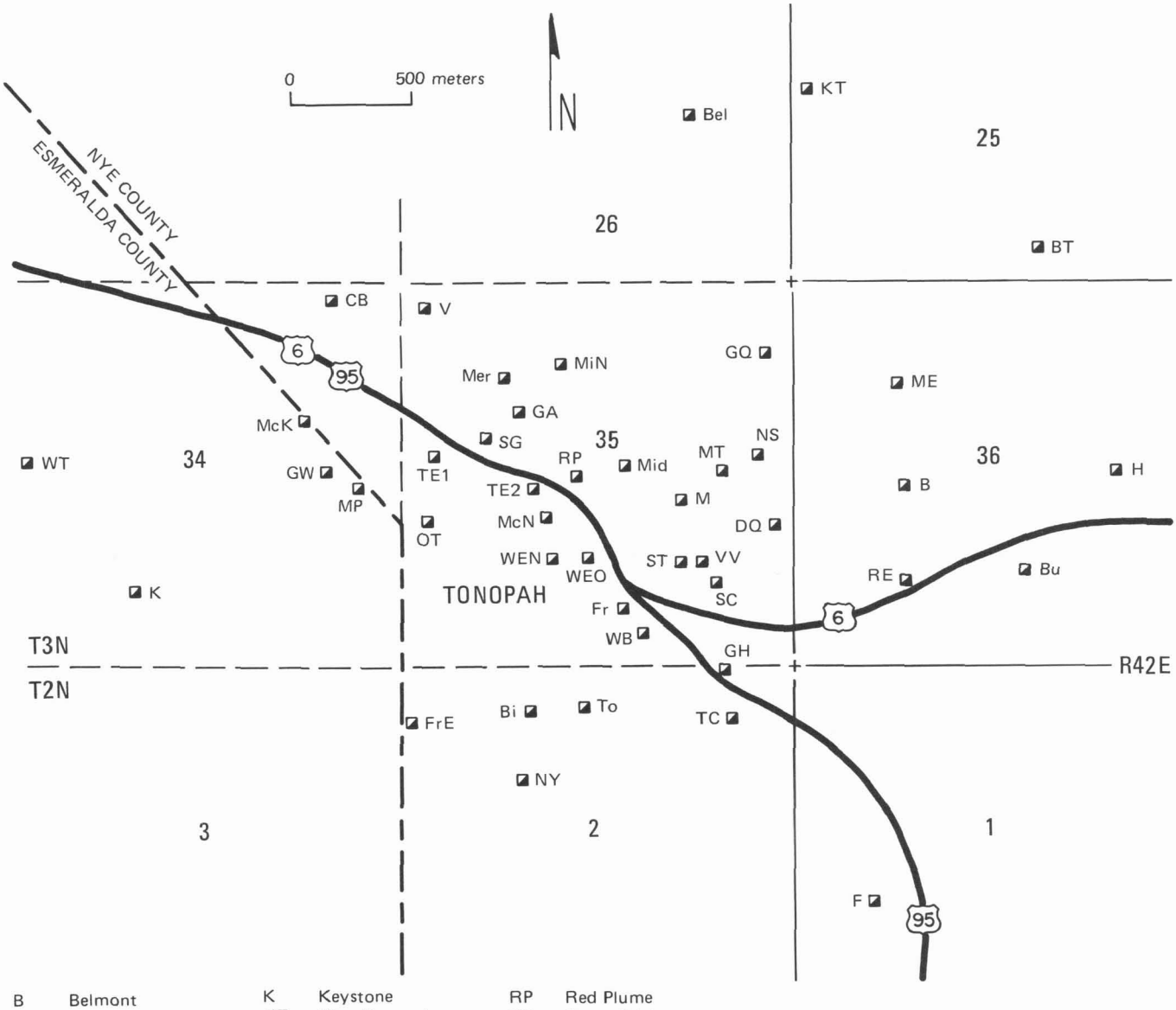
According to Zartman (1974), lead-isotope data indicate that the source material for the lead in the Tonopah ores as well as in many other ore deposits in central and western Nevada (within his area II) was probably late Precambrian and lower Paleozoic miogeosynclinal sedimentary rocks eroded from the adjacent Precambrian sialic upper crust.

Mineralogy

Tables 30, 31, 32, and 33 list the ore and gangue minerals found in the Tonopah vein systems. The chief ore minerals of silver at Tonopah are argentite (acanthite), polybasite, and pyrargyrite (fig. 76). Gold occurs in the Tonopah ores chiefly in the form of electrum, although bright-yellow native gold, probably largely of supergene origin, occurred in the oxidized ores. Silver haloids were important ore minerals at Tonopah in the shallow oxidized ores (Burgess, 1911).

Hydrothermal Alteration

The first published account of hydrothermal alteration of the wall rocks in the Tonopah district is that of Spurr



B	Belmont	K	Keystone	RP	Red Plume
Bel	Belle of Tonopah	KT	King Tonopah	SC	Stone Cabin
Bi	Big Tono	M	Mizpah (Siebert)	SG	Sand Grass
BT	Butte Tonopah	McK	McKane	ST	Silver Top
Bu	Buckeye	McN	MacNamara	TC	Tonopah California
CB	Cash Boy	ME	Mizpah Extension	TE1	Tonopah Extension No. 1
DQ	Desert Queen	Mer	Merger	TE2	Tonopah Extension No. 2
F	Fabbi	Mid	Midway	To	Tonopah City
Fr	Fraction No. 1	MiN	New Midway	V	Victor
FrE	Fraction Extension (Crescent)	MP	Monarch Pittsburgh	VV	Valley View
GA	Golden Anchor	MT	Montana Tonopah	WB	Wandering Boy
GH	Gold Hill	NS	North Star	WEN	New West End
GQ	Great Western	NY	New York Tonopah	WEO	Old West End
H	Halifax	OT	Ohio Tonopah	WT	West Tonopah
		RE	Rescue Eula		

FIGURE 73. Location of principal shafts in the Tonopah mining district. *From an unpublished mine structural survey of the Tonopah mining district by George H. Holmes, Jr.*

(1905b). He gives an excellent description of the mineralogy of the alteration zones developed in the "andesite" of the Mizpah Formation. He also includes a number of chemical analyses of "andesites" from the Mizpah Formation which indicates a range of alteration extending from weak to pervasive. From these data he constructed diagrams showing gains and losses of major elements in the rocks with increasing intensity of alteration.

Spurr's (1905b, p. 210–211, 237) deductions concerning the chemical composition of the "mineralizing waters" and the change in composition of the ore fluid as it migrated outward from the veins is a perceptive treatment and is still an accurate generalization. In fact his main conclusion is remarkably similar to that reached by such modern authorities as Meyers and Hemley (1967, p. 203), ". . . that the chemical effects of the same mineralizing waters became continually different as they penetrated to a greater and greater distance from the circulation channels." (Spurr, 1905b, p. 210.)

Spurr (1905b, p. 32) also recognized that the alteration was zoned around the productive veins. He states, "As a rule, however, the rocks may be divided according to their

TABLE 29. Production, Tonopah district, 1900–1961.

[Data from Nevada Bureau of Mines and Geology files and U.S. Bureau of Mines Minerals Yearbooks]

Year	Tons	Gold (ounces)	Silver (ounces)	Copper (pounds)	Lead (pounds)	Total value
1900	1					$ 600
1901	2,534	9,774	623,516			576,145
1902	11,258	26,463	2,434,453			1,764,271
1903	9,055	25,298	2,404,180			1,898,782
1904	22,703	18,703	2,115,191			1,594,893
1905	91,651	58,357	5,369,439			4,449,486
1906	106,491	63,114	5,697,928			5,122,289
1907	214,608	57,250	5,330,398	5,939	195,508	4,739,966
1908	273,176	78,585	7,172,386			5,425,861
1909	278,743	67,742	7,872,967	1,784	1,488	5,494,600
1910	365,139	111,442	10,422,869	942	6,902	7,932,475
1911	404,375	114,479	10,868,268			8,126,677
1912	479,421	107,219	10,144,987	14	700	8,463,079
1913	574,542	126,445	11,563,437	1,150	9,001	9,598,733
1914	531,278	128,117	11,388,452	2,284	924	8,946,987
1915	516,337	107,836	10,171,374			7,385,870
1916	455,140	93,925	8,734,726			7,688,891
1917	470,122	74,481	7,068,737			7,364,168
1918	501,190	62,300	5,929,920			7,217,665
1919	268,658	37,339	3,568,875			4,768,944
1920	387,489	51,136	4,816,055			6,306,486
1921	367,909	48,335	4,623,901			5,622,995
1922	472,865	57,053	5,436,080			6,615,382
1923	371,946	53,571	5,176,306			5,351,900
1924	285,707	56,216	5,032,043			4,533,462
1925	197,409	33,073	3,070,409			2,814,487
1926	127,252	21,967	2,052,956	62		1,735,120
1927	125,790	22,256	2,167,694			1,689,127
1928	103,109	20,079	1,900,315			1,526,719
1929	121,447	20,059	1,965,595			1,462,291
1930	114,499	19,656	1,931,194	102	389	1,149,848
1931	16,534	9,583	823,872			437,004
1932	10,604	8,791	646,687			364,295
1933	4,786	4,679	400,379	136	220	236,863
1934	11,890	6,024	513,032		11,713	542,634
1935	196,710	10,708	874,860	191	4,669	1,003,818
1936	39,387	4,586	5,388			164,681
1937	118,407	11,289	916,513		300	1,104,101
1938	19,598	9,181	715,266		21,600	784,723
1939	18,767	6,925	596,173			647,050
1940	11,879	4,252	358,018			403,411
1941	11,243	4,121	377,534	400	5,000	412,333
1942	68,155	3,710	334,712	500		367,928
1943	5,123	1,709	159,141	500	500	173,084
1944	4,121	1,029	91,215			100,879
1945	1,845	596	48,434			55,302
1946	2,268	911	75,840	2,700		93,601
1947	1,993	941	76,091	1,400	20,000	104,971
1948	1,723	468	45,938	200	3,900	58,697
1949	91	38	3,817			4,785
1950	64	24	2,336			2,954
1951	?	?	?			?
1952	?	2	1			71
1953	?	?	?			?
1954	*					
1955	241	26	2,038		9,300	4,510
1956	650	290	25,909			33,599
1957	203	48	4,713			5,946
1958	*					
1959	*					
1960	*					
1961	*					
Totals	8,798,126	1,861,200	174,152,628	18,304	292,114	$154,474,839

*Production data from King Tonopah Mine during these years withheld. No production from district since 1961.

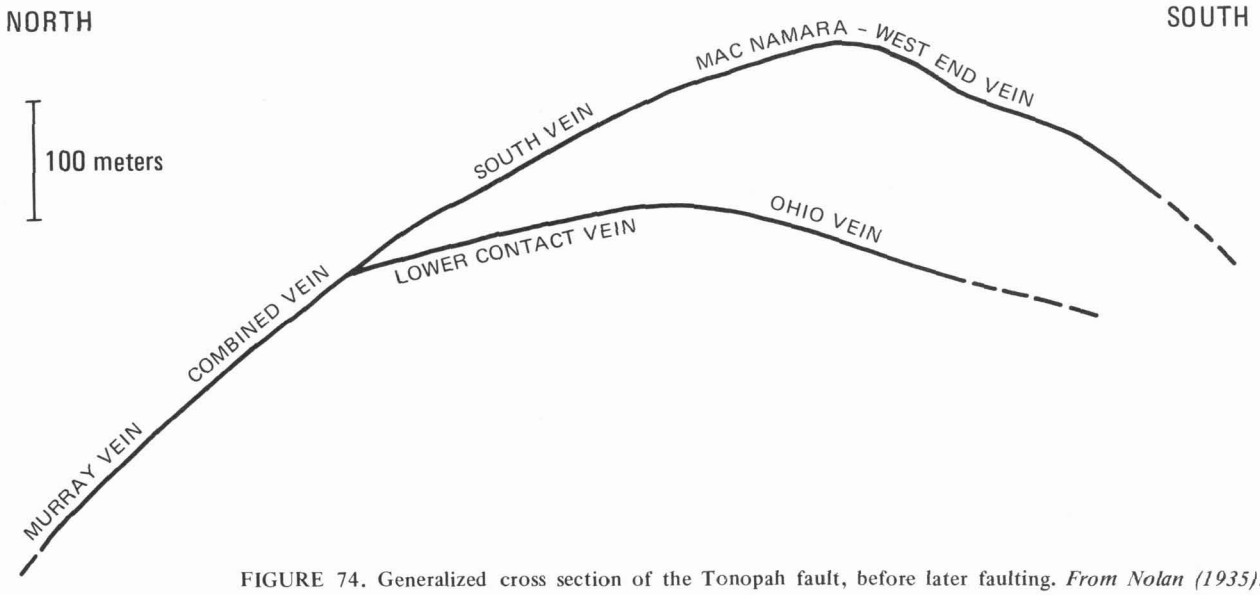


FIGURE 74. Generalized cross section of the Tonopah fault, before later faulting. *From Nolan (1935).*

processes of decomposition, as follows:

"1. Quartz-sericite-adularia-pyrite-siderite rocks; most abundant and most closely connected with the metalliferous veins.

2. Quartz-sericite-kaolin-iron oxide rocks; not infrequent; probably a modification of No. 1. Usually plainly associated with some fault or underground water channel.

3. Chlorite-calcite rock; not associated with the ores."

Spurr's chief error in interpreting the hydrothermal alteration phases in the Tonopah district was in not recognizing that his Later or Midway Andesite was simply propylitized intermediate volcanic rocks of the Mizpah Formation and not a separate formational unit. This error significantly influenced geologic thinking and the search for ore bodies in the district for many years. Nolan (1930, 1935) was the first to recognize that Spurr's "Midway Andesite" and the "Mizpah Trachyte" were alteration phases of the same unit.

Nolan (1935, p. 21–22) has described the general pattern of hydrothermal alteration in the Tonopah district and concluded that the most widespread alteration was the albitization of feldspars in the volcanic rocks. The next most widespread alteration was chloritization, which he described as being generally accompanied by pyrite and carbonate. The third alteration phase was quartz, sericite, adularia, which he stated was best developed in the central part of the district.

Campbell (1931) did a detailed petrographic study of the various formations exposed in the underground workings in the Tonopah district. This work included a thorough petrographic study of the hypogene alteration (1931, p. 149–187). Campbell's main conclusions parallel those of Nolan, which is hardly surprising, since Campbell worked as Nolan's assistant in the underground geologic mapping of the Tonopah district.

Albitization of original plagioclase is so widespread in the propylitically altered rocks in the district that Campbell (1931, p. 150–157) believed that albite was a primary mineral of the intermediate lava flows and breccias in the Mizpah Formation. Nolan (1930) also originally concurred in this conclusion but later (Nolan, 1935, p. 21) realized that it was a product of hydrothermal alteration of the volcanic rocks.

Campbell (1931, p. 167–172) described the alteration zonation in the district more concisely and in more detail than Nolan. He felt that the propylitization was a district-wide feature and was unrelated in its distribution to the major veins. He pointed out also that silicification, sericitization, and the occurrence of adularia are closely related to the mineralized veins in the district. He states (Campbell, 1931, p. 160) that this type of alteration is "always most severe next to veins and weakens perceptibly in a few feet or tens of feet."

Campbell (1931, p. 178–199) believed that propylitization was the earliest alteration phase developed in the district, that it was of a widespread or "regional" type unrelated to the main "channelways" in the district, and that it was followed by silicification and sericitization which were more closely controlled by "the dominant channelways." He felt that the ore minerals were deposited after the hydrothermal alteration had occurred. This postulated sequence of events obviously varies radically with Spurr's previously quoted conclusion that the same "mineralizing waters" that deposited the vein quartz and formed the quartz-sericite-adularia alteration also caused the propylitic alteration through changes in the chemical composition of the ore fluid as it migrated outward from the veins. It is interesting to note, as stated earlier, that Spurr's interpretation is more closely in accord with many modern studies on hydrothermal alteration processes than is Campbell's.

Broderick (1949) described the hydrothermal alteration in rocks of the Mizpah and Tonopah Formations in and adjacent to the King Tonopah Mine. His descriptions are based upon samples from diamond drill holes and the underground workings. He essentially agrees with the hydrothermal alteration phases described by Nolan (1935) and Campbell (1931); quartz-sericite-adularia alteration adjacent to veins, grading into chlorite-carbonate-albite-pyrite alteration in a few feet or tens of feet away from the veins.

Broderick (1949) states that veinlets of chalcedonic quartz containing adularia are a guide to mineralized veins and that such veinlets start to appear within 90 m of veins

and that, also, the amount of adularia present increases with proximity to the veins.

Core (1959) studied the hydrothermal alteration in the Mizpah Formation around the Valley View vein system in the central part of the Tonopah district. His study involved the use of X-ray diffraction and electron microscopy as well as petrographic techniques. Core concluded that there was a clay mineral zonation around the Valley View vein which could be subdivided into three zones, each named after the clay mineral which was predominant in the zone. His sample grid extended outward from the vein to a distance of about 35 m. He found an inner alteration zone several meters wide of quartz-sericite alteration which graded outward into a kaolinite-halloysite zone 10 to 15 m wide, which in turn graded outwards into a montmorillonite zone.

Core took only surface samples and his sampling did not extend into the main propylitic zone. Although all his samples were oxidized, he concluded that the clay mineral distribution was due to primary hydrothermal alteration because of its zonal distribution relative to the vein system. He also concluded that the alteration zonation was not due to successive alteration fronts related to changes in fluid chemistry in the main channelways, but rather was related to changes in the ore fluid as it interacted with the wall rocks in migrating outward from the veins.

In the course of the present study, many thin sections of intermediate flow rocks of the Mizpah Formation were examined. The rock samples ranged from completely fresh to pervasively altered. X-ray diffraction was used to identify some of the fine-grained alteration minerals in a few of the samples. Samples were collected from the surface, mine dumps, and underground workings.

