Geology of Northern Nellis Air Force Base Bombing and Gunnery Range, Nye County, Nevada

GEOLOGICAL SURVEY PROFESSIONAL PAPER 651

Prepared on behalf of the U.S. Atomic Energy Commission

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By E. B. EKREN, R. E. ANDERSON, C. L. ROGERS, *and* D. C. NOBLE

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Stratigraphy and structure of 2,400-square-mile area of dominantly Tertiary volcanic rocks in the Great Basin, with brief descriptions of small mines and prospects

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GEOLOGY OF NORTHERN NELLIS AIR FORCE BASE BOMBING AND GUNNERY RANGE, NYE COUNTY, NEVADA

By E. B. Ekren, R. E. Anderson, C. L. Rogers, and D. C. Noble

ABSTRACT

The area of study, covering about 2,400 square miles in Nye County, southwestern Nevada, lies east of Goldfield. Elevations range from 4,700 feet in the westernmost alluvial valley, Stonewall Flat, to more than 8,900 feet in the Reveille Range in the northeastern part of the area. The climate is arid; rainfall ranges from about 4 inches in the valleys to about 6 inches in the higher ranges and mesas. All the streams are intermittent and, with the exception of Thirsty Canyon and its tributaries, all end in closed basins, which make up about half of the total area. Igneous rocks of Tertiary age form at least 90 percent of the outcrops. The remainder consists of sedimentary rocks of late Precambrian and Paleozoic age and a single small horst of crystalline basement.

Rocks of late Precambrian age have an aggregate thickness of about 8,400 feet and include the Stirling Quartzite and the lower five-sixths of the Wood Canyon Formation; they consist of quartzite, siltstone, phyllite, and rather minor carbonate rock. The upper part of the Wood Canyon Formation is Early Cambrian in age and consists largely of micaceous siltstone and shale, with subordinate quartzite and a few carbonate layers.

The Wood Canyon Formation is overlain by the thin Zabriskie Quartzite of Early Cambrian age, which in turn is overlain by Lower to Middle Cambrian rocks that are at least 4,500 feet thick and are transitional between the older dominantly clastic rocks and younger dominantly carbonate rocks.

Younger rocks are dominantly of miogeosynclinal origin and belong to the eastern carbonate assemblage. At the base they include an incomplete section of the Middle and Upper Cambrian Bonanza King Formation (largely dolomite) and the Upper Cambrian Nopah Formation, which is about 3,000 feet thick and consists of the Dunderberg Shale and the Halfpint and Smoky Members.

Most of the Ordovician rocks occur in the Pogonip Group, which is also about 3,000 feet thick and consists of the Goodwin Limestone, Ninemile Formation, and Antelope Valley Limestone. The Pogonip is overlain by the Middle Ordovician Eureka Quartzite, about 315 feet thick, and this in turn is overlain by the Middle and Upper Ordovician Ely Springs Dolomite, which is about 340 feet thick.

The Ordovician rocks are succeeded by the dolomite of the Spotted Range, of Early Silurian to Early Devonian age. The dolomite is about 1,400 feet thick and is overlain by an incomplete section of the Nevada Formation. The Nevada is Early and Middle Devonian in age and at least 1,000 feet thick.

Most of the younger Paleozoic rocks appear to lie in the upper plate of a major thrust fault. They include a limestone and dolomite unit of Middle Devonian age, which has an exposed thickness of almost 1,300 feet, and the overlying Eleana Formation, which is Late Devonian to Mississippian in age and more than 4,000 feet thick.

Small, exposures of granite of Mesozoic age occur in the Cactus Range and southern Kawich Range. The granite is nearly void of mafic minerals and closely resembles the alaskite at Goldfield.

Rocks of Tertiary age form a composite section more than 20,000 feet thick. They include minor fanglomerate at base, numerous widespread ash-flow tuff sheets that range in age from about 27 to 7 m.y. (million years), thick piles of variegated lavas, and several sequences of interbedded ash-flow tuff and sedimentary rocks. The oldest volcanic rock is an ash-flow tuff of late Oligocene age named herein Monotony Tuff. The rock is rhyodacitic and contains abundant phenocrysts of plagioclase, quartz, and biotite. It is overlain by the tuffs of Antelope Springs in the western part of the mapped area and the Shingle Pass Tuff in the eastern part. Both units are dominantly rhyolitic and quartz latitic. The next higher unit of regional significance is the rhyolitic tuff of White Blotch Spring. This unit includes ash flows from more than one center, but all are characterized by abundant large crystals of quartz and sparse mafic minerals. In most areas the White Blotch Spring is overlain by minor sedimentary rocks and ash-flow tuff and then by widespread lavas of intermediate composition. The lavas were extruded from many vents that are widely scattered in the mapped area and beyond. They form the bulk of the outcrops in many parts of the area and are the principal host rocks for gold and silver ore at Goldfield and Tonopah adjacent to the area of study.

The Fraction Tuff, which overlies the lavas of intermediate composition, is more than 7,000 feet thick at the exhumed Cathedral Ridge caldera in the southern extension of the Kawich Range. The Fraction is a lithic-fragment-rich, crystal-rich, and generally quartz-rich ash-flow sheet of rhyolitic and quartz latitic composition. During a pause in volcanic activity after the eruption of Fraction Tuff, local areas were deeply eroded.

The period of relative quiescence and erosion was followed by extrusion of rhyolite lavas that overrode wide areas, and these eruptions in turn were followed by the extrusion of the Belted Range Tuff and related sodic rhyolites. The Belted Range is overlain by strata of the Paintbrush Tuff and by massive strata of the Timber Mountain Tuff of which two members are present: the Rainier Mesa Member and the Ammonia Tanks Member. In early Pliocene time, after the region had acquired a topography similar to that of the present, the Thirsty Canyon Tuff was extruded. This tuff, whose source was the Black Mountain caldera, forms the surface strata over broad areas in the western and southwestern parts of the area.

The project area contains eight structural blocks or units: the Belted Range, Kawich Range, Mellan Hills, Cactus Range, Trappman Hills, Mount Helen, Black Mountain, and Pahute Mesa. The Belted Range block exposes a major thrust fault having a displacement of several tens of miles. This fault places lower Paleozoic rocks over upper Paleozoic rocks and correlates with the C P thrust in the Yucca Flat area at the Nevada Test Site. Two normal fault systems are present throughout the mapped area, exclusive of Pahute Mesa and Black Mountain. The earlier system consists of two sets that strike northeast and northwest; the later system, a single set, strikes north. Both systems postdate the Tertiary volcanic rocks, but the older system is confined to rocks older than about 17 m.y.

Deposits of gold and silver occur in several localities, and small mines and prospect pits are abundant in parts of the Cactus Range and the southern Kawich Range. The deposits are small, and the combined gold and silver production to date is between 10,000 and 100,000 ounces.

Several localities within the area may provide favorable environments for underground nuclear testing.

INTRODUCTION

LOCATION AND GEOGRAPHY

The mapped area (fig. 1) lies within the Basin and Range physiographic province and consists primarily of alluvium-covered valleys separated by northerly trending mountain ranges. Pahute Mesa lies in the southern part of the mapped area and forms an east-west terminus to the north-trending mountains and valleys. Thick coalescing alluvial fans flank most of the mountain ranges. Relief in the area generally ranges from 1,000 to 3,000 feet; the lowest elevation, at Stonewall Flat on the west, is 4,729 feet, and the highest elevation, at Reveille Peak on the northeast, is 8,910 feet. All the streams are intermittent, and, with exception of Thirsty Canyon and its tributaries, all end in the closed basins of Cactus Flat, Reveille and Kawich Valleys, and

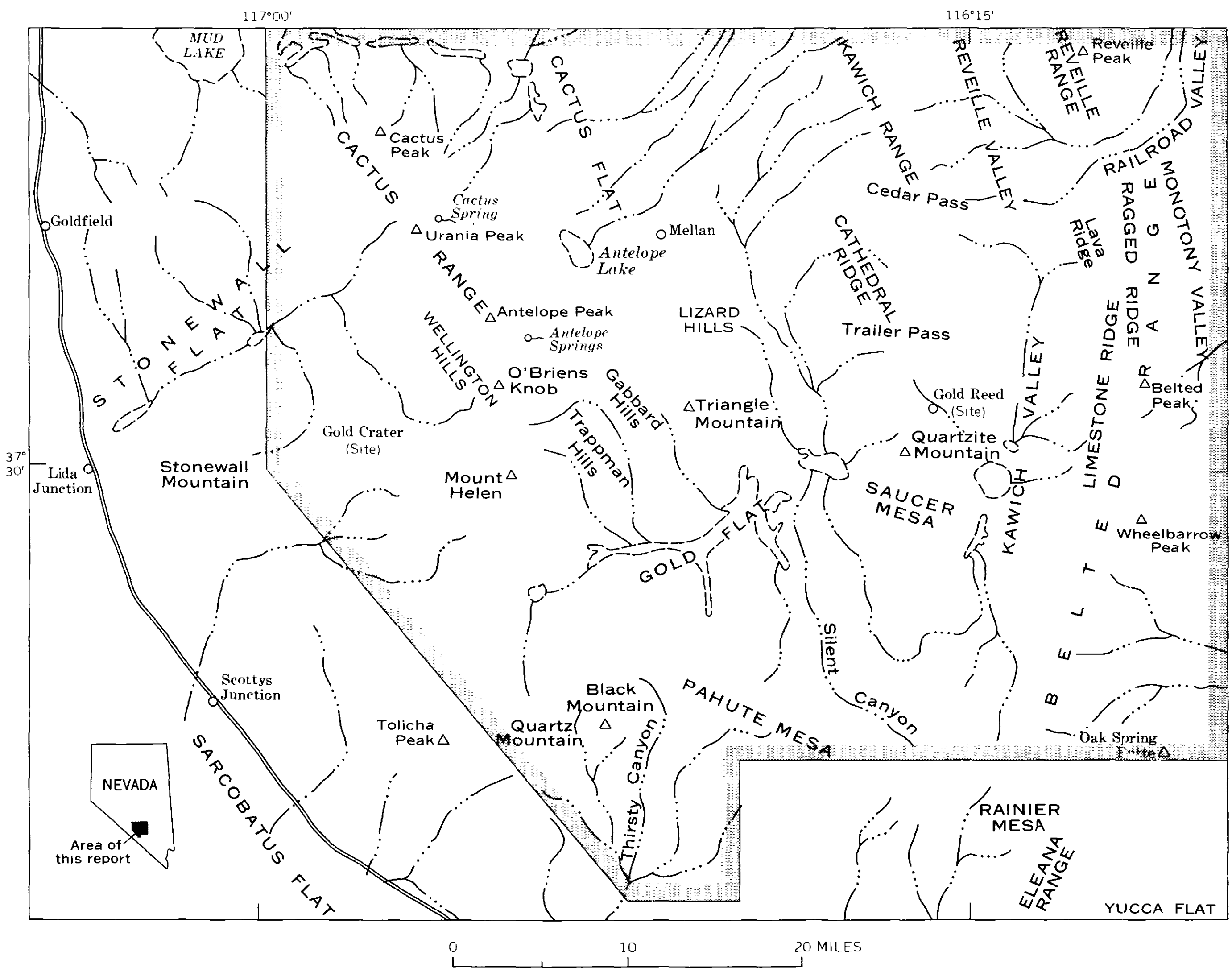

Figure 1.—Location of studied area (shaded outline) and major physiographic features.

Stonewall Flat. The basins are almost wholly enclosed by surrounding ranges and by Pahute Mesa.

Playa lakes occur in Gold Flat, Kawich Valley, and Cactus Flat. During the Pleistocene Epoch the lakes contained water several tens of feet deep as shown by former shorelines still outlined by thin zones of fine sand. The playas are used by the U.S. Air Force as bombing sites.

PURPOSE AND SCOPE OF THE INVESTIGATION

The northern Nellis Air Force Base Bombing and Gunnery Range was mapped as part of the long-range geologic investigations undertaken by the U.S. Geological Survey on behalf of the U.S. Atomic Energy Commission. The immediate objective was to provide geologic information necessary to predict whether parts of the area might be suitable for underground testing. The study included a detailed gravity survey to determine the subsurface configuration of the major basins in the area and the thicknesses of fill in the basins. The results of the gravity survey were described by C. H. Miller and D. L. Healey (written commun., 1964), and the gravity contours are shown on plate 1.

After Pahute Mesa was developed as an underground test area, consideration of the remainder of the Nellis Air Force Base Bombing and Gunnery Range for a test area was abandoned. As a result, this report has been written to provide general geologic information without specific emphasis on the evaluation of the area for nuclear testing.

CLIMATE, VEGETATION, AND WILDLIFE

The climate of the mapped area is arid (table 1) and the summer months are extremely hot. The most pleasant season is early fall, when the daytime temperatures range from low sixties to high eighties and high winds are rare. In the spring, the weather is extremely variable and few days are without strong winds.

Vegetation is sparse in the lower elevations but is fairly abundant on Pahute Mesa (table 2) and in the higher ranges. Grasses are abundant at elevations above 6,000 feet and support several herds of wild horses. Kawich and Reveille Valleys and Gold Flat are used by local ranchers as winter ranges for cattle, but the valleys constitute marginal grazing land at best. A herd of six or seven antelope inhabits the Gold Flat area, and a herd of about 20 antelope inhabits the Kawich Valley area. Deer are common in the higher ranges and on Pahute Mesa, and the mapped area is the home of many golden eagles. These can be seen nearly every day, and eagle nests are common in higher crags. Coveys of chukar partridge are abundant on Pahute Mesa, in the Belted Range, and in the vicinity of all flowing springs.

TABLE 1.—*Rainfall and temperature at Goldfield and Tonopah, Nev.*

[From U.S. Weather Bureau]

Year	Goldfield				Tonopah			
	Rainfall (inches)	Temperature (° F)			Rainfall (inches)	Temperature (° F)		
		Average	Extremes			Average	Extremes	
			Low	High			Low	High
1958					3.38	52.6	6	100
1959	2.87	53.4	6	100	2.37	52.7	0	103
1960	6.55	51.4	−2	99	3.69	52.6	0	104
1961	4.47	50.8	0	97	2.90	51.3	0	102
1962	6.23	51.9	−10	96	5.84	50.7	−15	97

TABLE 2.—*Plants in the northern Nellis Air Force Base Bombing and Gunnery Range*

[Identified and compiled by Helen Cannon, U.S. Geol. Survey]

Kawich Valley

For about 5 miles north and south from the playa the plant assemblage includes these xerophytic halophytes, which are very tolerant of salts:
- *Atriplex confertifolia*—shadscale
- *Kochia americana*—green molly
- *Artemisia spinescens*—budsage

For the next several miles both north and south, in soils that contain more alluvial material and less salts:
- *Eurotia lanata*—winterfat
- *Atriplex linearis*—narrowleafed saltbush
- *Tetradymia glabrata*—littleleaf horsebrush
- *Artemisia spinescens*—budsage
- *Atriplex confertifolia*—shadscale

In both ends of the valley and in washes along the sides of the valley, where water is available and the salt content is much lower:
- *Chrysothamnus* sp.—rabbitbrush
- *Artemisia arbuscula*—sagebrush

Higher in the drier parts of the alluvial fans:
- *Ephedra nevadensis*—Mormon tea
- *Grayia spinosa*—Hopsage

Gold Flat

The plants of Gold Flat are generally similar to those in Kawich Valley but there is more evidence of water. An assemblage of phreatophytes was noted along the south edge of the playa. They included:
- *Sarcobatus vermiculatus*—greasewood
- *Chrysothamnus viscidiflorus*—rabbitbrush
- *Atriplex canescens*—four-wing saltbush

A large area of selenium-indicator plants occurs in the center of the valley; however, these species do not indicate a very high concentration of selenium:
- *Astragalus lentiginosus*—Specklepod loco
- *Stanleya pinnata*—Princesplume
- *Aster abatus*—Mohave aster

Pahute Mesa

Trees:
- *Pinus monophylla*—pinyon
- *Juniperus osteosperma*—juniper
- *Quercus gambelli*—Gambels oak

Shrubs:
- *Ephedra* spp.—Mormon tea
- *Chrysothamnus* spp.—rabbitbrush
- *Tetradymia* spp.—horsebrush
- *Ribes montegenum*—gooseberry
- *Artemisia* spp.—sagebrush

TABLE 2.—*Plants in the northern Nellis Air Force Base Bombing and Gunnery Range*—Continued

Pahute Mesa
Purshia tridentata—antelope brush
Cowania stansburiana—Stansburys cliffrose
Symphoricarpos parishii—snowberry
Atriplex canescens—four-wing saltbush
Rhus trilobata—skunkbush
Cercocarpus ledifolius—mountain mahogany
Herbs—Many species of the following genera are common:
Lupinus—lupine
Cryptantha—cryptanth
Phacelia—heliotrope
Penstemon—penstemon
Castilleja—paintbrush
Arenaria—sandwort
Senecio—groundsel
Arabis—rockcress
Oenothera—primrose
Gilia—gilia
Eriogonum—wild buckwheat

FIELDWORK AND ACKNOWLEDGMENTS

The base map for this study was prepared by enlarging the Army Map Service Goldfield, 1° by 2° topographic sheet from its original scale of 1:250,000 to a scale of 1:125,000. Geologic mapping was done on aerial photographs, and the data were transferred to the topographic base by use of a Kelsh stereoplotter.

The following U.S. Geological Survey geologists participated in the mapping: Theodore Botinelly and J. E. Weir mapped with the authors during parts of 1962–63; in November 1962, E. J. McKay, J. T. O'Connor, and E. N. Hinrichs mapped parts of Triangle Mountain and Cathedral Ridge, and H. R. Cornwall mapped the Reveille Range and Reveille Valley. Credit for mapping quadrangles in the southern part of the area is given on plate 1.

E. G. Halligan (deceased) of the U.S. Army coordinated the ground surveying by the U.S. Geological Survey during 1962–64 with target schedules of the U.S. Air Force. The necessity of coordinating fieldwork with bombing schedules required that all project personnel work in limited areas for scheduled periods of time. As a result, none of the ranges or intervening areas was mapped entirely by one person; however, certain areas were designated as the responsibility of one or more geologists.

R. E. Anderson mapped most of the Cactus Range and wrote the descriptions of the stratigraphy and structure pertinent to that range. C. L. Rogers and J. E. Weir mapped most of the younger volcanic rocks exposed southwest of the Cactus Range, and Rogers also mapped nearly all the upper Precambrian and Paleozoic rocks in the project area. He is the sole author of the descriptions of these rocks in this report. E. B. Ekren mapped the geology of the Trappman Hills, and the volcanic rocks in the Belted Range, Mount Helen, and the Mellan Hills. Anderson, Ekren, and Rogers shared equally in the mapping of the Kawich Range and Cathedral Ridge area from the north boundary of the project area to the north rim of Pahute Mesa. Ekren and Anderson wrote the descriptions of the older volcanic rocks, and D. C. Noble, who participated in the mapping of most of the 7½-minute quadrangles along the south boundary (pl. 1), wrote the descriptions of the younger volcanic rocks. The sections on structure and on mines and mining were written by Ekren, Anderson, and Rogers.

We are indebted to R. L. Smith for his enthusiastic interest in the project and for his continued availability for consultation on problems pertaining to the volcanology of the area.

PREVIOUS WORK

The area between lat 36°30′ and 38°00′ and long 116° and 117°30′, which includes the present project area, was mapped in reconnaissance by Ball (1907). Ball delimited, with considerable accuracy, Paleozoic strata from volcanic strata, and the present authors marvel at the amount of geology he and his companions mapped in the very short field period of June–December 1905. Ball's study was made during the period of active mining in the area, and he described in considerable detail several of the mining districts that are now abandoned.

STRATIGRAPHY

Sedimentary, igneous, and metamorphic rocks that range in age from Precambrian to Holocene are exposed in the area. Tertiary lavas, ash-flow and ash-fall tuff, and intrusive rocks form at least 90 percent of the outcrops (table 3).

The pre-Tertiary rocks, exclusive of a small area of crystalline basement, are about 29,000–30,000 feet thick and include three distinct sequences. The lower part of the section—which is 10,000–11,000 feet thick and consists of quartzite, siltstone, shale, and minor carbonate—is late Precambrian to Middle Cambrian in age. It is overlain by a section—which is more than 14,000 feet thick and consists of limestone, dolomite, and minor siltstone, quartz and chert—that is Middle Cambrian to Devonian in age. This part of the section is of miogeosynclinal origin and is part of the eastern or "carbonate" assemblage as defined by Silberling and Roberts (1962, p. 5).

The Antler orogeny greatly modified the Cordilleran geosyncline in middle Paleozoic time, and during the remainder of the Paleozoic, deposition took place only locally in shallow restricted waters. Within the mapped

TABLE 3.—*Major geologic rock units in the northern Nellis Air Force Base Bombing and Gunnery Range*

Age	Rock unit		Stratigraphic thickness (feet)	Lithologic character
Quaternary and late Tertiary	Alluvium and colluvium		0–3, 000+	Valley and stream alluvium, terrace and pediment gravels, talus and landslide debris.
Pliocene	Basalt		0–100	Lava flows; a few dikes and one small cinder cone.
	Basalt		0–100	Lava flows; many dikes.
	Thirsty Canyon Tuff		0–500	Trachyte, trachytic sodic rhyolites, comendite, and pantellerite.
	Timber Mountain Tuff	Ammonia Tanks Member	0–350	Rhyolitic welded tuff.
		Rainier Mesa Member	0–600	Do.
Miocene	Paintbrush Tuff		0–500	Rhyolitic ash-fall tuff and intercalated rhyolite lavas.
	Rhyolite lavas and tuffs		0–1, 000	Sodic rhyolite lava flows, welded tuff, ash-fall tuff.
	Belted Range Tuff and associated lavas		0–1, 000	Comendite, trachytic sodic rhyolite, trachyte.
	Tuff of Tolicha Peak		0–400	Rhyolitic welded tuff.
	Rhyolite		0–1, 600	Lava flows and numerous dikes and plugs of rhyolite and rhyodacite.
	Sedimentary rocks		0–800	Ash-fall tuff, tuffaceous sediment, and thin-bedded lake sediment.
	Fraction Tuff		0–7, 200	Rhyolitic welded tuff, composite ash-flow sheet
	Lavas of intermediate composition		0–3, 000	Lava flows, dikes, plugs, and small stocks.
	Tuff of Wilsons Camp and bedded tuff		0–500+	Rhyolitic welded tuff, ash-fall tuff, and tuffaceous sedimentary rock.
	Tuff of White Blotch Spring		0–3, 000	Rhyolitic welded tuff.
	Shingle Pass Tuff		0–1, 000	Rhyolitic welded tuff.
	Tuffs of Antelope Springs		0–4, 000+	Rhyodacitic and rhyolitic welded tuff; several cooling units.
Oligocene	Monotony Tuff		0–2, 300	Rhyodacitic welded tuff.
	Unconformity			
Mississippian and Late Devonian	Eleana Formation		5, 000±	Argillite, quartzite, and conglomerite; some limestone and limestone conglomerate at base.
Middle Devonian	Limestone and dolomite		1, 285+	Limestone, silty limestone, and dolomite.
Middle and Early Devonian	Nevada Formation		1, 000+	Dolomite, sandy dolomite, and dolomitic sandstone, with subordinate limestone, siltstone, and chert.
Early Devonian and Late and Middle Silurian	Dolomite of the Spotted Range		1, 415	Dolomite; sandy at top, and locally cherty.
Late and Middle Ordovician	Ely Springs Dolomite		340	Dolomite, with abundant chert.
Middle Ordovician	Eureka Quartzite		315	Quartzite; gradational into overlying and underlying units.
Middle and Early Ordovician	Pogonip Group		3, 010±	Limestone and dolomite, silty in part; subordinate calcareous siltstone, chert, and shale.
Late Cambrian	Nopah Formation	Smoky Member	950±	Limestone and dolomite; scattered chert.
		Halfpint Member	1, 900±	Limestone and dolomite; laminae of silty limestone and dolomite; abundant chert.
		Dunderberg Shale Member	200±	Shale; intercalated limestone.

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TABLE 3.—*Major geologic rock units in the northern Nellis Air Force Base Bombing and Gunnery Range*—Continued

Age	Rock unit		Stratigraphic thickness (feet)	Lithologic character
Late and Middle Cambrian	Bonanza King Formation		3, 300+	Dolomite and limestone; silty in part; minor chert.
Middle Cambrian	Limestone, silty limestone, and shale		1, 323+	Limestone and silty limestone, local chert; shale sequence at top.
Middle and Early Cambrian	Carrara(?) Formation		1, 577	Shale, and subordinate limestone, silty limestone, and siltstone.
Early Cambrian	Zabriskie Quartzite		150	Quartzite and subordinate siltstone.
Early Cambrian and Precambrian	Wood Canyon Formation		3, 750	Quartzite and siltstone, partly micaceous; carbonate beds in upper and lower parts.
Precambrian	Stirling Quartzite	Upper part	2, 300	Quartzite and siltstone, partly micaceous, and silty phyllite; subordinate carbonate material.
		Lower part	2, 970+	Quartzite, subordinate micaceous siltstone and quartzite and minor phyllite.
	Gneiss and schist of Trappman Hills area			Gneissic quartz monozonite and biotite-amphibole schist.

area this period is represented solely by the Eleana Formation of Late Devonian and Mississippian age, which is largely clastic, consisting dominantly of argillite, siltstone, quartzite, and conglomerite. This formation is at least 4,000 feet thick.

Although the Paleozoic strata have been telescoped by a thrust fault system of Mesozoic age, the total displacement was insufficient to juxtapose the western or detrital-volcanic assemblage. Some of the Devonian rocks in the Belted Range, however, may represent a transitional facies introduced by the large-scale thrusting.

PRECAMBRIAN

LOWER PRECAMBRIAN—GNEISS AND SCHIST OF TRAPPMAN HILLS AREA

Gneissic quartz monzonite and biotite schist of probable early Precambrian age crop out in the Trappman Hills (pl. 1) in an area about 3 miles long and 1 mile wide between Mount Helen and Gold Flat. The rocks are poorly exposed and form low rounded hills.

The gneissic quartz monzonite, which forms at least 70 percent of the outcrops, is light gray to brownish gray, fine to medium grained, locally pegmatitic, and generally moderately to well foliated. The rock contains 33–46 percent quartz, 26–30 percent orthoclase, about 25 percent plagioclase, and 1–15 percent muscovite and biotite. The potassium feldspar is generally fresh and clear, and a few grains are perthitic. The plagioclase is cloudy, and in zones of hydrothermal alteration the rock contains sericite, calcite, clay, abundant limonite, and cubes of pyrite. Biotite is altered to chlorite, sericite, and iron oxide. Biotite, muscovite, and chlorite occur as tiny isolated flakes and as lenticular masses along foliation planes. Quartz grains have been intensely strained, and undulatory extinction is pronounced in eight thin sections from widely separated outcrops.

The gneissic quartz monzonite contains xenoliths of schist, and in many outcrops it appears to have intruded the schist lit-par-lit. Contacts between schist and gneiss are very sharp in most areas; however, in places the contacts are gradational between mica-poor gneissic quartz monzonite and mica-rich schist.

The schist is of variable composition. Some contains the same minerals as the quartz monzonite but has more biotite and actinolite or tremolite. Other schist is very calcareous and contains abundant clinozoisite. Float of argillite and quartzite of probable Precambrian age is common on some of the hills, but these rocks were not observed in place.

The quartz monzonite and schist are cut by a few thin aplite dikes and by many quartz veins. The quartz veins range in width from a fraction of an inch to more than 50 feet and in places are several hundred feet long. They contain some pyrite and gold and were mined in the early 1900's. Ball (1907, p. 138) visited the Trappman Hills in 1905 when the quartz veins were being mined and concluded that there were three distinct periods of vein formation. He considered the first to be of pegmatitic origin related to the quartz monzonite, which he considered to be Mesozoic in age, and the second and third to be of Tertiary age.

UPPER PRECAMBRIAN—STIRLING QUARTZITE

DEFINITION AND DISTRIBUTION

The Stirling Quartzite was named by Nolan (1929) for exposures on Mount Stirling, about 5 miles east of the Johnnie mine, in the northwestern part of the Spring Mountains, Nye County, Nev. In the type locality it is 3,700 feet thick and is composed mainly of crossbedded quartzite, with minor amounts of siltstone and shale.

In the Groom district, east of the mapped area, the Stirling is 3,400–3,500 feet thick, as estimated by Barnes and Christiansen (1967), and consists dominantly of nonmicaceous quartzite, with less abundant siltstone and micaceous quartzite and a few thin beds of limestone. In the mapped area the Stirling Quartzite is exposed mainly in the southern extension of the Kawich Range and in one very small area on the west flank of the Belted Range. Quartzite Mountain, which has a total relief of about 2,500 feet and is a major landmark in this region, is composed entirely of Stirling Quartzite.

A nearly complete section was measured by J. H. Stewart and C. L. Rogers in the southern extension of the Kawich Range, in secs. 13, 24, 26, 27, and 35 (all unsurveyed), T. 4 S., R. 50 E. This was a composite section measured in six parts extending from the west flank of Quartzite Mountain to a point about 5.8 miles north-northwest of Quartzite Mountain. The section has a total thickness of almost 5,300 feet and, according to Stewart (oral commun., 1964), who has made a regional stratigraphic study of the formation (Stewart, 1970), is the thickest known section of the Stirling Quartzite. The lithology is intermediate between predominantly quartzite lithology to the southeast and predominantly siltstone lithology with conspicuous carbonates to the northwest.

LITHOLOGY

The base of the Stirling is not exposed in the Quartzite Mountain area, but the lowest beds exposed resemble the basal beds of the formation in other localities and probably lie only a short distance above the contact with the underlying Johnnie Formation. The remainder of the formation is complete, and at the north end of the outcrop the uppermost beds of the Stirling are overlain by beds of the Wood Canyon Formation. In this report the formation is divided informally into lower and upper parts. This bipartite division is a natural one, for although the lower part is dominantly quartzite, the upper part is dominantly siltstone and silty phyllite, with subordinate quartzite and an appreciable amount of carbonate material. The formation is further divided into five informal members, A through E, which are correlative with members A through E described by Stewart (1966) in the Spring Mountains-Death Valley area, and elsewhere (1970). They are summarized as follows:

	Thickness (feet)
Stirling Quartzite	5,290+
Upper part	2,320
Member E: largely siltstone and quartzite	1,195
Member D: dolomite and limestone	285
Member C: largely silty phyllite	840
Lower part	2,970+
Member B: quartzite, silty sandstone and siltstone; partly micaceous	1,130
Member A: largely quartzite	1,840+

Member A is about 1,840 feet thick and is almost wholly quartzite except for thin partings of greenish-gray micaceous siltstone or phyllite, which become more abundant from the base upward. The lowest beds of the formation in this area, which are well exposed on the west flank of Quartzite Mountain, are composed of gray to dusky-grayish-purple laminated to thick-bedded quartzite that weathers reddish brown. The quartzite forms somber-looking cliffs and steep rubble-covered slopes. The quartzite is fine to coarse grained and contains rather abundant thin conglomeratic lenses that are generally composed of granules and pebbles less than 5 millimeters in diameter but may include a few fragments as much as 1 centimeter in diameter. Many beds are laminated to cross laminated, and a few show rather poorly developed graded bedding. Ripple marks occur at some horizons but are nowhere abundant. Thin sections reveal that the quartzite consists mainly of subrounded to subangular quartz, 5–10 percent altered feldspar, a few quartzite fragments, minor red jasper, a variable amount of sericite that occurs interstitially and as an alteration product within the feldspar grains, finely disseminated limonite or hematite, and a small amount of heavy minerals such as magnetite, sphene, zircon, and tourmaline.

The upper part of member A contains a zone 35 feet thick that is predominantly medium-light-gray to olive-gray phyllite, with subordinate grayish-purple micaceous fine-grained quartzite. Above this zone is a sequence 375 feet thick, in which dark quartzite grades upward into lighter quartzite and in which micaceous siltstone and silty sandstone laminae are fairly common. This sequence is medium dark purplish gray to pinkish and yellowish gray on fresh surfaces and weathers to light reddish brown.

Member B, which overlies the lighter quartzite of member A, is about 1,130 feet thick. Its lower part, which is less resistant than the underlying quartzite and forms slopes and saddles, is composed of nonmicaceous to highly sericitic silty sandstone, quartzite, and siltstone, and it weathers to platy or flaggy fragments. The member is partly laminated to thick bedded, but it is predominantly thin bedded. The rock types are all gradational, and they characteristically alternate from purple to green. These rocks become gradually coarser and less micaceous toward the top and grade into a pinkish-gray to grayish-purple quartzite that is about 210 feet thick. The quartzite is mostly fine to medium grained, laminated to thin bedded, and contains a small amount of silty sandstone. The upper 110 feet of member B, which is composed of phyllitic, platy-splitting siltstone with subordinate pinkish-gray quartzite, represents a transition to the upper part of the formation.

The upper part of the Stirling Quartzite, which is about 2,320 feet thick, is a heterogeneous sequence that originated largely as fine-grained clastic sediments with subordinate carbonate material. Individual members are distinctive and could be easily mapped.

Member C is a relatively nonresistant sequence of rocks that is about 840 feet thick and is estimated to be 90 percent silty phyllite or phyllitic siltstone and about 10 percent quartzite. Quartzite is most abundant in the basal beds, which consist of micaceous siltstone and quartzite interbedded with silty to sandy phyllite. These rocks are dark steel gray to almost black, with occasional purplish hues, and are laminated to medium bedded. In thin section the quartzose rocks consist largely of subangular quartz grains in a fine-grained sericitic matrix. The quartz grains range in size from silt to sand, having an average diameter of about 0.05 mm and a maxium diameter of about 0.2 mm. The thin sections also contain a few feldspar grains, minor chlorite, calcite, and dark opaque minerals, minor tourmaline, and rather abundant small carbon flecks that occur predominantly along the micaceous laminae. The phyllitic interbeds are characterized locally by a conspicuous slaty cleavage.

Above the basal beds, member C consists largely of laminated to thin-bedded silty phyllite or phyllitic siltstone. To a point about 600 feet above the base the member is predominantly medium gray to grayish purple, with numerous greenish-gray zones, but toward the top it is almost wholly green. This green sequence exhibits some variation laterally from a silty phyllite to a silty argillite, and it is not clear whether this simply reflects some difference in the degree of metamorphism, or whether it reflects a change in lithology and the presence of a minor unconformity. The first explanation seems more likely. The phyllitic rocks are light greenish gray to greenish gray and may have a silky sheen or a distinctly schistose look, depending on the coarseness of the mica. Two specimens that were examined in thin section contain 30–50 percent silt-sized quartz and a little feldspar in subrounded to subangular grains, embedded in a very fine grained matrix of chlorite and sericite. These specimens also contain a considerable amount of iron oxide, both disseminated and filling small fractures. The argillite is a friable olive-drab rock that in thin section contains scattered small quartz grains in a very fine grained sericitic groundmass. The quartz grains average 0.02–0.03 mm in diameter and probably form 10–20 percent of the rock. The rock also contains a few feldspar grains, common disseminated limonite, and minor tourmaline. The limonite occurs as a stain and in euhedral and anhedral grains that are probably pseudomorphous after pyrite.

Near the base, member C generally contains several zones of dolomite 1–3 feet thick. The dolomite is light gray on fresh surfaces but weathers to grayish orange. Several thin zones of yellowish-brown dolomite also occur near the top of the member, and the highest beds are gradational into the overlying carbonate unit, member D. The basal dolomite beds may be lenticular, because they apparently are absent in some areas.

Member D is a carbonate unit about 285 feet thick. It is light to medium gray and aphanitic to fine grained; it ranges in composition from limestone to dolomite. It is predominantly laminated to thin bedded, and locally crosslaminated. The upper one-third is somewhat silty and includes some limestone that has weathered to brown. Some beds contain small platy to rodlike structures suggestive of poorly preserved algae and other fossils. According to J. H. Stewart (oral commun., 1964), this carbonate unit is probably correlative with part of the Reed Dolomite in the region to the west. The nearest exposure of Reed Dolomite lies only a short distance beyond the west boundary of the project area, near the northwest corner of Stonewall Mountain.

Member E, which overlies the carbonate unit, member D, is a heterogeneous sequence that is almost 1,200 feet thick; it is composed predominantly of siltstone and quartzite and contains very minor sandstone and carbonate. The lower 440 feet consists of silty to sandy argillite, micaceous siltstone, rusty limonitic sandstone, quartzite, and carbonate beds. The argillite and siltstone range in color from gray to greenish gray, olive drab, buff, and various shades of rusty brown. They are laminated to thin and medium bedded and weather to small platy fragments. In thin section the rock was found to contain abundant subangular quartz grains in a very fine grained sericitic and chloritic groundmass. The quartz grains are about 0.02–0.15 mm in diameter and form 40–50 percent or more of the rock, which ranges in composition from a silty argillite to a phyllitic siltstone and which contains rather abundant finely disseminated limonite, minor feldspar, and sparse small grains of tourmaline. The carbonate layers weather to reddish gray and yellowish gray and are similar to the rock in the underlying member. Carbonates occur throughout this zone but are somewhat less abundant in the upper part. The sandstone is greenish gray to yellowish gray and pale yellowish brown, fine to medium grained, laminated to thin bedded, locally crosslaminated, and commonly calcareous. The sandstone locally grades into quartzite. The quartzite in the upper two-thirds of this zone is predominantly pinkish gray, laminated to thick bedded, and relatively clean; it contains little mica.

The middle part of member E, 355 feet thick, is composed largely of interbedded siltstone, quartzite, and micaceous siltstone. The quartzite is increasingly abundant from the base upward and occurs in layers 1–3 feet thick.

The upper part of member E is a cliff-forming quartzite 400 feet thick; it has a few thin layers of micaceous siltstone in the upper part. The quartzite is predominantly a pinkish-gray clean-looking rock consisting largely of fine- to medium-sized quartz grains, with a small percentage of feldspar and rather abundant iron oxide specks. Thin lenticular pebble beds are common, and the rock is laminated to thin bedded with common cross-laminations.

AGE

No identifiable fossils have been found in the Stirling Quartzite. Its stratigraphic position indicates a probable late Precambrian age.

PRECAMBRIAN AND CAMBRIAN—WOOD CANYON FORMATION

DEFINITION AND DISTRIBUTION

The Wood Canyon Formation was named by Nolan (1929) for exposures in Wood Canyon in the northwestern part of the Spring Mountains, Nye County, Nev. In the type locality it comprises 2,100 feet of thin-bedded quartzitic sandstone and sandy shale with a few carbonate beds near the top.

The formation is exposed only in the two major belts of sedimentary rocks in the Belted and Kawich Ranges. In the Belted Range the unit occurs beneath a major gravity slide or thrust fault, and all but the basal part is well exposed. In the Kawich Range only the lower part is exposed.

LITHOLOGY

A section of the Wood Canyon Formation in the Belted Range, in an unsurveyed area about 2.5 miles west-southwest of Cliff Spring and 5.5 miles southwest of Belted Peak, was measured by J. H. Stewart and C. L. Rogers. Because the area contains numerous small faults and several rhyolite dikes, the thicknesses obtained may be slightly in error. The measured thickness is about 3,750 feet, and this represents an increase of about 1,465 feet over the nearest measured section, which lies approximately 20 miles to the east-southeast in the Groom district (Barnes and Christiansen, 1967).

In the Belted Range the contact of the Wood Canyon with the underlying Stirling Quartzite is masked by alluvium, and small differences in attitudes between the highest exposed Stirling beds and the lowest Wood Canyon beds suggest the possibility of a concealed fault. In the Kawich Range the contact with the Stirling Quartzite is transitional. Because the lower contact in these areas cannot be precisely located, the thickness of the lower unit could only be determined approximately at 1,320 feet.

Three informal units of the Wood Canyon are recognized in the Groom Range, outside the project area, and these have also been recognized within the project area. They are described separately as lower, middle, and upper units but are not shown separately on the geologic map.

The lower unit is composed largely of siltstone in the lower half and quartzite in the upper half. The siltstone is olive or olive gray to grayish red, platy, and variably micaceous. The quartzite is yellowish to greenish gray and pale yellowish brown, predominantly fine grained, evenly laminated to thin bedded, and locally micaceous. The unit also contains three carbonate zones which, according to J. H. Stewart (oral commun., 1964), are very persistent and have been recognized in widely separated areas. In the Kawich Range the lowest carbonate zone, which is 25 feet thick and lies about 360 feet above the base of the unit, is a grayish-orange, brownish-weathering, finely crystalline, sandy dolomite that grades locally to dolomitic sandstone and calcitic dolomite. In the Belted Range the lowest carbonate zone is 33 feet thick, and the overlying carbonate zones, which are similar in lithology, are 3 and 23 feet thick, respectively. Stewart believes that the basal carbonate zones in the two areas are correlative, and if this is true, it would indicate that the underlying sequence is considerably thicker in the Belted Range, because the lowest carbonate zone in the Belted Range apparently lies about 640 feet above the Stirling Quartzite. Much of this basal sequence in the Belted Range, however, is covered with alluvium, and the contact with the Stirling Quartzite can only be approximately located. Also, concealed faults in this covered interval may cause some duplication of beds.

The middle unit is about 1,115 feet thick and, because it is predominantly quartzite with subordinate siltstone, is more resistant than the neighboring units. The quartzite ranges in color from pale red to grayish red and yellowish gray and is fine to coarse grained, but predominantly fine grained. The beds in the unit are 1–6 inches thick and some are crosslaminated. The basal beds, 10–20 feet thick, are partly conglomeratic and contain granules and small pebbles of quartz and quartzite. The siltstone, which may constitute as much as 30 percent of the unit, is grayish purple to grayish olive, platy, and micaceous in varying degrees.

The upper unit is about 1,315 feet thick and is predominantly micaceous siltstone with smaller amounts of quartzite and carbonate rock. The siltstone is grayish olive to dusky yellow and platy. The quartzite is pale yellowish brown to yellowish gray, fine grained, laminated, and micaceous in part. Quartzite is rather sparse in the lower part of the unit but is increasingly abundant upward and may be dominant in the upper part. The carbonate rock is mainly concentrated in a zone 100 feet thick that lies about 850 feet above the base of the unit. This zone is estimated to contain about 60 percent carbonate rock, 30 percent quartzite, and 10 percent siltstone. The carbonate rock is largely dolomite or calcitic dolomite, except for a few feet of limestone near the base, and is pale yellowish brown and pale red on fresh surfaces, predominantly weathering to a dark reddish brown. The rock is finely crystalline or oolitic and in some parts contains disseminated sand grains. It is generally laminated to thin bedded and is locally cross-laminated. A few thin dolomite layers occur above the main zone. In the uppermost part of the unit, which is somewhat transitional in character, the siltstone grades into a finer grained rock that is more shaly in appearance and is similar in lithology to some of the shaly rocks in the overlying Zabriskie Quartzite and Carrara(?) Formation.

AGE

The lower and middle units and the basal part of the upper unit contain only indeterminate worm trails and borings and are considered to be Precambrian in age. Rocks in the upper 635 feet of the Belted Range section contain olenellid trilobites, vertical worm borings known as *Scolithus*, pelmatozoan debris, and some poorly preserved brachiopods. These rocks are considered to be Early Cambrian.

CAMBRIAN

ZABRISKIE QUARTZITE

DEFINITION AND DISTRIBUTION

The Zabriskie Quartzite was described by Hazzard (1937) in the Nopah-Resting Springs area of Inyo County, Calif., and was considered by him to be a member of the Wood Canyon Formation. The unit was redefined by Wheeler (1948, p. 26) as a formation between the underlying Wood Canyon Formation and overlying Carrara Formation.

The Zabriskie crops out only in the southern part of the Belted Range, where it can be traced for about 4 miles and is cut by numerous small transverse faults. The quartzite has been mapped with the Wood Canyon Formation on plate 1 because it is too thin to be shown separately. Its thickness is about 150 feet in the Belted Range, 220 feet in the Groom district (Barnes and Christiansen, 1967) 20 miles to the east-southeast, and 1,150 feet in the Bare Mountain area more than 50 miles to the southwest (Cornwall and Kleinhampl, 1961). The Belted Range section was measured by J. H. Stewart and C. L. Rogers.

LITHOLOGY

The lower one-third of the Zabriskie is a poorly exposed zone that is transitional into the underlying Wood Canyon Formation and is composed of interbedded quartzite and siltstone. This sequence has been arbitrarily included with the Zabriskie Quartzite, but a study of better exposures, if they could be found, might change this assignment to the underlying formation.

The upper two-thirds of the Zabriskie is a conspicuous ridge former and is composed of yellowish-gray to pale-yellowish-brown quartzite that is characteristically massive in appearance, although it is laminated and cross laminated in places. It contains a few thin lenticular conglomeratic layers containing pebbles and small cobbles of quartzite and red chert that are generally less than 1 cm long. The Zabriskie Quartzite is different from the quartzite in the older formations in that it is completely free of feldspar. A zone, 40 feet thick, at the top of the formation contains subordinate fissile olive-drab shale, and it apparently represents a transition into the overlying Carrara(?) Formation.

AGE

The only fossil evidence in the Zabriskie consists of vertical *Scolithus*-like worm borings. However, the stratigraphic position of the formation is sufficient for dating purposes, and it is clearly Early Cambrian in age.

CARRARA(?) FORMATION

DEFINITION AND DISTRIBUTION

The Carrara Formation was named by Cornwall and Kleinhampl (1961) for an abandoned mining camp located 8 miles east-southeast of Beatty, Nev. It lies between the Zabriskie Quartzite and the Bonanza King Formation and is transitional between the older dominantly clastic rocks and the younger dominantly carbonate rocks. In the type locality the Carrara consists of 1,785 feet of shale and limestone with relatively small amounts of quartzite, sandstone, and siltstone. The lower half consists mainly of shale with very subordinate limestone, but the upper half consists almost wholly of carbonate rock.