It now appears clear, both from our own observations and those of previous workers, that three main zones, or phases, of hydrothermal alteration can be recognized within the Tonopah district. These alteration phases are zoned around the veins. The innermost zone, immediately adjacent to the veins, is a potassium silicate zone consisting essentially of quartz, sericite, and adularia accompanied by disseminated pyrite. Sulfide ore minerals occur in this zone only in quartz veinlets and not as disseminations in the wall rock. The potassium silicate zone grades outward into an intermediate argillic zone, which can be divided into two subzones, an inner subzone of kaolinite-halloysite, plus some quartz and sericite; and an outer subzone of montmorillonite, plus some kaolinite and sericite. Disseminated pyrite is also present in this zone. Rocks of both the potassium silicate and intermediate argillic zones are bleached to a white or light gray. The intermediate argillic zone grades outwards into the propylitic zone, which can also be subdivided into several subzones.

The zone of propylitic alteration is the most extensively developed alteration phase in the district. The outer fringe, or subzone, of the propylitic alteration halo, in the trachyandesites and dacites of the Mizpah Formation is marked by the alteration of hornblende (and augite when present) to calcite, magnetite, and amorphous clays. Some of the plagioclase is also partially altered to calcite. The rock is commonly grayish red-purple to pale red. Biotite is still fresh and the fine-grained potassium feldspar in the matrix is unaltered.

Proceeding inward towards the center of the district, the next alteration subzone is marked by moderately abundant zeolitic alteration of the matrix. Plagioclase is partially to completely albitized and replaced by calcite and montmorillonite. Biotite is altered to chlorite and Fe-Ti oxides (fig. 77). Hornblende is altered to calcite, chlorite, plus or minus montmorillonite and Fe-Ti oxides. Some hydrothermal potassium feldspar is present in quartz veinlets. The main zeolite mineral is mordenite. The rock is still pale red to grayish red-purple or dark greenish gray.

The next inner subzone is marked by nearly complete albitization of plagioclase with subsequent partial replacement of albite by quartz, sericite, and calcite. Biotite is completely altered to chlorite, rutile, and Fe-Ti oxides; former sites of hornblende crystals are occupied by quartz, chlorite, calcite, and Fe-Ti oxides. Quartz veinlets containing adularia and chlorite transect the rock. The matrix of the rock is composed of chlorite, albite, calcite, and potassium feldspar. The rock is greenish gray in color.

The innermost subzone of the propylitic alteration phase is essentially similar in mineralogy to the one just described except that disseminated pyrite occurs in the rock, principally as a replacement of Fe-Ti oxides (fig. 77). Also, the albitized plagioclase is partially to completely altered to calcite and sericite. Quartz occurs as clots, lining vugs, and in veinlets accompanied by some chlorite and adularia. Propylitic alteration extends both laterally and vertically away from the veins.

In the central part of the district, in the only locality in which mineralized quartz veins of ore grade crop out, the vein spacing is close enough so that the alteration envelopes of most of the veins overlap. Consequently, most of the altered wall rock in the central part of the district belongs to the potassium silicate zone of alteration (fig. 78); some intervening areas of intermediate argillic alteration are also present. The propylitic zone of alteration does not crop out in this area. Veins are less closely spaced in the periphery of the district and individual veins are surrounded by alteration envelopes, beginning at the veins and moving outward, of the potassium silicate, intermediate argillic, and propylitic zones. Widths of the potassium silicate and intermediate argillic zones vary from 1 to 40 or more meters. Mineralized quartz veins in the peripheral part of the district terminate upwards into quartz and calcite stringer zones. Pyrite is essentially the only sulfide present in the stringer zones and they contain little to no silver or gold. Propylitic alteration extends for a vertical distance of up to 200 m above vein tops.

Age of Mineralization

There are two distinct periods of hydrothermal alteration and precious-metal mineralization in the Tonopah district. The bonanza silver-gold deposits, for which the Tonopah district is famous, formed during the first period of mineralization. These silver-gold ore bodies occur in quartz veins and are confined to rocks of the Tonopah Formation, the Mizpah Formation, the Extension Breccia and the West End Rhyolite (Nolan, 1935, p. 13). The Fraction Tuff, as redefined in this report, is also older than the first period of mineralization in the district (see discussion in section on Fraction Tuff). Rocks of the Siebert Formation and the Heller Tuff unconformably overlie mineralized veins of the first period. The Oddie and Brougher rhyolites intrude these mineralized quartz veins (Nolan, 1935, p. 27–28) and are definitely younger than the first period of mineralization in the Tonopah district.

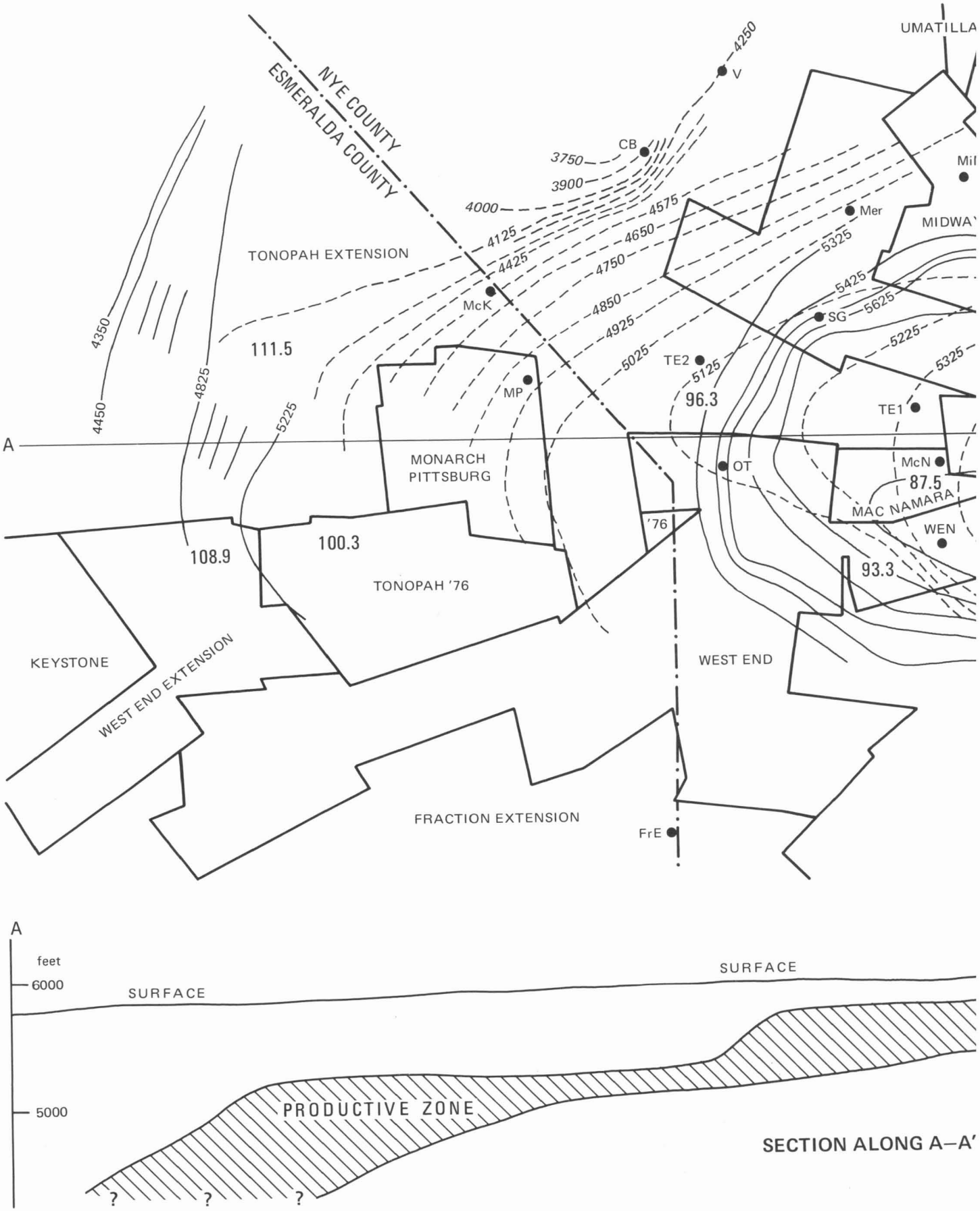


FIGURE 75. Sketch contour map and section of productive zone at Tonopah. *From Nolan (1935).*

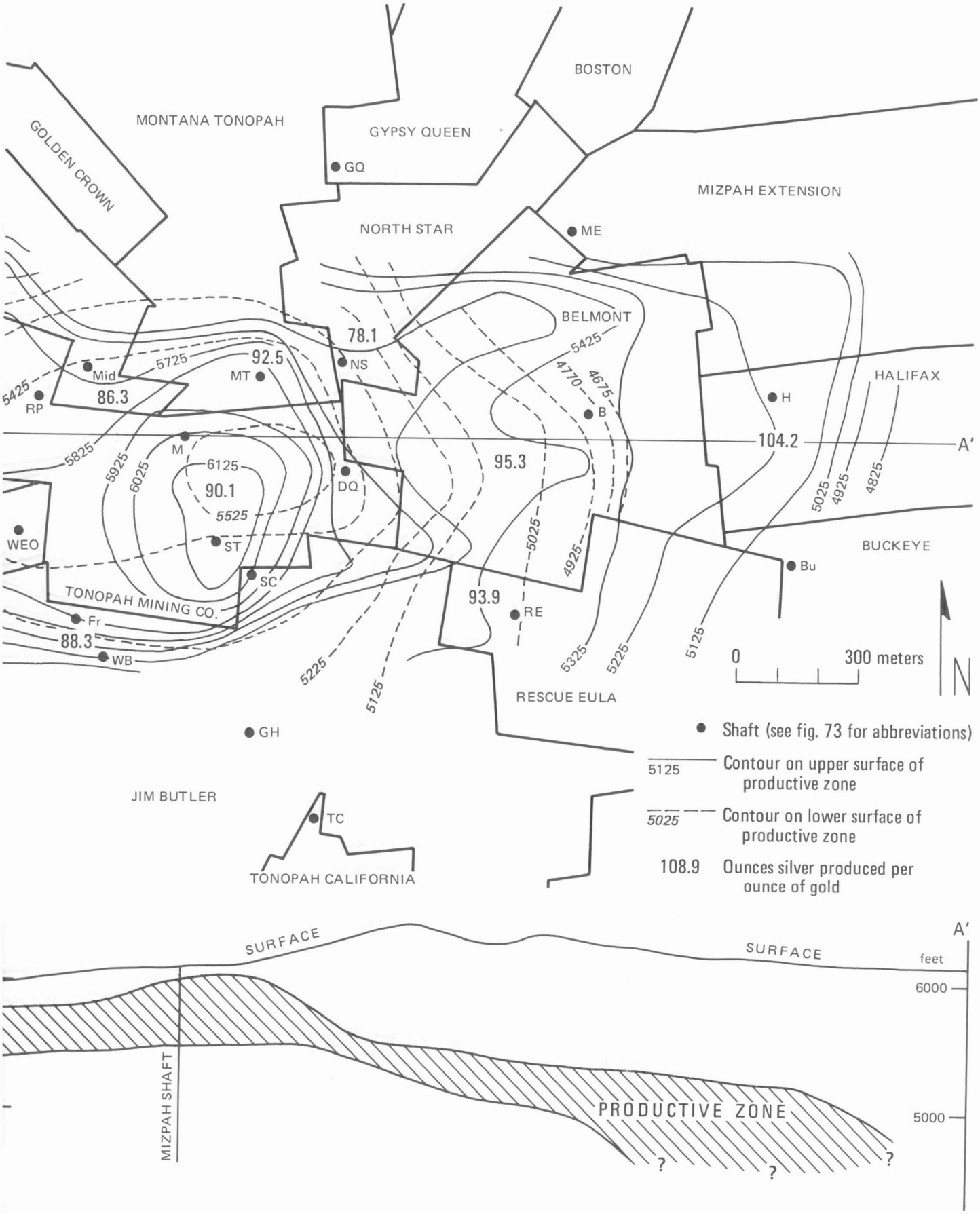

BOSTON
MONTANA TONOPAH
GYPSY QUEEN
GOLDEN CROWN
GQ
MIZPAH EXTENSION
NORTH STAR
ME
BELMONT
78.1
5425
92.5
5725
NS
MT
Mid
86.3
RP
4770
4675
B
HALIFAX
H
104.2
A'
M
6125
95.3
5825
5925
6025
90.1
DQ
5525
5025
4925
4825
WEO
ST
BUCKEYE
Bu
SC
TONOPAH MINING CO.
93.9
RE
Fr
88.3
WB
5225
5125
5325
0
300 meters
N
RESCUE EULA
GH
Shaft (see fig. 73 for abbreviations)
5125 Contour on upper surface of productive zone
5025 Contour on lower surface of productive zone
108.9 Ounces silver produced per ounce of gold
JIM BUTLER
TC
TONOPAH CALIFORNIA
SURFACE
SURFACE
A'
feet
6000
5000
MIZPAH SHAFT
PRODUCTIVE ZONE
?
?
?

TABLE 30. Minerals and their modes of occurrence in the Tonopah district, as reported by Melhase (1935).

Apatite ($Ca_5FP_3O_{12}$). Occurs in the Valley View vein as minute crystals lining crevices on the 440- to 640-foot levels. Snow white crystals of apatite with iodyrite crystals implanted upon them and others coated with a glaze of clear hyalite were found here.

Argentite (acanthite) (Ag_2S). Occurs as both primary and secondary, either massive or well crystallized in vugs. It is commonly reticulated or arborescent in distorted octahedral or cubo-octahedral crystals.

Azurite [$Cu(OH)_2 2CuCO_3$]. Occurs as earthy light-blue masses with malachite.

Barite ($BaSO_4$) Not common, but occasionally found in masses of white crystals covering several square feet of the fissure walls.

Cacoxenite [$Fe_2(OH)_3PO_4 \cdot 4.5H_2O$]. On the 500-foot level of the Montana–Tonopah as golden yellow radiating tufts implanted on drusy quartz which is coated with velvety black layers of manganese oxides, the whole forming a most beautiful specimen.

Calcite ($CaCO_3$). All of secondary origin. In the Mizpah vein at the 200-foot level good crystals of steep rhombohedral habit were found upon malachite. Some of these were colored a beautiful green by included malachite.

Cerargyrite (AgCl). Abundant over extensive areas in kaolinized feldspar. The crystals are translucent, pale grey, in minute cubes and octahedrons.

Chalcopyrite ($CuFeS_2$). Small grains throughout the veins and often found as inclusions in polybasite.

Cinnabar (HgS). Occurs rarely in thin streaks in the ores of the West End Mine.

Cuprite (Cu_2O). Occurs in small masses in the oxidized zone.

Embolite (AgBr). Occurs as imperfect cubes and octahedrons on psilomelane. Crystals usually bunched or grouped.

Feldspar ($KAlSi_3O_8$). Adularia, more or less kaolinized, is a common constituent of the gangue of this district.

Galena (PbS). Associated with sphalerite and chalcopyrite all through the mines. It carries a high percentage of gold.

Gold (Au). Occurs as grains and flakes in argentite, sometimes arborescent.

Gypsum ($CaSO_4 \cdot 2H_2O$). Not common and noted only as thin coatings on the fissure walls.

Hematite (Fe_2O_3). Occurs with limonite in the weathered zone in impure earthy masses seamed with brown jarosite and often associated with iodyrite and cacoxenite.

Huebnerite ($MnWO_4$). Occurs as black platy masses in quartz or, again, as thin plates in cavities. Sometimes almost transparent crystals, deep red in color are found.

Iodyrite (AgI). Common in the lower zone of oxidation as small, bright-yellow crystals in pockets and cavities in the veins. The crystals are usually loose and sometimes associated with flakes of jarosite as in the Valley View vein on the 500-foot level. These iodyrite crystals are excellent examples of the rare dihexagonal-pyramidal class of symmetry.

Jarosite [$KFe_3(OH)_6(SO_4)_2$]. Occurs in flaky masses of light-ochre-yellow to reddish-brown color. Abundant in the lower part of the oxidized zones where it is associated with iodyrite.

Kaolinite [$Al_4(OH)_8Si_4O_{10}$]. Occurs as soft white clay often filled with crystals of horn silver.

Malachite [$Cu_2(OH)_2(CO_3)$]. Occurs in delicate acicular masses in the Mizpah vein.

Manganite [MnO(OH)]. Abundant in the zone of oxidation. It occurs in pockets in long, vertically striated rods or needles.

Manganocalcite ($MnCaCO_3$). A calcite of light-brown color containing manganese. From the 1,000-foot level of the Belmont Mine.

Opal ($SiO_2 \cdot nH_2O$). Is found in the Valley View vein as colorless hyalite opal sprinkled with a frosting of white apatite crystals which sometimes enclose iodyrite crystals.

Pharmacosiderite [$Fe_3(OH)_3(AsO_4)_2 \cdot 5H_2O$]. On the 370-foot level of the Montana–Tonopah Mine as light-yellowish-green cubes, diagonally striated coating quartz.

Polybasite [$(Ag, Cu)_{16}Sb_2S_{11}$]. Occurs a platy crystals in cavities and seams in quartz. It is cherry red on broken surfaces.

Pseudomalachite [$Cu_5(OH)_4(PO_4)_2$]. Occurs as small globular incrustations on quartz. Bright green in color, finely fibrous, and associated with huebnerite and rhodonite.

Psilomelane [$BaMn^{11}Mn^{4}{}_8O_{16}(OH)_4$]. Occurs in botryoidal or small mammillary masses.

Pyrargyrite (Ag_3SbS_3). Occurs as fissure fillings in quartz, often intergrown with argentite, polybasite, and wire silver.

Pyrite (FeS_2). Mostly secondary in the gangue, but scarse in the vein material. Sometimes found as inclusions in polybasite.

Pyrolusite (MnO_2). Occurs as finely fibrous or feltlike coatings on the fissure walls.

Quartz (SiO_2). Occurs as white masses or in crystal druses with fine granular silver minerals.

Rhodochrosite ($MnCO_3$). Of rare occurrence; found only in crevices of quartz in the Montana–Tonopah Mine.

Rhodonite [$(Mn, Ca, Fe)SiO_3$]. Occurs as pinkish bands in the quartz.

Sericite [$K_2Al_4(OH)_4Si_6Al_2O_{20}$]. A secondary mineral occurring in soft pearly flakes in the ores of this district.

Siderite ($FeCO_3$). Occurs very rarely in this district.

Silver (Ag). Occurs as wires, films, and spongy masses associated with argentite, polybasite, tetrahedrite, or pyrargyrite.

Sphalerite (ZnS). Brown sphalerite occurs with galena below the 900-foot level of the Mizpah shaft.

Stephanite (Ag_5SbS_4). Occurs with polybasite.

Tetrahedrite [$Cu_{10}(Zn, Fe, Cu)_2Sb_4S_{13}$]. Occurs as thick tabular plates in a quartz-feldspar gangue with wire silver at the Belmont Mine.

Turquoise [$CuAl_6(OH)_8(PO_4)_4 \cdot 5H_2O$]. On the 600-foot level of the Mizpah Mine in masses of pale green to white. Associated with manganese oxides, kaolinite, and abundant iodyrite.

Wad ($MnO \cdot nH_2O$). Occurs as impure soft velvety coatings with jarosite crystals implanted upon them.

Wavellite [$Al_6(F, OH)_6(PO_4)_4 \cdot 9H_2O$]. Occurs in small white spheres of concentric radiated structure implanted on vein quartz.

Wulfenite ($PbMoO_4$). Occurs in thin basal plates, colorless, with twinned iodyrite crystals implanted upon them.

Stratigraphic limits on the age of the first period (main stage) of mineralization in the Tonopah district are defined by the age of the unaltered rock in the Mizpah Formation, which are preore; and the ages of the Heller Tuff and Oddie Rhyolite, which are postore. K-Ar ages of 20.4 and 20.5 m.y. (table 4) were obtained on unaltered flow rocks from the Mizpah Formation. The Heller Tuff has K-Ar ages of 16.9 and 17.1 m.y. (table 4) and the Oddie Rhyolite has K-Ar ages of 16.4 and 16.9 m.y. (table 4). Therefore, the hydrothermal alteration and mineralization related to the main-stage silver-gold mineralization in the Tonopah district occurred between 20.5 and 17 m.y. ago. As further evidence for the age of mineralization, K-Ar dates of 19.1 m.y. on vein adularia (Belmont Mine) and 18.1 m.y. (table 4) on a whole rock sample from the potassium silicate alteration zone (Valley View vein) both fit into the period between 20.5 and 17 m.y. However, hydrothermal alteration and precious metal mineralization continued to occur

TABLE 31. Hypogene ore minerals in the Tonopah district.
[After Bastin and Laney (1918)]

Mineral	Abundant	Moderately abundant	Minor constituent	Occurrence reported
Argentite (acanthite) (Ag_2S)		X		
Argyrodite (Ag_8GeS_5)				X
Arsenopyrite (FeAsS)			X	
Chalcopyrite ($CuFeS_2$)	X			
Electrum (Au,Ag)			X	
Galena (PbS)	X			
Polybasite [$(Ag,Cu)_{16}Sb_2S_{11}$]		X		
Pyrargyrite (Ag_3SbS_3)		X		
Pyrite (FeS_2)		X		
Selenium (Se)			X	
Sphalerite (ZnS)	X			
Stephanite (Ag_5SbS_4)				X
Wolframite [$(Fe,Mn)WO_4$]		X		

within the district after the main-stage period of silver-gold mineralization because, locally, rocks of the Oddie Rhyolite and the Siebert Formation are hydrothermally altered and contain low-grade gold-silver mineralization.

Very little ore has been produced to date in the district from rocks mineralized in this later period of hydrothermal activity. Generally, the mineralization is distinctly lower grade than in the earlier phase and has a higher gold/silver ratio. Mineralized veins of this later period occur on Mount Oddie and Ararat Mountain. Disseminated, low-grade, gold-silver mineralization also occurs in silicified, tuffaceous sediments of the Siebert Formation and in the Oddie Rhyolite that form the three hills 1 km northwest of Siebert Mountain.

Because unaltered rocks of the Brougher Rhyolite unconformably overlie hydrothermally altered rocks of the Siebert Formation, the age of the Brougher Rhyolite places a lower limit on this later period of mineralization in the Tonopah district. The Brougher Rhyolite in the Tonopah district has K-Ar ages of 16.1 and 16.3 m.y. The available evidence indicates that this second period of mineralization in the Tonopah district is the same age as the mineralization in the Divide district and is probably genetically related to it, as adularia and adularized whole rock from mineralized lodes in the Divide district were dated by the K-Ar method at 16.3 and 16.4 m.y.

Degree of Erosion of the Mineralized Veins

Although quartz veins of ore grade crop out in the central part of the Tonopah district, where they are overlain unconformably by rocks of the Siebert Formation, the Heller Tuff, and by thin, Quaternary alluvial deposits, we believe, for the following reasons, that relatively little erosion of the ore-bearing portions of the quartz veins has occurred:

1. The productive zone or shell (fig. 75) in which the Tonopah ore bodies occur is of about the same thick-

TABLE 32. Supergene ore minerals in the Tonopah district.
[After Bastin and Laney (1918)]

Mineral	Abundant	Moderately abundant	Minor constituent
Argentite (acanthite) (Ag_2S)		X	
Bornite (Cu_5FeS_4)			X
Calamine (hemimorphite) [$Zn_4(OH_2)Si_2O_7 \cdot H_2O$]			X
Cerargyrite (AgCl)		X	
Chalcopyrite ($CuFeS_2$)			X
Covellite (CuS)			X
Embolite (AgBr)			X
Gold (Au)			X
Iodyrite (AgI)			X
Malachite [$Cu_2(OH)_2(CO_3)$]			X
Manganese oxides (MnO)	X		
Polybasite [$(Ag,Cu)_{16}Sb_2S_{11}$]		X	
Pyrargyrite (Ag_3SbS_3)			X
Pyrite (FeS_2)		X	
Silver (Ag)		X	

TABLE 33. Gangue minerals in the Tonopah district.

[After Bastin and Laney (1918)]

Mineral	Abundant	Moderately abundant	Minor constituent	Occurrence reported
Adularia[2] ($KAlSi_3O_8$)		X		
Albite[2] ($NaAlSi_3O_8$)		X		
Barite[3] ($BaSO_4$)		X		
Calcite[1] ($CaCO_3$)				X
Dahllite[1] ($3Ca_3P_2O_8 \cdot CaCO_3$)			X	
Epsomite[1] ($MgSO_4 \cdot 7H_2O$)			X	
Gypsum[1] ($CaSO_4 \cdot 2H_2O$)		X		
Kaolinite[3] [$Al_4(OH)_8Si_4O_{10}$]		X		
Opal[1] ($SiO_2 \cdot nH_2O$)			X	
Quartz[2] (SiO_2)	X			
Rhodochrosite[2] ($MnCO_3$)		X		
Sericite[2] [$K_2Al_4(OH)_4Si_6Al_2O_{20}$]		X		

[1]Supergene minerals.
[2]Hypogene minerals.
[3]Supergene and hypogene minerals.

ness in areas where the quartz veins either crop out or are overlain unconformably by later rocks, as it is in areas where the ore bodies were blind. Nolan (1935, p. 44) has described one possible exception to this generalization. He believes that postore erosion caused the thinning of the productive zone in the area between the West End Mine and the West End Extension.

2. No significant, gold-silver placer deposits are known to occur anywhere within the district, either in Quaternary alluvial deposits or in rocks of the Siebert Formation.
3. Very little detrital, ore-grade vein material is present in either the Siebert Formation or in Quaternary alluvial deposits in the district.

Underground Temperatures in the Tonopah Mining District

In several mines at Tonopah anomalous underground temperatures have been reported. In the Ohio Tonopah shaft, temperatures up to 25.6°C were found at 232.9 m and temperature gradients as high as 7°C/100 m were reported in dry rocks at depths less than 250 m (Spurr, 1905b, p. 263–265; Darton, 1920). Water temperatures up to 41.1°C were reported by Bastin and Laney (1918, p. 29) from depths of 450 to 704 m in the central part of the mining district. Large flows of hot water were encountered in the Tonopah Extension Mines (Broderick, 1949, p. 9), and during the mid-1920's approximately 11 million liters per day of hot water were pumped from the deeper mines (Carpenter and others, 1953). Some of this water was utilized in a greenhouse to grow fresh vegetables.

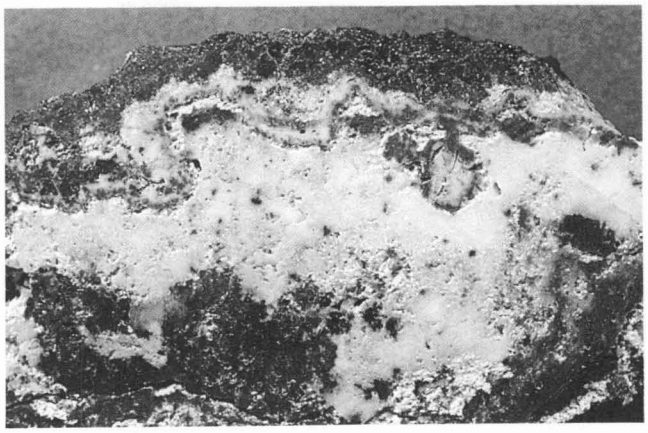
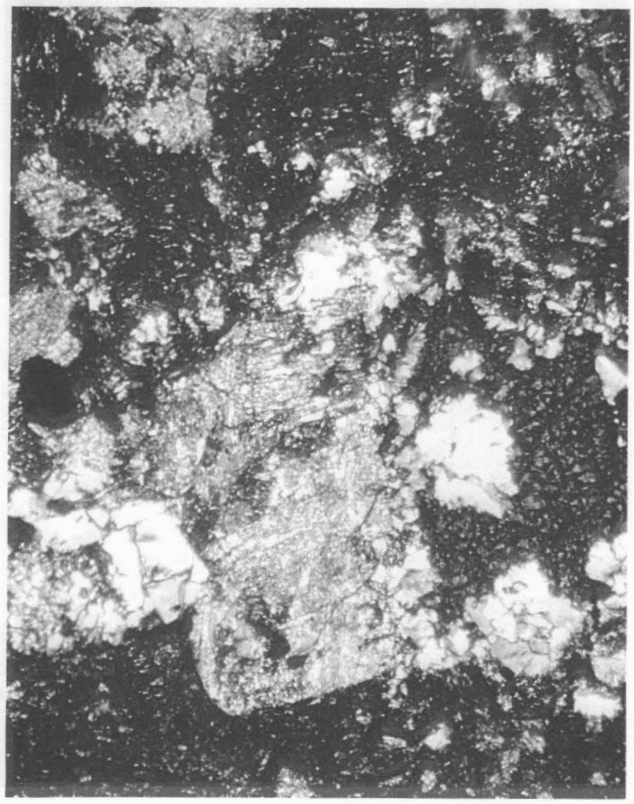


FIGURE 76. Typical high-grade primary silver ore from the Tonopah district. Dark-colored bands consist predominantly of argentite (acanthite). 1 X

Possible Exploration Targets in the Tonopah Area

Nolan (1935, p. 47–48) delineated several areas in the central and western portions of the Tonopah district where unexplored segments of known productive veins might occur. He suggested also that a thorough sampling program of the walls of the Mizpah vein and other large productive veins in the district might well develop large low-grade ore bodies. We have no information as to whether or not any of Nolan's suggestions were acted upon. If not, they would seem worthy of careful study considering the current (1979) high prices for silver and gold.

He suggested further that the area to the north of Tonopah, in the footwall of the Halifax fault zone (pl. 1), was a potentially favorable area for the occurrence of ore bodies similar to those found in the main portion of the Tonopah district. Nolan (1935, p. 48) felt that much of this area was covered by rocks of the postore "Esmeralda" Formation and thus evidence of mineralization in this area could be obtained only by subsurface exploration beneath the "Esmeralda" rocks. As has been shown in this report, however, much of the outcrop in this area consists of welded ash-flow tuff of the Fraction Tuff, which is preore in age. We concur with this conclusion that the area north of Tonopah is a favorable area to look for possible ore bodies of the Tonopah type, particularly in the footwall of the Halifax fault zone. Our conclusion that the Fraction Tuff, as herein redefined, is preore in age, however, has



.2mm

A. Biotite phenocrysts are altered to chlorite and Fe-Ti oxides. Hornblende and pyroxene are altered to chlorite, calcite, and Fe-Ti oxides and locally completely replaced by quartz, which occurs also in veinlets and filling vugs. The matrix consists of a fine-grained aggregate of albite, alkali feldspar, chlorite, calcite, quartz, and Fe-Ti oxides.

2mm

B. Plagioclase phenocryst is albitized and partially altered to calcite and sericite. Other alteration products similar to A.

0.2mm

C. Essentially similar to A. and B., except that Fe-Ti oxides are replaced by pyrite.

FIGURE 77. Propylitic alteration in dacite of the Mizpah Formation.

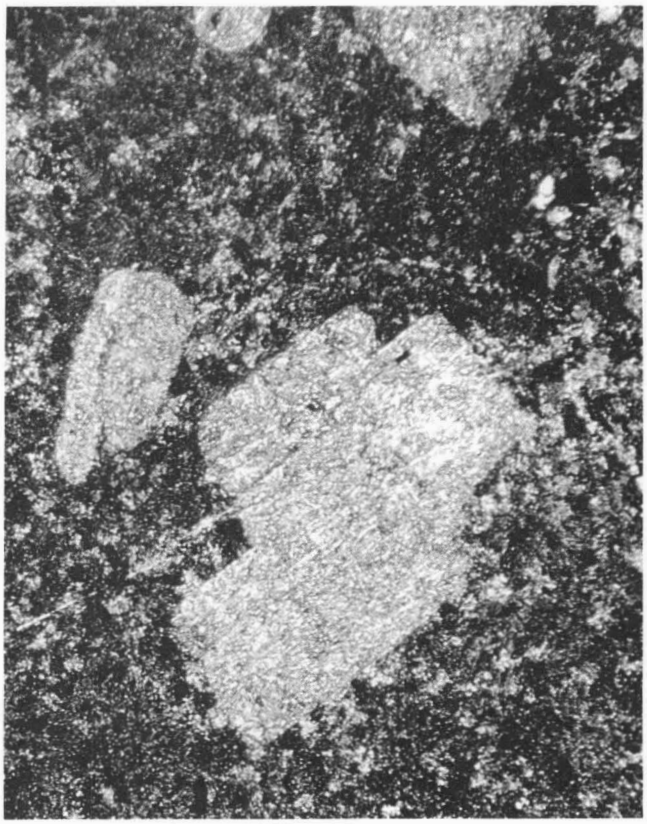
significant implications for locating potential blind ore bodies in this area.

We recommend that geochemical sampling be done along the Halifax fault zone in the area north of the King Tonopah Mine. The Fraction Tuff is hydrothermally altered along the trace of the Halifax fault zone in this area and locally is silicified and contains quartz stringers. No ore-grade material crops out at the surface in this area, however, and any productive veins present would be blind, as were all of the productive veins in the western part of the Tonopah district.

Nolan's suggestion for prospecting the Halifax fault zone north of Tonopah was followed by the Calumet and Hecla Consolidated Copper Company in 1946 when they found rocks showing quartz-sericite-adularia alteration on the dump of the King Tonopah Mine, which is located in this area (Broderick, 1949, p. 11–12). An exploration project was launched which involved the drilling of eight diamond drill holes to depths of between 245 and 610 m (fig. 79). The Calumet and Hecla Consolidated Copper Company announced in their 1948 annual report:

> "The drilling operations at Tonopah, Nev., carried on by the subsidiary Tonopah Development Company encountered quartz veins carrying gold and silver in favorable geological conditions similar to those in the old camp nearby. These results justify further exploration to determine whether or not they are of commercial importance."

In 1950 Calumet and Hecla optioned the Tonopah Development Company's holdings to the American Smelting and Refining Company, which, in 1950 and 1951,



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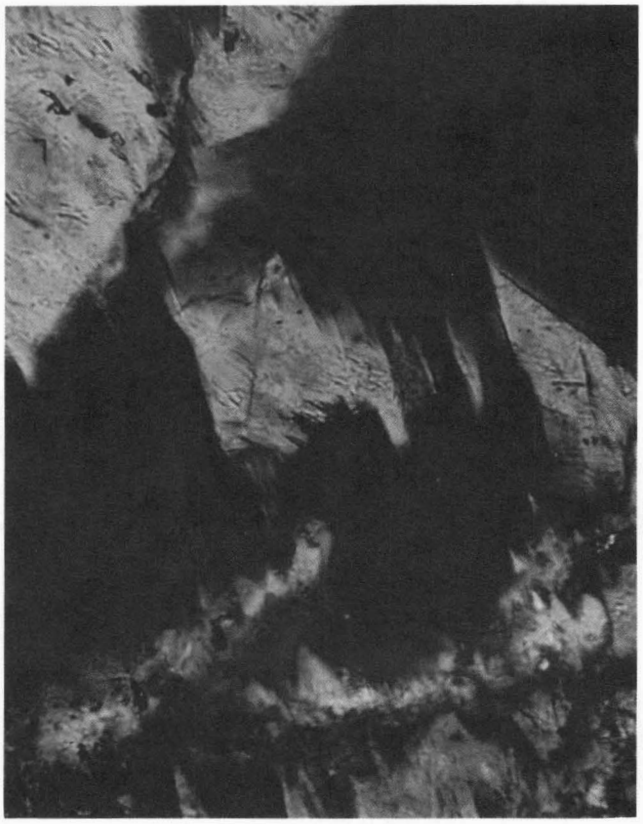
A. Sericitic alteration of albitized plagioclase phenocrysts. Matrix is composed of quartz, sericite, and adularia.