In the Belted Range the rocks lying above the Zabriskie Quartzite are intermediate in lithology between the typical Carrara Formation in the area to the southeast and the typical Emigrant Formation in Esmeralda County to the west. Rather than introduce a new stratigraphic name for these transitional rocks, the authors have resorted to a compromise. The lower part, which is about 1,577 feet thick and resembles the lower part of the Carrara, is called Carrara(?) Formation, and the upper part, which is about 3,000 feet thick and more closely resembles the Emigrant Formation, is identified simply as "limestone, silty limestone, and shale of Middle Cambrian age."

The Carrara(?) Formation is exposed over an area of several square miles on the west side of the Belted Range (pl. 1) and in several small isolated outcrops along the west base of a ridge 5 miles west-southwest of Mount Helen. These isolated outcrops are too small to be shown on the geologic map, but they are near the exposures of Eureka Quartzite in that area. In the Belted Range, in an area 2 miles southwest of Cliff Spring (unsurveyed secs. 21 and 22, T. 5 S., R. 52 E.), the formation was measured by J. H. Stewart and C. L. Rogers.

LITHOLOGY

For descriptive purposes, the Carrara(?) Formation is divided into four units, which correlate only in part with the units described by Barnes, Christiansen, and Byers (1962, 1965), and by Barnes and Christiansen (1967) in the Halfpint Range and the Groom district southeast of the project area. The four units are as follows:

	Thickness (feet)
Carrara(?) Formation	1,577
Unit D: limestone, silty limestone, calcareous siltstone, and shale	237
Unit C: papery shale	400
Unit B: shale, with rather minor siltstone, sandstone, and limestone	710
Unit A: shale and limestone in roughly equal proportions	230

Unit A is about 230 feet thick and consists of about equal parts of shale and limestone. The shale generally is grayish olive to green, and it contains sparse to rather abundant fine-grained mica. Some zones are less fissile and more resistant and are more accurately described as siltstone. The limestone is generally medium gray, finely crystalline, and thin to medium bedded, but it contains some buff silty limestone in discontinuous irregular laminae and a few thin layers that are silty throughout. The major limestone sequence, which is about 80 feet thick, occurs at the top of the unit. The lithology and fossil evidence indicate that unit A, though thinner, is the approximate equivalent of members A and B of Barnes and Christiansen (1967) in the Groom district, about 20 miles east-southeast of the Belted Range.

Unit B is about 710 feet thick and is composed largely of shale with relatively small amounts of silstone, sandstone, and limestone. The shale is generally grayish olive, though locally it is greenish gray to medium dark gray, and in the upper part of the unit is characterized in part by relatively coarse grained mica, giving it a schistose appearance. The upper part of the sequence also contains more abundant resistant siltstone layers and a few thin beds of greenish-gray micaceous sandstone. The limestone forms several thin zones near the base of the unit and a sequence about 20 feet thick at the top of the unit.

Unit C, about 400 feet thick, is a homogeneous sequence of papery pale-olive shale that weathers light yellowish gray or gray. The shale contains abundant fine-grained sericite, which imparts a silky sheen to the cleavage surfaces.

Units B and C, although more than twice as thick as member C, may be roughly equivalent to it in the Groom district. According to A. R. Palmer (written commun., 1964), the limestone zone at the top of unit B is comparable stratigraphically and in faunal content to a similar zone in the Groom section that forms the only prominent ledge between members B and D of that area. Trilobites collected from this limestone zone in the Belted Range and from the shales immediately above it are of earliest Middle Cambrian age.

Unit D, about 237 feet thick, is transitional in character. It is composed of alternating zones of limestone and clastic to semiclastic rocks ranging in type from yellowish-weathering micaceous shale near the base to thin-bedded buff- to brownish-weathering calcareous siltstone and silty limestone in the upper part. The limestone becomes more abundant upward and is generally medium to dark gray, aphanitic to finely crystalline, and laminated to medium bedded. Some beds are rather coarsely oolitic, and some limestone contains thin laminae of brown dolomite.

No fossils have been collected from unit D, but the general lithology and the fossil evidence obtained from neighboring units suggest that it represents member D of the Groom District.

AGE

An Early and Middle Cambrian age is assigned to fossils collected from the Carrara (?) Formation in the Belted Range and identified by A. R. Palmer (written commun., 1964).

Limestones in unit A yielded abundant fragments of the olenellid trilobites *Olenellus* and *Paedumias*, a smaller number of specimens of a nonolenellid trilobite that are probably referable to *Antagmus*, *Bristolia*, *Sombrerella*, several poorly preserved orthoid brachiopods, and numerous examples of *Girvanella*, an algal form, which may occur as scattered individuals or as clusters in biostromelike masses. This assemblage indicates an Early Cambrian age.

The limestone layer at the top of unit B yielded *Poliella*? sp. and a kochaspid trilobite, *Dictyonina* sp. and orthoid brachiopods, and *Chancelloria* sp.; shales in the basal part of unit C yielded *Pagetia* sp., *Oryctocephalus* sp., and undetermined ptychoparoid trilobites. The trilobites from these two horizons are of earliest Middle Cambrian age. *Girvanella* was collected from the top of unit C.

Collections from the small isolated exposures of possible Carrara beds in the western part of the project area, which were also studied by A. R. Palmer (written commun., 1964) contained abundant specimens of *Girvanella*, an indeterminate olenellid trilobite, trilobites referable to *Crassifimbra*, and a capuliform mollusk referable to *Scenella*. Palmer stated that it is difficult to make a formational assignment because, although these rocks are clearly Early Cambrian in age and equivalent to the lower part of the Carrara Formation, the locality lies between the Nye County and Esmeralda County Lower Cambrian areas, which have almost totally different formational sequences. The exposures that were found consist of thin- to medium-bedded gray to yellowish-gray silty limestone and thin interbeds of brown-weathering silty dolomite.

LIMESTONE, SILTY LIMESTONE, AND SHALE OF MIDDLE CAMBRIAN AGE

In three localities in the Belted Range the Carrara (?) Formation is overlain by a sequence that is referred to simply as limestone, silty limestone, and shale of Middle Cambrian age. The unit, which is incomplete and on the east is faulted against Tertiary volcanic rocks, can be divided into three units:

	Thickness (feet)
Limestone, silty limestone, and shale of Middle Cambrian age	2,970±
Upper unit: fissile shale	700±
Middle unit: limestone with minor silty limestone and chert	2,000±
Lower unit: limestone and silty limestone	270

The lower unit is about 270 feet thick and is composed of alternating zones of medium- to dark-gray aphanitic to fine-grained limestone and a buff- to brown-weathering silty limestone that grades locally into a calcareous siltstone.

Only the lower 450 feet of the middle unit has been measured, owing to an abundance of small-scale folds in its upper part. However, it is estimated that the total thickness of the unit may be as much as 2,000 feet. The middle unit is composed largely of medium- to dark-gray aphanitic to finely crystalline laminated to medium-bedded limestone, with scattered partings or thin interbeds of silty limestone or calcareous siltstone. Locally the beds have a wavy appearance, and, in the upper half of the unit, they contain scattered thin lenses of black chert. Chert increases in amount gradually upward, and near the top it is locally abundant.

The lower and middle units are lithologically similar to the Emigrant Formation (J. H. Stewart, oral commun., 1964) and, as shown by fossils, are partly correlative with it. The Emigrant Formation was named by Turner (1902) for exposures lying to the south of Emigrant Pass in the Silver Peak Range of Esmeralda County, Nev., and its age was revised by Albers and Stewart (1962) to Middle and Late Cambrian. It is equivalent in part to the upper part of the Carrara Formation and in part to the overlying Bonanza King Formation in the Groom and Jangle Ridge areas.

The upper unit, which is about 700 feet thick, is composed of gray to slightly greenish-gray fissile shale that weathers to various shades of brown and breaks into small platy to elongate fragments. It occurs only in the northernmost exposure of the sequence being described and is in normal-fault contact with volcanic rocks on the east. It seems probable that this shale occurs in approximately normal stratigraphic sequence and that it corresponds to a shaly unit in the Emigrant Formation. The contact between the shale and the underlying limestone cannot be determined because of poor exposures, however, and the shale may represent a sequence in the lower part of the Carrara (?) Formation that has been repeated by faulting.

AGE

In the lower unit, fossil material was collected by A. R. Palmer, J. H. Stewart, and C. L. Rogers and was identified by Palmer (written commun., 1964) as *Ogygopsis typicalis* (Resser), *Pagetia* sp., *P. clytia* Walcott, and *P. maladensis* Resser, *Oryctocephalus* sp., *Tonkinella*? sp. and ?*Tonkinella idahoensis* Resser, "*Agnostus*" *lautus* Resser and cf. "*Agnostus*" *lautus* Resser, *Alokistocare* sp., undetermined ptychoparioid trilobites, *Hyolithes*, and *Girvanella*. According to Palmer, this assemblage is approximately equivalent to the *Albertella* zone, which lies immediately below the Jangle Limestone Member of the Carrara Formation in the area east of Yucca Flat and which is Middle Cambrian in age.

The middle and upper units are probably Middle Cambrian in age, but no determinable fossils were found in them.

BONANZA KING FORMATION

DEFINITION AND DISTRIBUTION

The Bonanza King Formation was named by Hazzard and Mason (1936) for the Bonanza King mine on the east side of the Providence Mountains, San Bernardino County, Calif., where the formation consists of about 2,000 feet of dolomite and minor siltstone, silty limestone, and chert.

To the south and east of the project area the formation crops out widely in the C P Hills and in the Halfpint and Groom Ranges. A virtually complete stratigraphic section of the formation, 4,600 feet of limestone and dolomite, was measured across Jangle Ridge and Banded Mountain in the northwestern part of the Halfpint Range by Barnes, Christiansen, and Byers (1962, 1965), who divided the formation into Papoose Lake and Banded Mountain Members. In the Groom Range a complete section of the formation, which is 4,355 feet thick, is also largely limestone and dolomite with minor siltstone and silty limestone (Barnes and Christiansen, 1967). Within the project area the formation occurs mainly in the extreme southeast corner, where a thick, though incomplete, section is exposed. These rocks are tentatively assigned to the Papoose Lake and Banded Mountain Members, but the members are not separately mapped.

LITHOLOGY

In the main outcrop area an incomplete section of the Papoose Lake Member is about 1,450 feet thick and is composed almost wholly of dolomite. The dolomite is light to medium and dark gray, locally laminated but generally medium to thick bedded, and fine grained and is characterized in some places by a sugary texture. The lowest beds contain a small amount of buff platy silty dolomite; small lenses of gray chert were noted at one horizon. This part of the formation contains a large amount of light-colored secondary silica, some of which lies along fractures but most of which occurs in abundant very small, thin irregular lenses that on weathered surfaces bear a superficial resemblance to chain corals. The rocks have been dolomitized and extensively silicified, and as a result their original lithologic character has been largely obliterated. The Papoose Lake Member has been divided into three informal units by Barnes and Christiansen (1967), but these have not been recognized in the project area, perhaps owing to the extensive alteration of the rocks.

The upper part of the Bonanza King Formation, which has an exposed thickness of about 1,850 feet, is tentatively assigned to the Banded Mountain Member. The top of the formation and the overlying Dunderberg Shale Member of the Nopah Formation may lie beneath the covered area to the north, for this interval is succeeded on the north by a large exposure of the Halfpint Member of the Nopah Formation, which is structurally concordant with the Bonanza King beds.

The Banded Mountain Member has been divided into four informal units by Barnes and Christiansen (1967), but these units cannot be recognized with assurance in the project area, owing to alteration and poor exposures.

The basal 35 feet consists of buff to brownish-buff weathering laminated to thin-bedded silty dolomite which, except for being dolomitized, is similar to part of a zone marking the base of the Banded Mountain Member in the Halfpint and Groom Ranges.

The next 915 feet is composed of light- to dark-gray dolomite. The lower part consists of thick-bedded dark-gray dolomite, which is overlain by a thick sequence, incompletely exposed, of light- to dark-gray laminated to thick-bedded fine-grained dolomite that closely resembles the rocks assigned to the Papoose Lake Member. The upper part is light-gray laminated to thin-bedded dolomite and silty dolomite that weathers to brown. The thin-bedded dolomite contains a minor amount of lenticular gray chert. Locally these rocks contain rather abundant secondary silica similar to that occurring in the Papoose Lake Member.

The next 550 feet is mainly medium- to thick-bedded light-gray fine-grained locally calcitic dolomite in its lower part and thick-bedded light-gray to very light-gray aphanitic to fine-grained limestone in its upper part. The limestone weathers to a smooth rounded surface that contrasts with the rough pitted surface of the dolomite, and some beds appear to have been marmorized.

The uppermost 350 feet is medium- to thick bedded light- to medium-gray fine-grained dolomite having a rather saccharoidal texture. In the darker beds, which occur in the lower part of the unit, are a few fossiliferous layers that contain poorly preserved brachiopods and numerous small ovoid forms with a concentric structure that resemble *Girvanella*.

Two small exposures tentatively identified as Bonanza King occur on the west side of the Kawich Valley west of the north end of the Belted Range. They are composed of light- to dark-gray aphanitic to fine-grained medium- to thick-bedded dolomite. The color banding is partly stratigraphic, but it has been modified by irregular bleaching. One exposure is adjacent to a granite porphyry stock, and the rocks in both areas exhibit some fracturing and brecciation, as well as bleaching and minor silicification. The general lithology and the presence of small ovoid structures resembling *Girvanella* suggest a correlation with the Bonanza King Formation. The rocks also contain some linguloid brachiopod fragments, but these are nondiagnostic for the purpose of identifying the Bonanza King Formation.

AGE

Most of the Bonanza King Formation is Middle Cambrian in age, but the uppermost part is of Late Cambrian age (Barnes and Palmer, 1961).

NOPAH FORMATION

DEFINITION AND DISTRIBUTION

The Nopah Formation was named by Hazzard (1937) for the Nopah Range in southeastern Inyo County, Calif., where it consists dominantly of varicolored dolomite.

The formation is widely exposed between the project area and the Nopah Range. Barnes and Christiansen (1967) have described and redefined the Nopah in the Groom district and have correlated its three members southwestward to Bare Mountain and the Nopah Range. It is about 2,000 feet thick in the Groom district and is divided into the Dunderberg Shale, Halfpint, and Smoky Members. This area is only a few miles east of the southeast corner of the project area (pl. 1), and owing to its proximity and to lithologic similarity between the Groom and Belted Range rocks, the authors have adopted the nomenclature employed by Barnes and Christiansen.

In the Groom district the Dunderberg Shale Member is about 310 feet thick and consists of highly fissile pale-reddish-brown to olive-gray shale, with thin interbeds of platy to wavy and nodular limestone. The upper part grades into the overlying Halfpint Member, and the top is placed at the point where shale gives way to limestone as the dominant rock type. The Halfpint Member is 1,055 feet thick and is composed of platy- to flaggy-splitting very thin bedded limestone, with intercalated laminae of clayey and silty limestone and very thin beds of chert. The Smoky Member is 670 feet thick and consists mainly of blocky- to massive-splitting limestone, with little or no chert and silty limestone.

In the project area the Nopah Formation is partially exposed for a length of about 9 miles on the west flank of the Belted Range, in several relatively small areas on the east flank of the Belted Range, and in the southeast corner in the vicinity of Oak Spring Butte. It may have a total thickness of at least 3,000 feet.

LITHOLOGY

The Dunderberg Shale Member, which forms the basal member of the Nopah Formation within the project area, crops out in a single locality on the west flank of the Belted Range, where an incomplete section occurs within a small fault block. The exposed part may be about 200 feet thick. The contact with the underlying Bonanza King Formation is not exposed, and there appears to have been at least minor gravity slide or thrust movement along the contact with the overlying Halfpint Member. The lower part of the section exposed consists of very fissile reddish-brown shale and scattered thin beds of medium-gray limestone that weather to brownish gray. The limestone becomes relatively abundant in the upper part of the section and occurs in thin nodular to wavy beds resembling the basal part of the Halfpint Member.

The Halfpint Member may be about 1,900 feet thick in the Belted Range, but the member cannot be measured accurately because of severe crumpling of the beds and some fault displacement.

The Halfpint Member is composed largely of thin-bedded medium-gray limestone and dolomite and intercalated laminae of silty limestone and dolomite which weather to reddish gray and brownish gray. The rock is mostly laminated and wavy bedded, and it breaks characteristically into fairly large platy or flaggy fragments. Thin lenses and nodules of medium- to dark-gray chert are rather abundant at many horizons, and locally the rock contains a large amount of secondary carbonate material which weathers to brownish gray along bedding planes and fractures and in small irregular masses. In the southeast corner of the project area and locally in the Belted Range, the member consists largely of limestone. In several small gravity slide or thrust plates in the Belted Range, the Halfpint Member is extensively broken, deformed, and dolomitized. The dolomite is secondary and may be structurally controlled, as shown by the dominantly limy character of equivalent rocks in the lower plates. The contact with the overlying Smoky Member is gradational and is placed in the zone where there is a change upward to thicker splitting beds and less chert. Locally along this contact, where some movement apparently occurred, the change in lithology is abrupt. In these areas the Halfpint Member has been altered to a sugary-textured dolomite that is buff to brown on weathered surfaces.

The Smoky Member is about 900 feet thick and is composed of thin- to thick-bedded light- to dark-gray limestone and dolomite; in many places it forms rather smooth-weathering massive-looking outcrops. In many exposures the member is characterized by conspicuous alternating bands of light- and dark-gray carbonate rock, the bands ranging from several feet to tens of feet in thickness. Laterally along strike, dolomite and limestone occur in highly variable proportions, although dolomite seems to predominate. The dolomite is fine to medium grained, sugary textured, and locally laminated to cross laminated. Some is obviously clastic in origin. In the Belted Range the Smoky Member is brecciated, fractured, and altered in many places and locally contains abundant light-gray to buff or brownish-gray relatively coarse-grained secondary dolomite that occurs along bedding planes and fractures and in small irregular masses. The member contains scattered small chert nodules, and some dolomite beds are characterized by light-gray to reddish-gray mottling. Well-developed stromatolites and *Girvanella* have been noted at several horizons in the Smoky Member in the southeast corner of the project area. They were not observed in the Belted Range, however, perhaps because they have been largely obliterated there by the extensive alteration that has taken place.

AGE

Most of the Nopah Formation in the project area, in the Groom district, and in the Halfpint Range (Barnes and Christiansen, 1967), is Late Cambrian in age. However, no fossils have been collected from the uppermost part of the Nopah Formation or the basal part of the Goodwin Limestone in this region, and the Cambrian-Ordovician boundary has not been accurately located.

ORDOVICIAN

POGONIP GROUP

DEFINITION AND DISTRIBUTION

The name Pogonip, which is taken from Pogonip Ridge in the Hamilton district 30 miles southeast of Eureka, Nev., has survived many changes in usage since it was introduced in 1878. In the Eureka area, Nolan, Merriam, and Williams (1956) used the term Pogonip Group for the rocks lying between the Cambrian Windfall Formation and the Eureka Quartzite of Middle Ordovician age, and it is in this sense that the name is now being used in the Nevada Test Site and adjacent areas. Nolan and his associates divided the group into three formations, the Goodwin Limestone, Ninemile Formation, and Antelope Valley Limestone, and these have been recognized and described in the project area. They are shown separately only in cross section.

The Pogonip Group (fig. 2) is exposed for a length of about 8 miles on the west flank of the Belted Range; it crops out in two small areas on the east flank of the Belted Range and is exposed for a length of about 2.5 miles in the trough of a syncline in the Carbonate Wash area. The Pogonip occurs also in one small exposure near the Oswald mine on the east boundary of the project area. Complete, well-exposed sections occur in both the Belted Range and Carbonate Wash areas; the section on the west flank of the Belted Range was measured by R. J. Ross, Jr., and L. A. Wilson. The area in which the section was measured is not surveyed, but it lies about 3 miles west-southwest of Belted Peak and 3.5 miles northwest of Cliff Spring. The Pogonip has a total thickness of about 3,000 feet.

GOODWIN LIMESTONE

The Goodwin Limestone is about 1,010 feet thick in the project area and can be divided into three units. The lower unit is about 400 feet thick and grades into the underlying Smoky Member of the Nopah Formation. This unit is composed of light- to medium-gray fine-grained limestone, dolomitic limestone, and dolomite, which are generally thin to thick bedded, but locally laminated to crosslaminated. It is silty in part and commonly weathers to a buff to orange hue. The limestone contains rather abundant lenticular gray chert and a small amount of intraformational conglomerate. The rock is most readily distinguished from the Smoky Member by its weathered color, but it is also characterized by a higher proportion of limestone, more abundant chert, and thinner splitting beds that form more distinctly ledgy outcrops. Generally it is a better ridge and cliff former.

The middle unit, about 230 feet thick, is a relatively soft sequence which forms topographic saddles and strike valleys. It is composed of silty limestone and calcareous siltstone, which weather to yellowish gray, and subordinate laminated to thin-bedded medium-gray limestone. Much of the limestone is lenticular to somewhat nodular. This unit has been widely recognized and described in southern Nevada but has not been named.

The upper unit, about 380 feet thick, is composed predominantly of laminated to thick-bedded medium-gray aphanitic to medium-grained limestone. The upper half contains rather abundant laminae of silty limestone that weathers to shades of yellow, brown, and red. Some silty limestone occurs in an irregular network resembling the "chicken-wire" pattern in the Antelope Valley Limestone. The thicker limestone beds

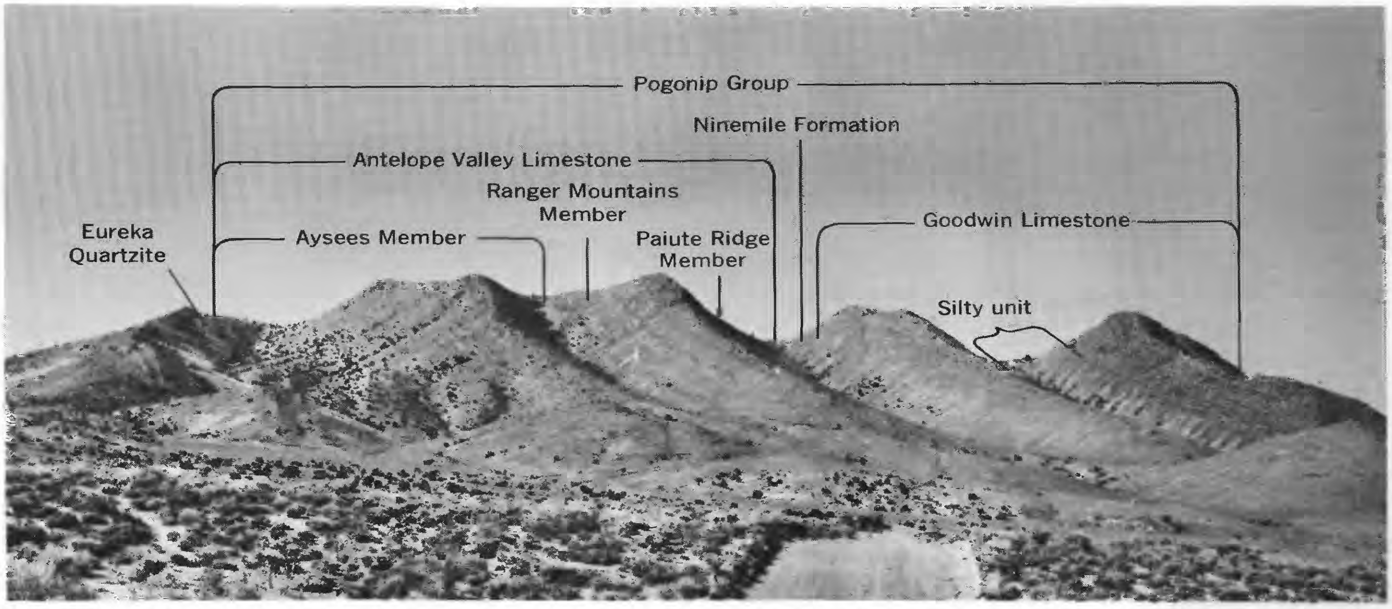

FIGURE 2.—Widest part of Limestone Ridge on the west flank of the Belted Range. This part of the ridge is composed of rocks of the Pogonip Group and Eureka Quartzite of Ordovician age. The Paleozoic rocks are in normal-fault contact with younger volcanic rocks in the foreground. View to the south.

in the upper part of the unit contain some intraformational conglomerate. Lenticular gray chert is common in the lower part of the section but sparse in the upper part.

The Goodwin Limestone is moderately fossiliferous and has been proved to be of Early Ordovician age. Fossils collected in the Belted Range, which were identified by R. J. Ross, Jr. (written commun., 1968), include two trilobites, *Hystricurus* sp. and *Symphysurina* sp., and a brachiopod, *Apheoorthis* sp.

NINEMILE FORMATION

In the project area the Ninemile Formation is a thin, easily eroded unit on which saddles and strike valleys have been formed, and exposures are generally poor. Its average thickness is about 300 feet, and it generally weathers to yellowish-gray. The Ninemile is composed of laminated to thin-bedded silty limestone and calcareous siltstone with intercalated fissile claystone. The unit includes a subordinate but rather variable amount of medium-gray fine-grained limestone that is commonly nodular to lenticular but may occur in persistent beds.

The Ninemile Formation is abundantly fossiliferous and is Early Ordovician in age, like the underlying Goodwin Limestone. Fossils from the Belted Range were identified by R. J. Ross, Jr. (written commun., May 9, 1968), and include two brachiopods, *Elliptoglossa* sp. and *Conotreta*? sp., collected from the southern part of Limestone Ridge on the west side of the range (USGS colln. D1409 CO), and two trilobites, *Ptyocephalus* sp. and *Lachnostoma*? sp., collected from an isolated exposure on the east side of the range (USGS colln. D1418 CO).

ANTELOPE VALLEY LIMESTONE

In the Belted Range and in the area north of Oak Spring Butte, the Antelope Valley Limestone contains three recognizable units that are correlated with the Paiute Ridge, Ranger Mountains, and Aysees Members. These members were defined by Byers, Barnes, Poole, and Ross (1961) and were named by them for features lying within and just east of the Nevada Test Site. They are well exposed in the Ranger Mountains, where they were mapped and described by Poole (1965), and have an aggregate thickness of about 1,530 feet. In the Belted Range the three members have an aggregate thickness of at least 1,600 feet.

The Paiute Ridge Member, about 400 feet thick, forms a bold ridge lying between two less resistant units. It consists of thin- to thick-bedded dominantly medium-gray fine-grained limestone with abundant silty limestone in regular laminae and beds and in the etched irregular networks which form a "chicken-wire" pattern and which are characteristic of this member (Byers and others, 1961). The silty limestone weathers to shades of brown and orange. Sparse small chert nodules occur in the member.

The Ranger Mountains Member is about 300 feet thick. It is a soft sequence characterized by poor exposures and consists of laminated to thin-bedded flaggy-splitting medium-gray fine-grained limestone interbedded with yellowish- to brownish- and reddish-gray siltstone and calcareous siltstone. The limestone may be wavy bedded to lenticular and nodular, and locally it contains numerous thin lenticular beds of black chert.

The Aysees Member, about 910 feet thick, can be divided into lower and upper parts. In the Belted Range the lower part is about 540 feet thick and is a ridge-forming sequence composed of medium-gray thin- to thick-bedded dolomite that is locally laminated and slightly silty. Weathered surfaces are pale gray to grayish and brownish orange. The upper part is about 370 feet thick and is a less resistant sequence composed of laminated to medium-bedded pale-gray- to yellowish-gray- and brownish-gray-weathering dolomite, dolomitic limestone, and limestone, which are slightly to strongly silty and which contain scattered small chert nodules. In places the silty rocks are gradational into siltstone and fine-grained quartzite. In the southeast corner of the project area the same division can be recognized, but in both lower and upper parts the rocks tend to be siltier and thinner bedded, and the yellowish-gray to brownish-gray weathering is more pronounced.

All members of the Antelope Valley Limestone are fossiliferous, and the formation is Early and Middle Ordovician in age.

Fossil material was collected from the formation in the Belted Range by R. J. Ross, Jr., and the authors and was studied by R. J. Ross, Jr., J. M. Berdan, J. W. Huddle, and O. L. Karklins.

Two trilobites were collected from a locality 165 feet above the base of the Paiute Ridge Member (USGS colln. D1501 CO) and were identified by R. J. Ross, Jr. (written commun., May 9, 1968), as *Ptyocephalus* sp. and *Nileus*? sp. This member also contains a few *Girvanella*.

A locality 460 feet above the base of the formation (USGS colln. D1500 CO), and in the lower part of the Ranger Mountains Member, yielded two trilobites, which were identified by R. J. Ross, Jr. (written commun., May 9, 1968), as *Ectenonotus* sp. and aff. *Miracybele* sp., and a number of conodonts, which were identified by J. W. Huddle (R. J. Ross, Jr., written commun., May 9, 1968) as:

Belodina aff. *B. inclinatus* Branson and Mehl
Ligonodina tortilis Sweet and Bergström
Oistodus sp.
Periodon sp.
Prioniodina sp.

According to Ross, this combination of trilobites and conodonts is characteristic of the *Orthidiella* zone in the Toquima Range of central Nevada, where it is found in the lower member of the Antelope Valley Limestone.

A collection from the Aysees Member of the Antelope Valley (USGS colln. D1089 CO) yielded three trilobites and three ostracodes. The trilobites were identified by R. J. Ross, Jr., and included *Illaenus* sp., *Pseudomera* sp., and *Isotelus*? sp.; the ostracodes were identified by J. M. Berdan and included *Schmidtella* sp., *Leperditella*? sp., and ?*Leperditella* sp. cf. *L. bulbosa* Harris. This unit also contains numerous examples of the gastropods *Maclurites* and *Palliseria*, but they were not collected.

Silty to sandy limestone lying 30–60 feet below the Eureka Quartzite yielded numerous fossils (USGS colln. D1499 CO) and might be considered as uppermost Antelope Valley or as equivalent to the lower part of the Copenhagen Formation.

This collection included pachydictyd (?), trepostome, and monticuliporid bryozoans, which were identified by O. L. Karklins (written commun., 1965) and indicate an age probably younger than the Oil Creek Formation and older than the Bromide Formation of Oklahoma. From the same collection R. J. Ross, Jr., identified the brachiopods *Syndielasma*? sp., *Valcourea* sp., and *Leptellina*? sp., as well as an indeterminate large fine-ribbed orthid and one trilobite, *Isotelus*? cf. *I. spurius* Phleger. From the same collection J. W. Huddle (written commun., March 9, 1965) identified the following conodonts:

Belodina cf. *B. ornata* (Branson and Mehl)
Cordylodus sp.
Dichognathus n. sp.
Distacodus sp.
Drepanodus sp.
Phragmodus undatus Branson and Mehl
Prioniodina? sp.
Trichonodella sp.
Zygognathus sp.

This conodont fauna is probably Middle Ordovician in age. The overall aspect of the fauna from the collection being described indicates, according to R. J. Ross, Jr. (written commun., May 9, 1968), a correlation with the upper part of the Antelope Valley Limestone exposed at Ikes Canyon in the Toquima Range of central Nevada; this interval may also be correlative in part with the lower beds of the Copenhagen of the northern Monitor Range in central Nevada.

EUREKA QUARTZITE

DEFINITION AND DISTRIBUTION

The Eureka Quartzite was named by Hague (1883, 1892) for outcrops near Eureka, Nev., but the type area was later transferred to the western base of Lone Mountain (Kirk, 1933) about 18 miles west-northwest of

Eureka, where the unit is better exposed and where it is 350 feet thick (Nolan and others, 1956).

The Eureka Quartzite and related quartzitic units of Ordovician age are remarkably persistent, as Ketner (1968) has recently pointed out, and extend from the Peace River in British Columbia to the Owens River in southern California. Ketner believes that the sand forming these deposits may have been derived fom Cambrian sandstone covering the Peace River-Athabaska arch in northern Alberta.

Small incomplete exposures of the Eureka Quartzite occur in several places around the margins of Yucca Valley. A complete section was measured and described by Byers, Barnes, Poole, and Ross (1961) and Poole (1965) in the Ranger Mountains, about 15 miles southeast of Yucca Flat. Poole reported that the section has a total thickness of 380 feet and consists of a basal quartzite unit 55 feet thick, which is dolomitic at the base; a carbonate unit 35 feet thick; a cross-laminated sandstone-quartzite unit 20 feet thick; a varicolored quartzite unit 150 feet thick; and an upper white quartzite unit 120 feet thick.

In the project area the Eureka Quartzite occurs mainly in the southeast corner, where it continues a short distance south into the Oak Spring quadrangle (Barnes and others, 1963); on the west flank of the Belted Range, where it occurs in four small exposures, the largest of which is about 1.3 miles long; at the Oswald mine in the northeast corner; and along the west base of a ridge 5 miles west-southwest of Mount Helen.

LITHOLOGY

A complete section of the Eureka Quartzite was measured by F. G. Poole, C. L. Rogers, and A. R. Niem about 1 mile northeast of Oak Spring Butte, where it is 315 feet thick and is readily divided into three major lithologic units that probably correlate with the five units recognized in the Ranger Mountains.

The basal 55 feet is poorly exposed and consists largely of laminated to thin-bedded silty limestone with smaller amounts of dolomite and dolomitic sandstone. It is correlated with the lower three units of the Eureka Quartzite in the Ranger Mountains and may be stratigraphically equivalent to the Copenhagen Formation in the Eureka district (F. G. Poole, oral commun., 1964). In the Belted Range the basal unit is largely covered by talus and may have been included in large part with the Antelope Valley Limestone.

The middle unit consists of 180 feet of varicolored quartzite, which weathers to shades of brown and gray, and, in the middle and upper parts, contains minor amounts of olive-gray argillite. The quartzite is generally laminated to thin bedded, but massive in appearance; many layers are cross laminated. The rock is composed of fine- to medium-sized well-rounded quartz grains, and it contains no feldspathic material.

The upper unit consists of 80 feet of homogeneous quartzite that is white to tan on weathered surfaces and only locally brown. It is characterized by poorly defined bedding, and only a few layers are laminated.

AGE

Fossils were found in the carbonate rocks of the basal unit, but no collection was made because material that was obtained previously from equivalent beds in the Ranger Mountains indicates a Middle Ordovician age for the formation. Vertical and horizontal animal borings are fairly abundant in the middle dark-weathering varicolored quartzite unit in the project area but are sparse in the upper light-colored quartzite unit.

ELY SPRINGS DOLOMITE

DEFINITION AND DISTRIBUTION

The Ely Springs Dolomite was named by Westgate and Knopf (1932) for exposures in the Ely Springs Range of the Pioche district, Lincoln County, Nev., where two measured sections total 525 feet and 770 feet, respectively. F. G. Poole (oral commun., 1964) has studied and remeasured the type section and has arrived at a total thickness of 685 feet. The formation is predominantly dark-gray dolomite and contains a considerable amount of chert.

Poole (1965) has measured and described the bipartite formation in the Ranger Mountains, a short distance east of the Nevada Test Site, where it is about 280 feet thick. The lower part (±130 ft) is dark- to medium-gray dolomite and the upper part (±150 ft) is medium-gray, light-gray-weathering dolomite. The lower part is unusually thin in the Ranger Mountains (F. G. Poole, oral commun., 1964).

Within the project area several small exposures of the Ely Springs Dolomite are present on the west flank of the Belted Range, but the least altered outcrops occur in the southeast corner of the area, north and northeast of Oak Spring Butte.

LITHOLOGY

A composite section of Ely Springs Dolomite totaling 340 feet was measured by F. G. Poole, C. L. Rogers, and A. R. Niem about 0.3 mile east-northeast of Oak Spring Butte. The formation may be comparably thick in the Belted Range to the north, but it is thinner in the Ranger Mountains and thicker in the Specter Range immediately south of the Nevada Test Site.

Near Oak Spring Butte the dolomite consists of two distinct parts. The lower part is 270 feet thick and is dominantly thin- to thick-bedded fetid medium- to dark-gray dolomite, which contains abundant poorly preserved small fragments of pelmatozoans and vaguely defined small round to ovoid forms that may be *Girvanella.* A brown and gray sequence about 30 feet thick composed of dolomitic sandstone and sandy dolomite crops out at the base immediately above the light-colored Eureka Quartzite. The lower part contains a persistent zone of layered chert about 20 feet from the top and numerous scattered blebs, lenses, and discontinuous layers of chert. In places part of the chert has been partly or wholly replaced by dolomite, and white secondary dolomite is rather common in small irregular masses as fracture fillings and as replacements of fossil debris.

The upper part is 70 feet thick and is composed of light- to medium-gray partly color-banded dolomite that is generally finer grained and more distinctly bedded than the dolomite in the lower part. It is laminated to thin bedded and may be slightly silty and clayey, as suggested by some yellow-weathering zones. It contains comparatively little chert. The contact between this part and the overlying Silurian and Devonian dolomite was difficult to determine because the quartz sand and oolitic or pelletal dolomite zones that characterize the top of the Ely Springs in many areas (F. G. Poole, oral commun., 1964) are not present. However, the Ordovician-Silurian boundary was approximately located by a persistent zone containing chain corals, which apparently mark the basal part of the Silurian in the Oak Spring Butte area.

AGE

Numerous fossils have been found in the Ely Springs Dolomite in other areas; these have established a Middle and Late Ordovician age for the formation (F. G. Poole, written commun., 1964). Within the project area it contains solitary and colonial corals, brachiopods, pelmatozoan debris, and *Girvanella.*

ORDOVICIAN AND SILURIAN DOLOMITE

Ordovician and Silurian dolomite crops out on Limestone Ridge about 2 miles southwest of Belted Peak in a gravity slide block or overthrust sheet that rests on Cambrian strata. (See "Structure.")

The lowermost strata consist of very cherty dark-gray dolomite, and they correlate with the Ely Springs Dolomite. The dark-gray dolomite grades upward to massive fine- to coarse-grained dolomite that is generally light to medium gray but locally is buff or reddish gray. It contains only minor chert. These strata are altered and recrystallized in most exposures, and bedding is indistinct or wholly missing. The uppermost beds must be of Silurian age, but because of the alteration they could not be separated from the Ely Springs.

Dolomite of Ordovician and Silurian age has also been mapped in the vicinity of the Oswald mine, on the northeast edge of the project area. The rock has been hydrothermally altered and is largely medium- to thick-bedded fine-grained light-gray dolomite with only minor chert and with no recognizable fossils.

SILURIAN AND DEVONIAN—DOLOMITE OF THE SPOTTED RANGE

The thick dolomite unit of Silurian and Early Devonian age that overlies the Ely Springs Dolomite is referred to informally as dolomite of the Spotted Range. The Spotted Range, where the dolomite is well exposed, lies immediately east of Mercury in the southeast corner of the Nevada Test Site.

LITHOLOGY

The dolomite of the Spotted Range is largely limited to the southeast corner of the project area, and a complete section, 1,415 feet thick, was measured by F. G. Poole, C. L. Rogers, and A. R. Niem about 1.5 miles northeast of Oak Spring Butte. It can be divided into two principal units, but these have not been shown on the geologic map.

The lower unit is about 465 feet thick and is probably correlative with unit C in the Ranger Mountains (Poole, 1965). It is composed of laminated to thick-bedded dolomite that is generally medium to dark gray on fresh surfaces but weathers to somewhat lighter shades of gray. In much of the unit bedding is rather vague and indistinct. The dolomite is locally aphanitic but generally fine to medium grained, and it contains scattered chert in blebs and lenses. Much of the chert occurs in two zones. One zone lies only 15–20 feet above the base of the section and contains rather regular thin lenticular beds of dark-gray to black chert that weathers to brown. The second zone lies 80–90 feet above the first and contains chert and dolomite in about equal proportions. The chert is gray but weathers to brownish gray; it occurs in rather irregular lenses and nodules that may coalesce to form a reticulate pattern. Where the section was measured the lower chert zone is about 25 feet thick and the upper zone about 60 feet thick, but the zones exhibit considerable variation in thickness owing apparently to partial replacement of the chert by dolomite in many places.

The lower unit is succeeded rather abruptly by a very thick sequence of dominantly light-gray dolomite of the upper unit. However, the boundary between light- and dark-gray dolomite is not everywhere stratigraphic, because it has been blurred by secondary bleaching, which may extend locally throughout the lower unit to its contact with the underlying Ely Springs Dolomite. The color change is very useful as a structural guide in areas where there has been no extensive alteration or bleaching and can be used to determine the relative movement and approximate magnitude of faults.

The upper unit is about 950 feet thick and contains three fairly distinct lithologic zones that may be equivalent to units, D, E, and F in the Ranger Mountains (Poole, 1965). To a point 215 feet above the base, the rock is a light-gray dolomite with some yellowish-gray and light-olive mottling. It is generally fine to medium grained, though coarsely crystalline in places, and massive in appearance, with rather indistinct bedding. The poorly bedded character is probably the result of extensive fracturing and recrystallization, which has left the bedding planes rather vaguely defined. Above this zone is a color-banded sequence about 500 feet thick consisting of light- to medium-gray and olive-gray dolomite, which is predominantly fine to medium grained and indistinctly bedded. This sequence is well preserved in places but locally is difficult to trace, owing to bleaching and alteration, and it is not a mappable unit. One zone only a few feet thick is medium-dark-gray laminated to thin-bedded dolomite containing poorly preserved spaghettilike forms that resemble *Amphipora*. The uppermost sequence, 235 feet thick, is a highly fractured light- to olive-gray dolomite that is finely crystalline and exhibits rather blocky splitting. The highest part of this sequence contains a zone about 35 feet thick that partly consists of sandy (quartz), color-banded, light- to dark-gray dolomite, which is locally fossiliferous.

AGE

The dolomite of the Spotted Range contains little good fossil material in the vicinity of Oak Spring Butte, but it can be dated by comparison with the equivalent rocks in and near the Nevada Test Site. Units A and B of the Ranger Mountains, which are Early Silurian in age, seem to be missing in the area north of Oak Spring Butte, and this absence indicates the presence of a major unconformity (F. G. Poole, oral commun., 1964). The remainder of the dolomite may be represented, however, and is probably late Early Silurian to Late Silurian and Early Devonian in age.

DEVONIAN

NEVADA FORMATION

DEFINITION AND DISTRIBUTION

The name Nevada Limestone was introduced by Hague (1892) and defined to include all the Devonian rocks in the Eureka district of Nevada. Merriam (1940) later divided the sequence on a faunal basis into the Nevada Formation and the Devils Gate Limestone. In the type locality the restricted Nevada Formation comprises almost 2,500 feet of limestone and dolomite.

In the project area the formation is exposed in the vicinity of Oak Spring Butte and to the northeast of Wheelbarrow Peak. North of Oak Spring Butte the Nevada forms a sharp ridge about 2.6 miles long and as much as 0.4 mile wide, where the base is well exposed but the upper part is missing. On the west the Nevada is faulted against rocks of the Pogonip Group. This incomplete section of the Nevada was measured by F. G. Poole, C. L. Rogers, and A. R. Niem about 1.5 miles north-northeast of Oak Spring Butte, where it is about 1,000 feet thick and can be divided into two informal units designated simply as lower and upper units. These have not been separately mapped, however.

LITHOLOGY

The lower unit is 430 feet thick. Its basal part, which is 180 feet thick, consists largely of light- to medium-gray and olive-gray finely crystalline laminated to thin-bedded sandy dolomite. About 80 feet above the base this sequence contains a zone 30 feet thick that is partly limestone and contains common brachiopods and cup corals. *Papiliophyllum elegantulum* Stumm, near the top of this zone, probably represents the upper part of the *Acrospirifer kobehana* and (or) the lower part of the *Eurekaspirifer pinyonensis* brachiopod zone; it indicates an Early Devonian age.

The upper part of the lower unit is 250 feet thick. At the base is a soft 40-foot-thick sequence which is poorly exposed in slopes and saddles and which consists largely of light-reddish-brown to brownish-red fissile siltstone. Interbedded with the siltstone are smaller amounts of calcitic partly sandy dolomite and silty pinkish-gray limestone. The siltstone is overlain by 210 feet of cherty limestone and dolomite, with minor laminae of silty limestone in the lower part. The limestone and dolomite are laminated to thick bedded, medium dark gray, and slightly sandy. The brownish-weathering chert is black on fresh surfaces and occurs in nodules and lenticular beds as much as 3 inches thick.

The incomplete section of the upper unit that was measured is 570 feet thick. The lower 300 feet is composed of alternating dolomite and quartz-sandy dolomite. The dolomite is light to medium gray, finely crystalline, and rather poorly bedded. The sandy dolomite weathers to brown and contrasts rather sharply with the gray dolomite. The quartz grains in the sandy dolomite are rather well sorted, well rounded, and fine to medium; they vary greatly in abundance. Locally the sandy dolomite and dolomitic sandstone are virtually quartzites. The lowest sandy beds contain some brown tubular structures that may be algae.

The upper 270 feet of the upper unit consists of light-, medium-, and dark-gray fine- to coarse-grained dolomite. The dark-gray dolomite contains coarsely recrystallized white dolomite in blebs and veinlets and as a replacement of fossil material; several layers contain abundant rodlike fossils that may be the stromatoporoid *Amphipora.*

AGE

The Nevada Formation is indicated by fossil evidence and stratigraphic position to be Early and Middle Devonian in age. In the Spotted Range, lying immediately southeast of the Nevada Test Site, it overlies dolomite of Early Devonian age and underlies the Devils Gate Limestone of Middle and Late Devonian age.

LIMESTONE AND DOLOMITE

An incomplete limestone and dolomite unit which is of Middle Devonian age, and which is at least partly equivalent to the Nevada Formation but represents a slightly more western facies, is exposed in the vicinity of Carbonate Wash in the southeast corner of the project area and occurs in one small area on the east flank of the Belted Range. These rocks appear to lie in the upper plate of a major thrust. (See "Structure.")

LITHOLOGY

The limestone and dolomite in the Carbonate Wash area, which was measured by F. G. Poole, C. L. Rogers, and Reginald Hammond, is 1,285 feet thick. It can be divided into three lithologic units.