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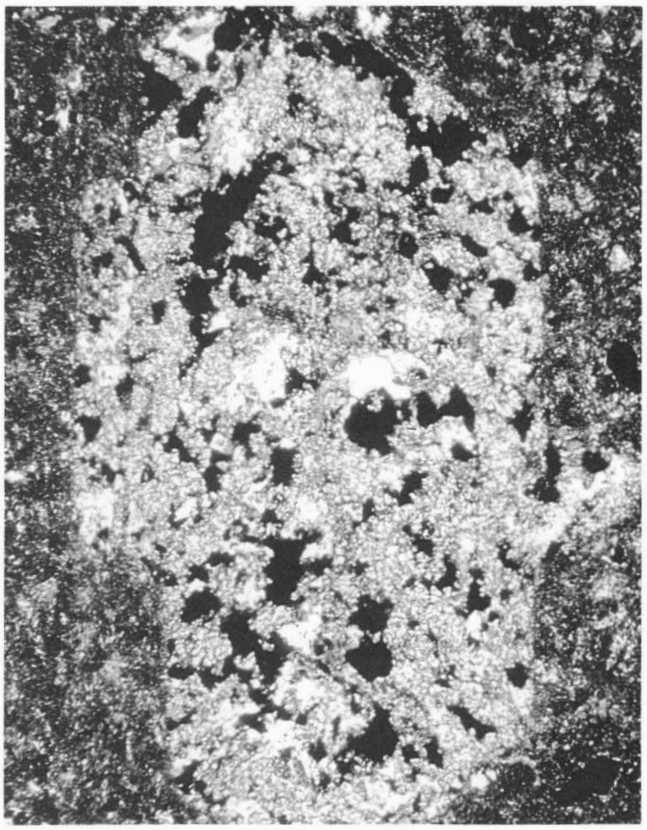
C. Adularia (light colored) replacing albitized plagioclase phenocryst (dark gray).



0.1 mm

B. Hornblende phenocryst replaced by quartz, sericite and adularia.

0.1 mm

D. Fine-grained adularia (diamond-shaped crystals) and quartz in a veinlet.

FIGURE 78. Potassium silicate alteration in dacitic rocks of the Mizpah Formation.

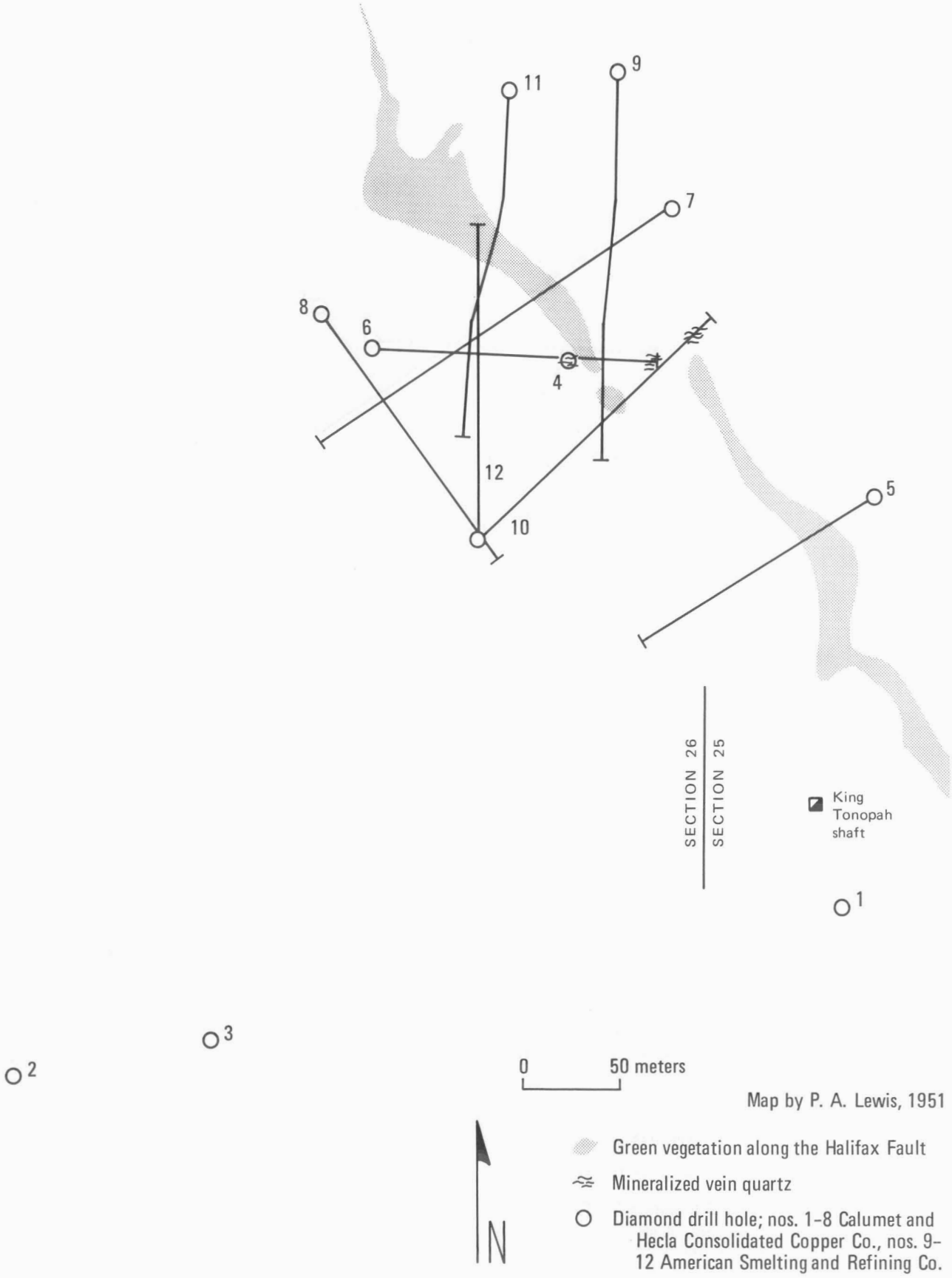


FIGURE 79. Horizontal plan view of King Tonopah Mines area showing location of diamond-drill holes.

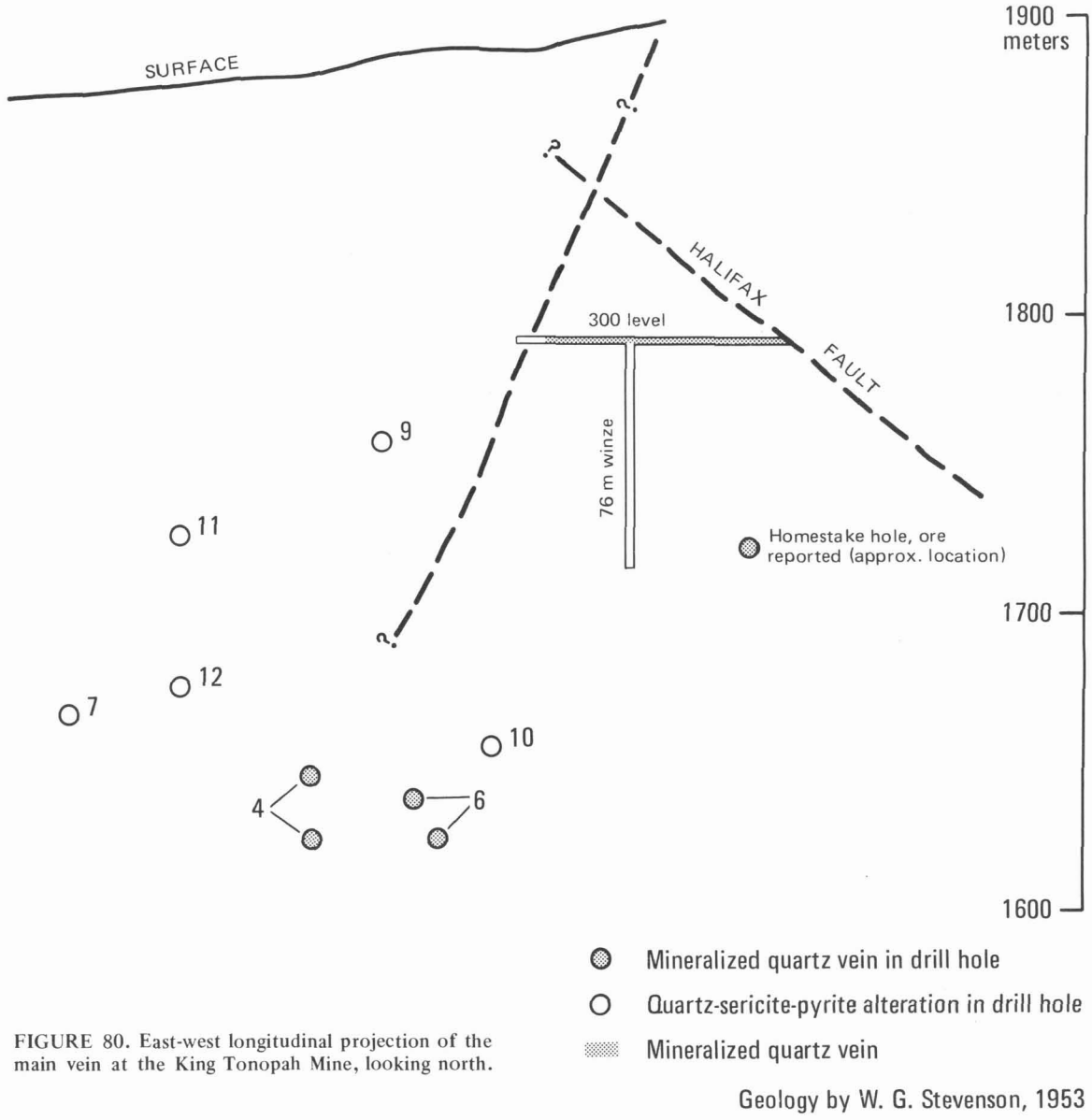


FIGURE 80. East-west longitudinal projection of the main vein at the King Tonopah Mine, looking north.

drilled four additional diamond drill holes in an area several hundred meters north of the King Tonopah shaft, where Calumet and Hecla had found a mineralized quartz vein at a depth of about 230 to 260 m. The four holes were drilled to depths of between 275 and 305 m (fig. 79) and were designed to determine the dip of the vein and to try to ascertain the possible existence of a significant tonnage of silver-gold ore. Two of the holes did intersect the vein, which was found to have an east-west strike and a steep southerly dip, but only low values in silver and gold were encountered. American Smelting and Refining Company concluded that the results of its drilling, plus the data from Calumet and Hecla, indicated that the quartz vein probably did not contain a large enough tonnage of silver-gold ore to justify further exploration, and they relinquished the property.

Later in 1951, Calumet and Hecla granted an option on the Tonopah Development Company's claims to Homestake and Summit King Mines Ltd. (subsidiary of Bralorne Ltd.). Summit King rehabilitated the King Tonopah shaft and drove a crosscut at the 300 level in a northerly direction toward the area where the diamond drilling referred to above had encountered the vein. In 1952, the crosscut encountered the quartz vein at a distance of about 286 m from the shaft (fig. 80). The vein at that point was 2.44 m wide and contained high-grade silver-gold ore with appreciable amounts of pyrargyrite and argentite. Subsequent underground exploration in 1953 and early 1954 disclosed that the high-grade ore extended only about 4.6 m above the 300 level and about 3 m below the 300 level (fig. 81). A winze was sunk from the crosscut to the 550 level with relatively discouraging results. At this time about 15,000 to 20,000 tons of ore averaging about 30 oz Ag and 0.3 oz Au had been blocked out, and Summit King decided to mine this limited tonnage of ore and abandon further underground exploration. The Company did not extend its underground exploration to the deeper portions of the vein where Calumet and Hecla had found ore-grade mineralization. The property was returned to Calumet and Hecla in 1954.

In August 1954, the chief geologist of Calumet and Hecla, Dr. Thomas Broderick, announced that the company planned to explore the mineralized quartz vein in the King Tonopah Mine at the 750 level and below, but apparently

the proposed deep underground exploration program at the mine was not carried out.

The King Tonopah Mine produced a small quantity of direct shipping ore in the years 1958–1961. Summa Corp. acquired the King Tonopah Mine in 1969, but did no exploration. The mine, together with other Summa Corp. holdings in the Tonopah district, was sold to Houston Oil and Minerals Corp. in 1977.

The available data show that high-grade silver-gold mineralization of the Tonopah type is present in the King Tonopah Mine area. If all the information from the drilling projects, and the underground exploration conducted by Calumet and Hecla, Summit King Mines Ltd. and Homestake could be obtained, it seems probable that worthwhile exploration targets could be developed in the King Tonopah area.

During the course of the present study, we found a large area of hydrothermally altered rocks in the Tonopah and Mizpah Formations near Fraziers Well north and east of Red Mountain. Quartz-sericite-adularia alteration is present in dacitic rocks of the Mizpah Formation in this area along with an extensive area of propylitic alteration. The altered rocks are cut by a prominent quartz vein up to 3 m wide and over 100 m in length and by numerous quartz and calcite veinlets and stringers. There are several shallow prospect pits in the area, none over 30 m deep. None of the prospects encountered ore-grade mineralization.

The area of alteration extends beneath a sequence of flows of the trachyandesite of Red Mountain, which, in general, forms a thin veneer, less than 50 m thick, covering the altered rocks. We believe that the combination of favorable alteration plus the occurrence of quartz and calcite veins and stringers in the altered rocks suggests that the present erosion surface may have transected the upper portion of an epithermal vein system and that the area represents a potential exploration target.

Divide District

The Divide mining district is centered around Gold Mountain in S26,27,T2N,R42E, 9 km south of the Tonopah district (figs. 82, 83). According to Knopf (1921, p. 147), gold was discovered in the district in 1902 and small gold-bearing veins on Gold Mountain were mined intermittently until 1917 when the discovery of silver ore started the Divide boom.

The discovery of silver ore in the Divide district was made accidently. A shaft was sunk approximately 200 m north of the gold-bearing veins being mined, and a crosscut was started at the 165 level to intersect the veins below the area that had been mined. During the course of this work, 6 m of mineralized rock averaging $53.80 per ton in silver and gold and 0.77 percent molybdenum were encountered. This discovery triggered one of the last major Nevada silver rushes. By 1919 an area of over 130 km^2 surrounding Gold Mountain had been staked, and over 100 mining companies had been formed in the district. The boom soon subsided as only a few of the properties were found to contain ore in minable quantities.

Much of the physical exploration in the Divide district during the period of the Divide boom followed the pattern of the initial silver discovery; shafts were sunk and crosscuts run out. In many cases, no careful examination of surface evidence of mineralization was made on claim groups prior to sinking a shaft. The net result was the sinking of a number of shafts in barren rock and the expenditure of sizeable sums of money in areas with little real promise. The initial boom subsided because of the failure to find minable, quantities of ore on most of the claims staked in the initial rush. Later exploration in the district was more carefully planned and executed.

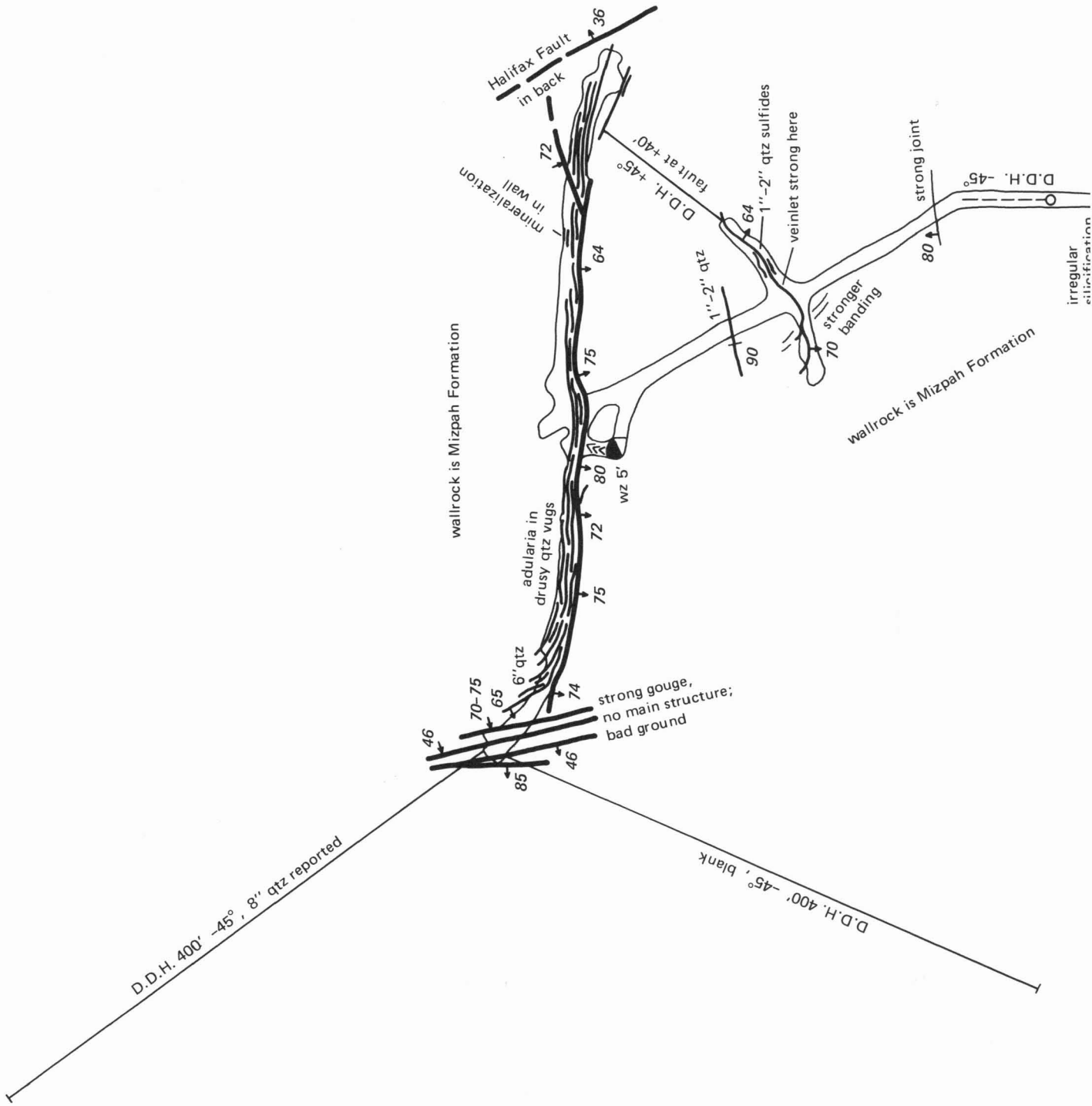
Most of the ore mined in the district was produced during the period between 1920 and 1929 and most of the production came from the Tonopah Divide Mine. Only 10 mines in the district produced over $5,000 of ore (see tables 34 and 35). The district has a total production of approximately $3.5 million from 3,275,079 ounces of silver and 32,474 ounces of gold of which the Tonopah Divide Mine produced about $2,800,000 (table 35).