The lower unit has an exposed thickness of 275 feet and is dominantly limestone and limestone conglomerate, which are commonly biohermal or biostromal and contain minor silty to clayey limestone in the matrix and in thin beds and partings. The limestone is aphanitic to coarsely crystalline, laminated to thick bedded, and medium to dark gray; it generally weathers to medium gray. It exhibits mostly flaggy to slabby splitting and locally contains a few black chert nodules. The conglomerate contains rounded to subangular fragments, which range in size from pebbles to boulders about 2 feet long and are lithologically similar to the flaggy limestone. The basal 20 feet of the unit contains the coral *Hexagonaria* sp., which may represent the lower part of the *Warrenella kirki* brachiopod zone.

The middle unit, about 445 feet thick, consists of relatively weak rock that weathers to a gentle slope. It is composed largely of interbedded limestone and silty limestone, but near the base it contains one layer of limestone conglomerate. The limestone is laminated to thin bedded, platy to flaggy splitting, aphanitic to fine grained, and medium gray to pinkish gray. The silty limestone is laminated, aphanitic to finely crystalline, and pale red to yellowish gray on weathered surfaces. A few small lenses and nodules of black chert occur locally in the unit. Corals and brachiopods from the upper 275 feet are representative of the *Warrenella kirki* faunal zone. Rocks near the base of the unit yielded styliolinids and a few specimens of *Nowakia.*

The upper unit, about 565 feet thick, is composed of relatively resistant rocks that form a ridge. The lower 230 feet consists of light-olive-gray to medium-gray limestone and, near the top, includes some thin dolomitized zones and minor cherty zones. The limestone is fine to coarse grained, laminated to thin bedded and commonly wavy bedded, and partly biostromal. The upper 335 feet consists almost wholly of dolomite, but near the base it contains local irregular zones of calcitic dolomite and unaltered limestone. The dolomite is medium to light gray, generally fine to medium grained, laminated to thin bedded, and locally cross laminated. On weathered surfaces it is yellow gray and light olive to medium gray and is commonly mottled or color banded. It contains common white coarse-grained dolomite in wisps and veinlets, and locally it is highly fractured and brecciated, with indistinct bedding.

About 350 feet above the base of the upper unit, F. G. Poole (written commun., 1967) collected silicified specimens of *Stringocephalus* sp., a large brachiopod that marks the upper part of the Nevada Formation in the Eureka district.

About 5 miles southeast of Belted Peak there is a small exposure of light-gray laminated to thin-bedded limestone that contains abundant rod-shaped fossils suggesting *Amphipora* of Middle to Late Devonian age (F. G. Poole, oral commun., 1963). It may be correlative with the formation being described.

DEVONIAN AND MISSISSIPPIAN

ELEANA FORMATION

DEFINITION AND DISTRIBUTION

The Eleana Formation was named by Johnson and Hibbard (1957) for incomplete exposures in the Eleana Range on the west margin of Yucca Flat. The formation has a probable minimum thickness of 7,700 feet and is known only by a composite of partial sections (Poole and others, 1961). Owing to structural complexities and partial cover by younger rocks, correlation of these sections is difficult and is considered tentative.

The Eleana Formation is exposed in the southeast corner of the project area and in several small areas on the east flank of the Belted Range. Rocks that probably correlate with the Eleana occur on the west flank of the Cactus Range, and these are described separately.

LITHOLOGY

The Eleana Formation contains six distinctive units in the southeast part of the mapped area. These correspond to units A–E and G of Poole, Houser, and Orkild (1961). Units A, B, C, and the lower part of D have been studied and remeasured by F. G. Poole, C. L. Rogers, and Reginald Hammond.

Unit A is about 112 feet thick and rather heterogeneous. It consists of limestone conglomerate, limestone, silty to sandy limestone, calcareous sandstone, sandstone, and quartzite. A 60-foot-thick zone near the base resembles a reef complex and consists of fossiliferous limestone conglomerate, limestone, and sandy limestone. The rock is medium to light gray, commonly mottled, and aphanitic to coarsely crystalline; the conglomerate contains subrounded boulders as much as 4 feet in diameter. Another major zone consists of platy- to flaggy-splitting beds of limestone and silty limestone, which are medium gray to pale red or brown, laminated to thin bedded, and aphanitic to finely crystalline. The quartzite is light gray to olive gray, medium grained, and laminated to thin bedded, and it weathers to brown and yellowish-to light gray; it commonly contains small cavities that may have formed by the leaching of carbonate material.

Unit B, about 1,230 feet thick, is composed largely of argillite and quartzite. The basal 240 feet, which appears to be gradational into the underlying unit A, consists of flaggy- to platy-splitting laminated to thin-bedded limestone, silty to sandy limestone, limy sandstone, laminated limy argillite, subordinate quartzite and limestone conglomerate, and, in the lower part, minor chert. Dominantly orange-pink to grayish-orange shaly partly calcareous argillite and sparse thin beds and lenses of quartzite form the upper part. These basal beds are overlain by about 470 feet of yellowish-brown to medium-gray and light-olive-gray thinly laminated shaly argillite that weathers to various shades of pale yellowish brown, gray, and green. The lowermost beds contain argillite, which locally grades to fine-grained quartzite, and in some places they contain sparse fine- to medium-grained quartzite. The argillite contains many cubic iron oxide pseudomorphs after pyrite and, in many places, small sinuous markings on bedding surfaces that are probably worm trails. The shaly argillite sequence is overlain by about 520 feet of dominantly platy- to slabby-splitting very fine to fine-grained quartzite with subordinate coarser grained quartzite and many shaly argillite partings. A few plant stem imprints occur throughout the sequence, and abundant convolute laminae occur in the fine-grained quartzite. These upper beds contain features characteristic of turbidites (F. G. Poole, oral commun., 1965).

Unit C, 430 feet thick, consists of quartzite, subordinate conglomerate, and minor argillite. The quartzite is olive gray but weathers to brown. It is fine to medium grained, laminated to very thin bedded, and characterized locally by convolute laminae. The rock exhibits partly flaggy to slabby splitting, and it contains scattered granules and pebbles of chert and sparse plant stem imprints. The conglomerate weathers to olive gray and contains rounded to subrounded pebbles of chert, quartzite, and argillite as much as 2 inches long, which are set in a vitreous quartzitic matrix.

The lithologic descriptions of units D, E, and G are based on a report by Poole, Houser, and Orkild (1961).

Unit D is about 400 feet thick at Carbonate Wash and is predominantly grayish-orange to yellowish-brown laminated argillite; it also contains numerous beds of pale-brown to grayish-brown quartzite that is fine to coarse grained, thin bedded, and characterized by abundant convolute laminae and small-scale cross strata. Many of these beds contain features characteristic of turbidites (F. G. Poole, oral commun., 1965). These rocks generally weather into sharp elongate fragments and form steep rubble-covered slopes. According to F. G. Poole (oral commun., 1965), the original measured thickness of 520 feet (Poole and others, 1961) for this unit may be excessive, inasmuch as the unit was originally measured in an area where faulting has probably resulted in some duplication of beds. A nearby section that may be nearly complete was later measured by Poole and C. L. Rogers and found to have a thickness of about 375 feet.

Unit E, about 2,400 feet thick, consists largely of argillite with minor interbedded quartzite. The argillite is yellowish brown to pale red and greenish gray to dark gray and is laminated to thin bedded. The quartzite is similar to that in unit D.

Unit G is 1,400 feet thick on Quartzite Ridge northwest of Yucca Flat, but only the lower part extends into the mapped area. The unit consists of quartzite, conglomerate, and argillite. The quartzite is brown to yellowish brown and gray, thin to thick bedded, and commonly cross-laminated. The conglomerate is brown to reddish brown and is composed of rounded fragments, as much as 2 feet long, of quartzite, chert, argillite, and limestone. The argillite is light brown to reddish, sandy, and laminated to thin bedded.

The exposure of the Eleana Formation located 5 miles southeast of Belted Peak (cross section *F–F′* of pl. 1) was visited by F. G. Poole (oral commun., 1963), who identified four major lithologic units that he tentatively correlates with the upper part of the Eleana Formation of Yucca Flat. If the correlation is valid, these units are much thinner than equivalent beds in the Yucca Flat area. The lowest beds consist of 100–200 feet of argillite and quartzite with minor conglomerite, and they may represent the top of unit E. The argillite exhibits numerous worm trails on bedding surfaces. These beds are overlain by 200–300 feet of quartzite and conglomerite that may correlate with unit G. The gravels are rounded to subangular and consist largely of greenish-gray and light- to dark-gray chert with some gray quartzite. Pebbles and cobbles are as much as 4 inches in diameter, but most are less than 1 inch. Unit H is probably represented by about 200 feet of light-gray to very light gray argillite that contains some plant stems. The highest beds exposed, which have an incomplete thickness of about 100 feet and which consist of gray cherty fossiliferous limestone, may represent the basal part of unit I.

Along the east side of the exposure southeast of Belted Peak the Eleana beds appear to be in fault contact with limestone that is probably Devonian in age (F. G. Poole, oral commun., 1963). The two units are separated by a limestone breccia with angular blocks as much as 2 feet long, but the rocks are poorly exposed in this area and their relations are obscure. It could not be determined whether the breccia is a sedimentary breccia in the Eleana Formation or a tectonic breccia related to faulting. However, it is more likely a tectonic breccia related to faulting, and if this is so, then a fault separates the two units.

The Eleana is also exposed in the area of Paleozoic rocks 3 miles northeast of Wheelbarrow Peak. The exposure is in a structural window and is very small, but because of its structural importance, it is slightly exaggerated on the geologic map (pl. 1). It consists largely of argillite and some conglomerate.

AGE

At its type locality in Carbonate Wash, located in the southeast corner of the project area, the Eleana Formation overlies rocks equivalent to the Nevada Formation of Early and Middle Devonian age and in the Yucca Flat area, lying a few miles to the south, underlies the Tippipah Limestone of Pennsylvania age. Its stratigraphic position and the available fossil evidence indicate an Early to Late Mississippian age for most of the formation; the basal part is Late Devonian in age (Poole and others, 1965). Initial fossil evidence suggested that the highest beds were of Pennsylvanian age (Poole and others, 1961), but recent fossil evidence indicates that these beds are Mississippian in age (Poole and others, 1965).

Numerous fossils have been collected from the Eleana Formation within the project area, and some of these have been of great importance in the solution of the age problem. Only fossil evidence not previously published will be presented here.

In the Carbonate Wash area F. G. Poole collected an impression of a bony plate from a quartzite layer in the upper part of unit A that was described by Edward Lewis (written commun., 1965) as being referable to an undetermined genus of archaic fish of the Class Placodermi, Order Arthrodira, and Infraorder Brachythoraci. It is probably Late Devonian in age.

According to F. G. Poole (written commun., 1968), a Late Devonian conodont assemblage, collected about 50 feet above the base of unit B and studied by J. W. Huddle, represents the *Palmatolepis crepida* zone of earliest Famennian age.

At the exposure of the Eleana Formation located 5 miles southeast of Belted Peak F. G. Poole (oral commun., 1963) found some silicified corals, crinoids, brachiopods, and other forms in the limestone of the highest beds, which may be correlative with unit I of the Yucca Flat area. The fossil collections from this locality were studied by Helen Duncan, E. L. Yochelson, I. G. Sohn, and J. W. Huddle and yielded some tiny gastropods, some ostracodes, a conodont, and three small horn corals. One of the horn corals might be a *Rylstonia*, and the other two appear to be zaphrentoids. However, neither the gastropods nor the corals are sufficiently well preserved to indicate whether they are Mississippian or Pennsylvanian in age.

ELEANA(?) FORMATION IN THE CACTUS RANGE

Most of the Paleozoic rocks exposed in the Cactus Range resemble the Eleana Formation and may correlate with it, although this has not been proved. A few hundred feet of strata is exposed and has been briefly examined, but the rocks have not been measured or studied in detail. They are uniform structurally—the beds strike north to north-northwest and dip 10°–20° W.

The rocks are composed chiefly of rusty-weathering thick-bedded to rather indistinctly bedded conglomerate that contains gray, brown, black, and green chert and quartzite fragments. Locally, the fragments also include micaceous quartzite and siltstone, phyllite, schist, quartz, pegmatite, and granite or related rocks of plutonic origin. Many of the metamorphic rocks resemble the Precambrian Stirling Quartzite in lithology. The fragments are well rounded to subangular and range in size from pebbles to boulders 3–4 feet in diameter. Some of the layers are strongly cemented with silica and can be described as conglomerite, but most of the rock contains little matrix and is friable, and as a result it disintegrates readily to form a rubble-covered slope. The conglomerate contains a few thin layers of argillite and a few beds of gray medium- to coarse-grained quartzite. The argillite contains plant stem imprints in a few places.

In the northernmost outcrop, about 3 miles south-southwest of Cactus Spring, the uppermost rocks contain two zones of predominantly limestone breccia whose aggregate thickness is about 250 feet. The carbonate fragments, which range in size from pebbles to boulders as much as 4 feet in diameter, are distinctly angular in contrast to the noncarbonate fragments. The fragments are largely monolithologic and consist of laminated to thin-bedded medium- to dark-gray silty limestone, with minor granular dolomite. The silty limestone contains sparse fossil material that includes linguloid brachiopod fragments and rodlike fossils resembling *Amphipora*, the latter suggesting a Middle to Late Devonian age. Immediately west of the area being described, the rocks of the Eleana(?) Formation are in fault contact with laminated to medium-bedded silty dolomite, which closely resembles the carbonate clasts in the limestone breccia and which has been tentatively assigned to the Halfpint Member of the Nopah Formation. This dolomite crops out adjacent to a small granite stock to the west and exhibits some contact metamorphic effects, such as recrystallization to dolomite and a rather fine color banding in shades of light to medium and dark gray. The outcrop has been exaggerated on the geologic map.

The Eleana(?) rocks in the Cactus Range are coarser than any Eleana within or near the Nevada Test Site that has been studied (F. G. Poole, oral commun., 1965), and this feature, together with the resemblance of the rock to fanglomerate and the angularity of the limestone fragments, suggests that the Cactus Range was near the source of the Eleana Formation. However, there is a marked difference between the limestone breccia and the cherty conglomerite, and the latter must have formed under somewhat different conditions. It contains abundant well-rounded clasts, which are widely diverse in lithology and which must have been transported a considerable distance.

MESOZOIC(?) GRANITE

Leucogranite of probable Mesozoic age intrudes Paleozoic limestone 2 miles south-southwest of Urania Peak (not shown on pl. 1) in the Cactus Range and Precambrian quartzite about 3 miles southeast of Quartzite Mountain in the Kawich Range. The granite masses in both areas are almost completely covered by alluvium, and their dimensions are unknown. The Precambrian rocks near Quartzite Mountain have been metamorphosed for a distance of nearly a mile adjacent to the granite outcrops, indicating that the intrusive mass in that area may be rather large.

The granite in both areas is pink to salmon colored, hypidiomorphic granular, and medium to coarse grained. The rocks are devoid of mafic minerals and contain only a fraction of a percent muscovite. Quartz makes up 30–40 percent of the volume, and the remainder is almost wholly perthite. Plagioclase averages less than 1 percent in the rock from the Kawich Range and less than 5 percent in the rock from the Cactus Range.

Alaskitic granite at Goldfield intrudes shale of Cambrian age and is probably of Cretaceous age (Ransome, 1909). The granite rocks in the Cactus Range and near Quartzite Mountain are probably also of Cretaceous age inasmuch as they are not known to intrude Tertiary strata and, in contrast with all known Tertiary intrusive rocks in the area, they are equigranular and coarsely crystalline. A postthrusting and postfolding age is suggested by the lack of features characteristic of dynamometamorphism. The feldspars are fresh and clear, and quartz grains show no strain effects.

TERTIARY

The mapped area includes some of the thickest and best exposed Tertiary volcanic sections in the Great Basin. These volcanic rocks are chiefly ash-flow tuffs but they include thick piles of silicic lavas and several sequences of interbedded ash-fall tuff and tuffaceous sedimentary rocks. The volcanic rocks form a composite section over 20,000 feet thick and range in age from about 27 to 7 m.y. with the oldest rocks exposed in the northern part of the area and the youngest (the Thirsty Canyon Tuff) exposed in the southern part. The area contains five major volcanic centers and parts of two others (pl. 1) that gave rise to thick sections of welded tuff and large volumes of silicic lava.

In order to keep cartographic units at a reasonable minimum for the small-scale map, many lavas and tuffs are combined into single map units. These composite map units include (1) lavas that show marked chemical similarities throughout the area, and that appear to be closely related in time, (2) ash-flow tuffs and ash-fall tuffs that form a mappable interval between easily recognizable marker beds, and (3) widespread sedimentary rocks of late Miocene age which are interbedded with volcanic rocks of limited areal extent and which reflect a comparative lull in volcanic activity.

The terminology used in this paper to describe ash-flow tuffs is that of Smith (1960) and Ross and Smith (1961); the size classification of pyroclastic fragments is that of Fisher (1960); and the classification for quartz-rich igneous rocks (tuffs and lavas) is that of O'Connor (1965). The textural terms are those of Williams, Turner, and Gilbert (1954).

FANGLOMERATE

Weakly cemented fanglomerate composed entirely of pre-Tertiary debris crops out in several fault blocks west of Mount Helen. The fanglomerate consists principally of angular cobbles and boulders of quartzite derived from the Stirling Quartzite, and it locally contains a few fragments of fossiliferous carbonates from Wood Canyon Formation. Contacts with adjacent strata are poorly exposed, and only in one locality was it determined conclusively that the strata rest directly on pre-Tertiary rocks. This occurrence, the total lack of volcanic detritus in the rock, and the juxtaposition of the rock with downdropped volcanic rocks dated elsewhere at 25 m.y. of age indicate conclusively that the rock predates the volcanic activity in the mapped area.

The source areas for the detritus probably were very close to the present outcrops; however, these have been downfaulted and blanketed by volcanic strata. The direction from which the detritus was derived can generally be determined from the wedge shape of most of the deposits.

MONOTONY TUFF

The oldest volcanic rock is an ash-flow tuff of late Oligocene age herein named Monotony Tuff for Monotony Valley in the extreme eastern part of the mapped area. The best exposures and the type locality are along the northeastern flank of Monotony Valley about 2.5 miles south-southeast of the Oswald mine, in secs. 2 and 3, T. 3 S., R. 53 E., where the tuff is about 2,300 feet thick, rests on Ordovician strata, and is overlain by the Miocene Shingle Pass Tuff. In the mapped area, the Monotony is perhaps the most widespread of the ash-flow sheets exposed; it occurs throughout the northern two-thirds of the area, where it has an average thickness of at least 1,000 feet. Beyond the mapped area, it was traced 50 miles northeastward to the Pancake Range (fig. 3) and 35 miles eastward to the northern Pahranagat Range. The west edge of the sheet is inferred to be near the west boundary of the mapped area. The northern edge is very indefinite. The south boundary, though vague because the contact between Paleozoic and Tertiary rocks is deeply buried in the region of Pahute Mesa, is inferred to be near the latitude of Quartzite Mountain and Gold Flat. At least one lobe of the sheet extended as far south as Groom Pass southeast of Quartzite Mountain within the Nevada Test Site, at lat 37° 12′ and long 116°.

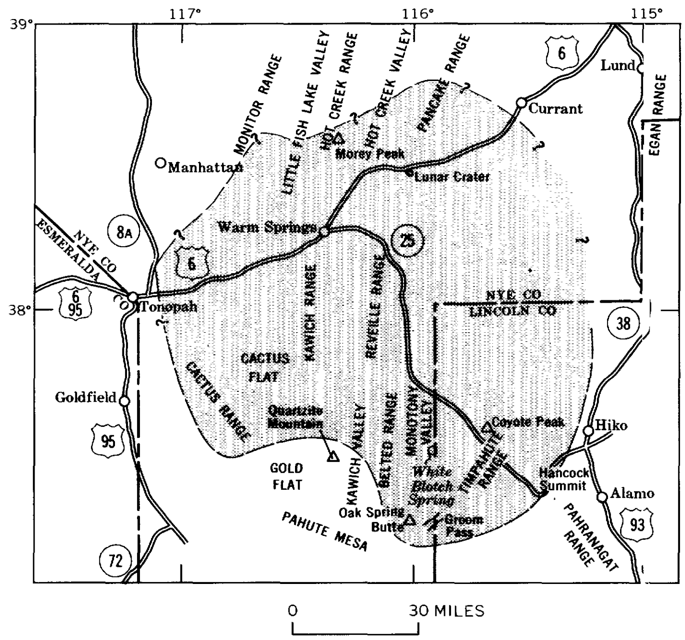

FIGURE 3.—Distribution of Monotony Tuff; edge of shaded area has queries where extension is doubtful.

Despite the indefinite northern edge, the Monotony Tuff has been correlated with reasonable certainty in an area about 100 miles in diameter. On the basis of an average minimal thickness of 500 feet, the unit had an astounding volume of more than 700 cubic miles.

The location of the vent area of the Monotony is uncertain, but it may have been the southern Pancake Range, as suggested by the following: (1) the southern Pancake Range lies near the center of the distribution area, and (2) the thickest sections known in the area—probably 2,000–4,000 feet thick—are exposed at the south end of the range and along the east flank of the Reveille Range. Whether these thick deposits lie within an area of collapse is unknown, but several arcuate post-Monotony Tuff collapse features are present farther north in the Pancake Range near Lunar Crater. The features include "scallops" similar to those around the edges of the Timber Mountain caldera (P. P. Orkild, oral commun., 1966), which probably are related to volcano collapse. Detailed mapping is necessary to determine the boundaries of the collapsed area and to define the volcanic history, but with the data now available, the Pancake Range seems the best choice for the source of the Monotony Tuff.

In outcrop the tuff characteristically weathers to rusty brown or green brown and forms gentle slopes and valleys between underlying and overlying more resistant rocks. The soft weathering habit results in a general paucity of good outcrops, although a few do occur as in Monotony Valley and in the Cactus Range just east of Wellington Hills where the tuff forms steep slopes along a receded fault scarp. The rock is densely welded in most exposures, but eutaxitic structure is vague, and the rock weathers to massive joint-controlled spheroidal outcrops and hoodoos very similar to weathered granite. Fresh rock is extremely scarce, but shards are visible in nearly all thin sections. Within the mapped area the Monotony appears to comprise a single compound cooling unit that is completely devitrified, mostly as a result of cooling-history crystallization (Smith, 1960, p. 152). In many other areas, however, part of the devitrification resulted from hydrothermal alteration which occurred after cooling and which commonly affected the mafic minerals. East of the mapped area, for example at Coyote Peake in the Timpahute Range (fig. 3), the rock is fresh and only partly devitrified, and two cooling units occur. These units are each 200–250 feet thick and are reddish gray to brown in their lower parts and light gray to very pale brown in their upper weakly welded tops.

Within the bombing and gunnery range the rock has a nearly constant phenocryst assemblage that shows only slight variation laterally and vertically. The rock contains 45–60 percent phenocrysts consisting of 15–20 percent clear to slightly smoky quartz (as much as 7 mm in diameter, average 2–3 mm), 15 percent biotite (commonly as much as 5 mm across), 5–15 percent alkali feldspar, 50–60 percent plagioclase, and less than 5 percent pseudomorphs after pyroxene and hornblende. The high ratio of plagioclase to alkali feldspar, the abundance of biotite, and the large quartz and biotite grains are distinguishing mineralogical features. The Monotony Tuff is very similar to the Hiko Tuff of Dolgoff (1963) exposed near Hiko, Nev., and at Hancock Summit in the Pahranagat Range, where the Hiko overlies the Shingle Pass Tuff. Petrographic study is commonly necessary to distinguish the two rocks; the Hiko generally contains abundant sphene, which is extremely rare in the Monotony; it contains much more hornblende, lacks clinopyroxene, and has a lower ratio of plagioclase to alkali feldspar. Both rocks have about the same amount of phenocrysts and both have similar "granitic" weathering habits.

Hydrothermal alteration of the Monotony in the type locality and also in the Belted Range has resulted in the partial replacement of mafic minerals by chlorite, calcite, and iron oxide. Locally, in the southern Belted Range due west of White Blotch Spring, the rock is weakly mineralized and was heavily prospected for gold and silver during the 1930's. A small mine was operated there during the late 1930's or very early 1940's. In the Kawich Range, the rock is similarly altered and is locally very weakly mineralized; the plagioclase phenocrysts are commonly albitized. In the Cactus Range, where the Monotony was subjected to various types of hydrothermal alteration, no fresh rock is known. The megascopic appearance of most of the altered rock, however, does not differ greatly from that of relatively fresh rock exposed in the other ranges. Thin sections show that few crystals have entirely escaped alteration. Alkali feldspar phenocrysts are commonly albitized and partly replaced by epidote; plagioclase phenocrysts are extensively sericitized, albitized, and partly replaced by calcite. Mafic phenocrysts are altered to chlorite, iron oxide, and locally calcite; groundmass constituents are altered to epidote, chlorite, sericite, calcite, and iron oxide.

Chemical analyses of five samples of relatively unaltered Monotony Tuff from widely separated areas are given in table 4. According to the classification for quartz-rich igneous rocks proposed by O'Connor (1965, p. B79–B84), the rock plots in the fields of rhyodacite and quartz latite (fig. 4).

Potassium-argon ages of 26.1 ± 0.71 and 27.6 ± 0.8 m.y. (average of two splits) were obtained from samples of Monotony Tuff from outcrops in the Belted and Timpahute Ranges respectively (table 5). These determinations indicate a late Oligocene age based on the time scale of Kulp (1961, p. 1105–1114) and the Geological Society of London (1964), or an early Miocene age based on the scale of Evernden, Savage, Curtis, and James (1964, p. 167). It is here considered late Oligocene in age.

PROBLEM OF CORRELATION

Recent reconnaissance mapping and stratigraphic studies by the authors and others north and east of the Nellis Air Force Base Bombing and Gunnery Range indicate that the lithology of the Monotony Tuff is far from unique. Tuffs that are megascopically and petrographically nearly identical with the Monotony occur both above and below the Monotony Tuff. The oldest of these probably exceeds 30 m.y. in age (F. J. Kleinhampl, written commun., 1966), and the youngest, the Hiko Tuff (Dolgoff, 1963, p. 885–888), is probably about 25 m.y. In most areas a definite correlation can be made on the basis of stratigraphic succession; however, in isolated fault blocks and in areas where units are missing, the problem of correlation is a major one. The Needles Range Formation (Mackin, 1960) in eastern and central Nevada (Cook, 1965) can be distinguished from the Monotony only by detailed study of many thin

TABLE 4.—*Chemical analyses and norms of Monotony Tuff*

[Analyses by P. L. D. Elmore, S. D. Botts, G.W. Chloe, Lowell Artis, and H. Smith, by rapid method described by Shapiro and Brannock (1962). Norms determined from chemical analyses recalculated to 100 percent minus H_2O+CO_2]

Sample	1	2	3	4	5
Laboratory No	160722	160980	160808	160969	159664
Field No	BP-28	QM-71	R-16E	M-220	PL-2374
Chemical analyses					
SiO_2	66.4	67.3	67.2	65.3	66.2
Al_2O_3	15.2	15.4	16.1	15.6	15.4
Fe_2O_3	2.5	2.4	2.8	2.3	2.0
FeO	.87	1.5	.64	2.0	1.1
MgO	.70	1.6	.73	1.5	1.6
CaO	4.0	2.9	2.9	3.3	3.1
Na_2O	2.5	3.0	2.6	2.8	2.8
K_2O	3.6	3.4	4.4	3.5	3.4
H_2O-	.87	.12	.72	.19	1.2
H_2O+	1.4	1.6	1.3	1.8	2.4
TiO_2	.43	.50	.43	.55	.46
P_2O_5	.13	.13	.15	.15	.14
MnO	.04	.08	.03	.13	.07
CO_2	1.2	.20	$<.05$	1.2	$<.05$
Sum	100	100	100	100	100
Norms					
Q	29.9	29.1	29.0	27.0	29.4
or	22.1	20.5	26.5	21.3	20.9
ab	21.9	25.8	22.4	24.4	24.6
an	19.7	13.8	13.7	15.8	15.0
C	.2	1.9	2.2	1.6	1.9
en	1.8	4.1	1.9	3.8	4.1
fs		.1		1.1	
mt	1.8	3.5	.9	3.4	2.5
hm			2.2		.3
il	.8	1.0	.8	1.1	.9
ap	.3	.3	.4	.4	.3

Sample, locality and description

[Numbers following mineral names are percent of total phenocrysts]

1. In Belted Range 2 miles southwest of Belted Peak. 52 percent phenocrysts: quartz 33, plagioclase 53, alkali feldspar 2, biotite 8, calcite 2. Crystals are mostly fragments, quartz shows some resorption.
2. In southern extension of Kawich Range 2½ miles northwest of Gold Reed. About 50 percent phenocrysts with about same proportions of minerals as sample 1. Rock is very fragmental—most of the crystals are broken.
3. East flank of Kawich Range, 1 mile north of Cedar Pass. Same crystal content as sample 1.
4. Southwest flank of Cactus Range, 1½ miles north-northeast of O'Briens Knob. 56 percent phenocrysts: quartz 22.3, alkali feldspar 3.4, plagioclase 59.6, biotite 14.7.
5. East side of Jangle Ridge 7½-minute quadrangle, south of project area at lat 37°9.5', long 115°64.7'. About 50 percent phenocrysts in about same proportions of minerals as sample 1.

sections. The Needles Range Formation probably is at least 28 or 29 m.y. old (Armstrong, 1963) and may be as old as 31 m.y. (D. C. Noble and H. H. Mehnert, written commun., 1966). The Needles Range Formation generally contains more hornblende and pyroxene than the Monotony Tuff and locally contains abundant sphene which is extremely sparse in the Monotony.

The possibility seems good that several major ash-flow sheets of Monotony lithology were erupted from centers in central and eastern Nevada in late Oligocene and early Miocene time. Two of these are the Monotony

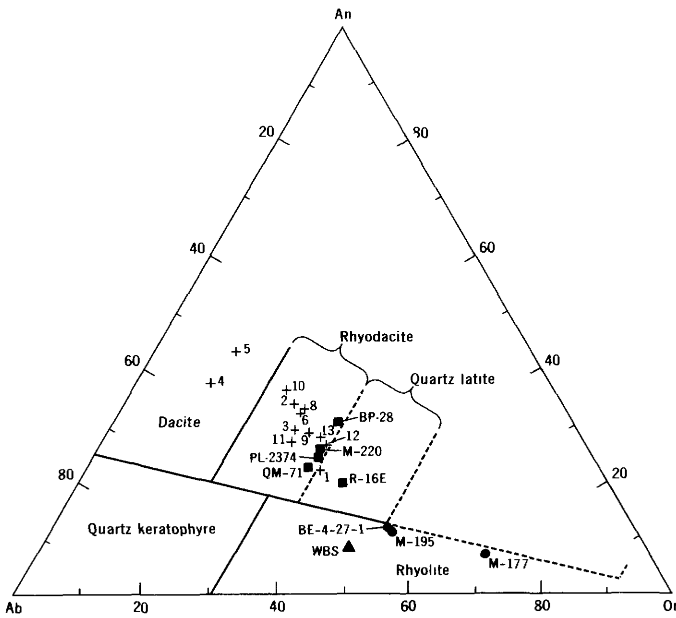

FIGURE 4.—Plot of normative albite-anorthite-orthoclase ratios. Squares, Monotony Tuff (from table 4); triangle, tuff of White Blotch Spring (average of four norms of samples 2, 3, 5, and 6 from table 6); crosses, lavas of intermediate composition exclusive of rocks from Mount Helen (from table 7); dots, rocks from Mount Helen (from table 8). Only rocks with more than 10 percent normative quartz are plotted. Fields are from O'Connor (1965).

Tuff and Needles Range Formation. Additional units will be found, with detailed mapping, that at present are correlated with either the Monotony Tuff or the Needles Range Formation largely on the basis of gross megascopic and petrographic features. Detailed mapping of the Tertiary strata in all the ranges in central and eastern Nevada is necessary before this stratigraphic problem can be resolved.

SEDIMENTARY ROCKS OF CEDAR PASS AREA

Clastic and tuffaceous sedimentary rocks more than 400 feet thick are exposed near Cedar Pass on the east side of the Kawich Range. The rocks are light to dark brown or light to dark gray; where hydrothermally altered they are white, pale green, or pale yellow. They consist of thin-bedded mudstone and sandstone with minor stratified shard tuff and pumice tuff.

The base of the unit is exposed 1.3 miles west of Cedar Spring. Here the clastic rocks rest on an erosion surface developed on Monotony Tuff, and they are overlain by highly altered welded tuff that correlates with either the tuffs of Antelope Springs or the Shingle Pass Tuff of early Miocene age. The sedimentary rocks are inferred to be also early Miocene in age.

TABLE 5.—*Summary of potassium-argon ages for volcanic strata in and near Nellis Air Force Base Bombing and Gunnery Range*

[Analysts: R. W. Kistler, H. H. Mehnert, R. F. Marvin, J. D. Obradovich, and Violet Merritt]

Sample	Field No.	Unit	Age (m.y.)	Analyzed material	Locality
		Thirsty Canyon Tuff:			
1	N80A	Labyrinth Canyon Member.	6.2±0.17	Alkali feldspar	4 miles northwest of Black Mountain; lat 37°18′ N., long 116°35′ W.
2	Age–11	Spearhead Member	7.5±0.20	do	3 miles north-northwest of Scrugham Peak, lat 37°38.5′ N., long 116°26′ W.
		Timber Mountain Tuff:			
3	Age–17	Ammonia Tanks Member	10.9±0.35	Biotite	Piapi Canyon; lat 36°59′ W., long 116°15′ W.
4	Age–16	do	10.8±0.40	Sanidine	Do.
5	Age–12	do	11.2±0.49	Biotite	6 miles west of south Timber Peak, lat 37°2′ N., long 116°35.5′ W.
6	Age–20	do	11.4±0.50	do	6 miles northwest of Scrugham Peak, lat 37°12′ N., long 116°28.5′ W.
7	Age–5	do	12.1±0.45	do	Massachusetts Mountain, lat 36°54.5′ N., long 115°58′ W.
8	GM–1–B	Rainier Mesa Member	11.3±0.3	Sanidine	Southeast corner of Pahute Mesa, lat 37°13.5′ N., long 116°16.7′ W.
		Paintbrush Tuff:			
9	Age–4	Tiva Canyon Member	12.4±0.46	Biotite	Piapi Canyon; lat 36°58.6′ N., long 116°14.5′ W.
10	BC–308	do	12.4±0.40	do	3 miles west of Rhyolite, Nev.; lat 36°54.5′ N., long 116°53′ W.
11	Age–2A	Topopah Spring Member	13.2±0.42	do	1 mile southeast of Topopah Spring; lat 36°54.5′ N. long 116°17′ W.
12	REA–62–SC	Rhyolite of Saucer Mesa	13.1±0.5	Nonhydrated glass.	Apache Tear Canyon; T. 6 S., R. 50 E. lat 37°24′ N., long 116°21′ W.
		Belted Range Tuff:			
13	WPN–23A	Grouse Canyon Member	13.8±0.6	do	Belted Range, Oak Spring Butte quadrangle; lat 37°20′30″ N., long 116°01′ W.
14	WPN–500	Rhyolite of Kawich Valley	14.8±0.6	Sanidine	Southern Belted Range; lat 37°21′10″ N., long 116°01′ W.
15	Age–24	Fraction Tuff	15.0±0.55	Biotite	Test well 8, 4,384 ft; lat 36°55.5′ N., long 116°16′ W.
16	Age–25	do	17.8±0.48	do	Trailer Pass, Kawich Range; lat 37°37′ N., long 116°19.5 W.
17	CS–817	do	15.7±0.5	Sanidine	Cactus Range; lat 37°45′ N., long 116°58′ W.
		do	16.4±0.5	do	Do.
18	EA–17–6	Dacite lava	18.7±0.7	Biotite	Gabbard Hills; T. 4 S., R. 48 E., lat 37°32′40″ N., long 116°32′ W.
		do	17.2±0.7	do	Do.
19 [1]	644–3	"Dacite vitrophyre" [2]	21.1±0.6	Biotite	South flank of Goldfield Hills.
20	OM–WBL	Tuff of White Blotch Spring	24.4±0.7	Sanidine	East flank of Monotony Valley; lat 37°45′ N., long 116°00′ W.
		do	25.2±0.8	Biotite	Do.
21	66–E–10	do	23.4±0.7	Sanidine	West flank of Kawich Range; lat 38°00′ N., long 116°34′ W.
		do	23.8±0.7	Biotite	Do.
22	438–6	do	21.5±0.5	do	Central Kawich Range; lat 37°56′ N., long 116°25′ W.
23	CS–796	do	22.9±0.7	Sanidine	Northern Cactus Range; T. 2 S., R. 46 E., lat 37°45′ N., long 116°52′ W.
		do	21.8±0.7	do	Do.
24 [1]	163–3	Shingle Pass Tuff	25.3±0.68	do	6 miles northeast of Belted Peak; lat 37°38′ N., long 115°59′ W.
25 [3]	15195–20	do	25.4±0.8	do	Southern Pancake Range; NE¼ sec. 6, T. 6 N., R. 54 E.
26	CS–869	Tuff of Antelope Springs	27.7±0.8	Alkali feldspar	Northern Cactus Range; lat 37°46′ N., long 116°53′ W.
		do	26.2±0.8	Biotite	Do.
27	MT–1	Monotony Tuff	27.4±0.8	do	Coyote Peak, Timpahute Range; T. 4 S., R. 56 E., lat 37°34′ N., long 115°40′ W.
		do	27.8±0.8	do	Do.
28 [4]	Age–26	do	26.1±0.71	do	West flank of Belted Range; lat 37°34′30″ N., long 116°06′ W.

[1] Samples collected by H. R. Cornwall.
[2] Named by Ransome (1909, p. 61); rock is a quartz latite welded tuff.
[3] Sample collected by Frank Kleinhampl.
[4] Hornblende and pyroxene are completely altered in this sample; biotite appears fresh but probably incipiently altered.

TUFFS OF ANTELOPE SPRINGS

A sequence of rhyolitic to rhyodacitic ash-flow tuffs crops out above the Monotony Tuff and beneath the tuff of White Blotch Spring in the western part of the project area. These rocks are here informally called tuffs of Antelope Springs after the excellent exposures near Antelope Springs in the Cactus Range, where the tuffs have a composite thickness of about 5,600 feet.

In almost all areas the tuffs of Antelope Springs are displaced and tilted by many normal faults, and nowhere is a continuous and unfaulted stratigraphic section available. Most of the rocks have been moderately to intensely altered by hydrothermal solutions. Rock textures normally used to interpret the cooling history of ash-flow tuffs (Smith, 1960) have been partially destroyed by this alteration. Also, the primary minerals (except quartz, apatite, and zircon) have been modified or replaced in the altered rocks. The rocks are generally drab, and many have greenish casts resulting from abundant secondary sericite, chlorite, and epidote in both phenocrysts and matrix. Low-silica varieties are yellowish brown where fresh but tend to be purplish gray where altered. The rocks are bleached to light gray, pink, or pale yellow adjacent to faults and intrusive masses where silicic and (or) argillic hydrothermal alteration has been intense.

Because these tuffs are generally faulted and altered, individual cooling units are very difficult to recognize and cannot be unambiguously correlated between separate areas. A broad tripartite division (lower, middle, and upper), based on the abundance of quartz and alkali feldspar and on color, was made in parts of the Cactus Range, but elsewhere the unit is undivided. Contacts between the three parts are depositional horizons not marked by bedded tuff or sedimentary rocks.

LOWER ASH-FLOW TUFFS

The lower ash-flow tuffs are 800+ feet thick in the southern Cactus Range. At the base the rock is pale green, weakly welded, and typically slabby weathering; it grades upward to greenish-gray densely welded columnar-jointed rock that contains about 15–20 percent phenocrysts. Phenocrysts of clear quartz and alkali feldspar averaging about 1.5 mm in diameter are conspicuous, but plagioclase and biotite, which are mostly replaced by white mica, are inconspicuous or unrecognizable megascopically. The greenish-gray rock is overlain by densely welded maroon to light-purple tuff characterized by conspicuous pink euhedral alkali feldspar phenocrysts. In six thin sections of this rock the penocryst content was 15–30 percent. The average phenocryst percentages are quartz, 16; alkali feldspar, 42; and plagioclase, 38. Altered biotite is recognizable locally.

All the lower welded tuffs are characterized by numerous greatly flattened small pumice lapilli that tend to be green in the greenish-gray rocks and purple in the light-purple and maroon rocks. These lapilli, which are generally less than 1 inch long, commonly occur as delicate wisps normal to the plane of compaction and as thin films in it. The rocks are notably poor in lithic fragments in contrast to some of the overlying upper tuffs of Antelope Springs that are similar in general appearance.

MIDDLE ASH-FLOW TUFFS

A decrease in abundance of alkali feldspar and quartz marks the lower boundary of the middle ash-flow tuffs, a sequence of rhyolitic to rhyodacitic ash flows that probably exceeds 2,300 feet in thickness, although nowhere is a complete section available. The rocks are well indurated, but it is not known whether the induration is everywhere due to original dense welding or to later postemplacement alteration. In an incomplete section that is well exposed on Antelope Peak 2 miles west-northwest of Antelope Springs, the lower 100–150 feet is dark gray to dark purple and locally brown, and it contains abundant dark-gray to black greatly collapsed pumice lapilli. The interval is generally very resistant and forms a dark cliff. Secondary epidote clusters as much as 1 cm in diameter are conspicuous. Phenocrysts make up about 20 percent of the rock and consist of 80 percent plagioclase, 5 percent quartz, and 12 percent alkali feldspar. Secondary epidote, chlorite, sericite, calcite, and clay occur in both the phenocrysts and groundmass of the rock.

The overlying rock, of which about 700 feet is exposed, is buff to light gray and weathers red to dark red. It is monolithologic, moderately altered, and pumice poor; it contains less than 10 percent phenocrysts. Tuff structures are very inconspicuous megascopically, but abundant shards and scattered tiny pumice fragments are clearly visible in thin section. Phenocrysts consist of plagioclase and minor iron-depleted biotite. Quartz is sparse to absent. The rock is massive in outcrop and weathers to steep slopes covered with angular blocky scree. Gradational contact relations observed near Antelope Peak indicate that this tuff and all the underlying tuffs of Antelope Springs may be part of a compound ash-flow tuff cooling unit.

A thick section of crystal-poor brown, tan, and gray densely welded rhyolitic(?) tuff is exposed between Roller Coaster Knob and Antelope Springs. These rocks, which are included with the middle tuffs on the basis of low quartz content, dip vertically to 25° SE.

It is not known to what extent these strata are repeated by faulting, and neither the base nor the top is exposed, but 1,900 feet probably is a conservative estimate of their total thickness. Phenocrysts, which make up about 5 percent of the rock, have been largely replaced by secondary minerals. The rocks are fractured and flow layered. Other exposures of this unit occur in Sleeping Column Canyon and on the northeast flank of Urania Peak, but they are not shown separately on plate 1.

A greenish-gray, greenish-brown, and locally brown slabby-weathering rhyodacitic welded tuff occurs locally above the typical crystal-poor tuffs just described. The rock contains 25–35 percent crystals, 82 percent of which are plagioclase and 12 percent, biotite. Biotite phenocrysts are preferentially oriented parallel to the plane of compaction. Pumice lapilli are either lacking or indistinct, and the rock is easily mistaken for a lava. The best exposures are about 2 miles northwest of Roller Coaster Knob, where an incomplete east-dipping section has an estimated thickness of 400 feet.

UPPER ASH-FLOW TUFFS

The upper ash-flow tuffs of Antelope Springs are about 2,000 feet thick at Antelope Springs. They appear to be much thicker in the northern Cactus Range, but they are intensely deformed there and thus cannot be measured accurately. The upper tuffs rest conformably on the middle tuffs in the southern part of the range and also in a single exposure on the northeast flank of Urania Peak (not shown on pl. 1). Between these two areas, about 3 miles southeast of Urania Peak, they apparently rest unconformably on the Monotony Tuff and contain lithic fragments and blocks of the middle tuffs of Antelope Springs. Only the upper tuffs are recognized in the northern Cactus Range. In contrast to the pervasive alteration of equivalent tuffs in the south and central parts of the range, the upper tuffs in the north are sufficiently unaltered to permit reliable modal analyses of phenocryst contents. In the descriptions that follow, the modal data given for the rocks in the north are inferred to apply to stratigraphically equivalent rocks in the central and southern part of the range.

At Antelope Springs, the upper tuffs comprise three distinctive zones, each of which probably represents an ash-flow cooling unit. The three zones are separated from each other by a few inches to several feet of bedded ash. The lower zone is about 1,000 feet thick and, in the lower half, consists of greenish-gray partially welded to densely welded tuff rich in lithic fragments of older welded tuffs, argillite, and quartzite; the upper half contains brown welded tuff rich in biotite, large red-stained quartz, and large pumice lapilli. The greenish-gray tuff also contains biotite, quartz, and pumice lapilli, but they are smaller and less abundant than in the overlying brown rock. The greenish-gray tuff contains less plagioclase and more alkali feldspar than the brown tuff.

The middle zone of the upper tuffs is about 300 feet thick and consists of slabby- to massive-weathered steel-gray to pale-purplish-gray densely welded tuff rich in lithic fragments of rust-colored carbonate and dacite lava. The rock contains conspicuous quartz and less biotite than the underlying brown tuff.

The upper zone is at least 700 feet thick and consists of a basal slabby-weathering pastel-green poorly welded tuff that grades upward to purple to light-brown densely welded tuff. This zone contains abundant small embayed quartz, alkali feldspar, and white pumice lapilli, and minor altered biotite. Plagioclase phenocrysts are completely altered to sericite and clay and are removed easily during weathering, leaving numerous small euhedral holes on weathered surfaces. Rocks in this zone form the prominent hogback ridges that mark the east edge of the Cactus Range north and south of Antelope Springs.