There has been no recorded production from the Divide district since 1950. However, since the demonetization of silver in 1965 and the subsequent increase in price of silver to over $4 per ounce (1977), there has been renewed exploration, principally for large low-grade, silver-gold ore bodies that would be amenable to open-pit mining methods.

Two main types of precious-metal deposits have been mined in the Divide district. Prior to the discovery of the high-grade silver ore body at the Tonopah Divide Mine, mining was confined to narrow veins, valuable chiefly for their gold content, occurring in the Oddie Rhyolite or silicified rocks of the Siebert Formation adjacent to the Oddie Rhyolite. These veins are relatively narrow, seldom exceeding 1 m in width, and are simple mineralogically. They contain, where unoxidized, fine-grained quartz, silicified angular fragments of wall rock, pyrite, free gold, and minor silver sulfides (fig. 84). Base-metal sulfides are rare to absent in the veins. Sulfides are present in the veins within a meter of the present surface in some of the underground workings and supergene enrichment of the veins is negligible. One vein of this type at the Tonopah Hasbrouck Mine on Hasbrouck Mountain, just west of Gold Mountain, was unusual in that the silver content of the ore greatly exceeded the gold content.

The second type of precious metal mineralization in the district is the silver-bearing lodes, from which most of the production of the district has come. The principal host rock for these lodes is the Tonopah Summit Member of the Fraction Tuff, although mineralization of this type also occurs in the Oddie Rhyolite and in the Siebert Formation. These lodes typically occur in fracture and fault zones in the Fraction Tuff and vary in width from a few centimeters to about 30 m (fig. 85). Their surface outcrops are marked by weakly to moderately silicified, iron-stained zones traversed by numerous fractures. The walls of the lodes are usually well defined and commonly slickensided. The Fraction Tuff where these lodes occur, is altered to an aggregate of quartz, sericite, and adularia. Numerous small quartz veinlets occur within the lodes but bold quartz veins typical of the Tonopah district do not occur at Divide.

The oxidized ores contained cerargyrite as the chief silver mineral and variable amounts of free gold. Ferrimolybdite and powellite occurred in oxidized ore at the Tonopah Divide Mine (fig. 86), and highly anomalous amounts of molybdenum (up to several thousand ppm) are present in many of the other mineralized zones in the district. Barite is present in many of the mineralized lodes, particularly in the southern part of the district.


D.D.H. 400', -45°, 8" qtz reported
D.D.H. 400', -45°, blank
wallrock is Mizpah Formation
wallrock is Mizpah Formation
adularia in drusy qtz vugs
6" qtz
strong gouge, no main structure; bad ground
wz 5'
mineralization in wall
Halifax Fault in back
D.D.H. +45°
fault at +40'
1"-2" qtz
1"-2" qtz sulfides
veinlet strong here
stronger banding
strong joint
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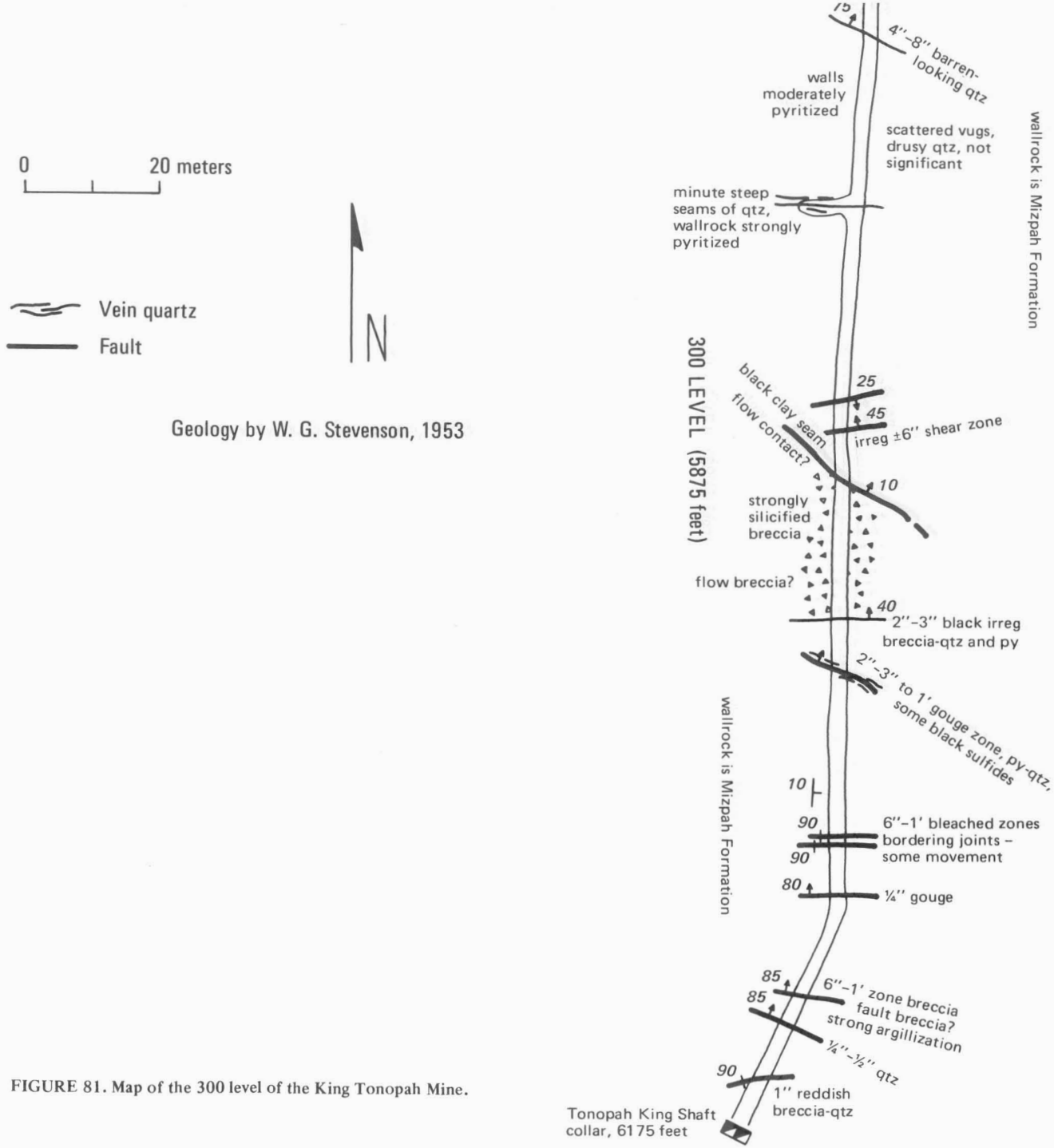


FIGURE 81. Map of the 300 level of the King Tonopah Mine.

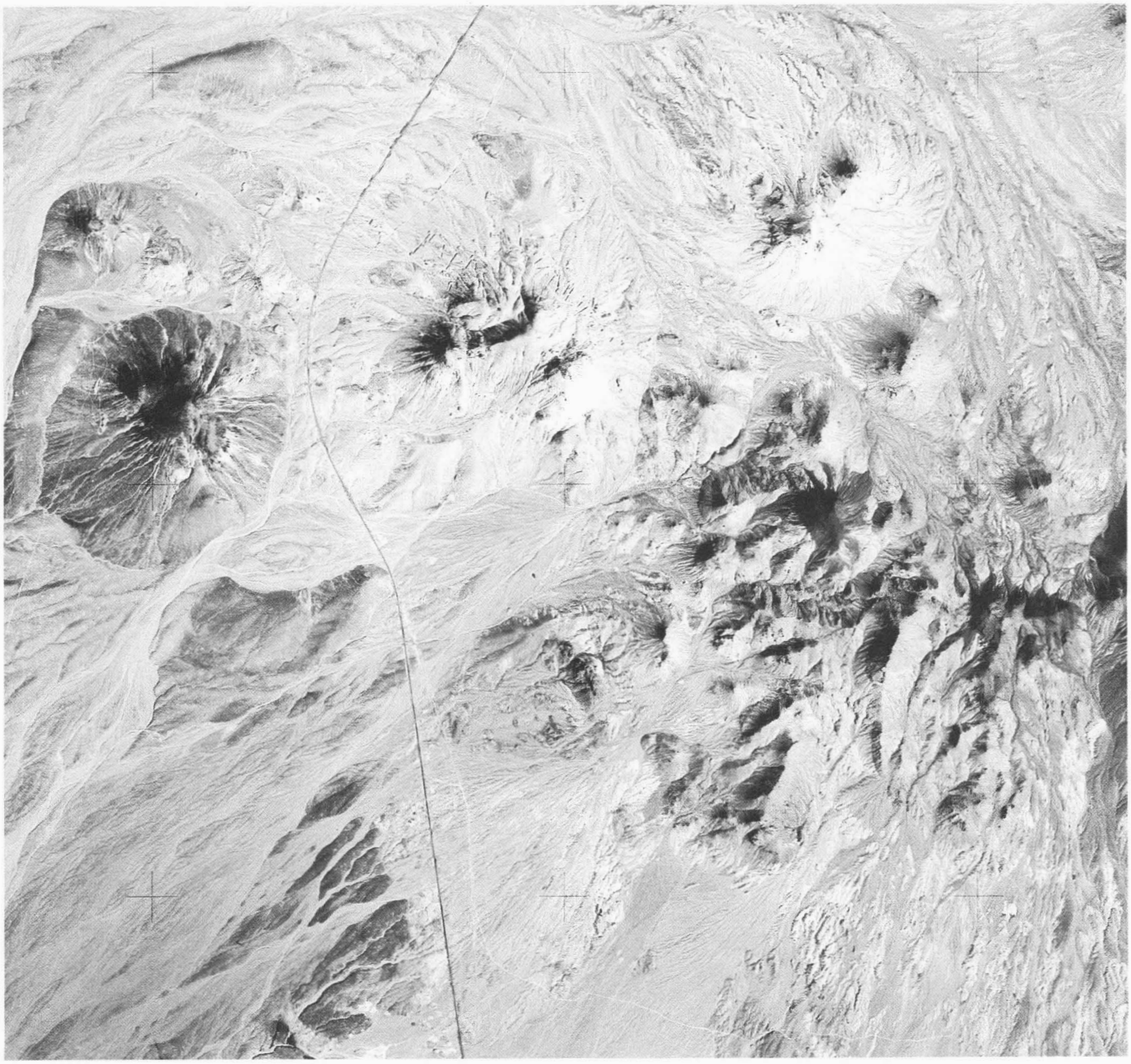


FIGURE 82. Aerial view of the Divide mining district and vicinity; Hasbrouck Peak to the left (west) of the highway and Gold Mountain to the right. ***From NASA RB-57 mission 249, photo 32–024, 29 Aug 73.***

According to Knopf (1921, p. 160), outcrops of the lodes are either barren or contain only very small amounts of silver. All lodes are oxidized to depths of 30 m or more, and very little ore was found in the district 30 m or less from the surface. Knopf (1921, p. 161) believed that the silver ore in the Divide district is the product of supergene enrichment of low-grade protore. He postulated a period of oxidation and leaching of the silver in the outcrops of the lodes and its subsequent migration downward in the lodes until the silver-bearing solutions contacted pyrite and reacted with it producing sooty argentite (acanthite). He then postulated that much of this supergene argentite (acanthite) was later oxidized by chloride-bearing ground water to cerargyrite. Knopf's theory seems to account satisfactorily for the generally low tenor of silver in the lodes from the surface down to depths of 30 m or more.

Supergene argentite (acanthite) and pyrite are the only sulfide minerals that Knopf described as occurring in the Divide district. At the time of his visit to the district in 1919, the deepest mine working was the Tonopah Divide shaft, which had reached a depth of 180 m. By 1923 the Tonopah Divide shaft had reached 420 m, but no study of the sulfide mineralogy of the primary ores in the Tonopah Divide Mine or in any of the other mines in the district was made when the deep workings were accessible.

At the present time (1977), none of the deep shafts in the Divide district are safely accessible and samples of sulfide ore can only be obtained from mine dumps. Specimens of sulfide-bearing rock taken from the dumps at the Tonopah Divide and Gold Zone Mines, which appear to be representative of the primary ores, contain pyrite, sphalerite, argentiferous galena, chalcopyrite, molybdenite and

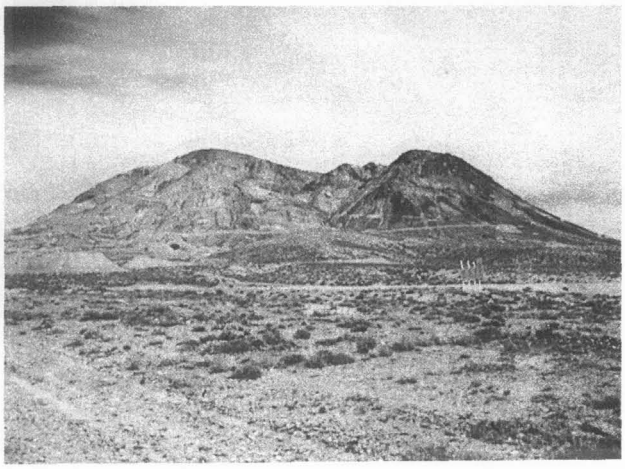


FIGURE 83. Gold Mountain, Divide district, looking east.

tetrahedrite(?) (fig. 84). An analysis of a typical specimen of primary sulfide ore from the Gold Zone Mine in the Divide district is shown in table 36. A partial chemical analysis of ore from the supergene sulfide zone at the Tonopah Divide Mine is shown in table 37. This sample is from the 500 level of the mine.

MINERALOGY

Age of Mineralization

The ore deposits in the Divide district were formed after the deposition of the Siebert Formation (13–17 m.y.) and prior to the emplacement of the Brougher Rhyolite (16.2 m.y.). Mineralized lodes in the north part of the district are cut by a dome of unaltered, locally glassy Brougher Rhyolite, and neither the Brougher nor any of the volcanic rocks in the Divide district that are younger than the Brougher, are hydrothermally altered or mineralized.

Six samples of mineralized rock from the Divide district were dated by the potassium-argon method (table 4). Two samples of sericitized biotite from the Belcher lode yielded K-Ar ages of 15.3 and 15.7 m.y. and muscovite from the Tonopah Hasbrouck Mine gave an age of 15.8 m.y. An adularia sample from a vein just north of Hasbrouck Mountain gave a mineralization age of 16.1 m.y. and samples of adularia and adularized whole rock from a silicified zone on Hasbrouck Mountain gave ages of 16.3 and 16.4 m.y. The adularia determinations are believed to represent the true age of mineralization most accurately.

Vertical Range of Precious-Metal Mineralization

On Hasbrouck Mountain in the Divide district the uppermost exposed beds in the Siebert Formation are silicified and mineralized, and the results of exploration drilling in this area (John Livermore, personal commun., 1976) indicate that the mineralization and silicification extend to depths of at least 300 m. Rocks of the Siebert Formation formed the bulk of the surface outcrops in the district at the time of mineralization. The Siebert Formation has a present maximum thickness of about 300 m in the Divide district. It seems highly unlikely that the Siebert was originally much thicker than this, because domes of Brougher Rhyolite, which intrude and overlie the Siebert and were emplaced at or near the Tertiary land surface, are only slightly eroded. The Brougher Rhyolite is only slightly younger than the Siebert Formation. It is probable, therefore, that the silicification and low-grade precious-metal mineralization in the Siebert Formation and the associated gold-bearing veins in and adjacent to the Oddie Rhyolite represent the conduits of old hot springs which vented onto the Tertiary land surface.

TABLE 34. Summary of gold-silver production, Divide district, 1910–1950.

[Production figures 1911–1932, Nolan (1936); 1910 and 1933–1950, U. S. Bureau of Mines Minerals Yearbooks. Couch and Carpenter (1943, p. 48) show a total production for the Divide district of $5,227,325 from 124,639 tons of ore for the years 1912–1940. Production figures unavailable, 1901–1909. No production reported, 1951–1976.]

Tons	Gold (ounces)	Silver (ounces)	Total value
134,948	32,474	3,275,079	$3,500,219

There is no positive evidence that the silver-bearing lodes in the Divide district extended to the Tertiary land surface, since the basal beds of the Siebert Formation are stratigraphically the highest rocks cut by the lode deposits. It is possible that they could have formed beneath 200 m or more of cover. The deepest workings (420 m) (fig. 86) on any of the silver lodes in the Divide district are those in the Tonopah Divide Mine. No commercial silver ore was found below a depth of 300 m at the Tonopah Divide Mine, but sulfide mineralization is present in the deeper levels of the mine.

Relationship of Mineralization to Igneous Rocks

The gold-bearing veins and the low-grade disseminated gold-silver mineralization in silicified rocks of the Siebert Formation in the Divide district are spatially related to intrusive phases of the Oddie Rhyolite. A similar relationship is present in the Tonopah district. It also is apparent that this type of mineralization was formed at relatively shallow depths in essentially a hot-spring environment.

It also seems logical to assume that the emplacement of the rhyolitic magma which formed the Oddie Rhyolite was the heat source for the meteoric waters which presumably formed the ore fluids in the hot-spring system. There is no direct isotopic evidence at Divide for a meteoric water

TABLE 35. Production of properties reporting a total of $5,000 or more Divide district.

[Data from Couch and Carpenter (1943, p. 52–53).]

Company	Period	Tons	Gross yield
Brougher Divide	1929–1938	2,528	$ 50,290
Calumet Divide	1927–1938	3,529	76,227
Divide Extension	1919–1921	1,008	84,952
Florence Divide	1919	1,530	192,574
Golden State Divide	1920–1922	723	16,368
Harmell Divide	1924–1925	99	7,353
Independence	1912	786	13,708
Knox Divide	1920–1921	1,159	24,403
Reorganized Silver King	1934	544	8,909
Silver Mines Corp.	1918	2,968	32,132
Tonopah Divide	1912–1940	113,794	2,789,242

A. Brecciated Oddie Rhyolite cemented by quartz. 1.5 X

B. Typical gold ore from vein on Gold Mountain. Fragments of silicified Oddie Rhyolite in a matrix of gray chalcedonic quartz and disseminated pyrite. 1.9 X

C. Typical sulfide ore from the Gold Zone Mine, Divide district. Brecciated fragments of Fraction Tuff in a matrix of fine-grained gray quartz containing disseminated pyrite, chalcopyrite, galena, sphalerite, and molybdenite. 0.8 X

FIGURE 84. Typical specimens of vein and lode material, Divide district.

source for the ore fluids, but similar epithermal deposits in Nevada and elsewhere (Taylor, 1973; O'Neil and Silberman, 1974) were formed by ore fluids which consisted entirely, or almost entirely, of meteoric waters.

The silver lodes in the Divide district, however, show no such obvious spatial and probable genetic relationship to a single igneous phase. They occur in the district over an outcrop area greater than 40 km^2 and are structurally and mineralogically distinct from the gold-silver mineralization discussed above. The wide areal extent of these silver lodes and of the hydrothermal alteration associated with them indicates that they are related to a large hydrothermal system.

The probable source of heat, and presumably the source for metals and sulfur, for this hydrothermal system is a composite stock, which is thought to underlie the Divide district and was the source of the Divide Andesite, the various intrusive and extrusive phases of the volcanics of Donovan Peak, and possibly the Oddie Rhyolite and the Brougher Rhyolite. The presence of such a buried pluton beneath the Divide district is suggested by a gravity high which is approximately centered on the district (Erwin, 1968).

It is postulated that the silver lodes of the Divide district represent fracture-controlled leakage haloes from a major hydrothermal system genetically related to a subjacent composite stock underlying the district. The occurrence of anomalous amounts of base metals, particularly

FIGURE 85. Belcher shaft, Divide district. Rugged outcrops in back of shaft are a silicified lode in the Tonopah Summit Member, Fraction Tuff.

molybdenum, in these fracture systems suggests the possibility of a buried, porphyry-type, molybdenum-copper deposit beneath the Divide district. The shallow level of erosion in the district also suggests that the stock and any associated porphyry deposits would be at a depth of at least 1 to 2 km. Detailed geologic, geophysical, and geochemical studies will be necessary in order to locate more accurately the buried intrusive center in the district.

Attitude of Mineralized Lodes

There does not appear to be a dominant or systematic pattern present in the attitudes of the mineralized lodes in the Divide district. The main lode at the Tonopah Divide Mine strikes northwest and has a nearly vertical dip, the Sutherland Divide lode strikes N. 55°–65° E. and dips 55° SE, the Belcher lode strikes east-west and is nearly vertical, and the Divide Extension lode strikes N. 10° E. and is vertical. A similar variation in attitude can be found throughout the district.

Hydrothermal Alteration

Approximately 40 km^2 of hydrothermally altered rock is present in the Divide district. The hydrothermally altered area is approximately centered on Gold Mountain. The hydrothermal alteration is zoned around fractures and fault zones. The rock within and immediately adjacent to the fracture and fault zones, principally Fraction Tuff, but including Divide Andesite, Oddie Rhyolite, and sedimentary rocks of the Siebert Formation has been pervasively altered to quartz and sericite, or quartz, sericite, and adularia (fig. 87). Disseminated pyrite and other sulfides occur in these zones of phyllic and potassic alteration in unoxidized rocks. Surrounding the central zones of phyllic and potassic alteration are pervasively propylitized rocks consisting of montmorillonite, calcite, chlorite, illite, quartz, albite, alkali feldspar, and pyrite. These pervasively propylitized rocks, in turn, grade outward into less intense propylitic alteration which has affected the rocks on a district-wide scale. Sulfides do not occur in this outer propylitic zone.

The propylitized rocks of the Fraction Tuff grade outward into zeolitized tuff in which the original pumice and shards have been completely altered to mordenite. It is uncertain whether the zeolitization of the tuff is a fringe hydrothermal effect or whether the hydrothermal alteration has been superimposed upon zeolitized tuff.

In the outer district-wide propylitic zone, plagioclase is altered partially or completely to albite, calcite, and illite; biotite is chloritized; hornblende is altered to chlorite, calcite, and montmorillonite; alkali feldspar appears fresh but exhibits patchy extinction and has undergone at least partial equilibration with the hydrothermal fluids. Pumice and shards in ash-flow tuff are variably altered to aggregates of quartz, calcite, montmorillonite, and alkali feldspar. Propylitized ash-flow tuff of the Tonopah Summit Member is typically greenish gray. Propylitized Divide Andesite is pale red to light greenish gray.

Tuffaceous sedimentary rocks, including mud and siltstones, sandstone, and conglomerate of the Siebert Formation have been brecciated and thoroughly silicified on Gold and Hasbrouck Mountains. Besides fine-grained quartz, adularia, sericite, and disseminated pyrite, the silicified rocks contain disseminated, low-grade gold-silver mineralization. Gold occurs as micron-size particles of free gold; the form in which silver occurs has not been determined. The area of mineralized and silicified Siebert Formation on

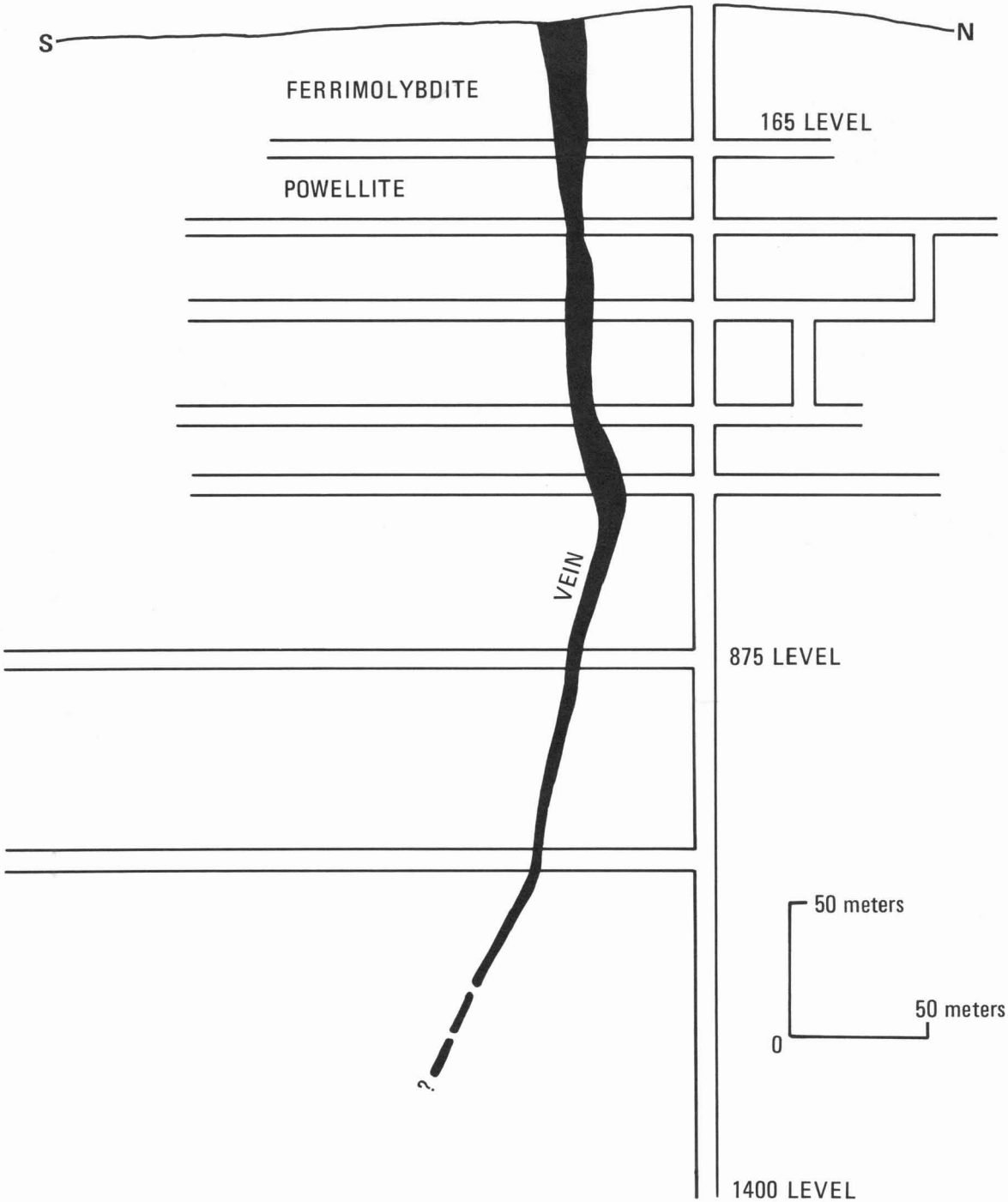


FIGURE 86. Simplified cross section of the Tonopah Divide Mine, Divide district, Esmeralda County.

Hasbrouck Mountain was explored in 1975–76 as a potential open-pit, precious-metal deposit. Sixteen samples from the silicified sedimentary rocks on Hasbrouck Mountain average .06 ounce Au/ton and 1.26 ounces Ag/ton.

The silicified rocks on Gold Mountain surround a central core of intrusive Oddie Rhyolite. Small areas of intrusive rhyolite occur also on Hasbrouck Mountain but are much less abundant than on Gold Mountain. The silicified rocks are surrounded by an envelope of argillic alteration in the tuffaceous sedimentary rocks of the Siebert Formation. Precious-metal mineralization is essentially restricted to the silicified rocks.

Silver Ace Prospects

The Silver Ace area is located immediately to the north and east of Thunder Mountain. A number of small prospects at Silver Ace are located in an area of hydrothermally altered rock that crops out on a dissected pediment surface covering an area of several km^2.

Prospects in the Silver Ace area are located in silicified zones in both the tuffs of Rye Patch and in the rhyolite of Silver Ace. The silicified zones are surrounded by an envelope of quartz-sericite-adularia alteration which grades outward into propylitically altered rocks. The only sulfide

TABLE 36. Chemical analyses, sulfide ore, Gold Zone Mine, Divide district.

	ppm
Au	3.4
Ag	415
Ba	464
Mn	136
Cu	325
Pb	100
Zn	1510
Mo	500
Sb	15
Se	5
Te	3

mineral visible in any of the outcrops or on the dumps is pyrite. Hydrothermally altered dacite is present beneath the tuffs. Samples of silicified tuff and rhyolite contain up to half an ounce of silver per ton and several ppm gold.

Inspiration Consolidated Copper Co. drilled a number of shallow (30 to 50 m) diamond drill holes on the Silver Ace group of claims in 1968–69. The limited depth of the holes suggests that their target was a shallow, low-grade, silver ore body that could be mined by open-pit methods. The results from this drilling project have not been released, and no additional exploration has been conducted in the area.

The occurrence of numerous silicified fracture zones in the tuffs with anomalous values in silver and gold suggests that the mineralized fractures may represent the upper portion of an epithermal vein system. The mineralized fractures could develop into well-defined veins in the dacite flows and breccias which underlie the tuffs. Additional, deeper exploration in the Silver Ace area would seem warranted.

Ray Mining District

The Ray mining district is located about 16 km north of Tonopah in unsurveyed S14,T4N,R42E. Most of the mines and prospects are in the vicinity of the old townsite of Rays, but some workings are also present about 1.5 km to the northeast. The district was apparently discovered shortly after 1900, as Turner (1908) reports prospecting and shafts to 90 m during a visit in 1904. Except for Turner's (1908) brief description, no other published or unpublished reports were located during this study. Production is unknown, but probably small, and was probably included with that reported for the San Antone mining district which lies about 13 km to the northwest. One inclined shaft is reported to be more than 90 m deep, with 180 m of drifts (Turner, 1908); it is not known to which shaft this report refers. We estimate that several other shafts in the district are more than 60 m deep.

TABLE 37. Analyses for gold, silver, and molybdenum in sulfide ore, Tonopah Divide Mine, 500 level.

	Oz/ton	Percent
Au	0.338	
Ag	71.5	
Mo		0.53

All mines in the district were worked for silver and gold, but details of the mineralogy are not known. Turner (1908) reports argentiferous galena from some of the workings, and samples of vein quartz taken during this study contained visible galena, and copper- and iron-oxide minerals. These same samples contained up to 779 ppm silver and 3,300 ppm zinc, as well as anomalous amounts of barium (2,500 ppm) and mercury (2,430 ppb). Narrow, altered dikes are present in some mineralized areas, and Turner (1908) reports that gold-silver ores are associated with this rock type.

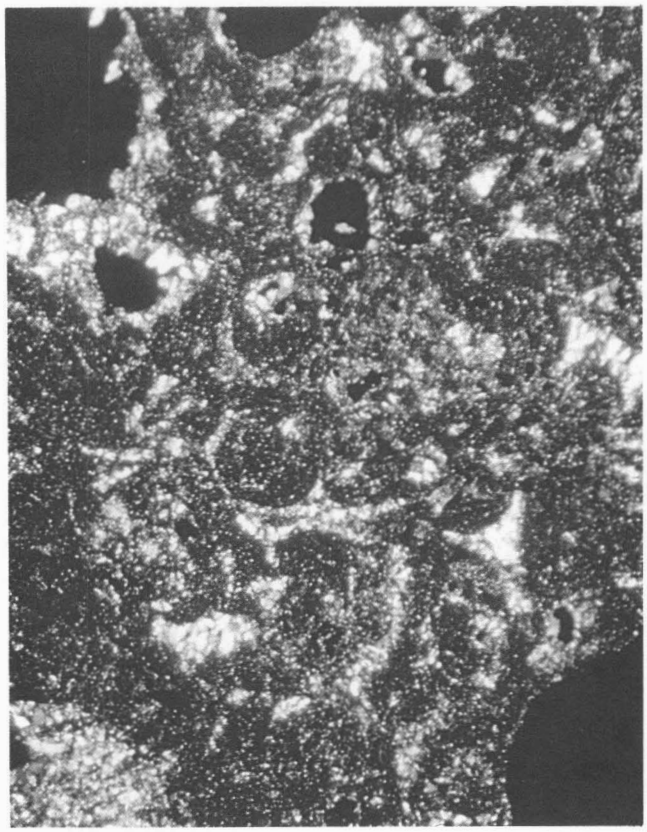
The dominant mineralization is localized in narrow quartz stringers in fault breccia zones 1 to 3 m in width. Chemical analyses and physical examination of selected vein quartz samples indicate that the hypogene veins probably contained copper, lead, zinc, and silver sulfide minerals. Several mines and prospects are located along a fault zone (fig. 88) which strikes N. 50° W. and dips 80° SW. and extends for over 1 km to the southwest of the old Rays townsite; minor mineralization is localized along a thrust fault which separates Mississippian limestone from Valmy(?) Formation argillites. Samples containing anomalous lead, zinc, silver, and copper values were also taken from workings about 1.5 km northeast of the Rays townsite. Mineralization is in quartz stringers located in upper-plate Mississippian rocks along northeast-trending faults that separate jasperoidal limestone from phyllite. Much of the Mississippian limestone is silicified or jasperized in the area, especially those areas exposed at higher elevations. This jasperoid does not seem to be directly associated with the mineralization.

Peg Leg Mine

The Peg Leg Mine (Tonopah Pegleg or Greenstock property) is a contact-metasomatic (tactite) deposit along the margin of the granodiorite of Fraziers Well in the SW/4 SE/4 S31,T4N,R43E. There, the tactite is developed in a gray marble unit of the Valmy(?) Formation which is exposed around the perimeter of the pluton. The tactite zone pinches and swells from 0 to 10 m along the intrusive contact (fig. 89).

At the mine, the marble unit strikes N. 35° E. and dips 60°–70° SE., away from the main intrusive mass. In the vicinity of the mine, tactite lenses are found at several localities along the main marble-granodiorite contact and also near a granodiorite dike. The minerals in the tactite include garnet, epidote, pyroxene, quartz, and minor pyrite. Scheelite occurs in a garnet-rich zone adjacent to the granodiorite, and in places flakes of molybdenite 1 cm in diameter are found in the tactite. Molybdenite is apparently more common in quartz-rich parts of the tactite, and in some places appears to be closely associated with scheelite. Visual estimates of the fluorescent color of scheelite indicate that it contains from approximately 0.35 to slightly over 1 percent molybdenum, and is variable between crystals.

The mineralized tactite zone is 8 to 10 m wide at the main shaft. However, the zone usually varies from 0 to 1 m



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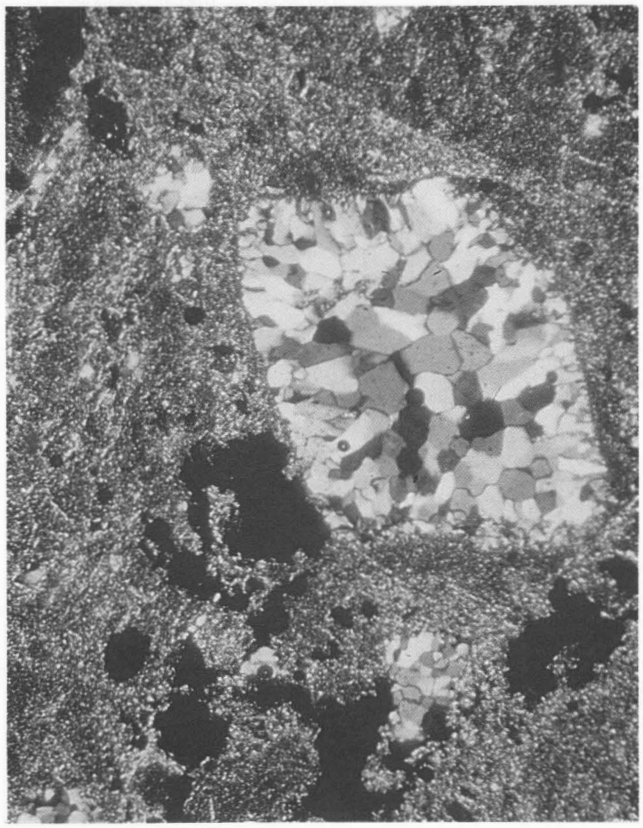
A. Nearly undeformed shards replaced by quartz, sericite, and adularia. Tonopah Summit Member, Fraction Tuff. Phenocrysts also altered to an aggregate of quartz, sericite, and adularia.