The stratigraphy of the upper tuffs of Antelope Springs in the northern Cactus Range is poorly understood owing to the structural complexity of that area. Most of the rock exposed probably correlates with the lower zone at Antelope Springs. The rocks equivalent to the lithic-rich lower part of that zone are generally brown to reddish brown, locally gray, and are composed of as much as 50 percent lithic fragments, some of which are 10 feet in diameter. The predominant lithic fragments are Monotony Tuff, argillite and quartzite of pre-Tertiary age, pink granite of Mesozoic(?) age, lower and middle tuffs of Antelope Springs, and porphyritic pilotaxitic dacite. Rocks equivalent to the brown tuff are widely distributed. They are generally brown with abundant yellowish-brown pumice lapilli and blocks but are locally purplish gray with light-gray pumice. They contain about 40 percent phenocrysts consisting of 15–28 percent quartz as much as 3 mm in diameter, 8–20 percent alkali feldspar, 50–56 percent zoned plagioclase, and 8–12 percent mafic minerals consisting of biotite and altered hornblende(?). Magnetite, zircon, and apatite are the principal accessory minerals. The rock generally contains 1–2 percent of small lithic fragments of welded tuff, dacite(?), and quartzite. Other welded tuffs of unknown stratigraphic position are poor in mafic minerals and contain as much as 43 percent alkali feldspar; still others are quartz latitic and contain as little as 7 percent quartz.

UNDIFFERENTIATED TUFFS

In the area between Stonewall Mountain and Wilsons Camp, numerous scattered exposures of quartz-bearing calc-alkaline welded tuffs are mapped as tuffs of Antelope Springs, undivided. Most of these rocks probably correlate with the upper tuffs just described. At Mount Helen, however, the tuffs exposed at the top of the sequence include two units, each about 750 feet thick, which are separated by at least a partial cooling break and which are not recognized with certainty at Antelope Springs. The lower unit is a densely welded purple tuff that contains abundant small grains of quartz, chatoyant alkali feldspar, minor biotite, argillized plagioclase, and indistinct pumice lapilli; it crops out on both sides of the mountain. This rock is overlain by a unit several hundred feet thick that is identical with the underlying rock except that it contains larger phenocrysts of quartz and alkali feldspar. The tuff with the smaller quartz grains closely resembles the tuff that forms the prominent hogback ridges at Antelope Springs, but it is different in that it lacks conspicuous white pumice lapilli and contains catoyant alkali feldspar. The tuff with the larger quartz grains apparently is not present at Antelope Springs or in the central core of the Cactus Range; it is thickest in the vicinity of Mount Helen. These tuffs, although they resemble some of the upper tuffs of Antelope Springs, are inferred to have been extruded from a different volcanic center, presumably the Mount Helen volcano.

SHINGLE PASS TUFF

The Shingle Pass Tuff was named by Cook (1965, p. 20) for a highly welded dark-red to pale-purple vitric ignimbrite exposed at Shingle Springs "just west of a dirt road that leads through Shingle Pass in the Egan Range, in sec. 8, T. 8 N., R. 63 E., Lincoln County." Scott (1965) later correlated the Shingle Pass with two to 10 chemically similar ignimbrites above the Needles Range Formation in the Grant Range, about 50 miles northeast of the Nellis Air Force Base Bombing and Gunnery Range. The name is used herein for several closely similar ignimbrites or ash-flow tuff cooling units exposed in the eastern part of the mapped area, some of which are probably the direct equivalent of units in the Grant Range. Whether any of the units, however, correlate with the single ignimbrite at the type locality remains to be proved by detailed mapping.

The rocks included in the Shingle Pass Tuff in the area of study lie between the Monotony Tuff and the tuff of White Blotch Spring. They are correlated with certainty only within the Belted Range, Monotony Valley, and as far south as the Jangle Ridge quadrangle in Nevada Test Site, where a single cooling unit occurs, called informally the "red welded tuff" by Barnes, Christiansen, and Byers (1965). The tuff is extensive northward, northwestward, and eastward, but the westward extension within the bombing and gunnery range is extremely vague. Two hydrothermally altered red and orange cooling units east of Quartzite Mountain in the southern extension of the Kawich Range are tentatively correlated with the Shingle Pass Tuff, and a unit north of Cedar Pass in the Kawich Range may be an equivalent, but because of intense hydrothermal alteration there, this correlation is uncertain. The rocks in both areas are shown on plate 1 as tuffs of Antelope Springs and Shingle Pass Tuff undivided. In Cactus and Gold Flats the interval between the Monotony Tuff and the tuff of White Blotch Spring is poorly exposed, and the few rocks that are exposed are also hydrothermally altered. They most closely resemble the tuffs of Antelope Springs that were extruded from the Cactus Range. Thus, the western limit of the Shingle Pass Tuff appears to lie somewhere between the Kawich and Cactus Ranges, and the southern limit is just south of the mapped area at about lat. 37°10′ N.

The tuff in the Belted Range and Monotony Valley occurs in a mosaic of fault blocks. It consists of four to possibly as many as seven separate cooling units. Most of the units average less than 100 feet in thickness and the combined sequence averages about 700 feet. Most of the flows are nonpersistent, a feature which probably reflects the great distance from the source area—presumably at least several tens of miles to the northeast. Probably only two or three of the thickest flows persist throughout the Belted Range. Everywhere the rocks are slightly to intensely hydrothermally altered and are more altered and fractured than the overlying tuff of White Blotch Spring. All the flows are dominantly red, orange, or grayish purple except for their chilled nonwelded bases which commonly are yellow, white, or green; all are densely welded, and most have conspicuous black to dark-greenish-black basal vitrophyres 5–20 feet thick. Nearly all units contain conspicuous lithophysal or gas-bubble zones that start below the contact between the basal glassy vitrophyres and devitrified rock and grade upward well into the devitrified densely welded interiors. Many of the lithophysae apparently formed in collapsed pumice fragments, but many others formed in shard tuff almost wholly devoid of pumice. In all the cooling units some pumice occurs, and eutaxitic structure is generally well defined. Several units have a vague planar structure that formed as a result of slight flowage after the units were emplaced.

With the exception of a red welded tuff about 50 feet thick that occurs locally near the base and contains fairly abundant small phenocrysts of quartz, the cooling units are quartz poor and contain 8–20 percent phenocrysts consisting of plagioclase and alkali feldspar—in ratios that range from 6:1 to about 1:4—biotite, minor quartz, sparse corroded pseudomorphs after olivine or clinopyroxene, and sparse hornblende. One cooling unit exposed along the east flank of Monotony Valley east of the mapped area contains biotite as the only mafic mineral in a crystal-poor base, but in a more crystal-rich upper part it contains both biotite and clinopyroxene. This unit is as much as 450 feet thick in Monotony Valley and at least 200 feet thick throughout the exposures in the Belted Range. It is the only unit in which pyroxene was an appreciable constituent in thin section. Allanite was noted in several thin sections from cooling units at the base of the sequence and in one thin section from an upper cooling unit exposed in Monotony Valley.

A potassium-argon date of 25.3 m.y. was obtained from an outcrop of Shingle Pass Tuff on the east flank of Monotony Valley, sampled by H. R. Cornwall, and 25.4 m.y. from an outcrop in the Pancake Range about 40 miles north of the Belted Range, sampled by F. J. Kleinhampl. These dates (table 5) indicate an early Miocene age.

The contact between the Shingle Pass and the underlying Monotony Tuff appears to be conformable throughout the Belted Range area. In places, however, the upper weakly welded top of the Monotony Tuff was completely removed by erosion prior to the deposition of the Shingle Pass. The gentle basal contact contrasts with the upper contact, which in most places is a surface of considerable relief marked by rubble zones containing boulders and cobbles of Shingle Pass Tuff as well as fragments derived from the Monotony Tuff.

LACUSTRINE SEDIMENTARY ROCKS OF THE CACTUS RANGE

Sedimentary rocks that include abundant siltstone and shale rest unconformably on a surface of considerable relief developed on tuffs of Antelope Springs and Monotony Tuff in the central Cactus Range. In this area the rocks are at least 800 feet thick, they are everywhere hydrothermally altered, and they are locally baked to dense dark-brown and black hornfels adjacent to intrusive masses. Where intensely silicified or argillized, the rocks are light gray to white, and where propylitized, they are brown to greenish brown.

The strata consist of siltstone, shale, sandstone, and ash-fall tuff; tuff is most abundant in the lower 300 feet. The upper strata, which are thin bedded, consist of approximately 20 percent coarse arkose and volcanic conglomeratic sandstone and 80 percent dark-gray silicified shale and siltstone. Most siltstone and shale beds are only a few inches thick, and most sandstone beds are less than 10 feet thick. The persistent thin and even bedding indicates deposition in water without vigorous currents, and a lacustrine environment is inferred. No fossils have been found in these strata. Although tuff of White Blotch Spring is not seen resting on them, these sedimentary rocks are inferred to be pre-White Blotch Spring in age. They probably accumulated in a lake that developed after collapse related to the withdrawal of magma to form the upper ash-flow tuffs of Antelope Springs. These sedimentary rocks probably were deposited over a broader area than that in which they now occur. They may have been removed from the northern part of the range and other areas during and after a stage of postcollapse doming.

TUFF AND RHYOLITE OF GOLD FLAT

Several isolated exposures of welded tuff occur in Gold Flat south of Coyote Cuesta along the northern flank of Pahute Mesa. The rocks crop out beneath rhyolite lavas that underlie the tuff of Wilsons Camp (p. 42). The stratigraphic position of the rock with respect to older volcanic strata in the project area is unknown.

The base of the tuff has not been observed, although a vitrophyre, probably basal, is present in several exposures. If the vitrophyre is actually at or near the base, the tuff is about 100 feet thick. The rock is pastel pink, red, and green on fresh fractured surfaces and weathers pinkish gray. It is densely welded, poor in pumice and crystals, and fairly rich in small rhyolite and andesite lithic fragments. Crystals make up 10–20 percent of the rock and include zoned plagioclase, alkali feldspar, quartz, and very sparse clinopyroxene, hornblende, and biotite.

Rhyolite crops out in a few isolated areas beneath the tuff of Wilsons Camp and above the welded tuff just described. The rhyolite has abundant tiny spherulites and is light gray to red, highly flow layered and laminated, brecciated at the base, and void of crystals. It weathers to small flat angular fragments.

TUFF OF WHITE BLOTCH SPRING

The name tuff of White Blotch Spring is applied to a sequence of quartz-rich welded tuff that crops out throughout the bombing and gunnery range. The sequence forms a readily mappable unit of strikingly similar strata from range to range, but slight differences in the type and abundance of phenocrysts are evident, and marked differences in nonbasal accumulations of lithic fragments indicate that the unit as mapped contains ash flows from different centers. Each center seemingly stamped its identity on its ash flows by means of lithic fragments that are representative of the crust through which the magma was erupted.

The Cactus Range and the northern Kawich Range (beyond the mapped area) have been identified as two of the centers of ash-flow eruptions. An unidentified third center is inferred near the east boundary of the mapped area. Potassium-argon dates indicate a slight progressive decrease in age of volcanic activity from east to west, but the similarity of strata strongly suggests a common substratum source.

The ash-flow tuffs exposed in the eastern, central, and western parts of the mapped area probably are juxtaposed at depth in the intervening valleys. They may also be juxtaposed in the ranges, but this cannot be demonstrated conclusively with the available data.

EASTERN PART OF MAPPED AREA

Rocks mapped as tuff of White Blotch Spring in the eastern part of the mapped area are distributed widely in the ranges on both sides of Monotony Valley, where they are 800–900 feet thick and rest disconformably on the Shingle Pass Tuff in most exposures. They are as much as 2,000 feet thick in the southern Reveille Range, where three or more densely welded cooling units occur that weather to massive reddish-gray and brown cliffs and steep slopes. (The Reveille Range was mapped by Cornwall (1967), and it was examined only briefly by the authors.) As far as is known, the base of the tuff of White Blotch Spring is not exposed in the southern Reveille Range. Reconnaissance mapping by Ekren in 1966 in the northern part of the range where older tuffs are exposed failed to disclose the Shingle Pass Tuff. The possibility should not be overlooked, therefore, that the tuff of White Blotch Spring in the Reveille Range predates the Shingle Pass.

Exclusive of the Reveille Range, the strata consist of two cooling units, each about 400 feet thick, that are separated locally by bedded tuff. Where bedded tuff is absent, the break between cooling units is extremely subtle, as in the exposures at White Blotch Spring in the locale of the measured section. (See p. 82.) Starting about 1 mile north of the spring, however, the break is easily recognized and can be traced northward to the Oswald mine, where the bedded tuff between cooling units is as much as 450 feet thick. In addition, a welded ash flow, 20–50 feet thick, is present in several exposures a few feet below the upper cooling unit. This rock contains 14 percent phenocrysts of plagioclase and alkali feldspar, in a ratio of about 2 : 1, and 0.5 percent biotite. Quartz is absent. Despite its occurrence between ash flows of the tuff of White Blotch Spring, this welded tuff obviously comprises a genetically unrelated cooling unit. The "alien" tuff was observed only in the eastern part of the area, and it is presumed, therefore, that its source lies east of the project area.

In Monotony Valley and the Belted Range the two cooling units of tuff of White Blotch Spring form a series of cliffs and slopes (fig. 5) produced by differential erosion of zones that differ slightly in welding and devitrification. Several of the cliff-forming zones display columnar jointing. The rocks range in color from light grayish tan and pinkish tan at the base, through alternating light brown and medium brown, to light reddish brown in an upper cliff-forming zone (upper cooling unit). Weakly welded rock above the highest cliff (not visible in fig. 5) is commonly light blue gray to white. Pumice fragments are generally small and indistinct in the lower cooling unit but are large (as much as 6 inches) and conspicuous in the upper unit. Lithic fragments, which are sparse and are confined to the lower one-third of the section, are chiefly vitrophyric cobbles and boulders of Shingle Pass Tuff but include lavas of intermediate composition and well-rounded boulders of massive Paleozoic quartzite. These fragments are inferred to be mostly basal accumulations—rocks picked up by the tuff as it rode over an irregular surface.

The two cooling units are petrographically nearly identical. Both contain 30–35 percent phenocrysts, of which quartz is the most conspicuous and commonly the most abundant mineral. The quartz occurs as euhedral bipyramids as much as 5 mm in diameter. The grains show slight embayment in thin section, and very few are "worm eaten" in hand specimen. Plagioclase and biotite are generally more abundant in the lower unit than in the upper, but some modal analyses show no differences. The plagioclase is commonly resorbed, "worm eaten," and charged with glass in the lower unit; it contrasts with the euhedral clear plagioclase in the upper unit. Allanite and zircon are conspicuous accessory minerals in the lower unit and are exceedingly sparse in the upper.

CENTRAL PART OF MAPPED AREA

Rocks mapped as tuff of White Blotch Spring in the central part of the mapped area crop out only in the Kawich Range, where two cooling units are present. Both units are characterized by abundant large crystals of quartz. These rocks were called "tuff of the Kawich Range" by Rogers, Anderson, Ekren, and O'Connor (1967). The lower cooling unit is poor in fragments and pumice; it could, on the basis of phenocryst content,

FIGURE 5.—Outcrop of tuff at White Blotch Spring, which is located just to the right of the area shown. In the high bluffs in the right background, strata include ash-fall tuff (forms slope) and quartz latite lavas. Pediment surface in right middleground is cut on Shingle Pass Tuff and also on downfaulted tuff of White Blotch Spring.

correlate with either of the cooling units exposed in the Belted Range and Monotony Valley. This unit, however, contains sparse but ubiquitous foliated quartzite lithics, fragments which were not observed in the eastern units. The foliation in the quartzite is defined by sparse flakes of biotite. This type of quartzite was observed also in all the cooling units exposed in the extreme northern part of the Kawich Range beyond the mapped area. The rocks there form the central dome of the resurged Kawich caldera and were undoubtedly extruded from that center. The unit is about 400 feet thick; it is densely welded, reddish gray, and mostly devitrified. Quartz makes up 25–50 percent of the total phenocrysts. Alkali feldspar and plagioclase occur in proportions that range from about 2:1 to 1:2; biotite is the sole identifiable mafic mineral, but pseudomorphs occur that appear to be after hornblende.

The upper unit, also about 400 feet thick, is rich in lithic fragments and pumice throughout its exposure. The lithic assemblage, in order of decreasing abundance, consists of red-brown Monotony Tuff, dark-gray argillite, dacite lava, quartzite, and sparse gneissic granite. This assemblage indicates that the unit does not correlate with either of the two cooling units exposed in the eastern part of the mapped area. The phenocryst assemblage, in contrast, matches very well. The rock contains 35 percent phenocrysts of which quartz is 30 percent, alkali feldspar is 37 percent, plagioclase is 27 percent, and biotite is 3–4 percent.

WESTERN PART OF MAPPED AREA

Western facies rocks of the tuff of White Blotch Spring have been mapped only in the northern Cactus Range, where they rest with steep angular unconformity on the upper tuffs of Antelope Springs. No continuous section is exposed in the Cactus Range, but the estimated composite thickness exceeds 3,000 feet. The rocks are intensely faulted and, except locally, are moderately to intensely hydrothermally altered. Cooling breaks possibly are present, although none were observed. The tuff of White Blotch Spring has not been identified in the Goldfield area to the west, the Tonopah area to the northwest, or the Monitor Hills to the north of the Cactus Range. Rocks younger and older than the tuff of White Blotch Spring are exposed in all those areas. Much of the rock mapped as tuff of White Blotch Spring and tuffs of Antelope Springs undivided in the area east of Mellan probably correlates with the tuff of White Blotch Spring in the Cactus Range. These rocks probably are widely distributed in the shallow subsurface south and west of Mellan. The tuff of White Blotch Spring is much more heterolithic in the Cactus Range than in the eastern area and somewhat more heterolithic in the Cactus Range than in the Kawich Range.

The tuff is characterized by a pale-orange-brown 100- to 200-foot-thick basal zone, which is rich in lithic fragments and which grades upward to drab brown-gray rock rich in yellowish-gray pumice lapilli and blocks (fig. 6) as much as 1 foot in diameter. The pumice-rich

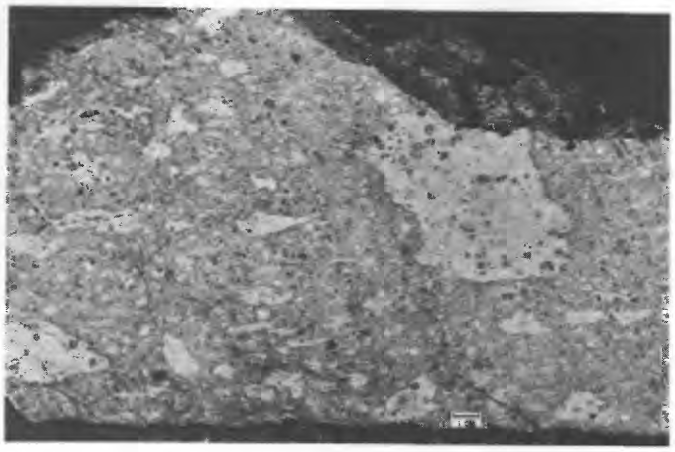

FIGURE 6.—Specimen of pumice-rich tuff taken a few feet above a basal lithic-rich zone in the tuff of White Blotch Spring, Cactus Range. The nonflattened inclusions are fragments of cognate tuff and not pumice blocks. Quartz forms the most conspicuous crystals, but feldspar grains are more abundant and are of equal size. Note that the largest phenocrysts are in the pumice and cognate inclusions.

zone averages about 700 feet in thickness. It is overlain by massive medium-gray densely welded tuff which is virtually free of lithic fragments and pumice lapilli. This tuff is well jointed and locally columnar jointed; it forms steep rugged slopes partially covered with dark-purplish-gray or dark-red-gray blocky talus and scree. The uppermost unit is light red brown to salmon, slabby to hackly weathering, and massive and densely welded. It is indistinguishable from the rocks in the Kawich Range that are poor in lithic fragments. The compaction foliation is extremely difficult to detect in both this and the underlying zone.

Lithic fragments locally make up 50 percent of the lower part of the unit in the Cactus Range and are commonly several feet in diameter. The most abundant fragments, in order of decreasing abundance, are Monotony Tuff, tuffs of the Antelope Springs area, and dacite. Pink Mesozoic(?) granite and sedimentary rocks of probable Paleozoic age are locally common. The fragments are also moderately abundant in outcrops near Mellan. The tuff is similar in general appearance and lithology to the upper tuffs of Antelope Springs exposed in the northern Cactus Range. Both units are characterized by abundant grains of quartz and locally by abundant large pumice lapilli and blocks; both contain similar assemblages of lithic fragments. The tuffs of Antelope Springs are richer in biotite. The two units can generally be distinguished by differences in color; exposures of the tuff of White Blotch Spring tend to be dominantly pale orange, brown, or buff, and exposures of tuffs of Antelope Springs are commonly lavender or purple and locally mottled in purplish gray and yellowish brown.

CHEMISTRY

Chemical analyses of the tuff of White Blotch Spring from White Blotch Spring and the Kawich and Cactus Ranges are shown in table 6. The abnormally high normative orthoclase and quartz and the low normative anorthite of sample CS–228 reflect not only the partial replacement of plagioclase by alkali feldspar but also the weak silicification of this rock. Weak silicification is also apparent in sample R–16D. The average normative albite, anorthite, and orthoclase for the other four samples plots within the rhyolite field (fig. 4, point WBS).

An early Miocene age is indicated for the tuff of White Blotch Spring on the basis of four potassium-argon dates from rocks exposed in the eastern, central, and western areas (table 5).

ROCKS BETWEEN THE TUFF OF WHITE BLOTCH SPRING AND FRACTION TUFF

The rocks between the tuff of White Blotch Spring and Fraction Tuff consist of tuffs and lavas without distinctive marker zones. The strata are interbedded and interfingered, and, as a consequence, beds that are lowest in one locality occur in the middle or near the top of the section in another. The chief units are (1) bedded tuffs, commonly zeolitized, that underlie and are interbedded with lavas of intermediate composition, (2) lavas of intermediate composition, (3) older rocks of Mount Helen, (4) the tuff of Wilsons Camp, which is probably interbedded with the lavas, (5) intrusive rocks of intermediate and rhyolitic compositions which occur in the raised central core of the Cactus Range and to a lesser extent in the Kawich and Reveille Ranges, and (6) rhyolite and interbedded ash-fall tuff and sedimentary rocks that overlie the lavas (chiefly at White Ridge in the Kawich Range).

ZEOLITIZED BEDDED TUFF AND SEDIMENTARY ROCKS

In most of the ranges the tuff of White Blotch Spring is overlain by bedded ash-fall tuff and sedimentary rocks that form a conspicuous slope between the relatively resistant welded tuff below and the hard lavas of intermediate composition above. Most of the bedded tuffs are zeolitized, but some are vitric; in the eastern part of the mapped area the vitric tuffs predominate.

In the Belted Range the strata consist of 60–100 feet of dazzling-white well-stratified vitric ash-fall tuff that contains minor sandstone and conglomerate at the base. The tuff consists of fine shards and small pumice lapilli and contains phenocrysts of plagioclase, biotite, and minor quartz, an assemblage that persists throughout

TABLE 6.—*Chemical analyses and norms of tuff of White Blotch Spring*

[Analyses by P. L. D. Elmore, S. W. Botts, G. W. Chloe, Lowell Artis, and H. Smith, by rapid method (Shapiro and Brannock, 1962). Norms determined from chemical analyses recalculated to 100 percent minus H_2O+CO_2]

Sample	1	2	3	4	5	6
Laboratory No.	162061	162062	162063	160807	162064	162065
Field No.	CS-228	BE-10-15-3	BE-10-15-7	R-16D	WBS-4	WBS-5
Chemical analyses						
SiO_2	74.4	75.9	74.7	75.5	73.8	72.1
Al_2O_3	13.6	13.0	12.8	13.0	13.5	14.3
Fe_2O_3	1.3	1.1	1.4	.94	1.0	1.5
FeO	.40	.16	.12	.24	.24	.52
MgO	.46	.43	.05	.27	.48	.70
CaO	.22	.59	1.1	.24	.86	1.6
Na_2O	1.4	3.0	3.4	2.8	2.9	2.4
K_2O	5.7	4.5	4.7	4.7	4.9	4.3
H_2O-	.30	.41	.70	.42	1.0	1.0
H_2O+	2.0	.85	.75	1.2	1.1	1.0
TiO_2	.28	.20	.19	.17	.17	.30
P_2O_5	.09	.05	.04	.07	.09	.07
MnO	.03	.04	.04	.02	.03	.04
CO_2	$<.05$	$<.05$	$<.05$	$<.05$	$<.05$	$<.05$
Sum	100	100	100	100	100	100
Norms						
Q	44.5	39.9	35.2	41.4	36.6	38.3
or	34.4	26.9	28.2	28.6	29.6	26.0
ab	12.1	25.6	29.2	24.2	25.0	20.8
an	.5	2.6	5.3	.8	3.8	7.6
C	5.1	2.3	.2	3.1	2.1	3.0
en	1.2	1.1	.1	.7	1.2	1.8
mt	.6	.1	--------	.4	.4	1.0
hm	.9	1.1	1.4	.7	.8	.9
il	.5	.4	.3	.3	.3	.6
ap	.2	.1	.1	.2	.2	.2

Sample, locality and description

[Numbers following mineral names are percent of total phenocrysts]

1. About 1.5 miles west-southwest of Cactus Spring in Cactus Range. Rock is rich in white pumice lapilli; 30 percent phenocysts: quartz 36, iron oxide≈1, altered biotite 2.8, altered sanidine and plagioclase 58, epidote 2. Biotite is chloritized, plagioclase is partly replaced by albite, epidote, and clay.
2. Summer Spring on east flank of Kawich Range. 39 percent phenocrysts: quartz 52, plagioclase 13.5, sanidine 32, biotite 3.
3. About 1 mile northwest of Summer Spring, east flank of Kawich Range. Rock is richer in pumice than sample 2; 40 percent phenocrysts: quartz 37, sanidine 39, plagioclase 23, biotite 2.
4. Kawich Range just north of Cedar Pass. Rock has been slightly silicified; about the same mode as sample 2.
5. White Blotch Spring; upper part of slope-forming zone above lowest cliff. 35 percent phenocrysts: quartz 42, sanidine 36, plagioclase 21, biotite 1.7.
6. White Blotch Spring; base of highest cliff-forming zone. 33 percent phenocrysts: quartz 40, sanidine 20, plagioclase 31, biotite 8. This rock is fairly rich in devitrified pumice lapilli which contain more plagioclase than the matrix; the lapilli were counted in the mode.

the project area. The conglomerate contains pebbles, cobbles, and boulders of probable Cambrian or Precambrian age and densely welded tuff derived from the underlying White Blotch Spring.

In the vicinity of Gray Top Mountain and Lava Ridge in the northern Belted Range, 50–200 feet of tuff and sedimentary rocks crops out above a black andesitic basalt in the approximate middle of the lava pile. At Gray Top Mountain these rocks consist of gray well-bedded tuffaceous sandstone, gravel, conglomerate, and, at the base, minor massive-weathering tuff that is rich in lithic fragments, principally of intermediate lavas. On Lava Ridge west of Gray Top Mountain, the rocks also consist of massive lithic tuff at the base, but there the overlying sandstone and conglomerate is dominantly yellow brown, red brown, and dark gray. At the top, a red conglomeratic sandstone, rich in iron oxide, contains large boulders of rhyodacite lava. All the conglomerate beds are cross-stratified and most contain well-rounded pebbles and cobbles. This sedimentary sequence is not shown separately on plate 1.

In the Kawich Range, bedded tuffs beneath the lavas rest on an eroded surface of considerable relief. Near Gold Reed, for example, 200–500 feet of vitric ash-fall tuff rich in small pumice lapilli overlies altered tuffs mapped as Shingle Pass Tuff and tuffs of Antelope Springs undivided. South of Quartzite Mountain the bedded tuffs rest directly on Precambrian strata. The tuff of White Blotch Spring is absent in both areas. North of Gold Reed and south of Cedar Pass, in Tps. 2 and 3 S., R. 51 E., the bedded tuffs are very thin or absent, and in most of this area lavas of intermediate composition rest directly on the tuff of White Blotch Spring or on older sedimentary rocks of the Cedar Wells area (older than tuffs of Antelope Springs).

In the Lizard Hills, Wilsons Camp, and Mellan areas, the bedded tuff is zeolitized in nearly every exposure; it is fresh only in sporadic outcrops. In some outcrops the zeolitized tuff is massive and contains no visible bedding, and thus it is not easily distinguished from zeolitized tuff of Wilsons Camp (a weakly welded ash-flow tuff). In other outcrops the tuff is thin bedded and locally cross-stratified. It is composed chiefly of small pumice lapilli and fine shards, but locally it contains beds rich in coarse pumice fragments as much as 3 inches long. Where fresh, the tuff is dominantly white or light gray; where zeolitized, it is mostly yellow brown.

Near Mount Helen the bedded rocks are more diverse than in the Lizard Hills and Mellan areas. They are as much as 100 feet thick and contain coarse conglomeratic sandstone, thin-bedded siltstone, and ash-fall tuff rich in pumice lapilli. These strata lie beneath the oldest lavas and above a densely welded ash-flow tuff tentatively correlated with tuffs of Antelope Springs. In addition, bedded tuff, siltstone, and poorly stratified tuff crop out locally on the west and south sides, possibly between the oldest lava (andesitic basalt) and overlying lavas of quartz latite. Some of the poorly stratified rock on the west side, which includes ash-flow tuff, is rich in metamorphic lithic fragments that are identical with the gneiss and schist exposed east of Mount Helen in the Trappman Hills. The fragments possibly were picked up as the tuff rode over the gneiss and schist of Trappman Hills, but it seems more likely that they were derived from the crust at the Mount Helen volcano during extrusion, because the Trappman Hills rocks were probably completely covered by volcanic strata at that time.

LAVAS AND INTRUSIVE ROCKS OF INTERMEDIATE COMPOSITION

The rocks treated herein are exclusive of the rocks of Mount Helen and the intrusive rocks in the central cores of the Cactus and Kawich Ranges.

Lavas of intermediate composition are exposed in all the ranges within the mapped area. Beyond the mapped area they are widely distributed to the north, west, and east. The rocks were extruded from many widely dispersed vents, but their stratigraphic position indicates that they are of approximately the same age in all localities. They apparently were extruded principally from fissure-type feeders, several of which are exposed. The intrusive and extrusive rocks are petrographically and chemically very similar.

The intermediate lavas are light gray to black and commonly weather to somber shades of brown; in most outcrops they are flow layered and folded. They are generally more resistant to erosion than adjacent strata and tend to form steep ridges and rugged hills. Where the lavas have been weakly or moderately hydrothermally altered, they tend to form distinctive lavender or purplish-gray outcrops and soils. Where the lavas are intensely altered, as at Gold Reed, they are commonly bleached to pale gray, yellow, or pink. The rocks are described by area in a general progression from east to west.

Belted Range and Reveille Valley

Intermediate lavas nearly 1,000 feet thick form the bulk of the outcrops in the northern Belted Range. They crop out as far south in the range as Wheelbarrow Peak and also form a broad area of hills in Reveille Valley. The rocks are well exposed and show considerable variation in composition and texture. All are porphyritic and most contain about 30 percent phenocrysts. The groundmasses range from glassy to completely crystalline and consist predominantly of plagioclase and alkali feldspar microlites, iron oxides, and fine biotite. The principal phenocryst in all the rocks is plagioclase, whose sizes and zoning are varied and whose average composition is andesine-labradorite. Biotite is the chief mafic mineral, but hornblende occurs in nearly all the rocks, and augite and hypersthene occur in some. In general, the least silicic rocks and those richest in mafic minerals occur at or near the base of the lava pile; however, in most exposures within the Belted Range thin andesitic basalt lavas crop out near the middle of the sequence. These rocks are black where glassy and dark greenish gray where stony. They contain about 20 percent small phenocrysts of labradorite, augite and, hypersthene in a pilotaxitic groundmass of andesine microlites and iron oxide. The basalt is a major rock unit southeast of the Oswald mine and east of the mapped area.

Chemical analyses of two samples from the Belted Range are shown in table 7 (samples 1 and 2). Sample 1 is from the top of the pile at Lava Ridge, and sample 2 is from the approximate base; both contain abundant normative quartz, but only sample 1 contains quartz phenocrysts. Both samples, as shown on the plot of normative albite, anorthite, and orthoclase (fig. 4), fall in the rhyodacite and quartz latite fields.

Kawich Range

Intermediate lavas form two outcrop belts in the Kawich Range. The largest and best exposed belt strikes north-northwest and extends from the east side of Saucer Mesa to the west flank of the Kawich Range at Trailer Pass. The other belt lies entirely along the east flank of the range and extends roughly from the south boundary of T. 3 S., R. 51 E., to Cedar Pass in T. 2 S. The rocks in both belts are the same age, but they have been displaced from each other by several northwest-trending faults that are inferred to bound the Cathedral Ridge caldera.

East of Saucer Mesa the lavas are as much as 500 feet thick and crop out in a series of isolated knobs and hills. The oldest flows are rhyodacites. A modal analysis of one of these is given in table 7 (sample 3). The plagioclase phenocrysts are as much as 10 mm long and commonly are aggregates of several grains. The hornblende is brown and has a very small extinction angle. The groundmass, which is hyalopilitic, contains microlites of andesine and tiny grains of iron ore in brown glass. The rhyodacite is overlain by andesite lava which contains about 44 percent small phenocrysts of plagioclase, clinopyroxene, hypersthene, and iron ore. Except for a basal vitrophyre, the andesite has a completely devitrified groundmass composed of a dense felt of plagioclase microlites and interstitial iron ore. Apatite is a common accessory in both the rhyodacite and andesite.

North of Quartzite Mountain, where the lava belt is shifted westward by high-angle normal faults, an estimated 2,000–3,000 feet of lava is exposed. At Gold Reed these rocks are moderately to intensely hydrothermally altered and are weakly mineralized. The rocks are principally dacites and rhyodacites and they contain 30–40 percent phenocrysts of which plagioclase is always dominant. Mafic minerals are altered partly or wholly to chlorite, calcite, and iron ore. The chief pseudomorph appears to be after biotite, but several thin sections show relicts that are after hornblende and pyroxene.

TABLE 7.—*Chemical analyses and norms of lavas of intermediate composition exclusive of Mount Helen rocks*

[Analyses by P. L. D. Elmore, S. W. Botts, G. W. Chloe, Lowell Artis, and H. Smith, by rapid method (Shapiro and Brannock, 1962). Norms determined from chemical analyses recalculated to 100 percent minus $H_2O + CO_2$]

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13
Field No.	BP-57	BP-58	QM-88	QM-70	QM-75	QM-94	R-14C	R-16A	M-13	M-16	CS-326	CS-253	CS-392
Laboratory No.	160725	160726	160982	160979	160981	160983	160804	160805	160963	160964	162860	162058	162859
Chemical analyses													
SiO_2	67.7	60.5	63.0	60.9	59.6	59.3	53.7	59.8	63.3	57.2	62.5	59.5	62.6
Al_2O_3	15.2	16.6	16.0	17.1	16.2	16.0	15.4	16.9	16.8	17.6	15.0	16.1	14.3
Fe_2O_3	1.9	4.2	4.6	3.4	4.3	5.0	2.5	4.5	2.9	3.1	4.9	6.1	3.8
FeO	.97	1.9	.76	2.0	1.2	.56	5.1	1.2	1.4	3.7	.60	.40	1.1
MgO	1.0	2.0	2.1	3.3	3.1	.90	7.9	2.4	1.7	3.6	1.7	2.5	2.0
CaO	3.1	5.2	4.6	4.3	5.6	6.7	8.3	6.4	4.4	6.4	4.2	4.3	4.4
Na_2O	3.0	3.1	3.2	3.1	3.1	3.0	2.6	3.1	3.2	3.2	3.2	3.1	2.7
K_2O	3.8	3.0	3.3	1.0	1.4	3.1	2.0	3.3	3.6	2.8	3.2	4.1	3.4
H_2O-	.32	1.1	.70	.47	1.6	.77	.47	.64	.75	.31	.96	.84	.90
H_2O+	2.5	.94	1.0	2.9	2.8	1.3	.90	.87	.97	.84	1.7	1.4	2.8
TiO_2	.30	1.1	.77	.78	.79	.74	1.0	.86	.54	.96	.70	.81	.96
P_2O_5	.18	.37	.22	.32	.27	.32	.40	.36	.34	.40	.28	.38	.32
MnO	.04	.10	.07	.12	.05	.10	.12	.06	.08	.14	.07	.15	.07
CO_2	<.05	<.05	<.05	.07	.06	2.3	<.05	<.05	<.05	<.05	<.05	<.05	<.05
Total	100	100	100	100	100	100	100	100	100	100	99	100	99
Norms													
Q	28.9	18.5	20.1	27.5	21.3	18.2	2.9	14.6	20.3	9.5	22.1	14.5	24.1
C	1.0	----	----	4.2	.1	----	----	----	.5	----	----	----	----
or	23.1	18.1	19.8	6.1	8.7	19.1	11.9	20.0	21.7	16.7	19.6	25.0	21.0
ab	26.1	26.7	27.4	26.4	27.4	26.5	22.2	26.5	27.5	27.3	28.1	27.0	24.0
an	14.6	23.0	19.8	20.0	27.2	22.0	24.7	22.7	20.0	26.0	18.0	18.4	18.0
wo	----	.4	.8	----	----	4.4	6.0	3.0	----	1.6	.8	.1	1.3
en	2.6	5.1	5.3	8.5	8.1	2.3	20.0	6.0	4.3	9.0	4.4	6.4	5.2
fs	----	----	----	----	----	----	5.9	----	----	2.9	----	----	----
mt	2.5	3.3	.5	4.8	1.8	----	3.7	1.6	3.3	4.5	.1	----	1.1
hm	.3	2.0	4.4	.3	3.2	5.2	----	3.5	.7	----	5.0	6.3	3.2
il	.6	2.1	1.5	1.5	1.6	1.5	1.9	1.7	1.0	1.8	1.4	1.2	1.9
tn	----	----	----	----	----	----	----	----	----	----	----	.5	----
ap	.4	.9	.5	.7	.67	.8	1.0	.9	.8	1.0	1.0	.9	.8

Sample, locality and description

[Numbers following mineral names are percent of total phenocrysts]

1. Highest flow in northern part of Lava Ridge, Belted Range. Medium-gray vitrophyric rhyodacite; 28 percent phenocrysts: calcic andesine 62, biotite 17, hornblende 17, quartz 3, and minor sphene, magnetite and apatite.
2. Northern part of Lava Ridge, Belted Range. Dark-gray to black, dense rhyodacite; 17 percent phenocrysts: plagioclase 58, clinopyroxene and orthopyroxene 16, and magnetite 14; groundmass is trachytic to felty.
3. About 2.2 miles south-southeast of Gold Reed, Kawich Range. Reddish-brown rhyodacite; about 30 percent phenocrysts: plagioclase (as much as 10 mm) 70, brown hornblende 20, and minor clinopyroxene, biotite, magnetite and quartz; groundmass is hyalopilitic.
4. About 1.5 miles south of Trailer Pass near western limit of exposed dacite lavas, Kawich Range. Greenish-gray dacite; about 50 percent phenocrysts consisting predominantly of zoned plagioclase (sodic labradorite); mafic minerals include partly altered clinopyroxene and biotite and completely altered and unidentifiable grains that may have been hornblende. Note high corundum in norm; possibly indicates loss of alkalis through alteration. Also, plot of partial molecular norm (fig. 4) indicates possible loss of potassium.
5. About 3.5 miles northwest of Gold Reed, Kawich Range; just below base of Fraction Tuff. Reddish-brown dacite with phenocryst assemblage similar to sample 3 but with clinopyroxene as principal mafic phenocryst.
6. About 1.5 miles southwest of Gold Reed on north flank of Quartzite Mountain, Kawich Range. Red weakly altered rhyodacite; about 20 percent phenocrysts of plagioclase, altered mafic minerals, magnetite, and quartz in a pilotaxitic groundmass; calcite, hematite, and quartz are common secondary minerals.
7. About 4.5 miles south-southeast of Mellan. Black andesite; 30 percent phenocrysts: plagioclase (an_{52}) 39, diopsidic augite 38, magnesian olivine 20, and minor magnetite and hornblende, in a pilotaxitic groundmass of plagioclase, pyroxene, and iron oxide.
8. About 2.5 miles southeast of Mellan. Dark-gray to black rhyodacite; 32 percent phenocrysts: plagioclase (calcic andesine) 70, augite 20, biotite 5, and magnetite 5, in a dense trachytic groundmass that contains sparse small plagioclase laths.
9. Eastern part of Lizard Hills. Black rhyodacite dike; 33 percent phenocrysts: plagioclase (an_{50}) grains (as much as 5 mm) 72, biotite 14, green hornblende 7, and minor clinopyroxene and magnetite in a cryptocrystalline felty groundmass.
10. Northeastern part of Lizard Hills. Black rhyodacite; 35 percent phenocrysts: plagioclase 64, augite 15, hypersthene 9, magnetite 10, brown hornblende 2, and a trace of quartz in a cryptocrystalline felty groundmass.
11. About 2.5 miles east of Cactus Spring. Reddish-gray rhyodacite; similar to sample 13 but with sparse quartz phenocrysts and slightly more augite.
12. About 5 miles southwest of Cactus Peak. Olive-green rhyodacite; 20 percent phenocrysts: plagioclase (calcic andesine) 60, brown hornblende 22, biotite 10, and quartz 4, augite 2, and magnetite 2, in a hyalopilitic groundmass composed predominantly of plagioclase and magnetite.
13. East part of Goldfield Hills west of project area. Gray rhyodacite; 28 percent phenocrysts: andesine 75, biotite 11.5, augite 8.5, hornblende 2.3, and magnetite 2 in a hyalopilitic groundmass.

The plagioclase is extensively replaced by more sodic plagioclase and locally by calcite. Quartz phenocrysts are visible in nearly all the rocks, but they are subordinate to the mafic phenocrysts and plagioclase.

Northeast of Trailer Pass, in the second belt of lavas outlined above, most of the rocks are nearly identical with those already described; however, several flows in this area contain phenocrysts of alkali feldspar, as much as 2 cm in diameter, and moderate amounts of quartz. These flows have not been analyzed, but they are petrographically very similar to analyzed rocks that are quartz latites in composition. In this area the lavas locally rest unconformably on sedimentary rocks that predate the tuffs of Antelope Springs; this fact suggests extensive prelava erosion. North of Cedar Pass, on the east flank of the range, lavas of intermediate composition occur in isolated exposures. These rocks are similar megascopically to the lavas to the south and are presumed to be equivalent stratigraphically. They form part of the downfaulted margins adjacent to the raised central mass of the range.

Analyses of four rocks from the Quartzite Mountain (southern Kawich Range) area are shown in table 7 (samples 3, 4, 5, 6).

Mellan Hills Area

For simplicity the term "Mellan Hills area" is used for the area of ridges and hills lying between the Cactus and Kawich Ranges. It comprises the hills near the old townsite of Mellan, the Lizard Hills, Gabbard Hills, and Triangle Mountain.

The intermediate rocks exposed in the Mellan Hills area display a wide variety of colors and textures and range in composition from andesite to quartz latite. Most are lavas that form a group of fault-controlled northwest-trending ridges, and some are dikes that trend mostly northeast. In the area between Mellan and the old road between Antelope Springs and Trailer Pass, the lavas overlie the tuff of Wilsons Camp, which in turn rests on the tuff of White Blotch Spring or older rocks. The lavas, which are overlain by the Fraction Tuff or younger rhyolite lavas, are thin, rarely exceeding 50 feet. The thinness is probably due principally to shortening of the section by low-angle faults, but may be partly due to deep pre-Fraction Tuff and prerhyolite erosion. The rock still preserved in outcrop is dark-gray rhyodacite (sample 8, table 7). The rocks exposed between the Antelope Springs-Trailer Pass road and the Antelope Springs-Gold Reed road are mostly black and glassy with compositions ranging from andesite to quartz latite. The black latites and andesites are not easily distinguished from basalt. They contain about 30 percent small phenocrysts consisting of about equal amounts of plagioclase and pyroxene and minor hornblende, biotite, fayalite, and locally a trace of quartz. Magnetite is abundant as small phenocrysts and as tiny grains in a felty to hyalopilitic groundmass. The phenocrysts of hornblende and biotite consistently display thick reaction rims of magnetite. The andesites and latites are intruded by and locally overlain by rhyodacite and quartz latite which form the bulk of the outcrops southward to Triangle Mountain.

At Triangle Mountain three rock types occur in a steep west-dipping sequence. The easternmost and oldest rock is an andesite or dacite. The rock is black, glassy, and flow brecciated at the base and top and is brown and gray in the thin flow-layered stony interior. Bedded tuff at the base of the lava is fused for a distance of 2–5 feet from the contact, and the beds dip vertically or 70° W. The rock contains nearly 50 percent small phenocrysts of plagioclase, hornblende, biotite, augite, and hypersthene in a pilotaxitic to hyalopilitic groundmass composed of plagioclase microlites, specks of iron ore, and glass. The middle flow in the lava pile is flow layered light- and brownish-gray mostly devitrified dacite or latite that contains 30 percent phenocrysts of plagioclase, biotite, and hornblende in a dense groundmass of plagioclase microlites, "cryptofelsite," and glass. On the west flank, this rock is overlain by quartz latite that contains 30 percent phenocrysts of plagioclase, quartz, hornblende, biotite, augite, and fayalite. The plagioclase grains are commonly as much as 10 mm long, and the rock, therefore, is conspicuously porphyritic. This rock is in fault contact with the tuff of Wilsons Camp which is locally silicified for a distance of about 2 feet from the fault. Locally, the tuff of Wilsons Camp has been forced into steep dips along the fault zone, and older bedded tuffs are in contact with the quartz latite. On the southeast flank of the mountain the lava flows change strike from north-northwest to east and here the dip in the flow layering decreases from vertical and 70° W. to about 15°–25° S. In this area the conspicuously porphyritic quartz latite rests on latite or dacite, which in turn rests on zeolitized tuff. The andesite, which is the oldest flow in the exposures to the northwest, is not present.

The quartz latite at Triangle Mountain contains abundant inclusions of hornblende-rich rock with a peculiar pseudo-ophitic texture. Crystals in the inclusions consist of randomly oriented tabular plagioclase, hornblende, and minor clinopyroxene, and interstices are filled with brown glass. Hornblende is mostly in the form of very slender prisms or "needles" which are intergrown with the plagioclase; individual crystals commonly penetrate as many as five grains of plagioclase. The hornblende is pleochroic from olive to deep brown and has a maximum extinction angle of about 10°. The plagioclase is labradorite or calcic andesine and is weakly zoned. The clinopyroxene is commonly altered along crystal edges to hornblende. The inclusions, which range in size from a few millimeters to several feet, probably constitute early magmatic segregates that were brought to the surface in the form of semisolid masses of crystal mush.

Wilsons Camp

Intermediate lavas form several rounded hills east and south of Wilsons Camp. The oldest lava at Wilsons Camp is a dark-gray to dark-brownish-gray quartz latite. It contains about 30 percent phenocrysts consisting of glomeroporphyritic plagioclase (clots as large as 10 mm), minor quartz (as large as 3 mm), sparse alkali feldspar (as large as 1½ cm), and abundant mafic minerals consisting of about equal amounts of clinopyroxene and hornblende and minor altered biotite. The hornblende and biotite are largely altered to iron oxide, chlorite, and calcite; the clinopyroxene, in contrast, is fresh and clear. The groundmass is pilotaxitic with tiny plagioclase and alkali feldspar microlites, abundant dust and specks of iron oxide, and interstitial "cryptofelsite" and glass.

The youngest lava is a dacite or rhyodacite that is finer grained than the older rock and contains about 20 percent phenocrysts comprising, in order of decreasing abundance, plagioclase (as much as 5 mm), clinopyroxene, hornblende, hypersthene, and biotite (all less than 5 mm). The hornblende and biotite are largely altered to iron oxide. The groundmass consists of a dense felt of tiny plagioclase and alkali feldspar microlites. Apatite, in prisms nearly 1 mm long, is a conspicuous accessory mineral.

Cactus Range

In the Cactus Range, lavas of intermediate composition occur only on the flanks of the range, where they form isolated outcrops surrounded by alluvium. The basal contacts have not been observed.

In the northwestern part of the range, the lavas are about 600 feet thick. They are unconformably overlain by sedimentary rocks of pre-Fraction Tuff age. Both the lavas and sedimentary rocks are intruded by broad rhyolite dikes that were emplaced in faults along which the strata were tilted westward to moderate and steep angles. The strata are repeated several times by these faults and form discontinuous bands parallel to the range. The lavas are mostly reddish brown to dark gray and tend to weather to subdued dark ridges that are locally paralleled by ridges of contrasting lighter colored rhyolite. The lower part of the unit is commonly olive green as a result of the partial alteration of the groundmass to celadonite.

On the eastern flank of the range, east of Cactus Spring, rhyodacite lavas are reddish brown to reddish gray. These colors contrast sharply with the dark-greenish-gray to greenish-brown colors characteristic of the propylitized intrusive rhyodacites that lie southwest of these exposures. A small isolated outcrop of reddish-gray rhyodacite similar to the lavas near Cactus Spring is located in Civet Cat Canyon southwest of the Cactus Range, and small exposures of altered rhyodacite lava occur also in the extreme southern part of the Cactus Range near the Wellington Hills.

In the northern Cactus Range the reddish-brown lavas contain 20–30 percent phenocrysts consisting of 60–75 percent conspicuous plagioclase (calcic andesine) and varying proportions of biotite, hornblende, clinopyroxene, and magnetite. Clinopyroxene is sparse or absent in some rocks, and occasional large phenocrysts of quartz and alkali feldspar (as large as 1.5 cm) occur in some flows. Much of the reddish-brown color of these rocks is caused by pseudomorphs of hematite after biotite and hornblende. Clinopyroxene was generally unaffected by the alteration that gave rise to hematite in the biotite and hornblende. Some plagioclase grains show deep magmatic corrosion but are otherwise unaltered. In most rocks the groundmass is hyalopilitic to pilotaxitic and is composed predominantly of plagioclase, magnetite, biotite, and glass. Phenocrysts range in size from about 1 to 10 mm.

Chemical analyses of lavas from the east and west flanks of the Cactus Range are given in table 7 (samples 11 and 12, respectively). In thin section both rocks show some evidence of deuteric alteration, and sample 12 contains appreciable celadonite in the groundmass. For comparison, an analysis of unaltered lava from the east flank of the Goldfield Hills is also given (sample 13). All analyses plot in the rhyodacite field of figure 4.

Lavas of intermediate composition, similar to those in the Cactus Range, make up most of the Tertiary exposures in the Goldfield Hills, a volcanic center adjoining the west margin of the mapped area. These lavas rest on and are overlain by welded tuffs and tuffaceous sedimentary rocks that can be correlated unequivocally with rocks in similar stratigraphic positions in the Cactus Range. The lavas in the Goldfield Hills, therefore, are interpreted as belonging to the same period of eruptive activity as the lavas in the Cactus Range. A potassium-argon age of 21.1 m.y. (sample 19, table 5) was obtained from biotite from a quartz latitic welded tuff that overlies the lavas on the south flank of the Goldfield Hills (H. R. Cornwall, written commun., 1964). Thus an early Miocene or older age is indicated for the underlying lavas in the western part of the mapped area.

OLDER ROCKS OF MOUNT HELEN

Mount Helen was a source area for lavas of intermediate to basic composition. Intrusive rocks and lavas derived from this source make up most of the mountain and form many of the adjacent hills. These rocks form a mappable group that is related spatially and chemically. The lavas rest locally on thin-bedded sandstone, siltstone, and tuff, which in turn rest on welded tuff that probably was extruded from the Mount Helen area. The lavas are overlain by sedimentary rocks and the tuff of

Tolicha Peak. Three distinctly different rocks occur; from oldest to youngest they are andesitic basalt, rhyodacite, and quartz latite. The rhyodacite is described herein but is not shown separately on the geologic map.

In addition to these rocks, much younger basalt was extruded from the central feeder at Mount Helen. This basalt is described on page 65.

Andesitic Basalt

The andesitic basalt underlies Mount Helen and crops out sporadically around the perimeter of the mountain. It also forms several broad outcrops as far as 3 miles west of Mount Helen. The rock is largely a lava, but in places near the mountain it occurs as intrusive dikes and irregular apophyses. A small dike can be seen in the saddle south of the mountain on the old road to Wellington.

The andesitic basalt is dark gray to black where fresh and unaltered; it is brown and massive weathering without visible flow layering. The presence of highly vesicular zones near the top and of small pebbles of basalt in the overlying quartz latite lavas indicates that the rock is a lava.

The rock is porphyritic, containing conspicuous dark-green to black prisms of augite as much as 5 mm in length and 3 mm in diameter. The dense groundmass is composed of randomly oriented microlites of calcic andesine, tabular crystals of labradorite as much as 1.5 mm in length, a few small crystals of olivine, abundant magnetite, and very sparse interstitial alkali feldspar. A few thin sections contain sparse corroded microphenocrysts of biotite or hornblende as much as half a millimeter in diameter that are rimmed with iron oxide. Commonly the rock is altered and the augite has been replaced by iron oxide and chlorite, and the larger crystals of plagioclase have been replaced by calcite and yellowish-green clay or chlorite. The altered augite phenocrysts weather to cavities that closely resemble vesicles in outcrop.

A chemical analysis of the andesitic basalt is given in table 8 (sample 1).

Rhyodacite

Rhyodacite makes up a very small part of the rock at Mount Helen and is exposed only in small patches on the east and west sides, where it may be a single lava flow. The rock is dark greenish gray and, in contrast with the andesitic basalt, is conspicuously flow layered. It is porphyritic but the phenocrysts are small and inconspicuous, rarely exceeding 3 mm in length. Plagioclase (sodic andesine) is the most abundant crystal, followed by augite, hypersthene, and magnetite. The total phenocryst content is about 15–20 percent. The groundmass is glassy to cryptocrystalline.

Table 8.—*Chemical analyses and norms of rocks from Mount Helen*

[Analyses by P. L. D. Elmore, S. D. Botts, G. W. Chloe, Lowell Artis, and H. Smith, by rapid method (Shapiro and Brannock, 1962). Norms determined from chemical analyses recalculated to 100 percent minus H_2O+CO_2]

Sample	1	2	3	4	5
Laboratory No.	164094	165058	162066	160965	162067
Field No.	E8-8-1	E11-20-3	BE-4-27-1	M-195	M-177
Chemical analyses					
SiO_2	51.1	65.3	62.8	63.5	65.2
Al_2O_3	17.4	16.0	17.1	16.7	15.5
Fe_2O_3	6.4	1.3	5.0	4.8	3.3
FeO	1.3	1.4	.16	.32	.12
MgO	3.3	1.1	.40	.33	.47
CaO	9.1	3.6	2.4	2.1	2.1
Na_2O	3.2	4.0	3.2	3.4	2.2
K_2O	2.4	2.4	6.8	6.8	9.2
H_2O-	1.5	1.3	.37	.26	.17
H_2O+	1.1	2.7	.57	.68	.45
TiO_2	1.4	.49	.74	.78	.44
P_2O_5	.71	.23	.31	.26	.23
MnO	.07	.07	.06	.02	.05
CO_2	.54	.09	.08	.11	.67
Sum	100	100	100	100	100
Norms					
Q	4.2	24.8	13.5	15.4	12.2
or	14.7	14.8	40.6	40.7	55.0
ab	28.1	35.3	27.4	26.9	18.8
an	27.0	17.1	10.0	8.3	8.2
C		.9	.9	1.2	
wo	6.3				
en		2.9	1.0	.8	1.2
fs		.9			
mt	.4	2.0			
hm	6.4		5.1	4.9	3.3
il	2.8	1.0	.5	.7	.4
ap	1.7	.6	.7	.6	.6
ru			.5	.4	
tn					.6

Sample, locality, and description

[Numbers following mineral names are percent of total phenocrysts]

1. South flank of Mount Helen. Andesitic basalt lava; 20 percent phenocrysts consisting of labradorite, augite, hornblende rimmed with iron oxide, and magnetite in a pilotaxitic groundmass.
2. East side of Mount Helen. Rhyodacite lava; 18 percent phenocrysts: plagioclase 74, clinopyroxene 13.5, hypersthene 10, magnetite 2.5, and a trace of biotite in a glassy groundmass.
3. South flank of Mount Helen. Biotite-hornblende quartz latite outcrop. Rock is blue gray; about 30 percent phenocrysts of andesine, quartz, altered biotite, and hornblende; mafics are almost completely altered to iron oxide, chlorite and clay(?). Plagioclase is slightly altered to calcite and potassium feldspar; groundmass is aphanitic and contains much iron oxide dust. Rock (in outcrop) contains scattered potassium feldspar phenocrysts as much as 2 cm long (none of these believed to be in rock analyzed).
4. South flank of Mount Helen. Biotite-hornblende quartz latite. Rock is dark purplish gray and probably part of same flow as sample 3. Same phenocryst content; a few potassium felsdpar phenocrysts visible in thin section but andesine is dominant feldspar; mafic minerals are almost completely altered to iron oxide and chlorite; plagioclase partly altered to calcite and potassium feldspar.
5. South flank of Mount Helen. Biotite quartz latite; rock is light gray; 46 percent phenocrysts: quartz 19; alkali feldspar 29; andesine 28; biotite 19; hornblende 2. Plagioclase is partly replaced by alkali feldspar and calcite; biotite and hornblende are almost completely altered to iron oxide and calcite.

A chemical analysis of the rhyodacite is shown in table 8 (sample 2).

Quartz Latite

Rocks mapped as quartz latite consist of lavas, a few thin sills that were intruded at the base of the pile adjacent to Mount Helen, and a large feeder plug at the south end of Mount Helen. Two types of quartz latite are recognized. The older is dark green gray or dark blue gray, conspicuously flow laminated and layered, and characterized by sparse potassium feldspar phenocrysts that commonly are 2 cm long, rarely as much as 5 cm. This rock contains about 30 percent phenocrysts consisting of plagioclase that range in size from about 1 mm to about 1 cm, considerably less but more conspicuous potassium feldspar, biotite, hornblende, and minor quartz. Iron oxide is fairly abundant as small phenocrysts, as fine dust and specks in the groundmass, and as a replacement product of hornblende and biotite; in many thin sections it has entirely replaced the mafic minerals. The groundmasses of all rocks examined in thin section are too dense for point counting with the microscope. All contain tiny grains of quartz and microlites of alkali feldspar. A conspicuous feature is the partial replacement of plagioclase phenocrysts by alkali feldspar. A lack of twinning and the unusually high K_2O content of the rock (see samples 3 and 4, table 8) strongly suggest that the replacement feldspar is potassium feldspar rather than albite.

The younger quartz latite is characterized by abundant phenocrysts of quartz and biotite. It forms lavas in and adjacent to Mount Helen and occupies the central part of the feeder plug. This rock is light gray to medium gray and is also conspicuously flow layered. It contains as much as 50 percent phenocrysts that include oligoclase and potassium feldspar in ratios of about 2:1, abundant quartz and biotite, and sparse hornblende. The mafic crystals are largely replaced by iron oxide in most thin sections and entirely replaced in some.

The two types of quartz latite from Mount Helen are extremely rich in K_2O (table 8); the older quartz latite (samples 3 and 4) contains 6.8 percent K_2O. Because of the possibility that single very large potassium feldspar crystals were present in these analyzed samples, an additional analysis was made of several small fragments in order to preclude the occurrence of the large potassium feldspar grains. This analysis showed 7.7 percent K_2O and 2.3 percent Na_2O (W. M. Mountjoy, written commun., 1965). The younger quartz latite (sample 5) contains 9.2 percent K_2O and 2.2 percent Na_2O. The high K_2O contents indicate that all the alkali feldspar in the groundmasses of the quartz latite is probably potassium feldspar. The fact that plagioclase phenocrysts have been largely replaced by alkali feldspar suggests that much of the groundmass feldspar is probably similarly altered. Whether this alteration was hydrothermal or deuteric is not known. It appears to be confined to rocks in the immediate vicinity of Mount Helen. Prior to alteration the rocks may have been normal calc-alkalic types similar chemically to the lavas of intermediate composition that crop out throughout the project area.

TUFF OF WILSONS CAMP

The name tuff of Wilsons Camp is here informally applied to an ash-flow tuff sheet that crops out in Tps. 3, 4, and 5 S., Rs. 47, 48, and 49 E., and locally along the southwest flank of the Cactus Range. The fresh rock is best exposed between Coyote Cuesta and Triangle Mountain in T. 5 S., R. 48 E., about 5 miles southeast of Wilsons Camp.

The tuff comprises two cooling units, each of which is 50–300 feet thick. Both units are predominantly weakly welded and vitric, and both locally have thin vitrophyric zones at their bases. The tuff is characterized by abundant nonflattened to slightly flattened pumice lapilli and by blocks of light-gray to white silky pumice and greenish-gray and brown cindery pumice. The pumice fragments are as much as 4 feet in length but average less than 4 inches. They make up as much as 50 percent of the total rock. The tuff also contains abundant fragments of porphyritic lava of intermediate composition, rhyolite, basalt, and a few variegated metamorphic rocks—mostly argillite and quartzite. The fragments range in size from about 1 inch to 2 feet and are largest and most abundant at the base of the lowest cooling unit. The tuff matrix is light gray and weathers pale brown to buff. It contains 20–33 percent phenocrysts consisting of 4–16 percent quartz, 40–70 percent plagioclase, 10–30 percent alkali feldspar, and 8–15 percent biotite. Other mafic minerals are hornblende, clinopyroxene, and hypersthene; these are most abundant in the lowest unit. Magnetite, sphene (as much as 1 mm), and allanite are common accessory minerals.

Tuff that is mapped as tuff of Wilsons Camp in the valley east of Gabbard Hills and in the valleys northeast of Triangle Mountain is intensely zeolitized. The zeolitized rock is yellow, orange, and brown, and the abundant pumice lapilli and blocks which characterize the vitric tuff of Wilsons Camp are rare and obscure. Biotite is the only identifiable mafic mineral in thin section. Map unit identification, therefore, is tentative and the zeolitized strata may include cooling units that are older than the tuff of Wilsons Camp. If this is the case, the rocks are probably at least genetically related to the tuff of Wilsons Camp as shown by the same lithic fragment assemblage and nearly the same abundance of fragments.

At the old townsite of Mellan the tuff has been intensely silicified by hydrothermal solutions. The two cooling units are separated by 20–100 feet of siltstone, ashfall tuff, and conglomeratic sandstone, all of which are intensely silicified. Both cooling units are characterized by abundant cavities that originally contained pumice lapilli. The two cooling units and the sedimentary rocks that separate them are best seen in the hanging-wall block of a northwest-trending fault that displaces the tuff of Wilsons Camp down on the northeast against tuff of White Blotch Spring on the southwest. An inclined shaft follows this fault and penetrates about 300 feet of the lower cooling unit.

The tuff of Wilsons Camp is similar in general megascopic appearance to the Fraction Tuff (p. 50), and the two can easily be confused. The Fraction also contains a great abundance of fragments of intermediate rocks and has about the same percentage of phenocrysts; it is more densely welded, contains more metamorphic lithic fragments and less pumice and plagioclase, and, apparently, contains no pyroxene. It does contain both sphene and allanite.

INTRUSIVE ROCKS OF THE CENTRAL CORE OF THE CACTUS RANGE

The intrusive masses within the central core of the Cactus Range form a group of intergrading hypabyssal calc-alkalic rocks that range in composition from melanodiorite to rhyolite. This assemblage persists throughout, but high-silica varieties dominate in the northern part of the Cactus Range, and intermediate and low-silica varieties predominate in the central and southern parts. There is good evidence that the rocks ranged from the generally low-silica varieties to coarse-grained porphyritic rhyolite as intrusion proceeded, and they appear to be genetically related. All the rocks are porphyritic but the texture of many is medium-grained granitoid; such a texture suggests that they may have been intruded at moderate depth.

The rocks form dikes, sills, plugs, laccoliths, and stocks. These bodies range in size from apophyses a few feet in diameter to a large complex laccolithic mass exposed between Cactus Spring and Antelope Springs, herein named the Roller Coaster laccolith for exposures on Roller Coaster Knob. The laccolith is 8, and possibly 10, miles long and more than 3 miles wide. Only the larger intrusive masses are shown on plate 1. Probably more than 100 additional small isolated masses occur.

Most, if not all, of the larger masses are composite, and it is within them that the relative age of the various rock types has been established. North of the Wellington Hills, for example, the sequence of intrusion is low-silica porphyritic granodiorite followed by melanodiorite, biotite lamproyphyre, a high-silica variety of porphyritic granodiorite, and finally coarse-grained porphyritic rhyolite. In the Roller Coaster pluton the oldest rocks are aphanitic low-silica rhyodacites similar in composition to the low-silica variety of porphyritic granodiorite. These are intruded in turn by high-silica porphyritic granodiorite, quartz latite porphyry, rhyolte, and coarse-grained porphyritic rhyolite. Other rock types, gradational between these, may also occur among the aphanitic and fine-grained phases which cannot be accurately identified. Small isolated dikes and apophyses crop out around the peripheries of the larger masses and are presumed to be the same age as rocks of similar composition in the composite masses.

The intrusive rocks postdate the tuff of White Blotch Spring, and they probably predate the Fraction Tuff. The intrusive masses very possibly are equivalent in age to the lavas of nearly identical composition that flank the range and occur in adjacent areas.

Most of the intrusive masses are extensively propylitized and large areas of some are highly altered; unaltered rocks are exceptional. This alteration tends to obscure intrusive contacts between petrographically similar rocks, and it renders the recognition of subtle differences in texture and mineralogy very difficult. In certain bodies, where alteration is sufficiently mild to permit distinction of separate phases, it is apparent that too many phases occur to be shown on the geologic map. Similarly, other more altered masses, even if they could be differentiated by detailed field study, could not be shown at the scale of plate 1. For this reason many intrusive masses are shown as single cartographic units although several rock types are present. The rocks are divided into three broad units: (1) rocks of basic and intermediate composition, (2) rhyolite, and (3) coarse-grained porphyritic rhyolite.

Similar intrusive rocks occur in isolated masses in the Kawich and Reville Ranges. They are approximately the same age as the rocks in the Cactus Range and are included in the same cartographic unit.

Rocks of Basic and Intermediate Composition

Rocks in the basic and intermediate composition group include melanodiorite, biotite lamprophyre, low-silica granodiorite, rhyodacite, high-silica granodiorite, and quartz latite porphyry. Of these, only the quartz latite porphyry is mapped separately; the remaining rocks are mapped together and subdivided on the basis of texture into aphanitic and phaneritic varieties.

Melanodiorite.—The melanodiorite is dark gray to black and porphyritic; it occurs as dikes and plugs in the composite stock north of Wellington Hills and as irregular-shaped small apophyses and dikes which intrude the tuff of White Blotch Spring in the northern part of the range. The total area of all exposures probably does not exceed 1 square mile. The rock contains sparse euhedral phenocrysts of clinopyroxene and plagioclase as much as 33 mm in length and glomeroporphyritic clots composed mostly of clinopyroxene as much as 7 mm in diameter. The phenocrysts are set in a diabasic groundmass in which interstices between abundant plagioclase laths are filled with alkali feldspar, clinopyroxene, biotite, and iron oxide. The groundmass plagioclase laths are about 0.15–1 mm long. The finer grained varieties closely resemble basalt.

The typical melanodiorite contains strongly zoned labradorite (50 percent), augite (25 percent), and biotite, alkali feldspar, and iron oxide (about 6 percent each). Some rock is conspicuously porphyritic with euhedral labradorite and augite in a fine-grained granular groundmass. Alkali feldspar is more abundant in the groundmasses of the conspicuously porphyritic rocks than in the more equigranular diabasic varieties. The composition of zones in plagioclase ranges from calcic labradorite in the cores to albite in thin outer rims. Although chemical data are not available, the granular, porphyritic varieties are probably gradational between melanodiorite and granodiorite; the diabasic textured varieties are gabbroic in composition. Thus, a considerable range in composition is indicated for the melanodiorite.

Biotite lamprophyre.—The biotite lamprophyre is medium gray and has conspicuous abundant plates of biotite and subhedral to anhedral alkali feldspar in a medium-grained (about 1.5 mm) matrix composed predominantly of andesine, partly uralitized clinopyroxene, and magnetite. The large biotite and alkali feldspar grains are poikilitic; the biotite grains enclose euhedral andesine crystals, and the feldspar grains enclose euhedral to subhedral grains of andesine, unaltered clinopyroxene, biotite, and magnetite. The rock occurs only in the composite stock north of Wellington Hills.

Low-silica granodiorite.—The low-silica granodiorite is dark gray to black, porphyritic, and not easily distinguished from melanodiorite. It is similar to melanodiorite in abundance and areal distribution, and it also makes up a minor border phase of the large mass located northwest of the Antelope Springs (patterned area, pl. 1). In addition, it is similar in composition and is gradational in texture with the rhyodacite intrusive rock described below. Most of the rock has seriate texture with grains ranging in size from small microlites to crystals about 1 mm long. The larger crystals consist of andesine, augite, hornblende, and magnetite. Mafic phenocrysts are partly uralitized and chloritized. The groundmass is a granular aggregate composed of sodic plagioclase, alkali feldspar, magnetite, quartz, and secondary uralite and chlorite.

Rhyodacite.—Rhyodacite forms plugs, dikes, sills, and most of the larger Roller Coaster laccolith. These masses, which together make up about 15 square miles of outcrop, are distributed throughout the range but are most common in the south and central parts. Rhyodacite is the oldest rock in the Roller Coaster laccolith, which probably is a single large floored and roofed mass that was divided into northwest and southeast segments by intrusion of younger discordant masses of porphyritic granodiorite.

All the rhyodacite, except a few small isolated plugs and dikes, has been propylitically altered. The alteration ranges from incipient albitization of plagioclase and (or) chloritization of biotite and hornblende to complete replacement of phenocrysts and groundmass by chlorite, calcite, albite, epidote, and iron oxide in varying combinations and proportions.

The color of propylitically altered rhyodacite ranges from olive green through light greenish gray to dark greenish gray. Less altered rhyodacites are dark gray, black, or dark purple, and they commonly contain small flecks or spots of secondary green chlorite and (or) epidote. Most rocks weather to greenish brown. Flow alinement of crystals is common and upon weathering gives rise to an accentuated planar structure.

Thirty thin sections of rocks, collected from the Roller Coaster and satellite masses, show considerable petrographic variations. In most rocks plagioclase is the dominant phenocryst; quartz phenocrysts are not sparse, but generally only a few grains occur per thin section; alkali feldspar phenocrysts are sparse or absent. The mafic minerals are mostly altered, but the morphology of replaced grains commonly permits an estimate of original phenocryst assemblages. Some prealteration mafic mineral assemblages are (1) biotite-hornblende (either may dominate), (2) biotite-hornblende-pyroxene (any one may dominate), (3) clinopyroxene-hornblende, and (4) clinopyroxene. Common accessory minerals are magnetite, apatite, zircon, and allanite. Groundmass textures are hyalopilitic, pilotaxitic, trachytic, or granular. Plagioclase is the principal groundmass constituent and is accompanied by biotite, hornblende, and iron oxide. In general, the isolated small intrusive masses tend to be less silicic than the large masses.

High-silica granodiorite.—The high-silica granodiorite is medium gray to greenish gray and porphyritic, and it forms very irregular, mostly discordant masses. These occur in a band extending from 1 mile north of Roller Coaster Knob southwestward to Wellington Hills (patterned area, pl. 1), where it makes up the youngest intermediate intrusive rock. Most of the rock has been weakly propylitized and deuterically altered, but it is distinctly less altered than the rhyodacite just described. It is massive, nonfoliate, and fine to medium grained. Where the rock is fine grained, it is conspicuously porphyritic, carrying phenocrysts of plagioclase, hornblende, and pyroxene. Where it is coarse grained, it is only slightly porphyritic. The rock contains 40–50 percent plagioclase (andesine), about 10 percent hornblende, 10–16 percent quartz, 15–20 percent alkali feldspar, minor biotite, and magnetite. Alkali feldspar and quartz are commonly micrographically intergrown and are generally restricted to interstices between plagioclase and hornblende or pyroxene. The rock is gradational with low-silica granodiorite and is distinguished from it by its more conspicuous quartz. Some rocks gradational between low-silica and high-silica granodiorite contain as much as 20 percent augite. These rocks also contain less alkali feldspar than is typical for the high-silica phase.

Quartz latite porphyry.—Dikes, plugs, and laccoliths of quartz latite porphyry are exposed in a broad northwest-trending band in the north half of the Cactus Range. The bulk of the quartz latite occurs in a large intrusive mass near Sleeping Column Canyon. This mass has a flat-lying to gently dipping roof (fig. 7)

FIGURE 7.—Outcrops of quartz-latite porphyry laccolith (Tlp) and tuff of White Blotch Spring (Tws). The strata are repeated by normal faults that displace the rocks down toward the viewer. Both rocks are highly altered at the contact. Light dashed lines indicate formation contacts. Solid lines outline topography. Heavy dashed lines indicate faults. Fault traces are dotted where concealed behind hills; U, upthrown side; D, downthrown side. View to the northeast into the Cactus Range from a point 2 miles southwest of Urania Peak.

from which many dikes and small apophyses extend upward (not visible in fig. 7). The mass is inferred to be a laccolith, although its true shape is unknown because of extensive faulting. Like other large intrusive bodies in the Cactus Range, this laccolith is composite. Part is composed of plagioclase-rich quartz latite, in which alkali feldspar makes up less than 5 percent, and part is composed of coarse-grained porphyritic rhyolite, in which alkali feldspar is the dominant phenocryst. These rocks are not shown separately on plate 1.

In the northern part of the range the quartz latite porphyry is unaltered to weakly altered. Where unaltered, the rock is gray; where altered, it is green or greenish gray as a result of secondary chlorite and epidote. The freshest rocks contain about 40 percent plagioclase (commonly glomeroporphyritic clots of andesine), 8–10 percent biotite, 4–9 percent altered pyribole, 2–5 percent conspicuous large alkali feldspar (as large as 2 cm), 10 percent quartz, and 2.5 percent magnetite. The groundmass is mostly fine grained and felsic. The quartz latite porphyry is distinguished from other intrusive rocks by the sparse large and conspicuous alkali feldspar and quartz phenocrysts. Porphyritic rhyolite phases included in this unit are similar to those described below.

Rhyolite

The rhyolite is white to light gray, crystal poor, massive to flow layered, and generally silicified. It forms several large plugs and numerous small dikes and plugs. Phenocrysts comprise less than 5 percent of the rock and are predominantly quartz and alkali feldspar with minor plagioclase and biotite. The groundmass is felsic and is cryptocrystalline to fine-grained saccharoidal.

Coarse-Grained Porphyritic Rhyolite

Coarse-grained porphyritic rhyolite crops out discontinuously over about 2 square miles in the northern Cactus Range. Most of the rock is part of a gently dipping body that has a flat-lying roof. Contacts with enclosing tuffs are marked in many outcrops by altered zones several feet thick. The tuff of White Blotch Spring is the youngest rock intruded by the porphyry in this area.

The coarse-grained porphyritic rhyolite is light brown to light orange brown and weathers to light-brown grus-covered rounded knobs and hills that are not easily distinguished from outcrops of tuff of White Blotch Spring. Phenocrysts makeup 30–75 percent of the rock and consist of quartz (20–30 percent) and plagioclase (30–40 percent) that range in size from 1 to 5 mm, and alkali feldspar (40–50 percent) as much as 2 cm long. Biotite and magnetite are the only mafic minerals, and they constitute less than 1 percent of the phenocrysts. The groundmass is aphanitic and is composed predominantly of equigranular quartz and alkali feldspar. The abundance of quartz and the occurrence of pink to pale-orange alkali feldspar phenochysts are distinguishing mineralogical characteristics.

An impressive system of east- and northwest-trending dikes, some of which are as much as 6 miles long, transects the Cactus Range south of Cactus Spring. The dikes are composed predominantly of light-gray to light brown highly porphyritic rhyolite that is similar in general appearance and mineralogy to the rock just described. Many of the porphyritic dikes have thin selvages of white fine-grained flow-laminated rhyolite that grade within short distance (a few inches to 2 ft) into highly porphyritic rock. Where the dikes are narrow, they are composed entirely of white, crystal-poor rhyolite.

Chemistry

Chemical analyses and norms of 18 intrusive rocks in the Cactus Range are given in table 9. Samples 1–2 and 11–13 are of phaneritic rocks, ranging from quartz latite porphyry to melanodiorite, which are only incipiently or mildly altered in contrast to samples 3–7, 9, and 14–15, which are highly propylitized. This contrast in degree of alteration is reflected by the presence of less than 0.25 percent CO_2 in the first group and 0.9–3.2 percent CO_2 in the second group.

Chemical variation among these rocks is shown in figures 8 and 9. The trend lines are drawn on the figures as best visual fits to the points representing rocks with negligible CO_2 (dots). Tielines extend from the open circles to positions corresponding to ratios calculated after the reported CaO was reduced by an amount sufficient to form calcite from all the reported CO_2. Although the magnitude of shift between each pair of points is large for some rocks with high CO_2 contents, the direction of shift so nearly parallels the trend line that it is impossible to unambiguously determine whether CaO should be corrected for CO_2. There is, nevertheless, a slightly better fit of the trend line to the open circles than to the positions at the ends of the tielines; this fit suggests that calcium was not introduced along with CO_2 during the alteration process. On the basis of this relationship, the normative percentages for the altered rocks reported in table 9 were calculated assuming no addition of CaO. Water and CO_2 were removed and the analyses were recalculated to 100 percent before the norm was calculated. When the norm is calculated in this way, corundum appears in only three rocks (samples 9, 17, 18, table 9), whereas corundum will appear in the norms of all the altered rocks if the percentage of CaO is reduced by an amount sufficient to form calcite from all Co_2.

The general absence of corundum in the reported norms is assumed to indicate that only minor amounts of alkalis were lost during the alteration process. This conclusion is also supported by comparison of partial molecular norms (fig. 10) for unaltered and altered pairs of rocks. For example, sample 16 is of quartz latite porphyry that shows partial alteration of biotite phenocrysts to chlorite, hornblende to chlorite and epidote, and plagioclase to sericite. The rock contains no secondary calcite or albite and is considered to have undergone only incipient propylitic alteration. In contrast, sample 14 is of quartz latite porphyry that is completely altered to an assemblage of albite, quartz, sericite, calcite, epidote, and iron oxide. The partial molecular norms of the two rocks plot very close together when CO_2 is considered a mobile component (fig. 10). A similar comparison can be made between samples 5 and 6, which are rhyodacite from the Roller Coaster laccolith southeast of Cactus Springs. Both rocks are altered and both contain CO_2, but sample 5 is much more intensely altered. If the partial molecular norms for these two rocks had been calculated after correcting the CaO contents for CO_2, the points would be widely separated in figure 10. These comparisons

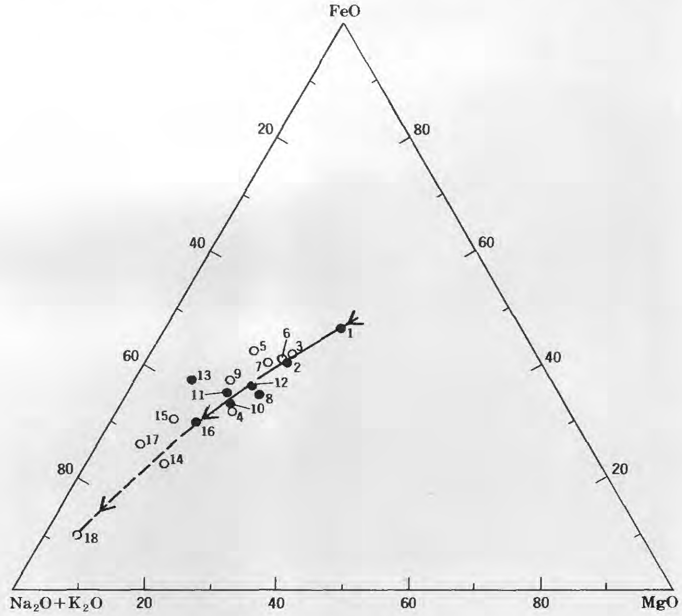

FIGURE 8.—Plot of $FeO:Na_2O+K_2O:MgO$ ratios of intrusive rocks from the core of the Cactus Range. Open circles correspond to rocks having appreciable CO_2; solid circles, to rocks having little or no CO_2. Numbers refer to sample numbers in table 9. Arrows point in direction of more siliceous and, in general, younger rocks. The dashed extension of the trend line is based on a single analysis of weakly altered porphyritic rhyolite (sample 18, table 9).

TABLE 9.—*Chemical analyses and norms of fresh and propylitically altered intrusive rocks in the core of the Cactus Range*

[Analyses by P. L. D. Elmore, S. W. Botts, G. W. Chloe, Lowell Artis, and H. Smith, by rapid method (Shapiro and Brannock, 1962). Norms determined from chemical analyses recalculated to 100 percent minus H_2O+CO_2]

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Field No.	CS-57	CS-61	CS-299	CS-227A	CS-83	CS-93	M-198	CS-291	CS-91	CS-383	CS-105	M-214	M-205	CS-379	CS-244	CS-371	CS-353	CS-76
Laboratory No.	162051	160949	162054	162057	164507	160951	160966	162052	164506	162861	160952	160968	160967	162858	162055	162857	162866	160950
Chemical analyses																		
SiO_2	50.2	58.1	53.8	56.1	57.1	59.1	59.3	60.4	61.5	63.5	61.4	61.7	62.9	62.8	65.3	68.1	69.4	67.2
Al_2O_3	17.7	16.3	16.7	17.6	15.9	16.1	16.2	16.9	16.5	14.1	16.1	16.2	16.1	15.7	15.5	13.3	15.6	16.1
Fe_2O_3	4.9	3.8	4.5	4.3	3.5	2.9	2.7	3.0	4.7	3.7	3.4	3.1	3.0	2.0	2.7	2.9	2.6	1.2
FeO	4.9	2.8	2.6	2.8	2.6	2.8	3.5	2.0	1.4	1.5	2.2	2.6	2.2	1.1	1.1	1.0	.40	.93
MgO	5.3	3.3	3.4	2.1	2.2	2.7	2.7	2.7	1.6	2.4	2.3	2.7	1.1	1.5	1.0	1.6	.67	.55
CaO	9.2	6.1	7.2	6.5	6.2	6.0	5.4	5.2	4.6	3.6	4.0	4.8	4.4	3.6	3.9	2.4	1.9	1.4
Na_2O	3.2	2.8	3.4	3.0	2.7	2.6	2.8	3.7	2.4	2.9	3.4	3.2	3.3	3.8	3.1	3.1	2.8	3.5
K_2O	2.3	3.1	2.5	3.2	2.9	2.7	3.2	2.4	3.1	4.4	4.2	3.7	3.8	4.6	3.8	4.0	4.4	6.0
H_2O-	.20	.32	.30	.18	.23	.29	.22	.88	.54	.33	.28	.17	.17	.17	.32	.44	.53	.26
H_2O+	.92	1.6	1.30	1.4	2.1	1.9	1.8	1.7	2.1	1.8	1.9	.94	1.4	1.6	1.0	1.6	1.3	1.1
TiO_2	1.3	.78	.95	.86	.74	.66	.73	.73	.79	.69	.69	.84	.69	.48	.48	.45	.42	.31
P_2O_5	.58	.39	.52	.32	.39	.27	.20	.35	.42	.36	.41	.33	.31	.22	.21	.20	.00	.12
MnO	.15	.12	.08	.08	.11	.10	.10	.09	.11	.09	.09	.10	.09	.08	.10	.04	.02	.08
CO_2	.07	.21	2.10	1.6	3.2	1.8	1.6	<.05	.12	.16	.07	<.05	<.05	1.2	1.2	<.05	<.05	.90
Total	100	100	99	100	100	100	101	100	100	100	100	100	100	100	100	99	101	100
Norms																		
Q		14.4	7.8	11.6	16.6	16.5	15.5	16.1	25.4	20.8	15.2	15.8	19.6	15.3	24.4	28.7	31.8	23.6
C									1.9								2.8	3.8
or	13.6	18.8	15.4	19.5	18.2	16.2	19.5	14.6	18.9	26.7	25.3	22.0	22.9	28.3	23.1	24.3	26.5	36.8
ab	27.1	24.3	30.1	26.2	24.2	22.9	24.5	32.1	20.9	25.2	29.3	27.3	28.5	33.5	27.0	27.0	24.1	30.8
an	27.2	23.9	24.0	25.9	24.1	29.1	22.9	23.0	20.7	12.8	16.6	19.1	18.3	12.7	17.7	10.9	9.6	.5
wo	6.2	1.5	4.1	2.2	2.4		1.4	.5		1.3	.2	1.2	.8	1.8	.4			
en	9.3	8.4	8.9	5.4	5.8	7.0	6.9	6.9	4.1	6.1	5.8	6.8	2.8	3.9	2.6	4.1	1.7	1.4
fs	2.2	1.0		.3	.9	1.9	3.3	.2			.3	1.0	.6					.4
fo	2.8																	
fa	.7																	
mt	7.1	5.7	6.2	6.4	5.4	4.4	4.0	4.5	2.7	3.2	5.0	4.5	4.4	2.5	2.6	2.1	.1	1.8
hm			.5						3.0	1.6				.3	1.0	1.5	2.6	
il	2.5	1.5	1.9	1.7	1.5	1.3	1.4	1.4	1.5	1.3	1.3	1.6	1.3	1.0	.9	.9	.8	.6
ap	1.4	1.0	1.3	.8	1.0	.7	.5	.9	1.0	.9	1.0	.8	.8	.5	.5	.5		.3

Sample, locality, and description

[Numbers following mineral names are percent of total phenocrysts]

1. About 2.5 miles southeast of Antelope Peak, Cactus Range. Medium-grained melanodiorite composed of strongly zoned plagioclase (sodic labradorite) 56, clinopyroxene 24, magnetite 5; 5 percent each of interstitial alkali feldspar and biotite and 4 percent secondary chlorite and sericite.
2. About 2.5 miles southwest of Antelope Peak, Cactus Range. Low-silica granodiorite; rock contains phenocrysts of plagioclase, clinopyroxene, hornblende, and magnetite in a very fine-grained groundmass composed predominantly of alkali feldspar, quartz, plagioclase, and magnetite.
3. Incipiently altered rhyodacite; plagioclase phenocrysts are fresh; secondary calcite, chlorite, and magnetite have completely replaced pyroxene and partly replaced hornblende; groundmass is a delicate felt of feldspar and iron oxide with small patches and veinlets of secondary calcite.
4. Small plug 1 mile southwest of Cactus Spring. Weakly propylitized low-silica granodiorite; mafic minerals are completely replaced by calcite, chlorite, and iron oxide; plagioclase phenocrysts (sodic labradorite) are fresh and commonly glomeroporphyritic; groundmass is pilotaxitic with andesine microlites and interstitial alkali feldspar.
5. Small satellitic intrusive mass west of Roller Coaster laccolith 1.5 miles southeast of Urania Peak. Intensely propylitized rhyodacite; principal secondary minerals are chlorite, magnetite, and abundant calcite (shown by high CO_2 content); minor secondary quartz; no epidote and only minor albite; mafic phenocrysts are completely replaced and plagioclase phenocrysts partly altered to calcite and sericite; groundmass is completely altered.
6. Roller Coaster laccolith 3.5 miles southeast of Cactus Spring. Moderately propylitized rhyodacite; principal secondary minerals are calcite, chlorite, epidote, magnetite, and clay; biotite, pyroxene, and hornblende are completely replaced, plagioclase phenocrysts and groundmass laths are mostly fresh; no apparent albitization.
7. Roller Coaster laccolith at Antelope Springs. Moderately propylitized rhyodacite; principal secondary minerals are chlorite, calcite, and clay; mafic minerals are completely replaced; no secondary epidote or albite.
8. About 1.5 miles south of O'Briens Knob, Cactus Range. Black vitric dacite lava containing 30 percent phenocrysts consisting of 70 percent plagioclase (an_{50}) and 30 percent augite, brown hornblende, and magnetite in a ratio of 2:2:1 and a trace of biotite set in a glassy groundmass containing tiny blebs of magnetite and small laths of plagioclase.
9. Thin sill 3 miles southeast of Urania Peak. Intensely propylitized and weakly pyritized rhyodacite; entire rock is altered to secondary albite, epidote, sericite, chlorite, quartz, iron oxide, and pyrite; notable lack of secondary carbonate.
10. About 2.8 miles southeast of Urania Peak. Weakly altered quartz latite porphyry.
11. About 1.2 miles west of Antelope Peak, Cactus Range. Granodiorite similar to 12.
12. About 1.2 miles southwest of Roller Coaster Knob, Cactus Range. Granodiorite similar to 13 with 40 percent plagioclase (an_{32}), 28 percent alkali feldspar, 10 percent hornblende, 16 percent quartz, 3 percent partially chloritized biotite and minor clinopyroxene, magnetite, sphene, and apatite.
13. About 1.5 miles northwest of Antelope Springs, Cactus Range. Greenish-gray porphyritic granodiorite with phenocrysts of plagioclase, hornblende, clinopyroxene, biotite, and magnetite in a medium-grained matrix composed predominantly of quartz, alkali feldspar, and plagioclase; biotite grains are wholly or partially chloritized.
14. About 2 miles south-southeast of Urania Peak. Highly propylitized quartz latite porphyry; rock is altered equivalent(?) of sample 16 but contains less quartz; principal secondary minerals are albite, epidote, sericite, calcite, chlorite, quartz, and magnetite; quartz phenocrysts are unaltered; alkali feldspar phenocrysts are partly replaced by sericite, epidote, and calcite; all other primary minerals are completely pseudomorphed.
15. About 2 miles south-southeast of Cactus Peak. Light-gray to light-greenish-gray quartz latite porphyry; 40 percent phenocrysts consisting of plagioclase 70, quartz 9, biotite 8, altered hornblende(?) 9, and minor alkali feldspar and magnetite in a fine-grained groundmass composed predominantly of quartz, alkali feldspar, and plagioclase.
16. About 1.2 miles southwest of Urania Peak. Quartz latite porphyry; 38 percent phenocrysts consisting of andesine 70, biotite 11, quartz 11, and minor alkali feldspar, pyrobole, and magnetite in a felsic fine-grained granular groundmass. Note anomalously high silica content—some of granular quartz in groundmass may be secondary; silicification is locally intense in adjacent terrain.
17. South side Sleeping Column Canyon 3 miles west of Cactus Spring. Quartz latite porphyry; about 30 percent phenocrysts which are, in order of decreasing abundance, plagioclase, alkali feldspar, biotite, and quartz in a granular groundmass of the same minerals plus magnetite. Rock is weakly argillized and may be weakly silicified.
18. About 2.5 miles south-southwest of Cactus Peak. Coarse-grained porphyritic rhyolite.