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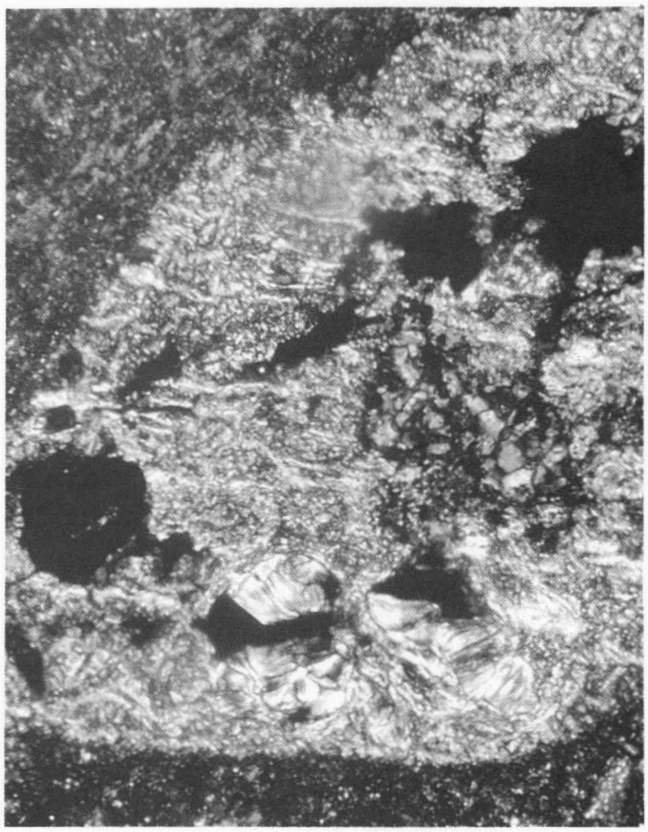
B. Plagioclase phenocryst replaced by quartz. Matrix of shards and pumice altered to quartz and sericite. Tonopah Summit Member, Fraction Tuff.



0.1m

C. Hornblende phenocryst replaced by sericite, Divide Andesite.

FIGURE 87. Photomicrographs of hydrothermally altered rocks, Divide district.

along the contact north of the main workings. Alluvium covers the zone to the south. The main shaft is about 15 m deep; other workings are shallower. Ore grades have been reported that show 1.47 percent WO_3, 3.2 oz of silver per ton and a small amount of gold. Kral (1951) collected samples across tactite zones exposed at the surface in the mine area and reported 0.24 to 0.70 percent WO_3. A grab sample collected from the dump of the shaft during the current study showed anomalous tungsten (112 ppm), zinc (111 ppm), and manganese (8,500 ppm) values. Production consists of 250 tons of ore containing 0.4 percent WO_3.

A pod of garnet-pyroxene tactite, about 20 m long and 3 to 5 m wide, occurs along the contact between the marble and the granodiorite approximately 1.5 km NW of Black Mountain (pl. 1). The tactite body contains a small amount of disseminated scheelite.

Klondyke Mining District

The Klondyke mining district (sometimes called Southern Klondyke) is about 17 km south of Tonopah and approximately 3 km east of U. S. Highway 95. Silver lode deposits were discovered in March 1899 by J. G. Court and T. J. Bell, although Chinese miners worked placers in the area in the middle 1870's (Chipp, 1969). Mines and prospects at Klondyke are concentrated in three localities (fig. 90) which Chipp (1969) has called the main mining area (SE/4 S24,T1N,R42E), the east Klondyke mining area (C S30,T1N,R43E), and the Klondyke Peak mining area (SW/4 S25,T1N,R42E).

FIGURE 88. Rays area. Dump at left center is from shaft located on a northwest-trending vein in Valmy(?) Formation argillite. Rugged outcrops in background are Mississippian carbonate rocks (in part altered to jasperoid) thrust over the Valmy(?) Formation.

The ore deposits at Klondyke have been described by Spurr (1903a, 1906a, 1906c), Ball (1906, 1907) and Chipp (1969). Lincoln (1923) gives a detailed list of older references. Nolan (1936) reports the production from 1903 to 1932 as 16,606 tons of ore yielding 2,405.64 oz gold, 425,583 oz silver, 10,861 lbs copper, and 257,080 lbs lead with a total value of $529,052.

The ore deposits are argentiferous quartz veins in siltstone and argillite units of the Cambrian Emigrant Formation. Ball (1906) reports a few veins in muscovite granite in the main mining area. Veins can be up to 3 m wide but are more commonly 30 to 60 cm in width. The veins occur in fault zones which are commonly parallel or subparallel to bedding, and often pinch out within a short distance (Chipp, 1969). In the east Klondyke mining area, mineralization is associated with a thrust fault that has emplaced Ordovician Palmetto cherts and limestones over the Cambrian Emigrant argillites (see figs. 67, 91). Most of the production is from shallow workings less than 30 m deep (Chipp, 1969), and hypogene sulfide minerals are rare. The workings consist of over 1,000 m of adits, shafts, drifts, and inclines (Ball, 1906).

Most of the oxide ore mined consisted of a mixture of cerrusite, jarosite, hematite, limonite, and manganese oxides. Also reported are malachite, chrysocolla, chalcocite?, digenite, covellite, and minor anglesite (Chipp, 1969), as well as rare calcite, gypsum, turquoise, and native sulfur. Cerargyrite is reported to be the main silver mineral but could not positively be identified during Chipp's (1969) study. Spurr (1960c, p. 375) reported the possible presence of stetefeldite, although it was not found by Chipp. Gangue minerals consist of milky-white quartz with a small amount of microscopic sericite. Supergene enrichment was apparently a major factor in the formation of the ore bodies, and Chipp (1969) reports that at depth the early miners rejected the denser vein material containing sulfides for the thin-walled quartz boxworks filled with oxidation minerals. Where cores of sulfide minerals are observed, bornite is replaced by digenite and covellite, and galena is partially altered to cerrusite.

Based on these observations, unoxidized hypogene veins probably consist of argentiferous(?) galena, pyrite, bornite, and possibly some unknown silver minerals localized in a quartz gangue. Scheelite was reported from one thin vein

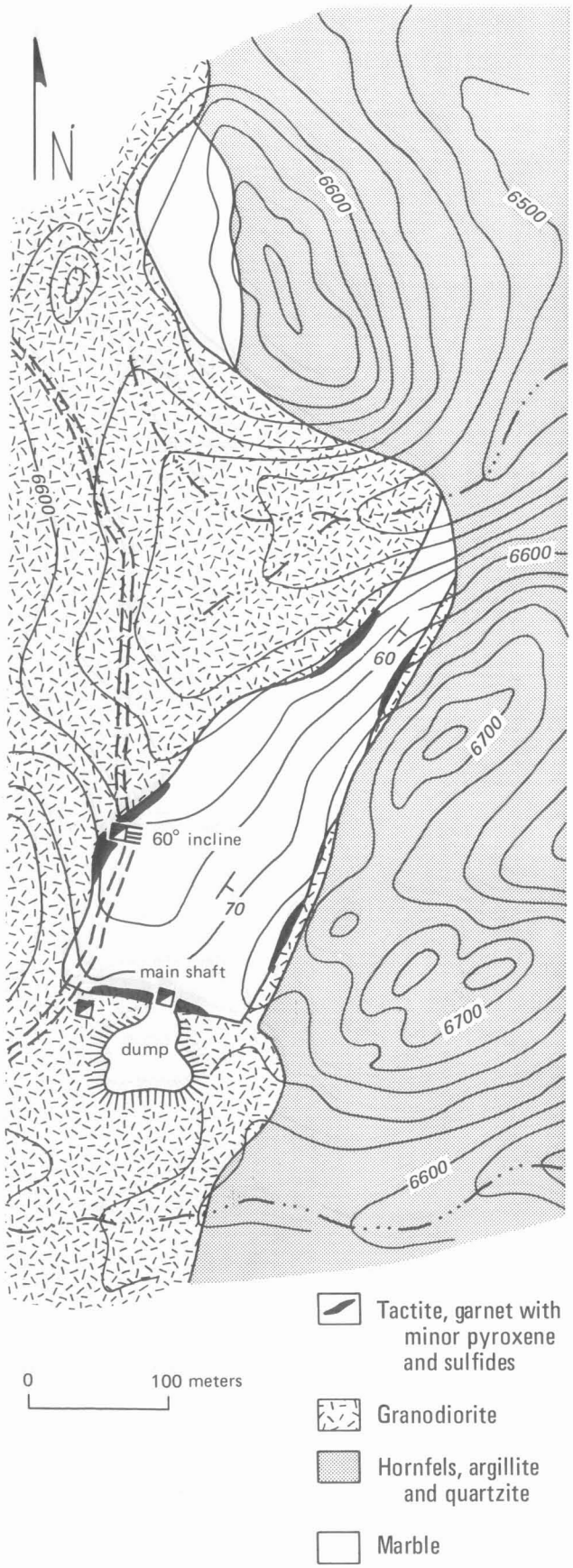


FIGURE 89. Sketch map of the Peg Leg (Tonopah Pegleg) Mine, SE/4 S31,T4N,R43E, Nye County.

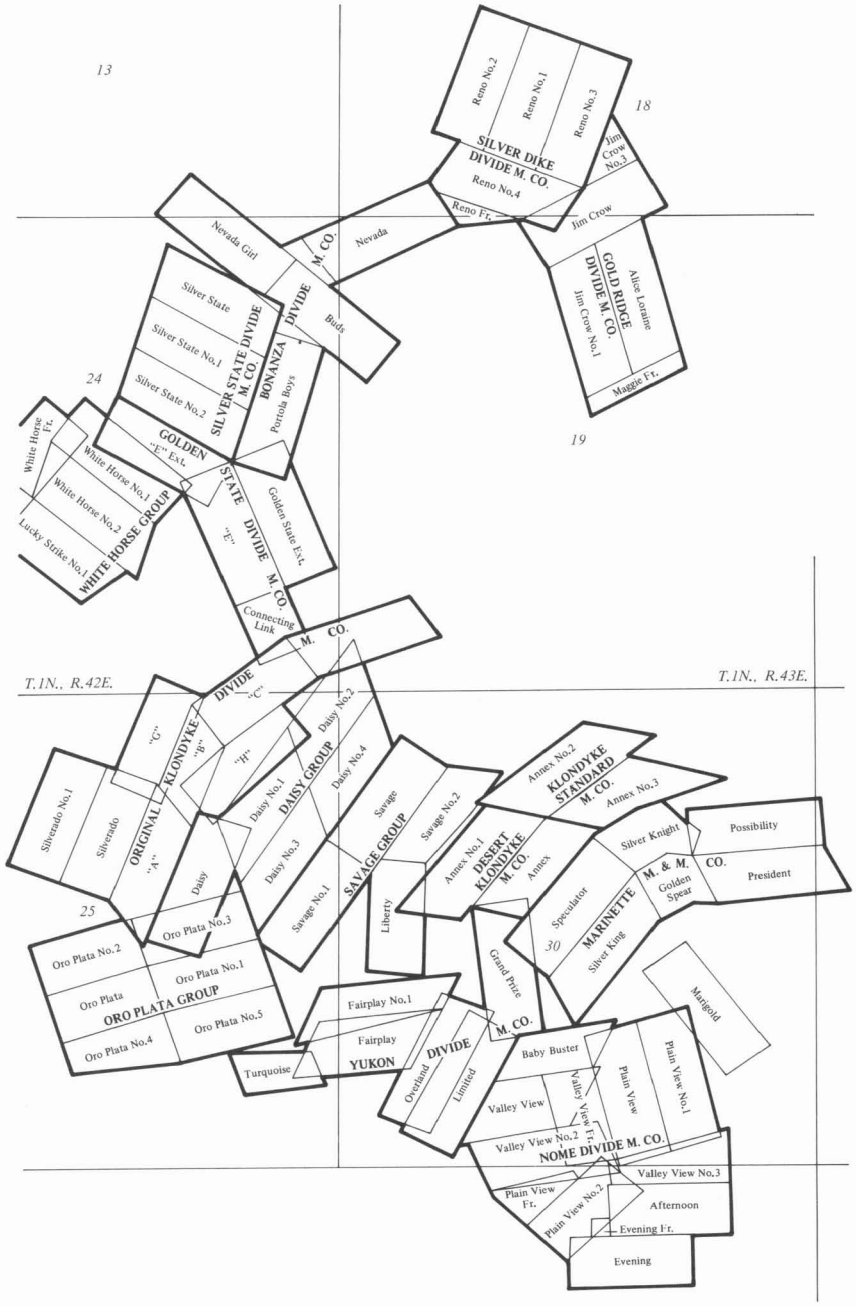


FIGURE 90. Claim map of the Klondyke mining district.

(Chipp, 1969). Assays of relatively unoxidized material assayed from 90 to 210 oz of silver and 0.13 oz of gold per ton (Chipp, 1969).

The muscovite granite at Klondyke is present near the mineralized area and contains a few silver veins. It is a distinctive rock, and is the only evidence of pre-Tertiary igneous activity in the area. We believe that the argentiferous vein mineralization is related to the muscovite granite and is probably of the same age or very slightly younger. Medium to coarse muscovite collected from the granite was dated at 104 m.y. (Silberman and others, 1975).

A turquoise property, the Smith Black Matrix Mine, is reportedly located in the district in the SW/4 S29,T1N, R43E. Turquoise occurs in veinlets that are reportedly up to 2 cm in width. A quantity was shipped from the prospect in 1910 by the California Gem Company (Morrissey, 1968, p. 9). Albers and Stewart (1972) have also reported iron from the Klondyke district. Several small bodies of specularite a few feet in maximum dimension occur in the Mule Spring and Emigrant Formations near the contact with muscovite granite.

Lone Mountain Mining District

The Lone Mountain mining district is centered on Lone Mountain, 25 km west of Tonopah. The mines at Weepah, 15 km to the southwest, and the General Thomas Mine, 11 km to the south, have often been included in this district. Thompson and West (1881) reported that Mexican miners prospected the Lone Mountain area for gold in the mid-1860's, but mining didn't begin in the area until shortly after 1900 when the Alpine Mine, on the west side of Lone Mountain, was opened up. The shallower workings within the map area on the east and northeast sides of Lone Moun-

tain (described below) were probably begun about the same time.

During the current study, field investigations of various workings within the district included only those within the area of the geologic map (see fig. 1 and pl. 1). Properties not studied include the Weepah Mine, the General Thomas Mine, and the Alpine Mine. Sonderman (1971) has described the Weepah Mine, and Ball (1907) has reported on the General Thomas Mine. The Alpine Mine has been described by Spurr (1906b) and Phariss (1974).

Numerous small mines and prospects are found at the northeast margin of Lone Mountain. A number of these are shown on the Lone Mountain 15-minute topographic quadrangle, although many more are present. At the north end of Lone Mountain (S33,T3N,R40E) are some fairly extensive workings, which are grouped under the name Heidi Mine by Albers and Stewart (1972, pl. 2). All of the above workings are in Precambrian carbonate rocks, commonly the Reed Dolomite. However, several deposits are in the Deep Springs Formation, and a few are in the Wyman and Harkless Formations as well as in the main pluton at Lone Mountain. These workings are shallow, usually less than 30 m deep, and only a few mines have discernable stopes. Production was obviously small from the northeast side of Lone Mountain, but the amount is unknown as it may have been included in production from the Alpine Mine on the west side of Lone Mountain.

The ore minerals at the prospects examined consist mainly of lead, zinc, and copper oxides. Hemimorphite, smithsonite, cerrusite, chrysocolla, and tenorite were recognized from several samples, and a number of geochemical samples of similar material contain as high as 35 percent zinc, 25 percent lead, 5 percent copper, and 15 oz/ton silver. Many samples that appear to consist mostly of iron-oxide minerals and silica contain several percent lead and zinc; some samples contain anomalous amounts of mercury (up to 7 ppm) and molybdenum (up to 0.28 percent). No silver minerals were recognized, but silver halides were probably important constituents of the ore.

Hypogene minerals were seldom recognized in surface exposures and shallow workings. Quartz gangue was not dominant in the veins, although it is nearly always present. The only sulfide mineral present in some narrow quartz veins sampled during the study was argentiferous tetrahedrite (freibergite). The quartz in these veins apparently protected the sulfide mineral from oxidation. The hypogene minerals are believed to resemble those described by Phariss (1974) at the Alpine Mine on the west side of Lone Mountain, where unoxidized samples from deeper workings contain galena, iron-rich sphalerite (marmatite), molybdenite, enargite, and ruby silver (proustite-pyrargyrite) in a manganosiderite gangue.

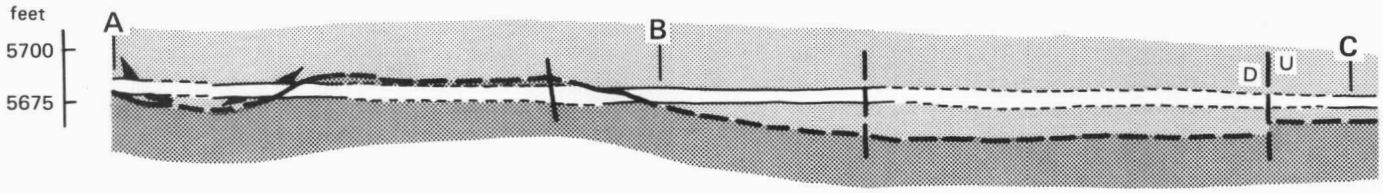
Many of the larger and better explored mines and prospects in the district are found along or near northwest-trending faults and granite porphyry dikes, which are common in the area. The dikes are pervasively sericitized (fig. 92) and appear to be older than the ore deposits, as they do not cut them. Also, ore is directly associated with brecciated granite porphyry at a few localities. A fission-track age on zircon from one dike yielded an age of 22.1 m.y. (Roger Ashley, written commun., 1975; table 4, this report). Because of the spatial association of the ore deposits and the dikes, it seems possible that the silver and base-metal mineralization could be related to fluids generated during emplacement of the dikes.