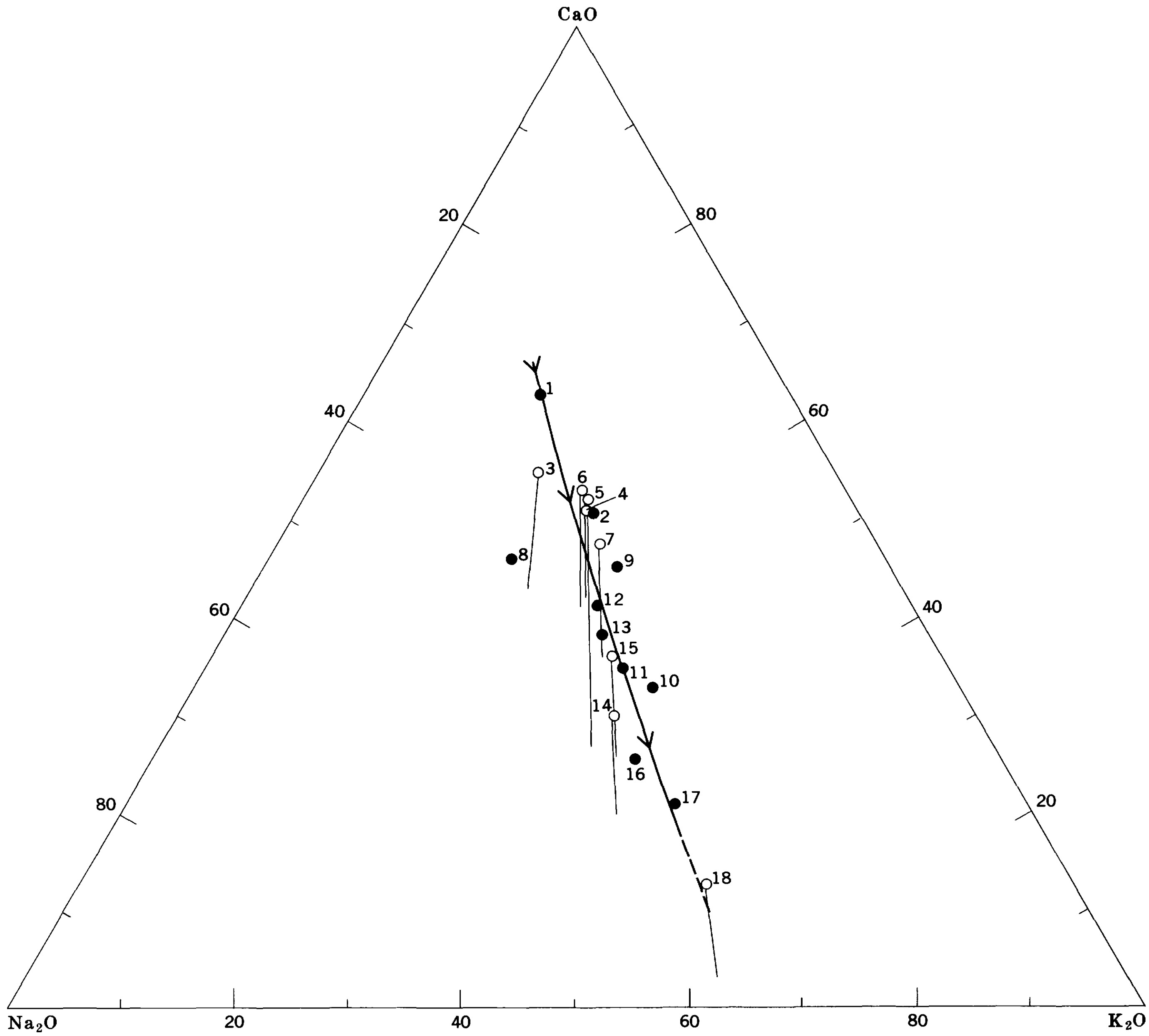

FIGURE 9.—Plot of CaO : Na_2O : K_2O ratios of intrusive rocks from the core of the Cactus Range. Open circles correspond to rocks having appreciable CO_2; solid circles, to rocks having little or no CO_2. Numbers refer to sample numbers in table 9. Arrows point in direction of more siliceous and, in general, younger rocks. The dashed extension of the trend line is based on a single analysis of weakly altered porphyritic rhyolite (sample 18, table 9). Tielines extend from the open circles to positions corresponding to ratios calculated after the reported CaO was reduced by an amount sufficient to form calcite from all the reported CO_2.

indicate that only minor gains or losses of alkalis and calcium occurred during propylitic alteration. This stability is in sharp contrast with a rather high mobility of sodium and calcium recognized in the silicic and argillic or "vein-forming" type of alteration based on unpublished analyses of rocks from the Cactus Range.

The arrows shown on the trend lines in figures 8 and 9 point in the direction of the more high-silica rocks. The positions of points along these lines correspond to a general decrease in age in the direction of the arrows. The rocks lowest in silica are from the early intrusive rocks in the Wellington Hills area and from the Roller Coaster laccolith. The progression passes through the low-silica variety of granodiorite, then through quartz latite porphyries, and finally to the porphyritic rhyolite, which is the youngest intrusive

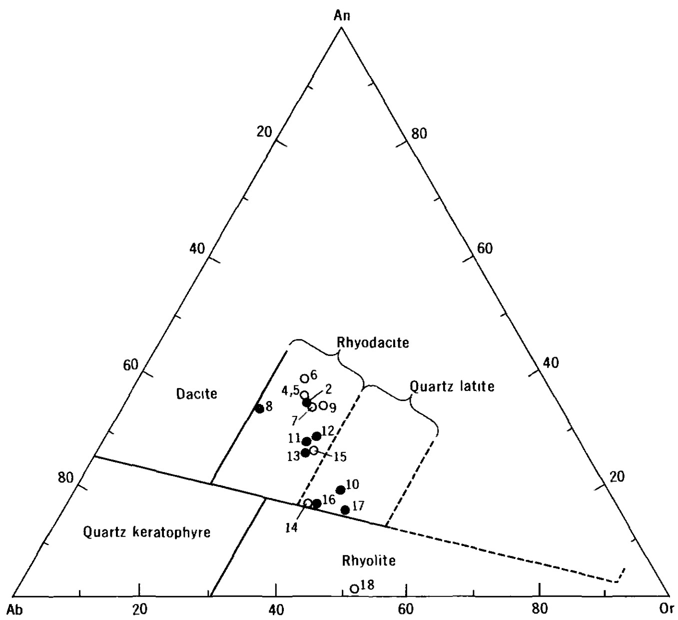

FIGURE 10.—Plot of normative albite-anorthite-orthoclase ratios of intrusive rocks from the core of the Cactus Range. Solid circles are plots of relatively unaltered rocks with little or no CO_2; open circles correspond to rocks with appreciable CO_2 and the norms of these rocks were calculated considering CO_2 as a mobile component. Numbers refer to sample numbers in table 9. Fields are from O'Connor (1965).

rock in the central core of the range. The concordance of this chemical trend with age is consistent with the interpretation that these rocks have a common parental magma.

RHYOLITE OF WHITE RIDGE AND TUFFACEOUS ROCKS

A small volcano from which ash-fall tuff and rhyolite lava were erupted is centered on White Ridge about 2.5 miles southeast of Cedar Pass in the Kawich Range. Stratified ash-fall tuff, which accumulated around the center to distances of a few miles, represents the earliest record of volcanic activity at the White Ridge volcano. The tuff was deposited on an erosional surface of considerable relief developed on dacite and andesite lava. The tuff is white to light gray and even bedded, and it contains sparse small phenocrysts of alkali feldspar, quartz, and plagioclase. Locally, the tuff is fused to greenish-gray and dark-gray vitrophyre adjacent to rhyolite intrusive masses that crop out in the center of the volcano and in several radial dikes. These fused zones are no wider than 50 feet. Other fused or welded bedded tuffs occur at distances of as much as 1 mile from the nearest visible intrusive mass. These tuffs are red brown to orange brown and contain collapsed vitrophyric pumice lapilli. They apparently accumulated very rapidly near the vent and retained sufficient initial heat to permit welding. Similar welded bedded tuffs around volcanic vents have been recognized by R. L. Smith (oral commun., 1964), who has suggested the term "agglutinate" for such tuffs.

The intrusive rhyolite is white to pale yellow, crystal poor, flow laminated, and locally brecciated. The only rocks that can be identified as lavas are exposed west of Cedar Pass, 5 miles northwest of the volcano. It is not known whether these were extruded from the volcano or from other unrecognized vents. The lavas are slightly richer in crystals than is the intrusive rhyolite. Alkali feldspar and quartz are the predominant phenocrysts; plagioclase and biotite occur in lesser amounts.

Rocks occupying the same position as the rhyolite of White Ridge crop out in both the Belted and Cactus Ranges. Although no genetic or absolute age equivalence is inferred for these widely separated rocks, they are mapped as the same cartographic unit as the rhyolite of White Ridge and associated tuffaceous sedimentary rocks. The rhyolite in the Belted Range is 50–100 feet thick and overlies about 30 feet of well-bedded ash-fall tuff which, in turn, overlies quartz latite lava. The rhyolite is crystal poor, pink to gray, and flow laminated, and at the base it contains a thick vitric flow breccia. About 4 miles southeast of these exposures ash-fall tuff and tuffaceous sedimentary rocks, having a combined thickness of about 500 feet, crop out. These strata rest on lavas of intermediate composition and are overlain conformably by Fraction Tuff. The strata are best exposed near White Saddle Pass, where the bulk of the rock consists of vitric to slightly devitrified ash-fall tuff. Tuffaceous sedimentary rocks containing fragments of dacite, rhyolite, quartzite, and chert crop out near the base. The rocks are commonly cross-stratified and range in color from pastel shades of brown and green to white.

About 400 feet of well-stratified mudstone, sandstone, gravel, conglomerate, and minor ash-fall and ash-flow tuff is exposed in the northwestern Cactus Range. These strata rest on dacite lavas and are overlain by Fraction Tuff and post-Fraction rhyolites. They dip about 50° W. and are repeated several times by faulting. Locally they are separated from the underlying lavas by remnants of quartz-bearing, plagioclase-rich, biotite-rich, quartz latitic welded tuff. This tuff probably correlates with the dacite vitrophyre of Ransome (1909), which is nearly identical with it and which occupies the same stratigraphic position. Ransome (1909, p. 64) noted the chemical similarity between the tuff (dacite vitrophyre) and the underlying dacite lavas and suggested that the two rocks are of nearly the same age. The present authors share this opinion and interpret the tuff as a late eruptive phase of igneous activity of dominantly intermediate composition. The sedimentary rocks are brown, greenish brown, reddish gray, and pastel shades of yellow and pink. The lighter colors are characteristic of zeolitized, silicified, or argillized rock. Pink pumice-rich massive air-fall(?) tuff is common in the upper part subjacent to the Fraction Tuff. Where the rocks rest on dacite lavas, they contain boulders and cobbles derived from the lavas. Much of the finer grained clastic rock is rich in plagioclase and biotite; this richness indicates that these clastic rocks were also derived in part from rocks of intermediate composition. The deposition of the clastic rocks is probably related to erosion of the central core of the Cactus Range as it was elevated following the extrusion of lavas and tuff of intermediate composition (p. 72).

A small exposure of brown sandstone rich in biotite and plagioclase is located 1 mile northeast of Antelope Springs. The sandstone dips about 15° E. and is overlain by minor zeolitized tuff and at least two flows of rhyolite of O'Briens Knob (p. 56). Biotite and plagioclase in the sandstone are unaltered. These fresh grains could not have been derived from any rocks now exposed in the central core of the Cactus Range. They are presumed to have been derived from tuffs or lavas that once covered the range and were stripped off when the range rose.

FRACTION TUFF AND RELATED ROCKS

FRACTION TUFF

The Fraction Tuff was first described by Spurr (1905), who named the unit the Fraction Dacite Breccia. The type area was given as the south half of the Tonopah mining district, where the rock overlies lavas of intermediate composition and underlies bedded tuffs and lake beds. Nolan (1930), realizing that the rock was not a dacite in composition, changed the name to Fraction Breccia. The Fraction Tuff is a major map unit in the project area, and in nearly all exposures it overlies intermediate lavas and underlies bedded tuffs or sedimentary rocks.

Distribution and Thickness

The known area of distribution of the Fraction Tuff extends from the Belted Range, where it is as much as 1,000 feet thick, to Tonopah, Nev., where it is at least 745 feet thick (Spurr, 1905). The thickest and best exposures in the project area are at Trailer Pass in the Cathedral Ridge caldera, where a composite measured section [1] indicates a thickness of about 7,200 feet. The tuff between Quartzite Mountain and Pahute Mesa has been faulted out or covered by younger strata, and its extent is therefore unknown. Thicknesses of 1,000 and 1,150 feet have been penetrated in two drill holes located about 30 miles south of Cathedral Ridge on the south flank of Pahute Mesa, and several hundred feet has been penetrated in a drill hole in northern Yucca Flat (W. J. Carr, oral commun., 1966). The tuff is absent from the vicinity of Coyote Cuesta and Triangle Mountain, where older lavas of intermediate composition are exposed, but several hundred feet is exposed north of Coyote Cuesta near Mellan. The rocks at Mellan are identical with those at Cathedral Ridge.

Ash-flow tuffs that are petrographically similar to the Fraction Tuff crop out on the northwest flank of the Cactus Range. These strata are mapped as Fraction Tuff (pl. 1), but the correlation is questionable. Common rock colors are light chocolate brown, charcoal gray, or salmon pink, none of which is characteristic of the Fraction elsewhere in the mapped area. Also, lithic fragments are sparse and those of metamorphic rocks are very rare.

In all the areas of outcrop there is evidence that Fraction Tuff was deposited on an erosional surface of considerable relief. The thinning of the Fraction toward Quartzite Mountain and at White Ridge probably indicates that these areas were topographically high during the period of Fraction Tuff eruption. In the Belted and Cactus Ranges the Fraction is locally separated from the underlying dacite lavas by 50–300 feet of tuffaceous clastic sedimentary rocks including coarse conglomerate containing well-rounded cobbles of pre-Tertiary quartzite and volcanic rocks; these rocks record an erosional interval of unknown duration. Subsurface investigations in the western part of the Tonopah mining district (Bastin and Laney, 1918; Nolan, 1935) have shown that the Fraction rests unconformably on lavas of intermediate composition, and ore-bearing veins are locally truncated by the tuff.

Lithology and Petrology

At Cathedral Ridge the Fraction Tuff is pinkish gray, pale brown, and light red; it weathers to pale brown, brown, and dark brownish gray. The tuff forms a prominent sequence of steep cliffs and slopes on Cathedral Ridge. The differences in hardness and weathering characteristics result from variations in degree of devitrification and argillic alteration rather than pronounced differences in the degree of welding. Pods and lenses of dark-gray to black vitrophyre, indicative of partial cooling breaks, occur at several intervals, and at least one vitrophyre can be traced the length of Cathedral Ridge. Thin zones of welded ash-fall tuff

[1] The lower approximately one-third part of the measured section is in a single fault block about 1 mile south of Trailer Pass; the upper two-thirds is in another block located about 2,000 feet south of the lower line of section. Covered intervals in the upper two-thirds may conceal small faults, and the total thickness, therefore, might be slightly in error. A gradual upward decrease in welding indicates that repetitions, if they do exist, are minor.

have also been recognized within the sequence in this area. Except for a nonwelded to poorly welded light-yellow zeolitized basal zone of variable thickness, this sequence of ash flows is densely welded and is interpreted as a compound cooling unit. South of Trailer Pass, however, at about 4,200 feet above the base, the tuff is very weakly welded and has a low bulk density. (See field No. Ttp–17, table 10.) In this locality a partial cooling break is inferred. The interval is poorly exposed and it is not known whether the poorly welded rock constitutes the upper or lower part of a cooling zone.

North of Wild Horse Draw in the Kawich Range, the formation loses its stratified appearance and weathers to massive, brown, devitrified outcrops without visible cooling breaks.

The assemblage of lithic fragments is a diagnostic feature of the Fraction Tuff throughout Cathedral Ridge, the Kawich Range, and at Tonopah. Indeed, it was the abundance of these fragments at Tonopah that led Spurr (1905) and others to consider the rock to be a breccia. The fragments, in order of decreasing abundance, are intermediate lavas, gneiss, schist, granite, and sedimentary rocks of probable Paleozoic age. At Cathedral Ridge the fragments increase in abundance and size from the base to the approximate middle of the section and remain fairly constant from the middle to the top. At the base of the section, fragments average less than 2 inches in diameter and make up less than 10 percent of the rock; near the middle they are commonly 10 inches long, rarely as much as 3 feet, and make up 20–30 percent of the rock. The increase in abundance of fragments upward in the section and the occurrence of metamorphic fragments indicate that the fragments were derived from the crust during the ascent of the Fraction magma and were not merely picked up by the tuff as it flowed over the ground surface. Pumice lapilli are common. They are flattened, black, and vitrophyric where the tuff is densely welded and white to light gray where it is weakly welded.

In the Belted Range the Fraction is 500–1,000 feet thick, and two cooling units are inferred to be present. The lowest unit is about 300 feet thick and has as much as 200 feet of nonwelded to partially welded light-gray tuff at base that grades upward to a weakly welded gray-tan top. The overlying unit is pale brown to gray brown and contains abundant dark-gray to black vitric pumice lapilli. This unit is partially welded at base, densely welded in the middle, and nonwelded at the top. The nonwelded top was deeply eroded prior to the deposition of overlying sedimentary rocks and is preserved in only a few localities. The entire sequence contains abundant lithic fragments of rhyolite and dacite and sparse fragments of gneiss and schist.

In the northern Cactus Range the rocks that are tentatively assigned to the Fraction Tuff include three cooling units totaling 450 feet in thickness. The lower cooling unit, about 100 feet thick, is pumice rich and light chocolate brown. The middle cooling unit consists of a basal white to pink nonwelded zone 50 feet thick, a pink shard-rich vitric densely welded zone 75 feet thick, and an upper partly welded vapor-phase

TABLE 10.—*Physical properties of Fraction Tuff and underlying lavas at Trailer Pass, Kawich Range, Nye County, Nev.*

[Analysts: E. F. Monk, W. H. Lee, and W. R. Eberle. All samples were thin rectangular slabs]

Lab. No.	Field No.	Rock type	Porosity (percent)	Dry bulk density (g/cc)	Grain density (g/cc)	Saturated bulk density (g/cc)	Magnetic susceptibility (10^6 cgs)	v_p longitudinal velocity (fps)	v_s Shear velocity (fps)	ν Poisson's ratio	*E* Young's modulus (10^6 psi)	*G* Shear modulus (10^6 psi)	*K* Bulk modulus (10^6 psi)
D700708	Ttp–1	Dacite lava	6.7	2.50	2.68	2.57	3,517	15,070	8,381	0.276	6.03	2.37	4.49
709	2	Latite lava	4.3	2.52	2.64	2.57	(1)	(1)	(1)	(1)	(1)	(1)	(1)
710	4	Welded tuff	6.3	2.46	2.63	2.53	254	13,497	7,840	.245	5.07	2.04	3.32
711	5	do	1.9	2.38	2.42	2.40	214	14,641	8,470	.249	5.74	2.30	3.81
712 [2]	6	Welded tuff, vitrophyre	1.7	2.38	2.42	2.39	223	12,502					
713	7	Welded tuff	9.0	2.36	2.59	2.45	146	14,155	8,142	.253	5.28	2.11	3.56
714	8	Welded tuff, vitrophyre	2.4	2.38	2.44	2.40	176	8,552	5,189	.209	2.09	0.86	1.19
715	9	Welded tuff	7.5	2.40	2.60	2.48	118	13,937	8,803	.168	5.85	2.51	2.94
716	10	do	10.1	2.34	2.60	2.44	22	12,891	7,258	.268	4.21	1.66	3.02
717	11	Welded tuff, vitrophyre	1.0	2.42	2.44	2.43	410	17,646	10,238	.246	8.52	3.42	5.59
718	12	Welded tuff	7.7	2.40	2.60	2.48	578	13,570	8,142	.219	5.22	2.14	3.10
719 [2]	13	do	6.5	2.45	2.62	2.51	304	12,262					
720 [2]	14	do	1.7	2.39	2.43	2.41	401	14,949					
721 [2]	15	do	7.7	2.37	2.57	2.45	916	13,254					
722 [2]	16	do	10.5	2.30	2.57	2.40	974	12,974					
723	17	do	27.7	1.77	2.45	2.05	331	12,285	6,898	.270	2.88	1.13	2.09
724	18	do	6.4	2.39	2.55	2.45	851	12,579	6,986	.277	4.01	1.57	3.00
725 [2]	19	Welded tuff, vitrophyre	3.0	2.38	2.46	2.41	596	11,562					
726	20	Welded tuff	12.5	2.25	2.57	2.37	609	10,827	6,723	.186	3.25	1.37	1.73
727	21	do	12.2	2.21	2.52	2.33	469	11,732	6,463	.282	3.19	1.24	2.44
728 [2]	22	do	17.5	2.08	2.53	2.26	548	9,293					
729 [2]	23	do	19.1	2.06	2.54	2.25	388	11,023					

[1] No sample received.
[2] S-wave indeterminable.

zone 25 feet thick. The upper cooling unit, about 150 feet thick, consists of completely devitrified partially welded charcoal-gray to pink tuff which is characterized by a distinctive clinkery aspect. The rocks contain 25–35 percent phenocrysts, which consist of subequal plagioclase, alkali feldspar, quartz, and accessory amounts of biotite, hornblende, allanite, and sphene. On the west flank of the range, 1 mile north of Kawich Road, these tuffs are at least 1,200 feet thick. An unknown thickness of similar tuffs is exposed on the south flank of the Goldfield mining district just west of the project area.

Petrographic studies of 16 thin sections from the measured section on Cathedral Ridge reveal mineralogical variation from plagioclase-rich, relatively mafic-rich quartz latite to alkali feldspar-rich, mafic-poor rhyolite. Modal data obtained from eight thin sections which represent the extremes of variation throughout the section together with modal estimates of the remaining eight thin sections are plotted in figure 11. The lowest specimen (sample 2) is quartz latite lava that crops out beneath the Fraction Tuff. This lava is very similar mineralogically to the tuffs directly above it. The tuffs are rich in zoned plagioclase and mafic minerals and poor in alkali feldspar. In the interval between samples 5 and 10, the rocks are poor in mafic minerals and contain approximately equal amounts of plagioclase and alkali feldspar. They are notably rich in quartz, which is the dominant phenocryst. Phenocryst assemblages in the rocks between samples 10 and 19 show wide variations, but in most of the rocks plagioclase is the dominant phenocryst and quartz averages about 30 percent. In these rocks, biotite is more abundant than in the underlying rocks, and hornblende is rare. Between samples 19 and 22 the rocks are rich in plagioclase and contain about 20 percent each of quartz and alkali feldspar. These rocks also contain less hornblende than biotite. In general, throughout the section plagioclase varies antithetically with alkali feldspar and sympathetically with biotite.

The Fraction Tuff exposed on the east flank of the Belted Range is similar petrographically to the alkali feldspar-rich, mafic-poor tuff that occurs in the interval between samples 5 and 10 in the section measured south of Trailer Pass on Cathedral Ridge (fig. 11).

Despite its varied phenocryst content, the Fraction Tuff can be distinguished from other tuffs in the region by (1) the lack of pyroxene even in mafic-rich varieties, (2) the presence of trace amounts of allanite, which is common also in the tuff of Wilsons Camp (see earlier pages), (3) the presence of plagioclase phenocrysts that generally show strong normal zoning and are commonly aggregates of several grains, and (4) by a distinctive assemblage of lithic fragments.

Chemical analyses and norms of six samples of Fraction Tuff are given in table 11. The tuffs are typically calc-alkalic. Corundum appears in the norm of all these rocks as an indication of their peraluminous character or of the leaching of alkalis. Petrographic studies showed that the amount of normative anorthite varies with the amount of modal plagioclase and that the amount of TiO_2 varies with the amount of modal sphene. A comparison of normative and model data is justified by a general parallelism of variations among analyzed specimens. Analyses 1 and 2 represent the approximate maximum mineralogical variation in the unit at the type area, and they are, therefore, assumed to approximate the maximum chemical variation. The tuff that crops out on the east flank of the Belted Range (sample 4) is chemically similar to the higher silica variety from the Cathedral Ridge (sample 1), but the latter rock has a slightly lower ratio of K_2O to Na_2O. These two rocks, plus a weakly altered sample of Fraction Tuff from the Belted Range and a sample of vitrophyre from the Cactus Range, plot in the rhyolite field; samples 2 and 3 plot in the quartz latite field (fig. 12).

Age

A Miocene age is indicated for the Fraction Tuff from a sample collected at Trailer Pass (table 5, sample 16). This age is compatible with that deduced by Spurr (1905) for the volcanic rocks that include the Fraction Breccia at Tonopah.

TUFFACEOUS CONGLOMERATE AND DEBRIS FLOWS

East of Cedar Pass and White Ridge in the Kawich Range, the Fraction Tuff is separated from older lavas and welded tuffs by a chaotic zone of very coarse clastic material, some of which is tuffaceous. In most areas the zone is thin, but just west of Cedar Pass it is as much as 400 feet thick. Because only the upper ash flows of the Fraction Tuff are known to overlie them, the clastic deposits are inferred to be interstratified with the Fraction Tuff (cross section *C–C′*, pl. 1). The deposits probably accumulated adjacent to the wall of the Cathedral Ridge caldera. The chaotic zone is composed of very crudely stratified beds of nontuffaceous debris flows, tuffaceous conglomerate, and massive tuffs rich in lithic fragments. Locally, the debris flows are composed of brecciated dacite or rhyodacite and elsewhere they are predominantly rhyolite. The tuffaceous conglomerates contain blocks of dacite or rhyolite as much as 100 feet long completely surrounded by tuff. Much of the tuff matrix is rich in crystals of plagioclase, quartz, alkali feldspar, hornblende, and biotite, an assemblage that is very similar to that of

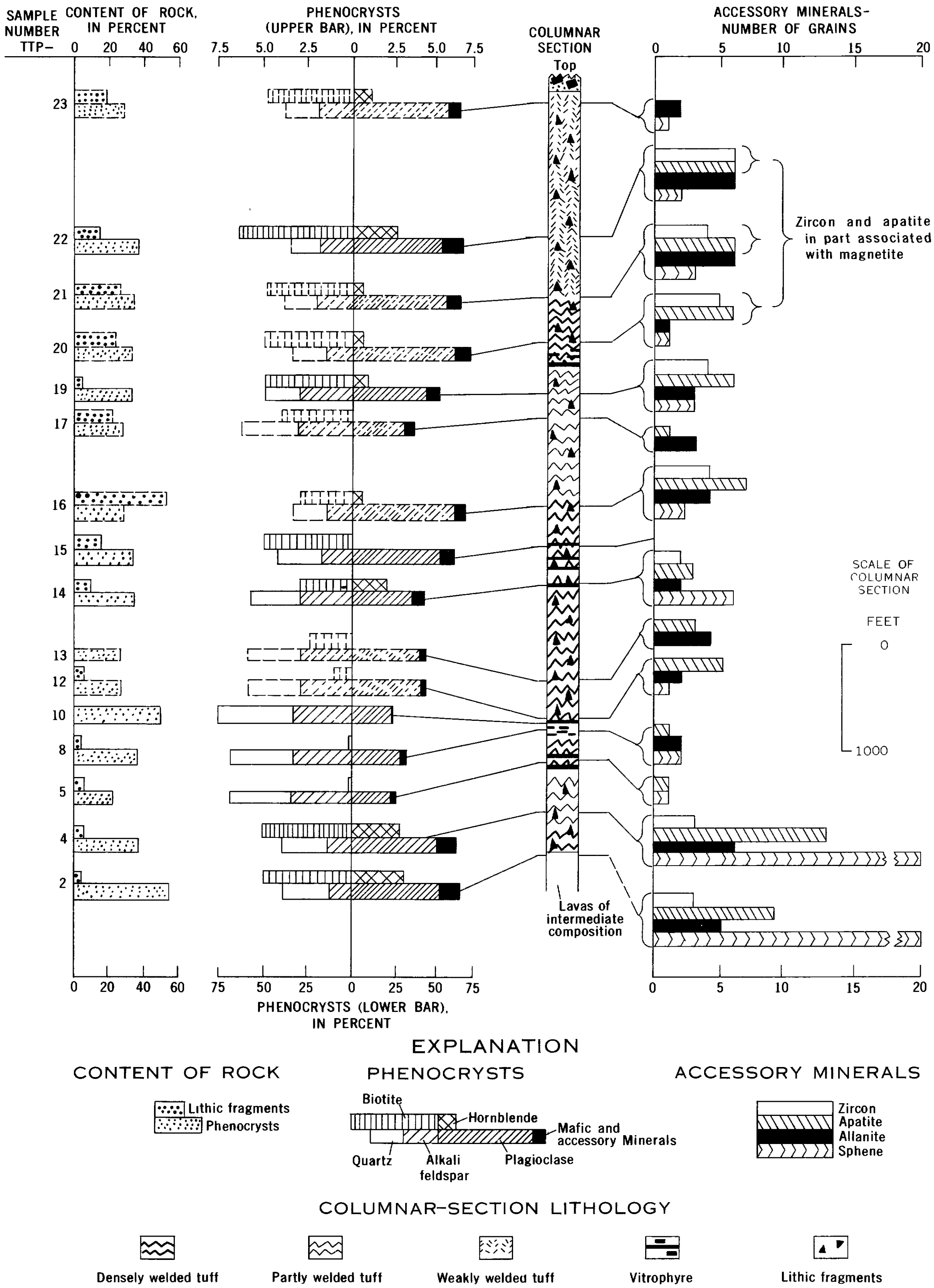

FIGURE 11.—Columnar section and thin-section petrography of Fraction Tuff near Trailer Pass in southern part of Kawich Range. Dashed bars and patterns indicate estimates. Petrography and compilation by F. M. Byers, Jr.

TABLE 11.—*Chemical analyses and norms of Fraction Tuff, rhyolite of O'Briens Knob, and andesite of Stonewall Flat*

[Analyses by P. L. D. Elmore, S. W. Botts, G. W. Chloe, Lowell Artis, and H. Smith, by rapid method (Shapiro and Brannock, 1962). Norms determined from chemical analyses recalculated to 100 percent minus H_2O+CO_2]

Unit	Fraction Tuff						Rhyolite of O'Briens Knob					Andesite of Stonewall Flat
Sample	1	2	3	4	5	6	7	8	9	10	11	12
Laboratory No	160974	160975	160976	160720	160724	160955	160723	160977	160954	162053	160956	162056
Field No	QM-3	QM-13	QM-17	BP-23	BP-33	CP-52	BP-32	QM-19	CS-24	CS-292	CP-8	CS-259
Chemical analyses												
SiO_2	73.8	70.2	71.1	75.1	72.7	73.7	68.7	70.2	72.2	70.2	73.6	53.0
Al_2O_3	12.6	14.8	14.5	12.7	12.7	13.9	15.0	15.6	13.4	14.1	13.5	17.4
Fe_2O_3	.51	1.8	1.5	.64	.85	1.2	1.3	1.5	.80	2.6	1.6	5.7
FeO	.18	.49	.37	.18	.10	.48	.97	.67	.37	.2	.21	2.6
MgO	.27	.55	.40	.31	.31	.40	.80	.61	.36	.71	.49	4.5
CaO	.66	2.1	2.2	.68	1.1	1.7	2.7	2.3	1.2	2.2	1.8	8.2
Na_2O	3.0	3.2	3.2	2.7	2.2	3.2	3.1	3.6	2.8	3.0	3.0	3.1
K_2O	4.6	4.4	4.2	5.3	5.6	4.4	3.5	4.0	4.9	3.9	4.5	2.0
H_2O-	.71	.45	.31	.43	2.2	.22	.71	.14	.26	1.2	.31	.75
H_2O+	3.3	1.1	1.8	2.0	2.0	.91	2.9	.86	3.1	1.4	.91	1.20
TiO_2	.11	.32	.28	.07	.08	.21	.29	.32	.16	.36	.24	1.0
P_2O_5	.00	.08	.07	.03	.02	.08	.13	.10	.05	.18	.08	.45
MnO	.06	.02	.05	.05	.03	.04	.06	.05	.05	.08	.04	.14
CO_2	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	.06	<.05	<.05
Sum	100	100	100	100	100	101	100	100	100	100	100	100
Norms												
Q	38.6	30.3	32.0	38.2	37.3	34.5	31.6	28.7	35.5	33.4	34.9	6.6
or	28.4	26.5	25.4	32.0	34.6	26.2	21.4	23.9	30.1	23.6	26.8	12.1
ab	26.5	27.6	27.7	23.4	19.4	27.3	27.2	30.8	24.6	26.0	25.6	26.7
an	3.4	10.1	10.7	3.3	5.6	8.0	13.0	10.9	5.8	10.0	8.5	28.2
C	1.6	1.2	.9	1.4	1.1	1.0	1.6	1.4	1.5	1.4	.6	------
wo												4.3
en	.7	1.4	1.0	.8	.8	1.0	2.1	1.5	.9	1.8	1.2	11.4
fs							.4					
mt	.5	.7	.6	.6	.2	1.1	2.0	1.4	.9	------	.1	6.5
hm	.2	1.3	1.2	.3	.8	.5	------	.5	.2	2.7	1.5	1.6
il	.2	.6	.5	.1	.2	.4	.5	.6	.3	.6	.5	1.9
ap		.2	.2	.1	.1	.2	.3	.2	.1	.4	.2	1.1

Sample, locality, and description

[Numbers following mineral names are percent of total phenocrysts]

1. About 350 ft above base of unit and directly above the lower plagioclase-rich zone at the reference area at Trailer Pass; dark-gray to black vitrophyric ash-flow tuff; stratigraphic position and mineralogy is about equivalent to that of specimen 5 in figure 12.
2. From dipslope on northeast flank of Cathedral Ridge. Densely welded vitric plagioclase-rich biotite-hornblende ash-flow tuff; stratigraphic position and mineralogy is about equivalent to that of specimen 22 in figure 12.
3. From base of unit 2.3 miles east of Wild Horse Ranch, Kawich Range. Gray vitrophyric crystal-rich plagioclase-rich biotite-hornblende ash-flow tuff; stratigraphic position and mineralogy is about equivalent to that of specimen 4 in figure 12.
4. From east flank of Belted Range at long 116°3′ W., lat 37°29.5′ N. Gray vitric weakly welded pumice-rich quartz-rich ash-flow tuff; ratio of quartz:alkali feldspar:plagioclase is approximately 5:3:2.
5. From east flank of Belted Range 2 miles northeast of Belted Peak. Light-tan partly devitrified welded ash-flow tuff; mineralogy is same as sample 4; some sodium probably leached by weak hydrothermal alteration.
6. From 2 miles southwest of Cactus Peak, Cactus Range. Partly devitrified vitrophyre, contains 32 percent phenocrysts consisting of plagioclase 35, alkali feldspar 29, quartz 28, biotite 6, and accessory hornblende, magnetite, allanite, sphene, and zircon.
7. From 2 miles north-northwest of Belted Peak, Belted Range. Gray vitrophyric rhyodacite flow containing 34 percent phenocrysts consisting of strongly zoned calcic andesine (?) 60, quartz 27, biotite 9, hornblende 3, and accessory magnetite and allanite.
8. From 3.5 miles east-southeast of Wild Horse Ranch, Kawich Range. Gray vitrophyric crystal-rich intrusive rhyolite, mineralogy is similar to sample 4.
9. From west flank of O'Briens Knob, southern Cactus Range. Dark-gray intrusive vitrophyric rhyolite.
10. From ridge 1 mile west of Sulfide Well, southern Cactus Range. Rock is a reddish-gray autobrecciated quartz latite intrusive containing 20 percent phenocrysts of andesine 69, biotite 19, quartz 3, magnetite 7, and minor zircon and apatite. Mineral assemblage is not typical of unit.
11. From 2 miles southwest of Cactus Peak, Cactus Range. Vitrophyric rhyolite dike containing 33 percent phenocrysts consisting of andesine 46, alkali feldspar 20, quartz 24, biotite 7, and accessory magnetite, hornblende, sphene, allanite, and apatite.
12. From 6.5 miles southwest of Cactus Peak, Cactus Range. Black, dense andesite dike rock, contains about 28 percent phenocrysts as much as 2 mm in diameter consisting of partly corroded sodic labradorite 63, augite 20 (commonly glomeroporphyritic), hornblende rimmed with iron oxide 8, iddingsite 5, and magnetite 3, in a hyalopilitic groundmass.

the Fraction Tuff. Locally, the tuffaceous conglomerate and tuffs rich in lithic fragments contain cobbles and blocks of welded tuff, some of which appear to be Fraction Tuff. The occurrence of these cobbles and blocks substantiates the inference that these deposits are interstratified with the Fraction.

North of Gold Reed the nonwelded upper part of the Fraction is overlain with apparent low-angle unconformity by a debris flow, tuffaceous conglomerates, and tuffs that together are at least 2,000 feet thick and possible as much as 3,000 feet. These rocks are interpreted as post-Fraction caldera-fill deposits. The lowest deposit consists of 50–300 feet of nearly monolithologic debris flow composed of boulders and smaller fragments of porphyritic dacite. The lack of a basal vitrophyre and the lack of baking in the underlying soft vitric tuffs indicate that the rock was cold when deposited and that it may have originated as a landslide. Locally, the flow contains a sandy tuff matrix and large fragments of Fraction Tuff, and in many places the matrix is moderately well cemented.

The debris flow is overlain by a thick sequence of conglomerate, a bed of limestone about 20 feet thick, ash-fall tuff, and minor ash-flow tuff. The strata consist of about 60 percent conglomerate and 40 percent interbedded tuff. A broad pediment surface bevels the area of outcrop, and pediment gravels and alluvium blanket the bedrock except where recent streams have cut into the pediment surface.

The conglomerate consists of large blocks, boulders, and smaller fragments of Fraction Tuff and dacite lavas in a tuffaceous sand matrix. The rock is weakly cemented and nonresistant, and it is not easily distinguished from the overlying unconsolidated pediment gravels. Crossbedding is visible locally, especially where the rock is moderately indurated. In places near the base the conglomerate contains abundant fragments of silicified wood, and locally logs as much as 2 feet in diameter and 100 feet in length may be found.

The interbedded tuffs are white, vitric, and rich in biotite, quartz, and plagioclase. Ash-flow tuffs occur near the middle of the exposed sequence and carry abundant pyroxene in addition to the minerals listed above. With the exception of a densely welded tuff at Gold Reed (not mapped separately), these tuffs are nonwelded to weakly welded. Some of the tuff was quarried for building stone in the early 1900's; the Kawich Post Office at Gold Reed was built with this stone. The densely welded tuff at Gold Reed is medium gray to dark brownish gray and vitrophyric, and contains 40–50 percent phenocrysts of plagioclase, quartz, biotite, and clinopyroxene. No alkali feldspar was observed.

The thick largely sedimentary sequence, which includes boulders of Fraction Tuff as much as 30 feet long, was unquestionably derived from a large nearby block that came into high relief following the formation of the Cathedral Ridge caldera. This block must have existed east and northeast of the area that received the deposits and has since been either downfaulted by basin-range faults or eroded and covered by younger deposits.

SEDIMENTARY ROCKS AND BEDDED TUFF

Exclusive of the tuffaceous conglomerate and debris flows in the Kawich Range just described, a large variety of sedimentary rocks and bedded tuff accumulated in adjacent areas after the extrusion of the Fraction Tuff and preceding the eruption of the rhyolite of O'Briens Knob. The evidence is good that this interval represents a long period of erosion and relative paucity of volcanic activity. The rocks were mapped as a single cartographic unit, although they were not deposited contemporaneously in all areas.

BELTED RANGE

Bedded strata above the Fraction Tuff in the Belted Range include thin beds of crossbedded conglomeratic sandstone at base, ash-fall tuff in the lower half, and interbedded sandstone and ash-fall tuff in the upper half. The strata are at least several hundred feet thick where exposed in Monotony Valley near Juniper Pass.

The tuff in the lower half is poorly bedded and, in places, probably includes nonwelded ash-flow tuff. The rock is light gray to white and rich in small pumice lapilli, and it contains quartz, biotite, and feldspar. The rock is vitric and unaltered except for local occurrences of abundant siliceous concretions as much as 2 inches in diameter. This rock is overlain by well-bedded ash-fall tuff and tuffaceous sandstone; the bedded tuff is generally poorer in crystals than the underlying tuff and is nearly void of biotite and other mafic minerals. The beds of sandstone are white to light gray, cross-stratified, rich in quartz, and commonly conglomeratic.

The interval just described is overlain by the Grouse Canyon Member of the Belted Range Tuff, a very distinctive and easily mapped ash-flow tuff. Bedded strata of the Belted Range Tuff probably underlie the Grouse Canyon Member. The lowest beds of the sedimentary rocks and bedded tuffs, however, may be nearly as old as the Fraction Tuff. Thus, a range in age of several million years is inferred for the beds in this interval in the Belted Range area.

CACTUS RANGE

Thick- to thin-bedded fine-grained to conglomeratic tuffaceous sedimentary rocks crop out on the north and east flanks of the Cactus Range and are downfaulted against the older volcanic and intrusive rocks that make up the central core of the range. These strata dip 10°–25° away from the range; they rest unconformably on rocks inferred to be tuffs of Antelope Springs, and they are interstratified with basalt lavas that are not mapped separately (pl. 1). The beds are overlain by the rhyolite of Cactus Peak (p. 57) and locally contain abundant inclusions of that rhyolite; these inclusions indicate that the deposition of the sediments coincided in part with the intrusion and extrusion of post-Fraction Tuff rhyolites. The sedimentary rocks are white, light gray, and pale yellow; they are locally vitric but mostly highly zeolitized. Similar tuffaceous sedimentary rocks and ash-fall(?) tuff are exposed in gullies west of Wellington Hills. These strata, which are mostly white and vitric, dip toward the range 15°–20°. Their age is known only as pre-Thirsty Canyon (p. 65) but they are inferred to be post-Fraction Tuff in age.

MOUNT HELEN

The sedimentary rock near Mount Helen consists of cross-stratified fluvial conglomerate and fine- to coarse-grained sandstone composed predominantly of poorly sorted volcanic detritus. Finely laminated siltstone and shale and thick- to thin-bedded ostracode-bearing limestone, all of lacustrine origin, are also common at Mount Helen. Thick beds of ash-fall tuff and three cooling units of the tuff of Tolicha Peak (p. 59) are interbedded with these strata. With the exception of medium- to dark-gray limestone, the rocks are yellowish brown to buff, pink, and white. Nearly everywhere they have been modified by hydrothermal or ground-water alteration, and locally they are intensely silicified.

Fossil wood fragments, ranging in size from less than an inch to a few large trunks 2 feet in diameter and as much as 100 feet long, are fairly abundant in the section, but they are so completely silicified that they can be identified only as conifer (R. A. Scott, oral commun., 1963).

Ostracode samples were examined by I. G. Sohn, who reported (written commun., 1964):

> The preservation is too poor for study of shell morphology, but one group, represented by steinkerns, has a diagnostic node on the surface of the valves. These were compared with described species of *Tuberocypris* Swain, 1947, described from the Salt Lake Formation of Utah that have a similar node. * * * The specimens on hand differ from the described species of *Tuberocypris*. The Russian workers have described a similar form as *Herpetocyprella* Daday, 1909, that ranges from the Miocene, Pliocene, and Holocene. The specimens on hand do not resemble any of the Russian species.

Sohn concluded that the ostracodes are probably of Pliocene age.

Vertebrate bone fragments collected from sandstone were examined by Edward Lewis (written commun., 1963), who reported that all 51 fragments are seemingly from a single individual camelid artiodactyl, but 32 are morphologically indeterminate. Morphologically determinate fragments are:

- one carpal—right pyramidal
- one tarsal—left cuboid
- one tarsal—left ecocuneiform
- four of a right metacarpal
- four of the shaft of a metapedial
- six of proximal phalanges of a manus
- two of a proximal phalanx of a pes

Lewis concluded:

> Camelids of this size occur commonly in lower Miocene (Arikaree) to upper Pleistocene (Wisconsin) rocks of North America. These nondiagnostic fragments most closely approach the morphology and size of camelids such as those of the genus *Procamelus* of the upper Miocene and lower Pliocene.

Fishes from calcareous siltstone were identified as killifishes of the family Cyprinodontidae by D. M. Dunkle (written commun., 1963). Dunkle pointed out that the fossils were too poorly preserved for precise determination but that they can be tentatively referred to the genus *Fundulus*. According to Dunkle, fish of this type are known from several localities in California and Nevada and are considered by Miller (1945) to be either Pliocene or Pleistocene in age.

The age of the strata at Mount Helen is not clearly indicated by the above paleontological data. The strata are interbedded with the tuff of Tolicha Peak for which a late Miocene age is inferred on the basis of potassium-argon dates of higher and lower strata. (See later pages.) The strata are here considered to be of late Miocene age.

RHYOLITE OF O'BRIENS KNOB

After the deposition of a large variety of sedimentary rocks and ash-fall tuff in the project area, silicic lavas ranging in composition from quartz latite to rhyolite were erupted from many widespread vents. These rocks are generally rich in crystals and have a distinctive phenocryst assemblage that enables correlation from one range to another. Hence, they are mapped herein as a single unit named informally for exposures at O'Briens Knob in the Cactus Range. Rhyolite and quartz latite that are very similar to the rhyolite of O'Briens Knob occur in ranges east, north, and northwest of the project area, and stratigraphic relations in these areas indicate that they are virtually the same age as the rhyolite of O'Briens Knob. These rocks include rocks equivalent to the Oddie Rhyolite and Brougher Dacite (quartz latite) mapped by Spurr (1905) at Tonopah and the Oddie Rhyolite mapped by Ferguson and Cathcart (1954) in the western Manhattan district 42 miles northeast of Tonopah.

Characteristically the rhyolite of O'Briens Knob is light to medium gray or reddish gray where devitrified and dark gray where vitrophyric. It weathers to form reddish-gray or reddish-brown rounded hills and slopes, but locally it forms rugged craggy outcrops, especially in areas where the rock occurs as flow breccia or in intrusive masses. The rhyolite is generally conspicuously flow layered with the layers averaging several inches in thickness, but locally it is massive without visible layering. The rock at the borders of intrusive masses is commonly vitrophyric and autobrecciated, containing abundant shattered and broken phenocrysts.

Phenocryst contents range from 5 to 45 percent, with the higher values greatly predominating. Crystal-rich varieties are distinguished by abundant conspicuous plagioclase phenocrysts (mostly andesine as much as 5 mm in diameter) and conspicuous quartz and biotite. Plagioclase, the dominant phenocryst, typically makes up 50–60 percent of the phenocrysts. The plagioclase generally shows oscillatory and strong normal zoning and complex twinning, and commonly it occurs as glomeroporphyritic clots. Other phenocrysts include grains of quartz (25–30 percent), sanidine (0–25 percent), biotite (5–10 percent), and minor hornblende, sphene, magnetite, and allanite. This mineral assemblage is also characteristic of the tuff of Wilsons Camp and Fraction Tuff.

Chemical analyses and norms of the rhyolite of O'Briens Knob from each of the ranges are given in table 11 (samples 7–11). These rocks fall in the rhyolite and quartz latite fields of O'Connor (fig. 12) with the exception of sample 7, a rock from the Belted Range which falls in the rhyodacite field close to the boundary of quartz latite.

The rhyolite of O'Briens Knob and the Fraction Tuff are very similar chemically, petrographically, and in the range of variation among the normative minerals. The only apparent difference between the two rocks, aside from one being a tuff and the other a lava, is the high lithic content characteristic of the tuff. These rocks possibly are genetically related. The fact that the rhyolite of O'Briens Knob occurs throughout such a broad area indicates that it, like the lavas of intermediate composition previously described, was withdrawn from a substratum that was broader than the mapped area.

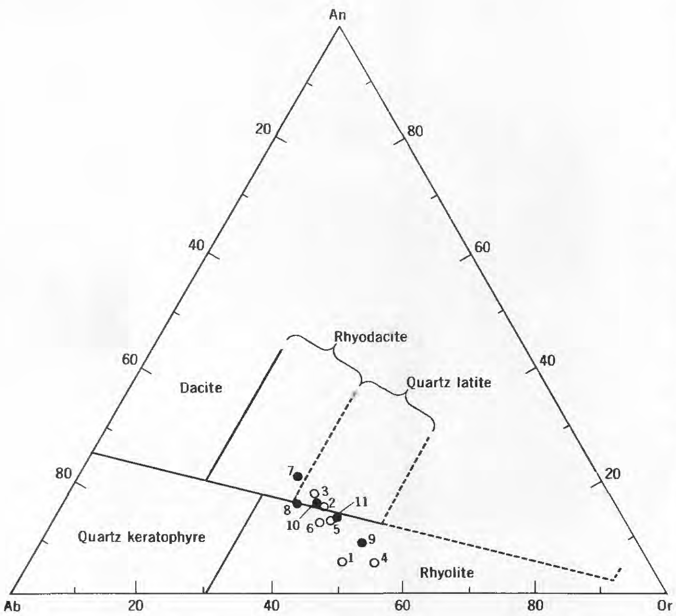

FIGURE 12.—Plot of normative albite-anorthite-orthoclase ratios for Fraction Tuff (open circles) and rhyolite of O'Briens Knob (solid circles). Numbers refer to samples in table 11. Fields from O'Connor (1965).

STRATIGRAPHIC RELATIONS AND AGE

In the Belted Range, the lavas rest unconformably on or intrude faulted eroded blocks of tuff of White Blotch Spring, lavas of intermediate composition, Fraction Tuff, and, locally, sedimentary rocks and bedded tuff. In the Kawich and Cactus Ranges, the rhyolite of O'Briens Knob occurs mostly as broad dikes and plugs, some of which intrude the Fraction Tuff. In the southern Belted Range, the rhyolite is overlain by the rhyolites of Belted Peak and Ocher Ridge, which in turn are overlain by the Belted Range Tuff dated at 13.8 m.y. (table 5). It seems reasonable to conclude that the rhyolite of O'Briens Knob is late Miocene in age.

In the west half of the mapped area, especially along the margins of Cactus and Gold Flats, rhyolites that are not typically of O'Briens Knob lithology were included in the same cartographic unit to keep rhyolite units at a minimum. Most of these rhyolites contain phenocrysts of plagioclase, and stratigraphic relations indicate that they are closely related in time to the rhyolite of O'Briens Knob.

RHYOLITE OF CACTUS PEAK

Several plugs, broad dikes, and flows of white to gray crystal-poor plagioclase-free rhyolite occur in the northern part of the Cactus Range. Cactus Peak, one of the most prominent landmarks in the area, is composed of this rhyolite. At several localities the rhyolite intrudes rocks mapped as rhyolite of O'Briens Knob. The rhyolite of Cactus Peak is massive to intensely flow layered and locally columnar jointed; it weathers to reddish gray where unaltered and light gray to pale yellow where silicified. It contains 1–10 percent phenocrysts of alkali feldspar, small resorbed quartz, and sparse biotite in a microcrystalline granular, felty, or spherulitic groundmass that generally contains some secondary zeolite and sericite. It is vitrophyric locally at the base of flows or at the border of intrusive masses. A thick pile of similar rhyolite crops out east of the Goldfield mining district and extends into the extreme northwestern part of the project area (pl. 1). Although the age equivalence is not established, these rocks are mapped with the rhyolite of Cactus Peak.

RHYOLITE OF BELTED PEAK AND OCHER RIDGE

Thick rhyolite lavas and several large rhyolite intrusive masses form the bulk of the southern Belted Range. Aside from the relatively young rocks that are genetically related to the sodic rhyolitic Belted Range Tuff, the rhyolites are calc-alkalic in composition and occur as two types. One type generally contains abundant phenocrysts (rhyolite of Belted Peak); the other contains few phenocrysts (rhyolite of Ocher Ridge). The rhyolite of Belted Peak characteristically contains moderately abundant and conspicuous flakes of biotite and abundant large phenocrysts of quartz. In contrast, no mafic minerals of any kind have been observed in the rhyolite of Ocher Ridge either in outcrop or in five thin sections taken from widely separated outcrops. Quartz phenocrysts are small. Both rocks contain alkali feldspar and minor oligoclase.

The rhyolites of Belted Peak and Ocher Ridge appear to have been extruded nearly simultaneously from several feeder necks and plugs that are alined north-south along the west flank of the Belted Range. Near Wheelbarrow Peak the rhyolite of Ocher Ridge is younger; to the southwest, however, rhyolite of Ocher Ridge is interbedded with rhyolite of Belted Peak. Several of the plugs are well exposed, and in these the discordant relations with country rock are visible (fig. 13). The rocks are definitely younger than the rhyolite of O'Briens Knob and older than the Belted Range Tuff.

RHYOLITE AND COARSE PORPHYRITIC RHYOLITE OF UNCERTAIN AGE

Rhyolite lavas and rhyolite porphyry intrusive masses that crop out (1) on the east flank of Stonewall Mountain, (2) near Mount Helen, (3) in the Kawich Range, and (4) in the Belted Range and northern Kawich Valley can be dated only as Tertiary in age. These rocks are included in a single cartographic unit.

On the east flank of Stonewall Mountain, the lavas are about 1,300 feet thick and are in fault contact with the Thirsty Canyon Tuff. They are light gray to pink gray and conspicuously flow layered. Most are moderately rich in phenocrysts of quartz, sanidine, plagioclase, biotite, and magnetite. Some of the sanidine crystals are as much as 10 mm long. The groundmass is glassy to finely crystalline.

Near Mount Helen the rhyolite is so intensely silicified that nothing is known of its original petrography except that the rock was probably poor in phenocrysts.

In the Kawich Range, rhyolite exposed in small patches north of Quartzite Mountain and as large masses north of Cedar Pass is petrographically dissimilar to the rhyolite at Stonewall Mountain. These rocks are very poor in crystals. They contain sparse

FIGURE 13.—Feeder plug about 2½ miles south-southwest of Belted Peak. Rock in the plug is gradational between rhyolite of Belted Peak and rhyolite of Ocher Ridge. It intrudes gently dipping Monotony Tuff and Shingle Pass Tuff. *A* (left), View to the east. *B* (right), View to the north along discordant contact with Shingle Pass Tuff on west side. Note that flow layering in the rhyolite parallels contact. (Man is standing in contact zone.) Rock in front of tree on left is nearly flat-lying altered tuff.

phenocrysts of alkali feldspar, quartz, and biotite. They are similar to the rhyolite of Cactus Peak but are not mapped with that rhyolite because of the uncertainty in age equivalence and because of the great distance separating the exposures.

A rhyolite porphyry plug located in the northern part of Kawich Valley and a rhyolite dike located southeast of Belted Peak intrude strata of Paleozoic age and the Monotony Tuff, respectively. The rock in Kawich Valley is massive weathering with only weak flow layering and is rich in crystals including alkali feldspar as much as 10 mm in length and quartz as much as 8 mm in diameter. Chloritized biotite is the only mafic mineral. The interior of the mass has a much coarser grained groundmass than the outer margins. The dike rock southeast of Belted Peak is petrographically similar, containing alkali feldspar crystals as much as 10 mm in length and abundant crystals of quartz and small crystals of biotite.

ANDESITE OF STONEWALL FLAT

Andesite dikes and plugs intrude Fraction Tuff along the northwest margin of Stonewall Flat. The rock is dark gray to black and produces a distinctive black pattern on aerial photographs. The rock weathers to dark-brown slopes composed of angular joint-faceted blocks. It is massively to very faintly flow layered and contains about 30 percent phenocrysts consisting of plagioclase, pyroxene, hornblende, magnetite, and altered olivine. A chemical analysis is given in table 11 (sample 12). The andesite predates Thirsty Canyon Tuff, but its age relative to other post-Fraction Tuff strata is not known.

TUFF OF TOLICHA PEAK

The tuff of Tolicha Peak is well exposed at Tolicha Peak, which is outside the project area about 2 miles west of Quartz Mountain. The best exposures within the area are 12 miles north-northeast of Tolicha Peak at triangulation station Pahute located on a large knoll or hill about half a mile east of Road D and 6 miles south-southwest of Mount Helen in T. 6 S., R. 46 E., Nye County, Nev. The rock is discontinuously exposed over a considerable area in this vicinity and adjacent to Mount Helen, and it has been correlated as far eastward as the southern Belted Range. It has been tentatively identified in drill cores from wells on Pahute Mesa. Its northern extent is unknown because vast areas to the north that were probably topographically low during the tuff eruptions are covered by Thirsty Canyon Tuff and alluvium. The Cactus Range was probably a topographic high during Tolicha Peak time, and the absence of the tuff there does not preclude the possibility that it originally extended that far north. The extent of the tuff west and southwest of the mapped area is unknown.

The tuff is about 300 feet thick at the triangulation station, where it forms a compound cooling unit with a conspicuous vitrophyre zone 30–50 feet thick at the base. The rock is densely welded there and weathers to hard clinkstone. It is gray, buff, and reddish brown where fresh and unaltered, and yellow or buff where zeolitized and silicified. In most exposures the tuff forms valleys or low hills. It contains less than 1 percent phenocrysts consisting of plagioclase, quartz, alkali feldspar, and sparse crystals of biotite and hornblende. The rock is composed dominantly of shards and pumice fragments that average less than half an inch in length and diameter. The pumice fragments commonly weather to elongated pits in exposures north of the triangulation station, especially where the tuff has been silicified. The pits together with incipient desert varnish, give the altered rock a distinctive rough and dingy aspect. The rock contains many small spherulites that average 1 mm or less in diameter. The spherulites are visible even where the enclosing matrix is highly zeolitized or silicified; they are a useful guide for recognizing the rock.

North of the triangulation station, at the south end of Mount Helen, three cooling units are present in the tuff of Tolicha Peak. These are separated from each other by fluvial and lacustrine sedimentary rocks and ash-fall tuff. The lowest of the three units crops out adjacent to the mountain, where it rests directly on eroded lavas of Mount Helen or on thin-bedded fluvial sandstone. This unit is massive weathering, contains abundant fragments of lavas of Mount Helen at the base, and is moderately rich in phenocrysts. It grades upward to crystal-poor tuff identical with that at the triangulation station. The tuff is about 200 feet thick and is overlain by 500–800 feet of crystal-poor ash-fall tuff, thin-bedded siltstone and limestone, and fluvial crossbedded sandstone. The middle cooling unit, which is thought to correspondent to the unit at the triangulation station, contains abundant rhyolite lithic fragments and has a thick altered vitrophyric zone at the base. It is overlain by ash-fall tuff and sedimentary rocks that include zones of sandy limestone as much as 15 feet thick and several zones of thinly laminated siltstone and shale. The bedded interval is at least 200 feet thick and possibly as much as 400 feet. It is overlain by weakly welded ashflow tuff that is nearly identical with the tuff of Tolicha Peak below but is different in that it contains virtually no lithic fragments. It is the youngest bedrock in the syncline valley in the SW. cor. T. 5 S., R. 47 E. All three units are zeolitized in the Mount Helen exposures, and locally they are intensely silicified. Because the three units are so strikingly similar in outcrop, no attempt was made to differentiate them. In fact, in many areas the tuff of Tolicha Peak includes not only the three units but the interbedded ash-fall tuffs and sedimentary rocks as well.

A single chemical analysis (table 12) of vitrophyre from the triangulation station shows the rock to be a salic rhyolite extremely low in femic constituents.

TABLE 12.—*Chemical analysis and norm of tuff of Tolicha Peak from 12 miles north-northeast of Tolicha Peak*

[Analysis of sample 1, laboratory No. 165058, field No. E 65-4-19-4, by P. L. D. Elmore, S. W. Botts, G. W. Chloe, Lowell Artis, and H. Smith, by rapid method]

Chemical analysis		*Norm*	
SiO_2	73.6	Q	40.8
Al_2O_3	12.2	C	1.8
Fe_2O_3	.48	or	26.2
FeO	.28	ab	26.8
MgO	.16	an	3.0
CaO	.57	en	.4
Na_2O	3	fs	.07
K_2O	4.2	mt	.74
H_2O-	.66	il	.22
H_2O+	3.9		
TiO_2	.11		
P_2O_5	0		
MnO	.07		
CO_2	.05		
Sum	99		

The source for the tuff of Tolicha Peak is not known with absolute certainty. The fact that several cooling units of the tuff are intercalated with thick sequences of lacustrine sedimentary rocks in and adjacent to Mount Helen suggests that collapse occurred there concomitantly with the extrusion of the tuff. The caldera may be centered south of Mount Helen on a small gravity low (pl. 1).

The age of the tuff of Tolicha Peak, as indicated by available data, is probably late Miocene. It is younger than the rhyolite of Ocher Ridge, which underlies the tuff along the southeast flank of Kawich Valley, and is older than the Belted Range and Paintbrush Tuffs, which overlie the tuff of Tolicha Peak in the southern Belted Range and near Tolicha Peak. The Belted Range Tuff (Grouse Canyon Member) has been dated at 13.8±0.6 m.y. (table 5, sample 13).

RHYOLITE OF QUARTZ MOUNTAIN

Calc-alkalic rhyolite lavas with minor basal ash-fall tuffs locally are at least 400 feet thick in the general vicinity of Quartz Mountain in the extreme southwest part of the project area. The rhyolite overlies the tuff of Tolicha Peak and underlies the Grouse Canyon Member of the Belted Range Tuff. In outcrop the rock ranges from grayish white to gray and buff. It contains 20–25 percent phenocrysts, which consist of subequal amounts of quartz, sanidine, and sodic plagioclase, 1–2 percent biotite, and accessory iron ore and sphene. The groundmass is typically vitric, although locally it is devitrified. Locally the rhyolite has been silicified and argillized by hydrothermal solutions.

Chemical analyses of two samples of the rhyolite are given in table 13.

TABLE 13.—*Chemical analyses of rhyolite of Quartz Mountain*

[Analyses by P. L. D. Elmore, S.W. Botts, G.W. Chloe, Lowell Artis, and H. Smith, by rapid method (Shapiro and Brannock, 1962)]

Sample	TP-12	BM-20
SiO_2	71.3	71.1
Al_2O_3	13.0	14.2
Fe_2O_3	1.2	1.4
FeO	.37	.46
MgO	.35	.40
CaO	1.3	1.1
Na_2O	3.4	3.6
K_2O	3.8	4.8
H_2O-	.43	.26
H_2O+	4.9	2.3
TiO_2	.20	.24
P_2O_5	.05	.04
MnO	.05	.08
CO_2	.05	.05
Sum	100	100
Powder density g/cc	2.38	2.38

Sample, locality, and description

TP-12. Vitrophyre from lava exposed 3 miles west-northwest of Quartz Mountain.
BM-20. Vitric rhyolite lava from 1.5 miles south of Quartz Mountain.

YOUNGER VOLCANIC ROCKS

In the southern part of the mapped area, the older Tertiary volcanic rocks described herein are overlain by relatively undeformed and virtually unaltered volcanic rocks of late Miocene and Pliocene age. These rocks consist of extensive sheets of silicic and intermediate ash-flow tuff with intercalated ash-fall and reworked tuff, and of local silicic to mafic lavas.

Most of the younger volcanic rocks belong to one of five major genetic groups, which, from oldest to youngest, are: Belted Range Tuff and associated lavas and tuffs, Paintbrush Tuff, Timber Mountain Tuff, Thirsty Canyon Tuff and associated lavas, and basalt of Basalt Ridge. The rocks of a genetic group are closely related chemically, petrographically, and with respect to their source areas.

The rocks of these five genetic groups are most widespread, thickest, and best exposed in the southern part of and south of the mapped area, where they have been mapped at a scale of 1:24,000 under the U.S. Geological Survey's long-range geologic studies project of the Nevada Test Site. A voluminous body of data on these rocks has been accumulated in conjunction with this 1:24,000-scale mapping, and a series of reports, both published and in preparation, describes their stratigraphy, structure, and petrology. For this reason, only short summary descriptions of these rocks are given here.

In addition, several genetically unrelated units, mainly lavas, interfinger with the rocks belonging to the five major groups. These rocks will not be described elsewhere and thus are described here in somewhat greater detail.

BELTED RANGE TUFF AND ASSOCIATED LAVAS AND TUFFS

Rocks of the Belted Range Tuff are widespread in the southern part of the mapped area (pl. 1) and are extensive south of the mapped area. The formation is composed of the Tub Spring and the overlying Grouse Canyon Members (Sargent and others, 1965; Hinrichs and Orkild, 1961), both of which are compound cooling units of ash-flow tuff. Both members were erupted from a vent area in eastern Pahute Mesa (pl. 1), which is the site of a caldera complex 7–10 miles in diameter (P. P. Orkild and K. A. Sargent, written commun., 1968; Orkild and others, 1968; Noble and others, 1968). In the general vicinity of the caldera, the two members are overlain, underlain, and locally separated by areally restricted units of lava, ash flows, and nonwelded and welded ash-fall tuff, which, as shown by field relationships, chemical composition, and petrography, are genetically related to the Belted Range Tuff. These lavas and tuffs are here subdivided into four informal units: the rhyolite of Kawich Valley, the rhyolite of Quartet Dome, the trachyte of Saucer Mesa, and the rhyolite of Saucer Mesa.

The composition of the rocks of the Belted Range Tuff and the associated lavas and tuffs, except the trachyte and some of the rhyolite of Saucer Mesa, is comenditic (table 14). Most of the rocks are peralkalic and contain a molecular excess of alkalis over alumina, as shown both by chemical analyses and by the presence of sodic amphibole and pyroxene in the groundmass of rocks that have crystallized in a nonoxidizing environment. The rocks are also characterized by relatively high contents of such trace elements as zirconium, niobium, beryllium, gallium, and the rare earths.

TABLE 14.—*Average major-element chemical compositions of rocks of younger volcanic units*

[These compositions are averages for densely welded devitrified tuffs and dense devitrified lavas. Some of the compositions are significantly different from the inferred original compositions of the unit prior to crystallization and prolonged contact with ground water. Averages are based on approximately 250 rapid and standard rock analyses made in the U.S. Geological Survey laboratories in Washington, D.C., and Denver, Colo.]

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	48	74	69.5	66	72.5	66	73.5	69	60.5	68.5	64	63	68.5
Al_2O_3	16.5	13	11.5	16	14	15	12.5	14.5	17	15	16.5	17.5	15.5
Fe_2O_3	4.5	1.9	4	2.1	1.8	3	1.9	3	3	2.8	2.7	2.2	3
FeO	7	.1	1.2	1.3	.2	.5	.3	.3	2.6	.7	1.7	1	.2
MgO	5.2	.4	.3	.4	.2	.5	.2	.4	1.3	.25	.9	.9	.4
CaO	8.5	.6	.5	1.5	.9	1.	.7	.8	2.8	.55	2.2	2.2	.6
Na_2O	4	4.2	5.2	5.3	4.2	5.1	4.5	4.8	5.2	5.1	4.8	5.1	4.8
K_2O	1.8	4.8	4.8	5.8	5.2	5.3	4.8	5.4	4.8	5.5	5	5.5	5.3
H_2O+	.7	.4	.6	.6	.5	.6	.2	.5	.6	.4	.6	.7	.4
TiO_2	2.2	.12	.3	.45	.15	.35	.15	.35	.9	.35	.85	.7	.45
MnO	.19	.08	.16	.16	.08	.08	.08	.15	.15	.15	.13	.15	.15
P_2O_5	.9	.06	.07	.10	.04	.16	.03	.07	.5	.04	.38	.35	.1
CO_2	<.05	.5	.05	.3	.2	.3	.1	.1	.05	<.5	<.05	<.05	.05

	14	15	16	17	18	19	20	21	22	23	24	25
SiO_2	61.5	76.5	68.5	72	74	76	74.5	69.5	69.5	76	65.5	75
Al_2O_3	17.5	13	16	13	11.5	11	12.5	14.5	14	11.5	15.5	11.5
Fe_2O_3	3.3	.5	1.5	2.6	2.5	2.1	1.4	2.2	2.6	2.3	4	2.1
FeO	1.7	.2	.7	.5	1	.4	.9	1.3	.7	.2	.7	.4
MgO	.85	.15	.8	.4	.1	.35	.1	.1	.3	.1	.35	.2
CaO	3	.6	1.7	1	.3	.5	.3	.8	.5	.2	1.1	.4
Na_2O	5.1	3.6	4.5	4.4	4.6	4.3	4.6	5.2	4.6	4.2	5.5	4.2
K_2O	4.6	4.8	5.2	5	4.6	4.7	4.7	5.2	5.2	4.5	5.6	4.5
H_2O+	.5	.5	.5	.9	.4	.5	.4	.2	.6	.3	.3	.3
TiO_2	.85	.15	.5	.35	.22	.15	.15	.30	.30	.16	.6	.15
MnO	.12	.06	.08	.15	.17	.07	.09	.20	.17	.11	.23	.07
P_2O_5	.34	.05	.2	.10	.02	.02	.02	.03	.04	.02	.16	.01
CO_2	<.05	.1	.1	.5	.05	.1	<.05	.1	.1	.05	<.05	.3

1. Basalt of Basalt Ridge.
2. Labyrinth Canyon Member, Thirsty Canyon Tuff.
3. Gold Flat Member, Thirsty Canyon Tuff.
4. Trail Ridge Member, Thirsty Canyon Tuff.
5. Trail Ridge Member, Thirsty Canyon Tuff, crystal-poor ash flows.
6. Trail Ridge Member, Thirsty Canyon Tuff, lower crystal-rich ash flows.
7. Spearhead Member, Thirsty Canyon Tuff, comendite ash flows.
8. Spearhead Member, Thirsty Canyon Tuff, trachytic sodic rhyolitic ash flows.
9. Trachyte of Hidden Cliff.
10. Rhyolite of Pillar Spring, middle trachytic sodic rhyolite lavas.
11. Rhyolite of Pillar Spring, lower trachyte lavas.
12. Trachyte of Yellow Cleft, trachyte lava.
13. Rhyolite of Ribbon Cliff, upper trachytic sodic rhyolite lavas.
14. Rhyolite of Ribbon Cliff, lower trachyte lavas.
15. Timber Mountain Tuff, rhyolitic ash-flow tuffs.
16. Timber Mountain Tuff, quartz latitic ash-flow tuffs.
17. Grouse Canyon Member, Belted Range Tuff, upper crystal-rich ash-flow sheet.
18. Grouse Canyon Member, Belted Range Tuff, lower crystal-poor ash-flow sheet.
19. Tub Spring Member, Belted Range Tuff.
20. Rhyolite of Saucer Mesa,
21. Trachytic sodic rhyolite of Saucer Mesa.
22. Tuff of Basket Valley.
23. Rhyolite of Quartet Dome.
24. Trachyte of Saucer Mesa.
25. Rhyolite of Kawich Valley.

Sodium-rich sanidine is the dominant phenocryst mineral; sodium-and iron-rich clinopyroxene, fayalite, zircon, and apatite are ubiquitous phenocryst minerals, but form less than 0.1 percent of the rock. Quartz phenocrysts are abundant in the rhyolite of Quartet Dome, the Tub Spring Member, and the rhyolite of Kawich Valley, and less abundant in rocks of the Grouse Canyon Member. Crystals of sodic amphibole of vapor-phase origin are common, particularly in the ash-flow tuffs.

Rhyolite of Kawich Valley

Numerous discontinuous bodies of petrographically similar commendite lavas, which were erupted in the general vicinity of Kawich Valley and in the southern Belted Range prior to the eruption of the Tub Spring Member, are here included in the rhyolite of Kawich Valley. The form and areal distribution of these lavas show that they were erupted from numerous vents.

Rocks of the unit are typically flow layered and highly contorted. The lavas are crystallized in most outcrops although vitrophyres are present locally. Spherulitic devitrification is common and zeolitic alteration is fairly common. Colors range from gray, bluish gray, and green to various shades of red and yellow. Phenocrysts, consisting predominantly of sanidine and subordinate quartz with minor fayalite and clinopyroxene, make up about 1–10 percent of the rock. The rhyolite has been dated at 14.8 ± 0.6 m.y. (table 5, sample 14).

Trachyte of Saucer Mesa

Peralkalic trachyte lavas crop out below the rim of Saucer Mesa on the southeast flank of Gold Flat and also in a strike valley southeast of Saucer Mesa. The rock is reddish gray or green and weathers to dark red or brown. Phenocrysts—which include sodium-rich sanidine-anorthoclase (10–30 percent), clinopyroxene (<5 percent), and sparse crystals of iron-rich olivine—are set in either a glassy groundmass or a trachytic groundmass of alkali feldspar and sodic amphibole.

Rhyolite of Quartet Dome

The rhyolite of Quartet Dome comprises several thick, small bodies of crystal-rich comendite lava which, as shown by their shape and structure, were emplaced at various times as relatively viscous bodies which erupted from a different volcanic vent. Some were emplaced before the eruption of the Tub Spring Member, others were emplaced after the eruption of the Tub Spring Member but before the eruption of the Grouse Canyon Member, and one was emplaced after the eruption of the Grouse Canyon Member. It is possible that some bodies of the rhyolite of Kawich Valley postdate some of the lavas of Quartet Dome in areas where stratigraphic relations are doubtful. When stratigraphic relations are straightforward, however, the rhyolite of Quartet Dome overlies the rhyolite of Kawich Valley.

Rocks of the unit are typically gray, crystallized, and well foliated on a large scale. Rocks of the various domes are petrographically nearly identical. Phenocrysts of sanidine and quartz, 1–4 mm in diameter, together compose 25–30 percent of the rock, and clinopyroxene and fayalite compose less than 1 percent. Vitrophyre and zones of spherulitic and zeolitic alteration are relatively uncommon.

In Grass Spring Canyon the rhyolite of Quartet Dome is underlain by a unit composed of poorly welded ash-flow or welded ash-fall tuff and nonwelded ash-fall tuff. This unit has the same phenocryst content as the overlying lavas, and locally it contains lithic fragments that are lithologically identical with those lavas. This tuff was probably erupted from the same vent immediately prior to the eruption of the rhyolite.

Tub Spring Member

The Tub Spring Member crops out on the east and south flanks of the Belted Range, east of Yucca Flat south of the project area, and locally in Kawich Valley and vicinity. It is as much as 300 feet thick.

Rocks of the member are typically buff or bluish gray, but locally they are brick red. The member is mostly devitrified, but at the base and top it contains poorly welded glassy tuff that is partly or completely zeolitized in many outcrops. Vitrophyre is locally present in the central part of the cooling unit, where the member is thick and densely welded. The member contains about 20–25 percent phenocrysts of sanidine and quartz, minor amounts of clinopyroxene and fayalite, and locally fragments of pumice, rhyolite, welded tuff, and Paleozoic sedimentary rocks.

Grouse Canyon Member

The Grouse Canyon Member has a much wider distribution than the Tub Spring Member. As inferred from its present known distribution, the Grouse Canyon Member originally covered at least 1,500 square miles.

The Grouse Canyon differs from the Tub Spring in being more densely welded and in having a much smaller percentage of phenocrysts. The various ash flows that make up the member contain about 0.01–25 percent phenocrysts, with an average of about 2–3 percent. In most places the member is densely welded (fig. 14) and, with the exception of a thin basal vitrophyre, is almost everywhere devitrified. The rocks are greenish gray to bluish gray to grayish buff and brown and locally are brick red.

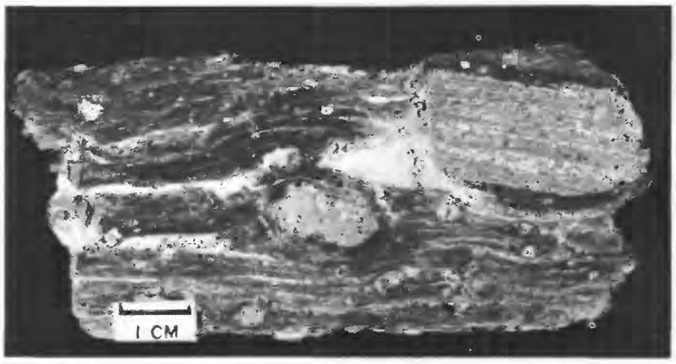

FIGURE 14.—Hand specimen of Grouse Canyon Member of Belted Range Tuff cut normal to prominent compaction foliation. Note that foliation parallels the boundaries of lithic inclusions of flow-banded rhyolite.

RHYOLITE OF SAUCER MESA

The rhyolite of Saucer Mesa consists of generally crystal-poor and well-flow-banded lavas that overlie the Grouse Canyon Member at Saucer Mesa and in Kawich Valley. The lavas and associated tuffs are locally as much as 1,000 feet thick.

The rocks range in color from bluish gray, greenish gray, and buff to reddish brown and red. Phenocrysts, consisting almost entirely of sodium-rich sanidine, compose about 1–20 percent of the lavas. The rocks of the upper part are almost entirely crystal poor, and they are bluish gray and greenish gray, whereas rocks of the lower part contain both crystal-poor and moderately crystal-rich flows. Although most of the rocks are comendites, trachytic soda rhyolite lavas (table 13) occur locally at the base of the unit.

The trachytic sodic rhyolite of Saucer Mesa and the tuff of Basket Valley, which are mapped separately on 1:24,000- and 1:62,500-scale maps, respectively, are included with the rhyolite of Saucer Mesa on plate 1.

ASH-FALL AND REWORKED TUFF

In most places the units of welded tuff and lava are underlain and separated by variable thicknesses of nonwelded ash-fall tuff, reworked tuff, and epiclastic tuffaceous material. Generally these rocks are bedded and partly or completely zeolitized. Crystal content is about 1–25 percent. Some tuffs, particularly those containing abundant crystals, contain numerous lithic fragments. Where too thin to be shown separately on the geologic map, ash-fall and reworked tuffs are, by convention, included with the overlying map unit.

Ash-fall and reworked tuff occurs stratigraphically above and below the Tub Spring Member (pl. 1). Above the Tub Spring the tuffs are almost wholly genetically related to the Belted Range Tuff and associated lavas, but in many places below the Tub Spring the tuffs appear to be related to older volcanic units.

RHYOLITE OF AREA 20, PAHUTE MESA

Calc-alkalic rhyolite lavas locally crop out beneath the Timber Mountain Tuff and between members of the Timber Mountain Tuff in the northern and southwestern parts of Pahute Mesa. The oldest, which is called the rhyolite of Area 20 by Orkild, Sargent, and Snyder (1969), is flow brecciated, vesiculated, and glassy at the top and base, and flow layered and devitrified in the interior. The rock contains phenocrysts of quartz, alkali feldspar, plagioclase, biotite, hornblende, and, locally, sphene. Drill-hole data on Pahute Mesa (P. P. Orkild, oral commun., 1966) show that this rhyolite, although it crops out directly below the Rainier Mesa Member of the Timber Mountain Tuff in Silent Canyon and tributaries, is actually older than the Paintbrush Tuff.

The youngest lava, which is called rhyolite lava of Timber Mountain Caldera Moat by Orkild, Sargent, and Snyder (1969), crops out in tributaries of Thirsty Canyon. The rock is light gray to purplish gray, massive to flow layered, dense to vesicular, and generally crystallized except for locally glassy tops and bases. It contains 5–10 percent phenocrysts—mainly quartz and alkali feldspar with minor plagioclase, biotite, and iron ore. In places the rock is quartz free and contains alkali feldspar and plagioclase in a ratio of about 2:1. Drill-hole data indicate that this rhyolite lies between the Ammonia Tanks Member and the Rainier Mesa Member of the Timber Mountain Tuff.

PAINTBRUSH TUFF

Two members of the Paintbrush Tuff (Orkild, 1965), the Stockade Wash Member and an unnamed unit of ash-fall and reworked tuff, are present in the southeastern part of the map area.

STOCKADE WASH MEMBER

The Stockade Wash Member is a simple cooling unit of buff poorly welded rhyolitic ash-flow tuff which locally is as much as 300 feet thick; in most places it is much thinner. Sparse phenocrysts include quartz, plagioclase, alkali feldspar, biotite, hornblende, and iron ore.

Ash-Fall and Reworked Tuff

The unit of ash-fall and reworked tuffs is approximately equivalent to the Survey Butte Member of former usage exposed on Rainier Mesa (Gibbons and others, 1963), but probably only the middle part of the map unit is genetically related to the Paintbrush. Tuffs immediately underlying the Rainier Mesa Member are undoubtedly genetically related to the Timber Mountain Tuff. Where the Stockade Wash Member is absent, ash-fall and reworked tuffs genetically related to the Belted Range Tuff and associated lavas and tuffs are locally mapped with the bedded tuffs of the Paintbrush Tuff. In the southern part of Kawich Valley a local unit of tuffaceous conglomerate, which in places is as much as 200 feet thick, is included in the unnamed unit.

LATITE OF SOUTH KAWICH VALLEY

Black latite lavas that closely resemble basalt in outcrop are here termed the latite of south Kawich Valley. The latite interfingers with the ash-fall and reworked tuffs in south Kawich Valley and at several localities north of Pahute Mesa on the southeast edge of Gold Flat. In the area north of Pahute Mesa the rock was emplaced as a series of thin flows generally no more than 30 feet thick, whereas in south Kawich Valley the unit is as much as 250 feet thick and covers an area of more than 1 square mile.

The rock is dark gray to black and sparsely porphyritic, containing a few phenocrysts of labradorite, clinopyroxene, olivine, and iron ore in a pilotaxitic groundmass. The plagioclase microlites in the groundmass, which appear to be oligoclase or andesine in composition, surround tiny grains of pyroxene, iron ore, and iddingsite. A few crystals of greenish- to dark-brown hornblende mantled with opaque iron oxide are visible in two thin sections from exposures near Gold Flat. The rocks contain an abnormally large amount of apatite, which occurs in the groundmass and as euhedral prisms as much as 0.3 mm long.

TIMBER MOUNTAIN TUFF

The Timber Mountain Tuff (Orkild, 1965) is composed of a sequence of silicic ash-flow tuffs that were erupted from sources in the immediate vicinity of Timber Mountain just south of the mapped area. The two most extensive members of the formation, the Rainier Mesa and the Ammonia Tanks, are present within the mapped area.

Devitrified rocks of both members range in color from gray and maroon to buff; glassy bases and tops of the cooling units are pink, buff, or dark gray. Degree of welding ranges from nonwelded and poorly welded to densely welded.

Within the mapped area the Rainier Mesa Member ranges in thickness from 0 to 600 feet, and the Ammonia Tanks Member, from 0 to 350 feet. Both members are thickest in the eastern part of Pahute Mesa. Numerous partial cooling breaks, reflected by alternating zones of dense and partial welding are visible in many places in thick sections of both the Rainier Mesa and Ammonia Tanks Members; no complete breaks have been observed.

Rocks of the Timber Mountain Tuff range in composition from rhyolite to quartz latite. In both members the ash flows that compose the lower parts are more silicic and less mafic than those that compose the upper parts. Average chemical composition for the rhyolite and quartz latitic phases is given in columns 15 and 16, table 14. Phenocrysts of quartz, sanidine, plagioclase, biotite, hornblende, and clinopyroxene compose 15–25 percent of both members. The Ammonia Tanks Member has an appreciably higher ratio of sanidine to total quartz and plagioclase than does the Rainier Mesa Member (F. M. Byers, Jr., oral commun., 1964).

In isolated outcrops it may be difficult to distinguish the two members. In many thin sections, however, the Ammonia Tanks Member may be recognized by the presence of abundant accessory sphene. In addition, in southeastern Pahute Mesa, the Ammonia Tanks Member may be distinguished by the presence of numerous fragments of red densely welded tuff of an older unit of the Timber Mountain Tuff, and by a thick and distinctive sequence of poorly welded pumice-rich ash-flow tuffs that makes up the lower and middle parts of the member in that area. The difference in the quartz: sanidine-plagioclase ratios and in the direction of remanent magnetization may also be used to identify rocks of the two members; studies by Gordon Bath (unpub. data, 1966) of the U.S. Geological Survey indicate that the Rainier Mesa Member is reversely polarized and the Ammonia Tanks Member is normally polarized.

BASALT OF STONEWALL MOUNTAIN AREA

Porphyritic basalt crops out between the Thirsty Canyon Tuff and the Rainier Mesa Member of the Timber Mountain Tuff in several localities in the southwestern part of the project area near Stonewall Mountain and at the south end of Coyote Cuesta. None of this basalt was examined in thin section or chemically analyzed. The rock contains small phenocrysts of labradorite and a few crystals of olivine largely altered to iddingsite. None of the basalt lavas are more than a few tens of feet thick. South of Stonewall Mountain, west of the project area, several basalt flows are separated by bedded tuff. The basalt and interbedded tuffs at Stonewall Mountain are several hundred feet thick (F. M. Byers, Jr., written commun., 1964).

YOUNGER ROCKS OF MOUNT HELEN

Local poorly exposed units of fanglomerate, alluvium, and basalt underlie the Thirsty Canyon Tuff in the general vicinity of Mount Helen. Although the Thirsty Canyon Tuff provides an upper limit on the age of these rocks, it is difficult to place definite lower limits on their age.

Alluvium

Weakly lithified alluvium, colluvium, and fanglomerate crop out beneath the Thirsty Canyon Tuff in several areas around the perimeter of Mount Helen, notably near Gold Crater. The unit is heterolithic; in places it consists of boulders, cobbles, and pebbles of Paleozoic rocks and fragments of volcanic rocks older than the Thirsty Canyon Tuff in a locally lithified matrix of sand or silt. Material that is clearly of alluvial-fan origin and that consists wholly of volcanic detritus crops out along the west and north flanks of Mount Helen. In the vicinity of Gold Crater, the alluvium apparently is dominantly the valley-fill type, although some may be of alluvial-fan origin. The alluvium is locally at least 50 feet thick, but it may be considerably thicker under Stonewall Playa, which appears to have been topographically low prior to the extrusion of the Thirsty Canyon Tuff.

Porphyritic Basalt

Basalt caps the south end of Mount Helen and the tops of several hills or buttes flanking Mount Helen. The lavas, which apparently were originally only a few feet thick, were erupted onto a fairly extensive erosional surface that sloped away from Mount Helen in all directions.

The rock is characterized by sparse to abundant phenocrysts of plagioclase that average about 1 cm in length but locally are as much as 10 cm. In thin section the groundmass is glassy to extremely dense. At the summit of Mount Helen, however, at or near the feeder vent for the basalt, the rock grades to porphyritic leucodiabase containing a few large plagioclase phenocrysts in a subophitic groundmass of calcic labradorite, 65 percent; olivine (fa_{35}), 11 percent; clinopyroxene, 15 percent; and iron ore, 3 percent. Less than 1 percent alkali feldspar is present interstitially and in the rims of plagioclase. The remainder of the rock is composed of 6 percent calcite, which occurs as vesicles and locally as an alteration product of plagioclase.

The presence of basalt boulders in alluvium beneath the Thirsty Canyon Tuff shows that the basalt is older than the Thirsty Canyon. The basalt itself rests on an erosional surface developed on a variety of older volcanic rocks. This surface was not extensively dissected until after Thirsty Canyon time, as shown by erosional remnants of Thirsty Canyon Tuff on or very near the same surface as the basalt. It seems, therefore, that the rock is not appreciably older than the Thirsty Canyon Tuff and is herein considered tentatively to be of early Pliocene age.

FANGLOMERATE OF TRAPPMAN HILLS

Weakly cemented fanglomerate composed dominantly of fragments of gneissic quartz monzonite and biotite schist forms gently rounded hills west and southwest of Trappman Hills. The fragments are about 1–12 inches in diameter, and in most exposures they contain less than 10 percent of Tertiary volcanic rocks. The percentage of volcanic fragments increases southward; in the southernmost outcrops volcanic material comprises about 50 percent of the fanglomerate.

Although the source of the metamorphic fragments is clearly the Trappman Hills, where the bedrock consists of identical rock, the age of the fanglomerate is not so simply deduced. Locally, the fanglomerate rests on tuff of Tolicha Peak; this fact suggests a Miocene or Pliocene age. However, the occurrence of boulders or fragments of gneissic quartz monzonite in rhyodacitic breccia (rocks of Mount Helen, pl. 1) suggests that the fanglomerate may have started to form prior to the deposition of the tuff of Tolicha Peak. The evidence here, however, is not straightforward inasmuch as the fragments could have been derived directly from Precambrian bedrock.

THIRSTY CANYON TUFF AND ASSOCIATED LAVAS

A complex sequence of genetically related tuffs and lavas had its source in the volcanic center of Black Mountain (Christiansen and Noble, 1965).

The ash-flow and closely associated ash-fall tuffs that erupted from the Black Mountain volcanic center are named the Thirsty Canyon Tuff (Noble and others, 1964). Five formal members are recognized within the Thirsty Canyon. From oldest to youngest, they are: the Rocket Wash, Spearhead, Trail Ridge, Gold Flat (Noble, 1965), and Labyrinth Canyon Members. On plate 1 the tuffs of the Rocket Wash, Spearhead, and Trail Ridge Members are combined. Each member consists primarily of ash-flow tuff that had completely cooled before the deposition of succeeding units of ash-fall or ash-flow tuff. A relatively thin unit of ash-fall tuff occurs at the base of the members in most outcrops.

The rock and cooling unit types of the members and their relative original volume are given in table 15, and average chemical compositions for the Spearhead, Trial Ridge, Gold Flat, and Labyrinth Canyon Members are given in table 14.

TABLE 15.—*Rock and cooling unit types and relative original volume of members of the Thirsty Canyon Tuff*

Member	Rock type	Cooling unit type	Relative original volume
Labyrinth Canyon.	Comendite	Single-flow (?) simple cooling unit.	1
Gold Flat	Pantellerite	Compound cooling unit.	2
Trail Ridge	Nonperalkaline rhyolite.	Multiple-flow simple cooling unit.	4
Spearhead	Comendite and trachytic sodic rhyolite.	Compound cooling unit.	5
Rocket Wash	Trachytic sodic rhyolite and comendite.	do	3(?)

With the exception of the Gold Flat Member, which is typically buff, ocher, or green, the rocks of the Thirsty Canyon Tuff are maroon, gray, buff, and locally pink. Phenocrysts of sodium-rich sanidine compose about 5–25 percent of the rock. Phenocrysts of fayalite and sodic clinopyroxene are ubiquitous, but each composes less than 0.1 percent of the rock. Sparse phenocrysts of an iron- and sodium-rich amphibole are present in the Spearhead, Gold Flat, and Labyrinth Canyon Members. Sparse phenocrysts of quartz and plagioclase are present in the Gold Flat Member, and flakes of biotite occur very sparsely in the Spearhead, Trail Ridge, and Gold Flat Members. Lithic fragments, mostly genetically related material derived from the Black Mountain volcano, and large blocks of pumice are common in many ash flows.

Trachyte and trachytic sodic rhyolite lavas underlie and interfinger with the Thirsty Canyon Tuff in the immediate vicinity of Black Mountain. These lavas are here divided into four informal units, which are, from oldest to youngest, the rhyolite of Ribbon Cliff, the trachyte of Yellow Cleft, the rhyolite of Pillar Spring, and the trachyte of Hidden Cliff. The rocks are typically gray or blue-gray holocrystalline rocks, which in many localities exhibit large-scale flow layering. Feldspar phenocrysts compose 10–30 percent of the lavas. The trachytic sodic rhyolites contain phenocrysts of sodium-rich sanidine and anorthoclase averaging almost a centimeter in diameter, whereas the trachytes contain somewhat smaller phenocrysts of plagioclase, thickly rimmed by anorthoclase or sodium-rich sanidine, in addition to phenocrysts of alkali feldspar. All the rocks contain phenocrysts of iron-rich olivine and clinopyroxene. Biotite phenocrysts are also sparsely present in a few of the lavas of Ribbon Cliff. The groundmass of the lavas consists principally of alkali feldspar, with minor amounts of quartz, iron ore, and aegirite or sodic amphibole. Average chemical compositions of the various units are given in table 14.

The rhyolite of Ribbon Cliff underlies the Rocket Wash and Spearhead Members east, south, and north of Black Mountain (pl. 1). The best exposures are at Ribbon Cliff, 5 miles east of the summit of Black Mountain, where the unit is more than 400 feet thick. Although most of the lava flows that make up the rhyolite of Ribbon Cliff are of trachytic sodic rhyolite composition (table 14), flows of trachyte are locally present at the base of the unit.