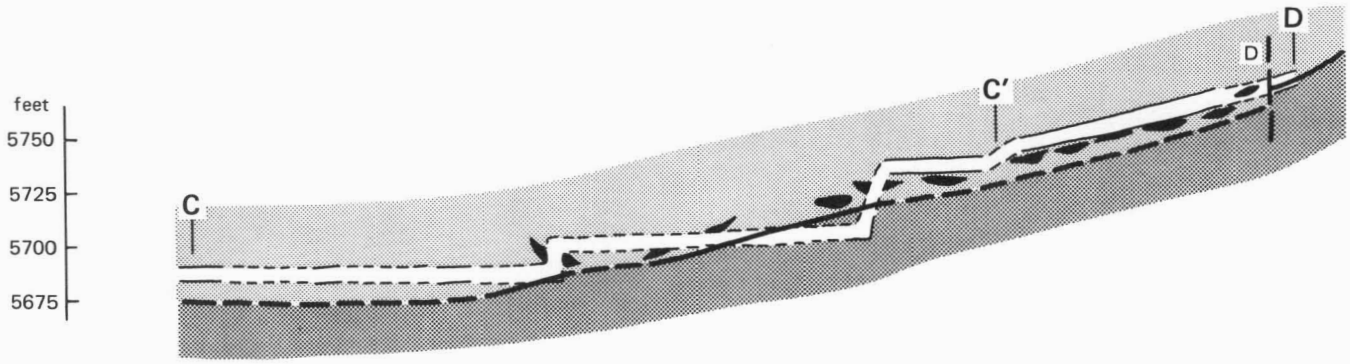
A molybdenite prospect in a quartz monzonite intrusive is located just south of the map area at Lone Mountain (N/2 SW/4 S30,T2N,R41E). The outcrop of quartz monzonite in which the molybdenite occurs extends into the map area and is described in the section on Mesozoic plutonic rocks. Molybdenite in quartz can be seen in samples on the dump of a shallow shaft. This shaft and several other shallow workings are along an east-west zone of faults and dikes. Quartz-sericite alteration is present along this zone, and copper oxide minerals are also present at one prospect. According to a short article in the Engineering and Mining Journal (1903) molybdenite was reported, ". . . on Lone Mountain, about 14 miles from Tonopah . . ."; it is uncertain whether this description refers to the above locality or an occurrence of molybdenum reported by Phariss (1974) in the replacement deposits at the Alpine Mine.

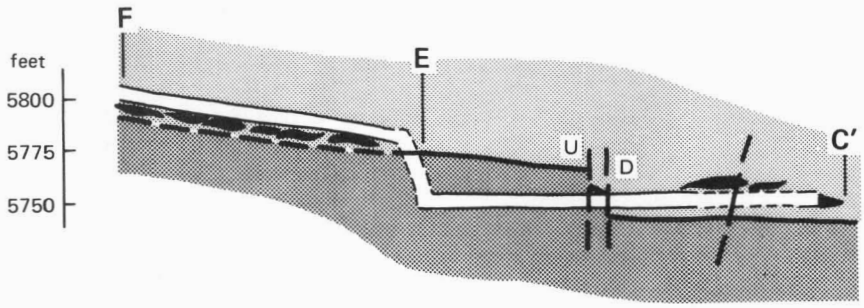
Uranium Occurrences Near Tonopah

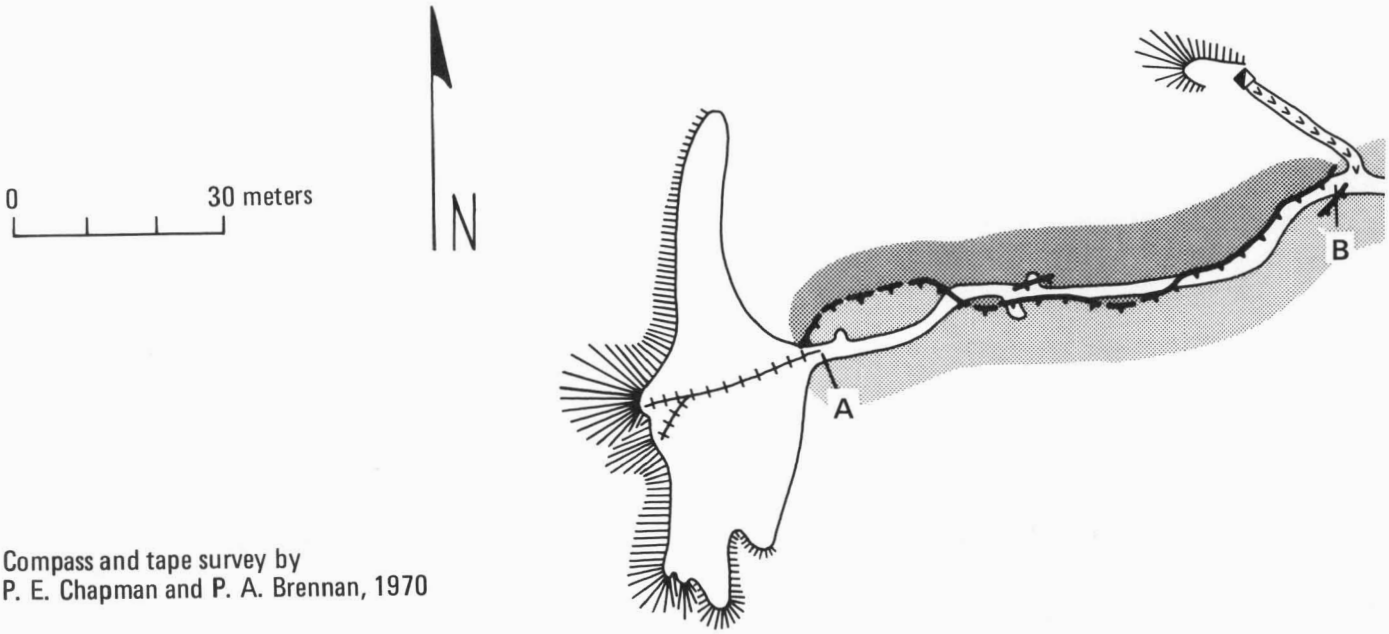
Uranium occurrences near Tonopah were first recognized in the 1950's by Victor and Domenico Lambertucci on their patented claims in the NE/4 S32,T3N,R42E. These claims were patented in the early 1900's following the silver discovery at Tonopah. They were given to the University of Nevada in 1969. Following the initial radioactive discovery, several other radioactive occurrences were found along a 13-km-long, north-south zone in the Siebert Formation west of Tonopah. The individual localities (about 31) have somewhat variable geology, but north-south faults are often present, or can be inferred. Linear trends of deposits, as seen in figure 93, are often associated with minor faults. However, the strike of the beds is also often north-south, and the alignment of localities might be due to uranium mineralization in a particular bed or series of beds. This explanation is probably inadequate for the entire 13-km-long zone as quite dissimilar beds are mineralized at either end of the zone. Davis and Hetland (1956) proposed a shear zone in the Siebert Formation along the trend of the radioactive anomaly based on the small displacement faults observed at uranium prospects south of U. S. Highway 95. They suggest that the mineralized faults and fractures noted are the surface expression of a major structure that might be older than the Siebert Formation. The faults as mapped and shown in this area (pl. 1) do not seem to confirm the existence of such a structural trend. Some of the northern uranium occurrences (in Nye County) are definitely related to small mappable faults, but these faults do not appear to continue to the south.

The prospects shown in figure 93 have been described individually by Garside (1973, p. 49–52, 90–91). They range from slightly radioactive to 50 times background, and chemical analyses of up to 0.18 percent U_3O_8 have been reported. No uranium minerals were recognized during this study, although Davis and Hetland (1956) reported yellow radioactive coatings on samples taken at the Silver Queen property in S32,T3N,R42E. Anomalous amounts of phosphate are also present in a number of samples collected from these prospects; one sample assayed 27 percent P_2O_5. The uranium is probably partly contained in collophanite (Davis and Hetland, 1956). In addition, surface geochemical samples from radioactive localities are anomalous (2 to 100









Compass and tape survey by
P. E. Chapman and P. A. Brennan, 1970

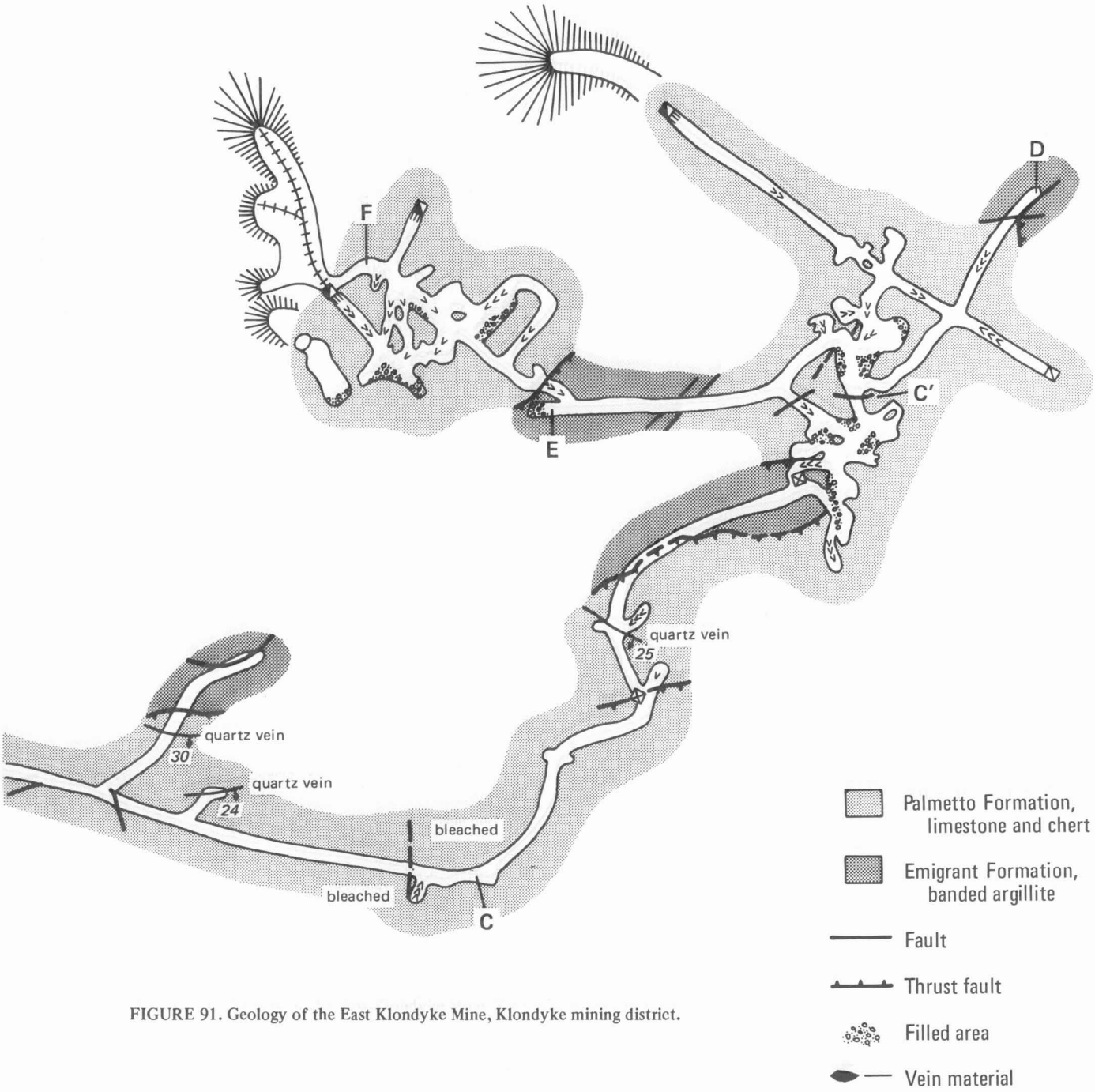


FIGURE 91. Geology of the East Klondyke Mine, Klondyke mining district.

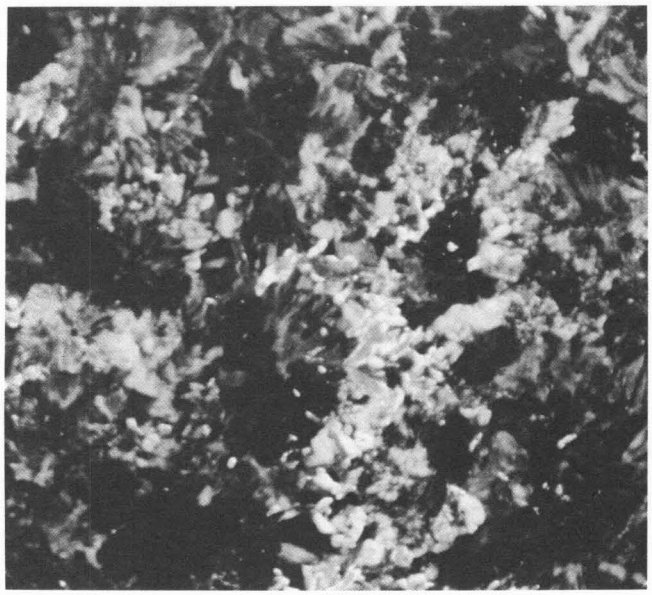


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FIGURE 92. Photomicrograph of a granite porphyry dike, Lone Mountain area. Plagioclase altered to sericite.

times background) in several elements in addition to uranium, including arsenic, bismuth, copper, mercury, molybdenum, lead, antimony, tungsten, and zinc. Iron oxides, which are common at many prospects, are probably related to the oxidation of pyrite in the tuffaceous shales, as pyrite was noted in nonradioactive unoxidized rock from drill-hole samples below 45 to 60 m.

All uranium localities are in lacustrine and fluvatile rocks, predominantly tuffaceous lacustrine shales, fluvatile feldspathic sandstones, and epiclastic volcanic sandstones and conglomerates. The mineralization at individual prospects is often confined to a single small area in one or more beds. At some prospects mineralization may be concentrated in the finer clastic beds in preference to the sandstones, although both are present. In other localities, mineralization is confined to one bed, but is present in that bed only on one side of a north-trending fault. At prospects near the northern end of the radioactive zone, in S25,36, T4N,R41E the uranium occurrences seem to be confined entirely to the east (footwall) side of the faults.

The source for the uranium in the Siebert Formation is not known, but volcanic ash is a commonly suggested source for leachable uranium, and the Siebert contains a large amount of rhyolitic volcanic ash and lapilli. However, there is disseminated gold mineralization of probable hot-springs origin about 2 km to the east in the Siebert Formation at the three hills northwest of Siebert Mountain, indicating the presence of thermal fluids in at least a part of the Siebert some time after its deposition. In addition, the anomalous amounts of other heavy elements present with the uranium are suggestive of a hydrothermal origin for the mineralization. The phosphate present in the Siebert shales, however, may be of syngenetic origin. Based on drilling data in the area south of U. S. Highway 95, the deposits seen at the surface today are contained in rocks which have undergone oxidation to a depth of 30 to 70 m. Thus, many of the controls on mineralization seen at the surface may be related to this oxidation zone. Data on any possible uranium deposits below the zone of oxidation are not available.

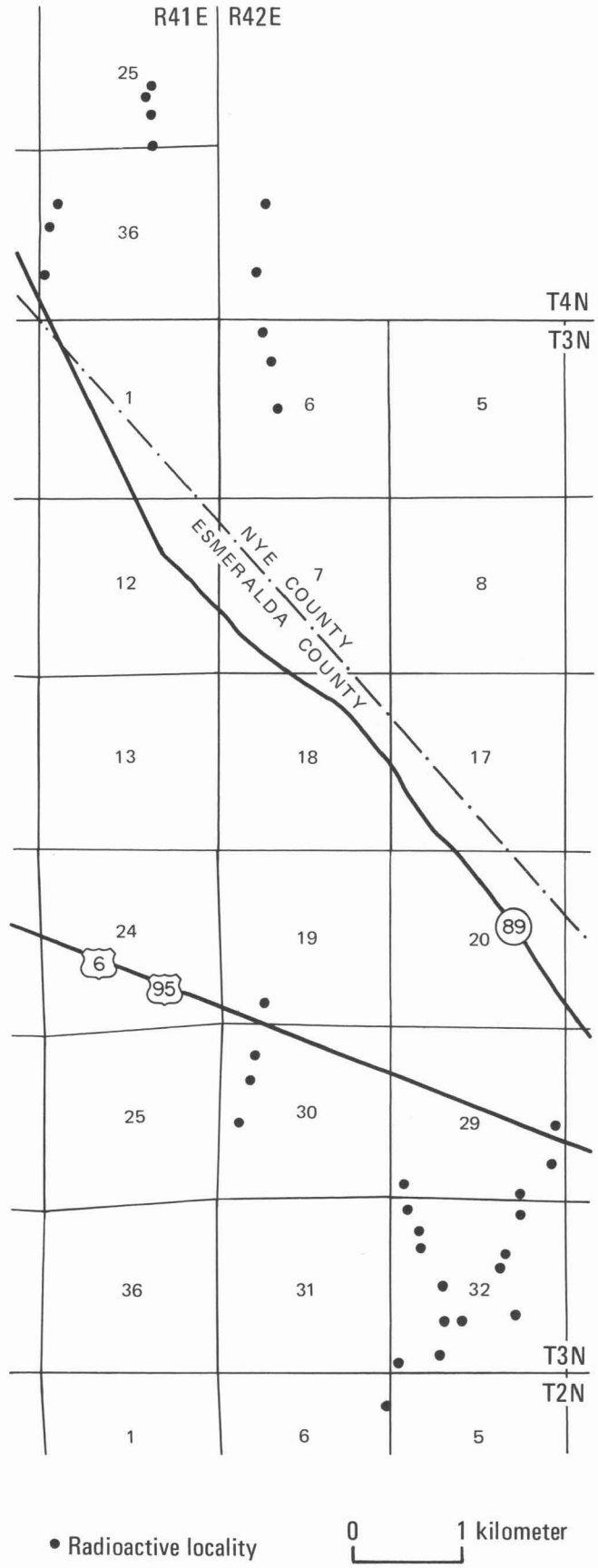

FIGURE 93. Radioactive localities near Tonopah, Nye and Esmeralda Counties.

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