A collapse caldera 7 miles in diameter centered on the summit of Black Mountain formed after the deposition of the rhyolite of Ribbon Cliff and the extrusion of the Rocket Wash and Spearhead Members. After collapse, the trachyte of Yellow Cleft, a complex sequence of lavas, tuffs, breccias, and hypabyssal intrusive bodies of trachytic and trachytic sodic rhyolite composition, was erupted within the depression.

The rhyolite of Pillar Spring was erupted during the interval between the deposition of the Trail Ridge and Gold Flat Members. The locality is at an informally named spring (pl. 1), 3 miles south-southwest of the summit of Black Mountain. Three distinct rock types can be recognized in the formation: a basal sequence of trachyte flows, and middle and upper units of trachytic soda rhyolite. With the exception of the upper unit, which has overflowed the northwest edge of the post-Spearhead depression, the rhyolite of Pillar Spring is presently, and probably was originally, restricted to the area of post-Spearhead subsidence.

The trachyte of Hidden Cliff, which is named for Hidden Cliff, located 1 mile east of the summit of Black Mountain, was erupted between the deposition of the Gold Flat and Labyrinth Canyon Members. These lavas, erupted from a vent near the present summit of Black Mountain, probably originally did not extend much beyond their present distribution.

BASALT OF BASALT RIDGE

Basalts younger than the Thirsty Canyon Tuff crop out at Basalt Ridge, at several localities west of Gold Flat, and in Thirsty Canyon and vicinity. Although the various outcrops are similar in lithology, they may vary considerably in age. No isotopic dates are available for the basalt of Basalt Ridge, but the topographic expression and degree of erosion of the various outcrops make a Quaternary age improbable. The basalt is here assigned a Pliocene age.

The basalts are porphyritic in most exposures, but on Basalt Ridge they are conspicuously porphyritic with about a third of the rock containing phenocrysts of plagioclase and clinopyroxene as much as 3 cm in length. In most thin sections the rock is seriate with grains of sodic labradorite, clinopyroxene, olivine (fa_{15}), and iron ore, which range in diameter from several millimeters to less than 0.1 mm. Groundmass texture is typically intergranular, but in some thin sections is subophitic or intersertal. The cores of the larger plagioclase phenocrysts are sodic labradorite and the smaller phenocrysts and microlites range from andesine to calcic oligoclase.

Chemically the basalt of Basalt Ridge is characterized by relatively high iron and alkalis. The average chemical composition (table 14) is similar to that of the average hawaiite described by MacDonald (1960).

TERTIARY AND QUATERNARY

BASALT

Basalt of Tertiary and Quaternary age crops out in Reveille Valley, along the west flank of Kawich Valley near Gold Reed, northeast of Mellan in Cactus Flat, and north of Cactus Peak. The rocks are dense black olivine basalts with sparse phenocrysts of plagioclase; none were examined in thin section.

The youngest basalt appears to be that in Reveille Valley, which, according to H. R. Cornwall (oral commun., 1964), was erupted from fissures in the Reveille Range and flowed out onto the valley where it rests on valley-fill alluvium (pl. 1). The basalt along the west flank of Kawich Valley near Gold Reed is probably older than basalt of Reveille Valley because it is largely covered by valley-fill alluvium. Dikes and highly pumiceous basalt rubble occur in an isolated knob, 4 miles north-northeast of Gold Reed, that probably marks the site of a vent zone or small cone that fed the flows in the Gold Reed area. The basalt northeast of Mellan, shown at the north boundary of the map, rests on an erosional surface developed on the Fraction Tuff.

ALLUVIUM AND COLLUVIUM

Approximately half of the mapped area is blanketed by alluvium and colluvium of Quaternary and Tertiary age. This category includes fan alluvium (locally fanglomerate) deposited on pediment surfaces that slope radially away from the mountain ranges, valley-fill alluvium, lake and shoreline deposits, and, locally, landslide deposits and talus. That some of this material is of Tertiary age is indicated by interbedding with volcanic rocks. For example, in the vicinity of Mount Helen, alluvial material that crops out beneath the Thirsty Canyon Tuff was mapped as older alluvium, but where the Thirsty Canyon is not present because of erosion or nondeposition, alluvium that is probably of pre-Thirsty Canyon age is not distinguished from more recent alluvium.

The alluvial material is thickest in the major basins, but the actual thicknesses are unknown. The basins in the project area are similar in size, areal extent, and geologic setting to the Yucca Flat intermontane basin in which the alluvial fill ranges in thickness from 0 to as much as 2,200 feet (W. P. Williams, W. L. Emerick, R. E. Davis, and R. P. Snyder, written commun., 1963). Gravity data (Healey and Miller, 1962) suggest that the alluvial fill and volcanic rocks may be as much as 4,500 feet thick in Kawich Valley and Gold Flat. Drill-hole data at Yucca Flat (W. P. Williams and others, written commun., 1963) show that the composition, texture, and physical properties of the alluvium vary according to the distance from the source, the types of rock at the source, the carbonate content and resultant degree of cementation, and the amount of compaction of the alluvium with depth. The bulk of the material cut by the drill within the project area is sand and clay. (See p. 84.)

Several of the canyons cut into Thirsty Canyon Tuff adjacent to playas have been partly filled with alluvium. For example, in Civet Cat Canyon south of Stonewall Flat, a well dug 75 feet into the floor of the Canyon bottomed in alluvium of post-Thirsty Canyon origin. The mechanism of this occurrence of aggradation is not perfectly understood, but it seems likely that the canyon was cut primarily during a pluvial cycle of the Pleistocene Epoch when increased rainfall probably gave rise to a perennial stream. With diminished rainfall after the Pleistocene Epoch, rock waste was moved into the canyon by constantly overloaded "gully washing" streams. This aggradation continued until the canyon was filled to a level slightly higher than its present depth, as indicated by several alluvial terraces flanking the streambed a few feet above the present stream level. The shift to downgrading may reflect a slight change to relatively heavier precipitation in fairly recent times or relative settling of the Stonewall Flat basin which effectively increased the stream gradient.

STRUCTURE

GENERAL SETTING

The mapped area is in the western part of the Basin and Range province, about 50 miles east of the average east border of the Cordilleran eugeosyncline as defined by Gilluly (1965). The eugeosynclinal border also approximately marks the east border of the region that is characterized by large granitic plutons of Mesozoic age that are related to the intrusion of the Sierra Nevada batholith. Granite plutons are present east of the line, but they are relatively small and widely scattered. The area lies east of a zone of transcurrent faulting first defined by Gianella and Callaghan (1934) and named the Walker Lane by Locke, Billingsley, and Mayo (1940). This zone divides southern Nevada into an area of north-trending ranges (includes most of mapped area) and an area of northwest-trending ranges (fig. 15). The eastern part of the Walker Lane as defined by Locke, Billingsley, and Mayo (1940) was named the Las Vegas Valley shear zone by Longwell (1960), who concluded that the zone was a right-lateral fault with at least 25 miles of displacement. Stratigraphic studies by U.S. Geological Survey personnel working at Neveda Test Site (F. G. Poole, oral commun., 1966) support Longwell's conclusion. The exact location and the nature of the shear zone in and adjacent to the area of study are problematical. Burchfiel (1965) concluded that the Las Vegas Valley shear zone and the Walker Lane do not form a single continuous fracture zone. Nevertheless, there is general agreement that these two faults together with others (for example, the Furnace Creek fault zone in Death Valley) define a zone of structural weakness in the crust along which there has been considerable right-lateral movement. Shawe (1965) prefers to extend one of the major transcurrent faults through Tonopah and southeastward from there through the Cactus Range. Although the present authors have found no unequivocal evidence of strike-slip movement in the area southeast of Tonopah, the prominent northwest-trending grain of the Cactus Range and the occurrence of numerous volcanic centers along a line [2] extending southeastward from the Cactus Range into Nevada Test Site (fig. 15) tend to suggest that a major crustal rift is present in the area along which magmas, generated at great depth, moved upward. That this zone is a major transcurrent fault may never be proved, but it certainly must be considered a reasonable possibility.

The structure of the adjacent Goldfield area, a volcanotectonic feature west of the mapped area (fig. 1), has been described by Ransome (1909) and recently by Albers and Cornwall (1967); the Tonopah area to the northwest, by Spurr (1905), Nolan (1935), and Ferguson and Muller (1949); and the structure of the Bare Mountain area to the southwest, by Cornwall and Kleinhampl (1961).

[2] P. P. Orkild (oral commun., 1962) of the U.S. Geological Survey was the first to note the alinement of volcanic centers, and he coined the expression "line of fire" to designate the concentration of centers.

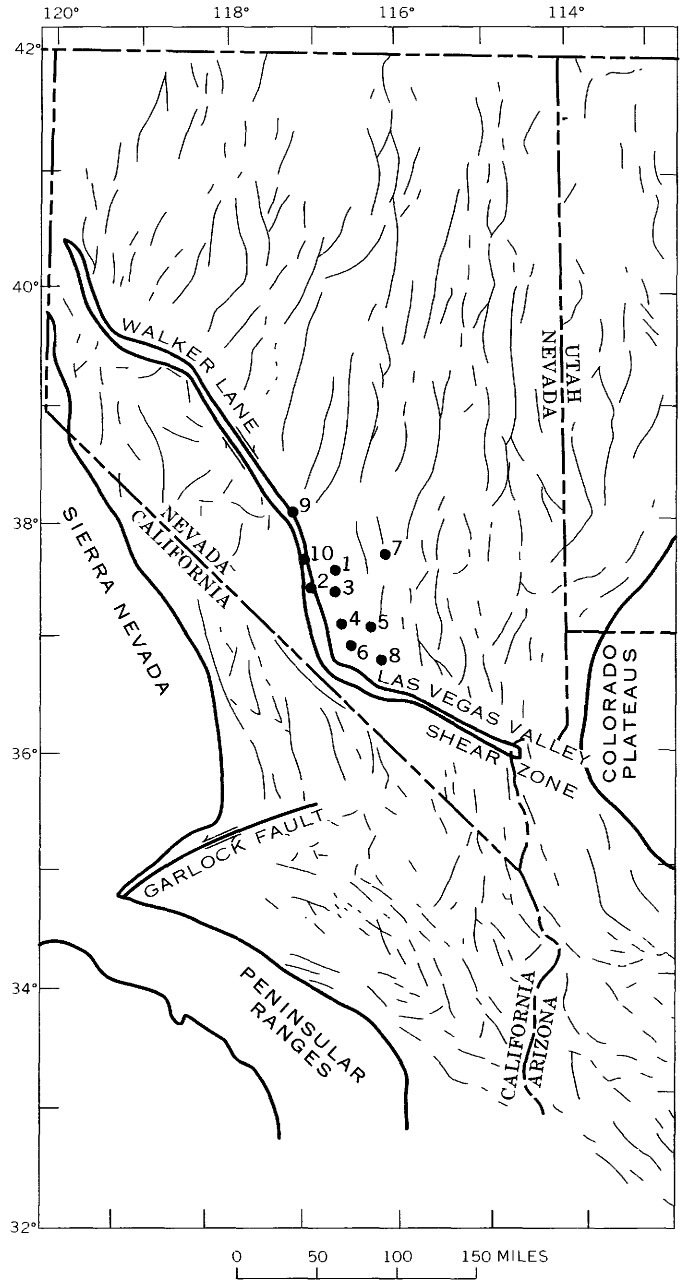

FIGURE 15.—The Walker Lane–Las Vegas shear zone and trends of the ranges in the Basin and Range province. Dots indicate location of major volcanic centers: 1, Cactus Range; 2, Stonewall Mountain; 3, Mount Helen; 4, Black Mountain; 5, Pahute Mesa; 6, Timber Mountain; 7, Cathedral Ridge; 8, Wahmonie; 9, Tonopah; 10, Goldfield. (Modified from Burchfiel, 1965.)

The mapped area contains eight structural blocks or units that lend themselves to separate descriptions, although the relations between units are not entirely clear. The units are separated from each other by structural basins and (or) faults. The units are the Belted Range, the Kawich Range-Quartzite Mountain Block, the Mellan Hills, the Cactus Range, Mount Helen, the

Trappman Hills, Black Mountain, and Pahute Mesa. Of these, only the Belted and Kawich Ranges appear to be predominantly basin-and-range type structural blocks; the others are entirely or in large part volcano-tectonic structural features.

BELTED RANGE BLOCK

The Belted Range block lies along the east border of the mapped area and includes all the topographically high ground between Railroad Valley on the north and Oak Spring Butte on the south. It is bounded on the west by Kawich and Reveille Valleys and on the east by Monotony Valley and an unnamed valley. The block, as a separate structural entity, probably extends beyond the mapped area as far south as the Eleana Range, which lies directly along the projection of the Belted Range and exposes strata of Paleozoic age.

Tertiary strata exposed in the block decrease in age from north to south and dip 20°–60° E. in the northern part of the range and about 5°–10° E. in the southern part. They are cut by numerous normal faults with displacements that range from a few feet to at least 1,000 feet. Paleozoic and Precambrian strata dip at steeper angles both eastward and westward and are cut by numerous normal faults and several low-angle faults, most of which are interpreted herein as gravity-slide faults.

PRE-TERTIARY FOLDS AND THRUST FAULTS

Pre-Tertiary strata in the Belted Range are very steeply dipping, and they contrast, for example, with the strata in the Quartzite Mountain-Cathedral Ridge area where dips on pre-Tertiary strata are nearly conformable to dips in the overlying volcanic rocks. Along Limestone Ridge vertical beds and overturned beds are a common feature. These steep dips are the result of the composite effects of folding, thrust faulting, gravity sliding, and tilting related to basin-and-range faulting.

The oldest beds (Precambrian Stirling Quartzite) crop out on the west flank of Limestone Ridge adjacent to Kawich Valley near Cliff Spring. The youngest beds (Eleana Formation of Mississippian and Devonian age) crop out in three localities on the east flank of the Belted Range between lat 37°16′ and 37°33′.

A thrust-fault system that occurs in the Yucca Flat area of the Nevada Test Site is regional in extent, and it appears to continue northward through the Belted Range and on into central Nevada (F. G. Poole, oral commun., 1966). Thrusting was from the west and northwest. In the part known as the C P thrust (Barnes and Poole, 1968), rocks of late to middle Paleozoic age are overridden by Cambrian and Precambrian rocks. A lower, subsidiary, part of the system, known as the Mine Mountain thrust, has moved Devonian and Silurian carbonate rocks over rocks of Mississippian and Pennsylvanian age.

Both thrust plates are present in the ridge that lies 2.5 miles northeast of Wheelbarrow Peak, at about lat 37°28′. The C P thrust can be observed in the central part of the ridge, where Eleana rocks are overlain by the Halfpint Member of the Nopah Formation and the fault is clearly flat to gently dipping. The upper plate in this area also includes younger rocks from the Smoky Member of the Nopah and from the lower part of the Pogonip Group. A continuation of the structure is the buried thrust shown in section F–F′ (pl. 1) which lies several miles to the north. The Mine Mountain thrust, which occurs in the south half of the ridge, consists mainly of the Nevada Formation with subordinate Silurian dolomite (not shown on pl. 1), and it forms a thin, highly deformed thrust remnant that rests on clastic rocks of the Eleana Formation.

A still lower thrust, known as the Tippinip, may extend from Yucca Flat into the Belted Range. It is covered by volcanic rocks in the Carbonate Wash area (southeast corner of pl. 1), but is believed by F. G. Poole and the authors to be present at depth and to form a structural contact between dolomite of the Spotted Range (pl. 1) on the east and limestone and dolomite of Middle Devonian age (pl. 1) on the west. The latter unit is, at least in part, stratigraphically equivalent to the Nevada Formation in this area, but is dominantly limestone rather than dolomite and represents a facies that is slightly more western and may be described as transitional (F. G. Poole, oral commun., 1967). The Tippinip thrust may also be present in the small Paleozoic exposure that lies on the east margin of the mapped area and 5 miles southeast of Belted Peak, where Eleana rocks may overlie a Devonian limestone.

Several additional thrust faults are present to the east of the Tippinip fault in the Carbonate Wash area, and one of these may have been the mechanism that overturned the Carbonate Wash syncline. A sizable thrust fault may also be present at depth in the vicinity of the Butte fault, and this may have caused the Carbonate Wash syncline to override the adjacent gently north-plunging anticline lying to the east.

The absence of deposits of Mesozoic age in the mapped area precludes accurately dating the period of thrust faulting. The thrust faults do not cut Tertiary strata and it seems reasonable to assume that the faults formed during the same orogeny that gave rise to thrust faults in adjacent areas. Thrust faults northwest of the mapped area, in the Hawthorne and Tonopah quadrangles, have been dated as Jurassic by Ferguson and Muller (1949). The earliest thrusting was from the north followed by thrusts from the northwest. Longwell (1949) dated intense thrusting in the Muddy Mountains near Las Vegas as Middle to Late Cretaceous, and Nolan (1962) dated the thrust faults at Eureka, Nev., as Early Cretaceous. The thrusts in the Belted Range are inferred to be Jurassic or Cretaceous in age.

GRAVITY SLIDE BLOCKS

The strata on Limestone Ridge north of the Kawich Valley-Cliff Spring road are part of a large gravity-slide block that is inferred to have moved from east to west (section *F–F′*, pl. 1). A higher block in the northern part of the ridge (section *E–E′*) and other blocks not shown in cross section are inferred to have the same origin.

The conclusion that these blocks slid into their present positions by gravity movement rather than by thrust faulting from the west is based entirely on the consistent west shift of stratigraphic marker zones in the successive overlying plates. For example, the beds on Limestone Ridge (section *F–F′*) decrease in age from west to east and can be restored to normal stratigraphic position with respect to the underlying beds by moving the overlying block about 4 miles to the east. Thrust faulting from the west would require shifting the east limb of one anticline over the east limb of another. The same relations apply to the higher block shown in section *E–E′*. The beds can be restored to their normal position with respect to the underlying beds by moving them approximately 2,000 feet to the east. Parts of a third and still higher block are found about 1 mile south of section *E–E′*. In this area beds of the Smoky Member of the Nopah Formation have moved about 1,500 feet westward with respect to the underlying strata. To thrust these beds from the west would again entail moving part of an east limb of one anticline over the east limb of another. That this is possible is not questioned; however, the possibility seems remote that each thrust movement could result in younger strata being moved over older strata, and that each thrust would superpose only the east limbs of anticlinal folds in the Limestone Ridge area.

Brecciation at the base of the gravity slide blocks is intense, and this feature largely masks any drag folds or other features that might be used to determine movement directions of the blocks. Thicknesses of breccia range from a few feet to as much as 100 feet, even in blocks that show only a few tens of feet of apparent lateral shift. Locally, the zones are intensely silicified and (or) dolomitized. In the northern part of Limestone Ridge, for example, a small block composed of the Nopah Formation and the Goodwin Limestone (section *E–E′*, pl. 1; and fig. 16) probably moved no more than 200 feet westward, but at the base this block has a breccia zone that is about 50 feet thick on the south and east sides. Brecciated rock is sparse on the west side of the block, but the lack of breccia there may be caused by a normal fault that drops the brecciated rock a few feet down to the east. The breccia fragments and the beds in the overlying block are coarsely recrystallized to dolomite, whereas the underlying strata, especially the Goodwin, are mostly fine- to medium-grained limestone. This occurrence indicates that some of the dolomitization in the Belted Range is related to groundwater or hydrothermal alteration that postdated the major folding and thrust faulting. The gentle dip of the fault plane (section *E–E′*, pl. 1; and fig. 16) resulted in part from eastward tilting, related to basin-and-range faulting, which eliminated part of the original west dip on the fault plane. Direction and degree of dips of the adjacent Monotony Tuff indicate that the fault plane could have been rotated as much as 30° during late Tertiary time.

The age of the gravity sliding apparently is pre-late Oligocene, because nowhere do the volcanic rocks appear to be involved in the sliding. The most likely time was immediately after the period of thrust faulting.

NORMAL FAULTS

Two ages of normal faults are recognized in the Belted Range and throughout the project area (Ekren and others, 1968). The oldest faults, which strike east, northeast, north-northeast, and northwest, are entirely pre-Belted Range Tuff in age. These faults have displacements of as much as several thousand feet. They are as abundant in Tertiary strata as in pre-Tertiary and it is presumed, therefore, that they are post-late Oligocene in age. The youngest faults, which strike north, displace all the strata and give rise to the north strike of the Belted and southern Kawich Ranges. Most of the north-trending faults within the ranges have displacements of only a few tens of feet; however, the range-front faults are inferred to have displacements that locally exceed 1,000 feet. For example, gravity data indicate that the fault that bounds the Belted Range on the west side near Cliff Spring has a displacement of at least 2,000 feet (D. L. Healey, oral commun., 1964). This fault is marked by a feeble lineament on aerial photographs and by small offsets of older alluvium along the east flank of Kawich Valley. The northward fracturing probably began just before the eruption of the rhyolites of Belted Peak and Ocher Ridge (late Miocene), as shown by the fact that these rhyolites were intruded along many north-trending fractures in sev-

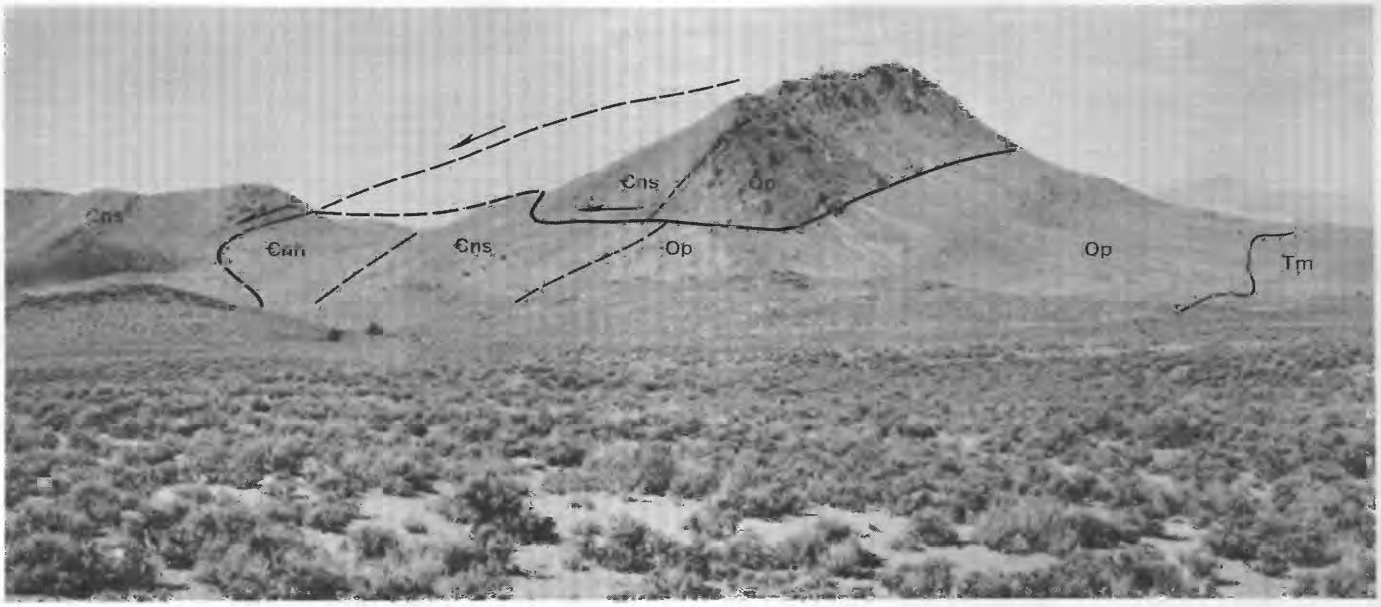

FIGURE 16.—Gravity-slide blocks in northern part of Limestone Ridge, Belted Range. The planes of movement are inferred to have dipped steeply to the west prior to late Tertiary faulting and subsequent eastward tilting. See also section *E–E'* (pl. 1). Tm, Monotony Tuff (Tertiary); Op, Pogonip Group (Ordovician); Ꞓns, Smoky Member, and Ꞓnh, Halfpint Member of Nopah Formation (Cambrian). View to the north.

eral areas, principally in the vicinity of Indian Spring. Evidence is good, however, that the basins and ranges controlled by the north-trending faults did not acquire their present configuration and relief until after the Timber Mountain Tuff was extruded. Drilling in Yucca Flat, for example, discloses that the tuffs are no thicker in the basin than on the flanks, an impossible situation if the basin had formed prior to the eruption of the tuffs from the nearby Timber Mountain volcanic center. By Thirsty Canyon time the area had virtually the same topographic grain but lacked the relief that it has today. This conclusion is deduced from the general distribution of the tuff, evidence of its lapping up against some of the ranges and hills, and its occurrence in old valleys and draws, especially in the vicinity of Lizard Hills in the central mapped area.

KAWICH RANGE-QUARTZITE MOUNTAIN BLOCK

The area of positive relief extending northward from Saucer Mesa and flanked on the east by Kawich and Reveille Valleys and on the west by Gold Flat is here designated the Kawich Range-Quartzite Mountain block. The part of this block that lies within the mapped area averages about 7 miles in width, and trends northward in the south two-thirds of the area and N. 35° W. in the north one-third. The block can be divided into three northwest-trending en echelon structural segments—the southern, central, and northern segments.

The southern segment, which consists predominantly of pre-Tertiary sedimentary rocks, extends from east of Saucer Mesa northwestward to Cathedral Ridge. The sedimentary rocks are nearly all of Precambrian age and are well exposed in a belt almost 12 miles long and as much as 3.5 miles wide. North of Quartzite Mountain the strata have an average strike of north-northwest and low to moderate easterly dips. On Quartzite Mountain and in the outcrops to the southeast, the sedimentary strata strike north, northeast, and northwest and dip about 20°–40° E. East of Saucer Mesa the Precambrian rocks are cut by numerous faults that trend east to northeast and northwest. The contacts with the adjacent volcanic rocks to the east, west, and south are almost wholly fault contacts, and some of these faults have displacements of several hundred feet. Quartzite Mountain itself is an upthrown block that is bounded on all sides by normal faults and is broken into a mosaic of small blocks by variously oriented faults, only a few of which are shown on plate 1. The faults bounding Quartzite Mountain on the west (section *D–D'*, pl. 1.) are inferred to be part of a major north-trending range-front fault system that truncates both the southern and central segments of the structural block. This fault or fault zone is concealed throughout most of its length, but at Quartzite Mountain a small exposure of Stirling Quartzite in the downthrown block indicates a stratigraphic throw of at least 4,000 feet. To the south the range front fault is interpreted as splitting into two faults of small displacement that cut Saucer Mesa; however, several other faults cutting the western part of the mesa may also converge northward beneath the alluvium to join the range-front fault zone.

The central segment, which lies en echelon to the southern segment and extends from Gold Reed to Cedar Pass, consists entirely of Tertiary igneous rocks, and it contains a structural depression named herein the Cathedral Ridge caldera. This collapse structure contains the thickest cogenetic sequence of ash-flow tuffs known to the authors—the Fraction Tuff that is more than 7,000 feet thick. This tremendous thickness suggests that this area subsided concomitantly with the extrusion of the tuff and is, therefore, part of the original caldera. The possibility that a large depression existed there prior to the Fraction Tuff eruptions seems most remote because where the tuff is thickest it rests directly on intermediate lavas without intervening thick deposits of basin fill. The presence of a volcanotectonic collapse structure or caldera in the vicinity of Cathedral Ridge is further suggested by geologic relationships in the area west of Cedar Pass and White Ridge, where some of the youngest ash flows in the Fraction Tuff are deposited on a thick sequence of tuffaceous conglomerate, rubble, and debris flows that apparently accumulated along the wall of the caldera subsequent to the first phases of subsidence (section *C–C′*, pl. 1). This zone of very coarse clastic material thus marks the location of the north and northeast margins of collapse. Rocks within the zone are mapped with similar debris flows and coarse tuffaceous sedimentary rocks north of Gold Reed, but it is not known whether these presumably younger strata at Gold Reed also mark the margin of the caldera. Much of the coarse clastic material north of Gold Reed consists of pre-Fraction debris that must have been derived from the east, presumably from a caldera wall that is now either eroded away or downfaulted into Kawich Valley. The south margin of the caldera is inferred to lie along the trace of two major normal faults that strike N. 65° W. northwest of Gold Reed. These faults have combined throws that total about 7,000 feet, almost equal to the thickness of Fraction Tuff exposed at Trailer Pass. The west margin is inferred to be downfaulted into Gold Flat and to be buried by basin-fill deposits.

The Fraction Tuff dips east and northeast at an average angle of about 25° throughout most of the caldera; this dip suggests that the entire structure was rotated eastward by basin-range faulting. Locally along the collapse zone west of White Ridge, the Fraction dips westward into the caldera at 10°–45°. The inferred area of collapse is elongate northwest and seemingly reflects control by the same forces that controlled the northwest-trending northern and southern segments of the Kawich Range-Quartzite Mountain structural block.

The northern segment, which extends from near White Ridge northwestward to beyond the mapped area (pl. 1), consists predominantly of Tertiary igneous rocks that are older than those of the central segment. This segment is a horst that averages about 4 miles in width and trends N. 35° W. Except for three small masses of Paleozoic sedimentary rocks that might be landslipped blocks totaling less than 1 square mile, it consists of Tertiary tuff, lava, and intrusive masses of pre-Fraction Tuff age. The horst is poorly defined south of Cedar Pass, where it consists mostly of lavas of intermediate composition and where, at White Ridge, it contains a well-defined rhyolite volcano. Lavas and bedded tuffs in that area dip gently southward and are cut by numerous normal faults that trend northwest and west-northwest. The east boundary of the horst south of Cedar Pass is probably buried in Kawich Valley, and the west boundary is nearly coincident with the collapse zone of the Cathedral Ridge caldera.

North of Cedar Pass the horst is composed predominantly of welded tuff of White Blotch Spring. The rocks in this sequence strike northwest and dip moderately to steeply near the north edge of the mapped area (pl. 1), but to the south they have more variable strikes with dips generally less than 20°. They are intruded by a large rhyolite mass, similar in composition to the rhyolite at White Ridge, and by other smaller less silicic intrusive masses. The possibility seems good that intrusive masses are widespread in the shallow subsurface and that their emplacement was a major factor in the uplift of the horst—as much as 3,000 feet on the southwest side. Aside from the range-front faults, numerous normal faults cut the horst with displacements ranging from a few feet to as much as 500 feet. These give rise to a mosaic of tilted blocks with random dips, a feature that contrasts with other ranges that constitute tilted east-dipping blocks rather than horsts; for example, the Belted Range. Although the rocks are well exposed throughout the range, the faults are generally concealed beneath talus and stream gravels, and their dips are rarely observable.

CACTUS RANGE

The Cactus Range is a northwest-trending raised structural block bounded on the east by Cactus Flat and on the west by Stonewall Flat. It terminates abruptly to the northwest a few miles beyond Cactus Peak; to the south and southeast it passes into numerous low hills that extend nearly to Mount Helen. The block is at least 18 miles long and its average width is about 5 miles; it strikes N. 40° W.

The Cactus Range is one of at least five separate mountain masses that lie along the Las Vegas valley-Walker Lane lineaments. In these mountain masses volcanic rocks of Tertiary age are steeply tilted, highly faulted, and invaded by numerous hypabyssal intrusive masses (R. E. Anderson and E. B. Ekren, unpub., data). In each area the steeply tilted strata are cut by wrench and low-angle faults. The similar structural patterns recognized in each area apparently result from superposition of structures of probable volcanotectonic origin on those resulting from wrench and related styles of regional tectonism. The structures are extremely complex and difficult to interpret. They are the subject of present field studies designed to evaluate the interrelationships between the volcanotectonics and regional tectonics. The present report includes only a summary of the major structural features in the range and brief tentative interpretations of the sequence of events that produced them.

The main mass or central core of the Cactus Range is composed of minor upper Paleozoic sedimentary rocks, one small exposure of Mesozoic granite, a thick sequence of widespread Tertiary extrusive and sedimentary rocks ranging stratigraphically from Monotony Tuff to tuff of White Blotch Spring, and a wide variety of intrusive rocks believed to postdate the White Blotch Spring and known to predate the Thirsty Canyon Tuff. The central core rocks are flanked locally by post-White Blotch Spring volcanic and sedimentary rocks that are downdropped along known or inferred faults that tend to gird the range. These younger strata include the Fraction Tuff, and they predate the Thirsty Canyon Tuff which laps onto the range.

The fault density throughout most of the range is much greater than shown on plate 1, where only faults that in most places juxtapose rocks of contrasting lithology are shown. Northwest, east, and northeast fault trends prevail, but locally the fault pattern is a random mosaic. The principal faults trend northwest. The pre-Tertiary rocks, for example, are restricted to a northwest-trending horst about 1 mile wide and 7 miles long along the west margin of the southern range. Also, major northwest-trending faults and related structures that may be of volcanotectonic origin occur in the northern range.

The Monotony Tuff was deposited on a surface of moderate relief developed on gently dipping upper Paleozoic rocks. Its deposition was followed by emplacement of the several ash-flow tuffs that make up the lower and middle parts of the tuffs of Antelope Springs. The first major event of structural significance in the Cactus Range appears to have been the eruption of the upper tuffs of Antelope Springs. That these tuffs were erupted from within or near the range is indicated by their great thickness, especially in the northern range, and by the local occurrence of many large lithic inclusions. The lithic assemblage in these tuffs includes all rock types known to have been present in the area prior to emplacement of the tuff and suggests derivation from disrupted roof rocks in or near the range. The assemblage would be anomalous in most other areas. Evidence for postextrusion collapse within the range is twofold.

1. Along the northern range axis the tuffs of Antelope Springs are steeply tilted, contorted, and locally sheared. In some places they are overlain by gently dipping to flat-lying tuff of White Blotch Spring; the deformation would thus be pre-White Blotch Spring in age. The intensity of this pre-White Blotch Spring deformation far exceeds that which could reasonably have been produced by normal block faulting. It is inferred to have been produced by postextrusion collapse along a northwest-trending rift or graben. The tuffs of Antelope Springs along the northwest margin of the range also dip steeply and are overturned locally, but similar attitudes prevail in the adjacent younger tuff of White Blotch Spring, and this fact precludes unambiguous assignment of a pre-White Blotch Spring age to the deformation there.
2. As much as 800 feet of thin-bedded lacustrine sedimentary rocks accumulated on relatively undeformed tuffs of Antelope Springs in the middle part of the range, and subsidence of the underlying rock is indicated. The sedimentary rocks are reasonably inferred to predate the White Blotch Spring. They may have been deposited in a less deformed southeastward extension of the postulated postcollapse rift or graben.

Partial resurgence within the inferred Antelope Springs collapse structure is suggested by deep pre-White Blotch Spring erosion of intensely deformed tuffs of Antelope Springs in the northern part of the range.

The second major event was eruption of the tuff of White Blotch Spring. Evidence for eruption of these tuffs from a source within or adjacent to the Cactus Range and for subsequent collapse is essentially the same as for the earlier tuffs. After eruption of the White Blotch Spring, subsidence may have occurred along a northwest zone as extensive as the present range. Steep northeast tilting and local overturning to the southwest of tuff of White Blotch Spring and older rocks occurred in a zone as much as 1 mile wide and at least 8 miles long flanking the northern range on the west. Some areas of complete structural chaos occur within the zone. The White Blotch Spring dips more gently or is locally flat lying east of this zone of deformation. Along the eastern range flank the White Blotch Spring dips moderately west toward the axis of the inferred rift. The fact that no zone of steep tilting is recognized there suggests that if the steep dips to the west are related to postextrusion collapse of a northwest rift or graben then the structure is asymmetric with maximum downthrow along the western edge. The pattern of deformation is similar to that produced in the upper tuffs of Antelope Springs along the range axis, and only locally is it possible to distinguish between these two periods of deformation. Subsidence of the central range is supported by intrusion of stocks, sills, and laccoliths of post-White Blotch Spring age into the post-Antelope Springs lacustrine rocks. The considerable thickness of overburden younger than the lacustrine rocks required for intrusion of these masses probably consisted of tuff of White Blotch Spring that accumulated to a much greater thickness in the subsiding block than outside it. This inferred thickness of White Blotch Spring is assumed to have been removed by erosion during later uplift of the range.

The third major event consisted of prolonged intense intrusive activity following the postulated subsidence related to extrusion of tuff of White Blotch Spring. An estimated 200 exposed intrusive masses were emplaced. Lavas and tuffs flanking the northern part of the range probably were erupted concomitantly with emplacement of the intrusive masses. These strata may have covered most of the area now occupied by the Cactus Range. During the latter part of this period of igneous activity, the range was uplifted to its present structural level. Uplift occurred along a system of faults that tend to gird the range. They are well delineated in the northern part of the range but are mostly inferred in the southern part. Little or no additional drag folding, tilting, or brecciation occurred along these fractures during uplift. The contrast between lack of deformation during uplift and intense deformation during subsidence indicates that the fractures along which postextrusion subsidence occurred dip inward. The volume constrictions required by collapse along inward-dipping fractures are assumed to have caused the intense tilting of the strata at the margins of the downdropped blocks or rifts. The volume increase required for the abundant dikes and plugs within the blocks may be related to the volume increase accompanying uplift along inward-dipping faults.

Emplacement of the stocks was accomplished mainly by upward displacement of large blocks of roof rock along preintrusive faults. The stocks are composed mostly of relatively low-silica granitoid-textured rocks and are among the oldest intrusive rocks in the range. They were presumably emplaced when the range was greatly depressed. Emplacement of laccoliths and sills was primarily along zones of sedimentary rocks, but locally these masses are markedly discordant. The dikes were intruded mainly along west- and northwest-trending faults. They are mostly aphanitic rhyolite and are the youngest intrusive masses in the range. As noted previously, their emplacement probably marks a period of volume inflation attending uplift of a volcanotectonic rift or graben.

Although the interpretation of the structural evolution of the Cactus Range is based largely on inference, there is little doubt that large volumes of rock were extruded from the area and that collapse occurred. The range is unique among reported deeply eroded volcanotectonic structures in that postcollapse uplift was of sufficient magnitude to elevate much of the floor of the structure. The range offers an unusual opportunity to observe the fracture zone along which collapse occurred, a feature normally buried beneath the "moat fill" of less eroded calderas.

THE MELLAN HILLS

The Mellan Hills are a series of north-northwest-trending topographically subdued lava ridges separated by valleys formed of soft tuffs. The geologic structure is so completely dominated by northwest- and northeast-striking faults that the area has a distinctly rectilinear, almost diagrammatic-appearing structural and topographic grain. The block is about 10 miles wide (east to west) and 20 miles long (north to south). It is separated from the Cactus Range by Cactus Flat and from the Kawich Range by the northern extension of Gold Flat. On the southwest, the hills merge topographically with the Trappman Hills, from which they are separated structurally by a major fault with large displacement that drops Tertiary strata in the Mellan Hills against Precambrian crystalline rocks in the Trappman Hills.

Despite low elevations and a consequent lack of vegetation, the hills have the poorest exposures of any bedrock area in the Bombing and Gunnery Range. This is due to the abundance of rubble-weathering flow breccias in the lava piles and the tectonic breccias that formed as the lava ridges were faulted, titled, and shifted eastward by northwest-striking very low angle faults (section *A–A′*, pl. 1). The rubble obscures most of the faults that are the key to understanding the area, and were it not for the recent experience gained by R. E. Anderson mapping in the Boulder City area in extreme southeastern Nevada, where remarkably similar geology is well exposed a sensible interpretation of the structure of the Mellan Hills probably would not have been possible.

Very few fault planes were actually observed. All that were observed show eastward dips of 25°–35° with slickensides alined directly downdip. Beds in the hanging walls (mostly lavas) display steep reverse dips of 50° to nearly vertical, averaging 70° into the fault plane. The footwalls are formed of zeolitized tuff of Wilsons Camp which is intensely silicified in a zone about 6 inches wide adjacent to the fault plane. The silicified rock weathers to hard rubble and bears a striking resemblance to flow-laminated crystal-poor rhyolite.

Some of the faults that are inferred in the valley areas where exposures are especially poor were located principally on the occurrence of the silicified "rhyolite" rubble. In other areas, especially along the western ridges where partially welded tuff of Wilsons Camp is mostly fresh and vitric, the fault zones are marked by float of fine-grained brown gouge that formed by the grinding of the tuff of Wilsons Camp in preference to the more competent lavas in the hanging-wall block. This type of float occurs in all instances within a few feet of the west margins of the west-dipping lava ridges, and it is inferred, therefore, that the ridges are all bounded very closely on their west flanks by low-angle faults.

The structural relations of a faulted lava ridge that is thought to be a typical example are well displayed northeast of Triangle Mountain near the east township line of T. 4 S., R. 48 E. Here one can see the controlling low-angle fault and also see beneath the lava ridge. The base of the topographic ridge clearly is also essentially the base of the west-dipping lava mass. It is apparent, however, that in addition to the eastward and downward movement along the main controlling fault, which dips 25° E. there has been some gliding of the lava mass at the base of the ridge along planes developed above the main fault in soft bedded tuffs. These planes dip at angles less than 10° E. Total movement along these gently dipping planes is obviously very minor for this particular ridge; however, this type of movement could have given rise to considerable displacement for some of the larger masses, especially the eastern ridge shown at the end of section *A–A′* (pl. 1). This mass is inferred to have moved eastward principally along a plane that probably dips about 5°. The lavas in the eastern ridge display flow layering that dips generally east, whereas flow layering in nearly all the other ridges dips about 70° W. The layering, however, is in marked discordance with dips in the subjacent bedded tuffs. This discordance and the lack of reverse dip into the fault plane suggest a different mode of faulting and transport, a mode consistent with movement along gentle glide planes similar to those visible in T. 4 S., R. 48 E.

A feature of the hills that is nearly as conspicuous on aerial photographs as the northwest-trending ridges is a series of lineaments and dikes that strike east-northeast, nearly at right angles to the ridges. The lineaments that are not occupied by dikes are extremely straight. There is an apparent horizontal offset of the lava ridges across some of the northeast-trending lineaments. The lineaments are inferred to mark the traces of lateral faults that have horizontal displacements of several hundred feet. The sense of movement is right lateral across some of the faults and left lateral across others; the total offset could be either right or left lateral. The occurrence of quartz latite dikes in the northeast set of faults indicates that faulting started before the intermediate rock volcanism had completely ended.

Thus far this description has been concerned with those rocks lying south of the Antelope Springs-Trailer Pass Road. A tectonic fabric that appears to be similar to that of the southern hills prevails north of the road. There the younger rocks, exclusive of the rhyolite, dip consistently 20°–30° E. and the older tuffs of Antelope Springs and White Blotch Spring dip as much as 70° W. Two interpretations are possible: (1) the Fraction Tuff and dacite lavas rest on the older tuffs with a nearly 90° unconformity, or (2) they have moved over the underlying rocks in a manner similar to the gliding transport inferred for the eastern lava ridge south of the road. We favor the gliding interpretation because of (1) the intensely broken nature of the dacite lava and the Fraction Tuff, and (2) the conflict that exists between a nearby flat outcrop pattern and an internal dip of 20°–30° E.

Either of the two possible explanations indicates, however, that the northern Mellan Hills was the site of profound tectonic activity that either postdated the Fraction Tuff (gliding hypothesis) or postdates the tuffs of Antelope Springs and White Blotch Spring and predates the Fraction Tuff (unconformity hypothesis). The rhyolite masses in the northern hills do not seem to be involved in the deformation that affected the Fraction and older rocks. The rhyolite contains rubble of dacite at its base and is clearly younger than the dacite. Poor exposures suggest that the rhyolite rests unconformably on the Fraction Tuff.

The rhyolite has not been dated isotopically. The lavas of intermediate composition that form the faulted ridges south of the road have been dated at about 18 m.y. (table 5), and they are overlain unconformably by the Grouse Canyon Member of the Belted Range Tuff dated at about 14 m.y. (table 5). If one ignores the unconformity hypothesis that is applicable only to the northern hills, the period of the intense structural activity seems to be bracketed by these dates.

The type of faulting that affected the Tertiary rocks of the Mellan Hills is not unique in the Basin and Range province. Longwell (1945) described strikingly similar faults in southeastern Nevada, and we have observed them in the Cactus Range. Anderson, studying such faults in a broad area in the vicinity of Hoover Dam, thinks that none of the several possible explanations currently in vogue to explain this type of faulting—for example, simple gravity sliding—fully satisfies all the data. At Mellan, the occurrence of northeast-trending dikes and tear faults that formed during a period of intermediate rock volcanism and virtually simultaneously with the development of northwest-trending low-angle glide faults indicates deeper seated control than mere gravity sliding would require. More data are needed on a regional scale before this type of deformation can be satisfactorily explained.

TRAPPMAN HILLS

The Trappman Hills form a north-northwest-trending horst bounded on the north by Cactus Flat, on the east by a syncline that is inferred to be the southward extension of Cactus Flat, on the west by a structural low that flanks Mount Helen, and on the south by Gold Flat. The hills are formed of Precambrian gneiss and schist, the only known occurrence of crystalline basement rocks in the mapped area. High-angle northeast- and northwest-trending faults bound the horst on the north, west, and east. Gravity data suggest that the horst extends southward for several miles beyond the outcrop area. The Precambrian rocks there are probably at shallow depth beneath alluvium and Thirsty Canyon Tuff. See Rogers, Ekren, Noble, and Weir (1968).

The Precambrian rocks are cut by several northwest-trending rhyolite dikes that nearly parallel northwest-striking foliation and by one dike of dark-gray rhyodacite. This dike follows a northeast-trending fault that drops upper tuffs of Antelope Springs against gneiss and schist.

The lack of upper Precambrian and Paleozoic rocks in fault blocks in and adjacent to the Trappman Hills suggests that these rocks are absent or very thin in and near the hills and that Tertiary rocks may directly overlie the basement strata adjacent to the horst block. This is suggested also at Mount Helen, about 5 miles west, where a tuff rich in lithic fragments crops out that is found in no other area and that is presumed, therefore, to be locally derived. The chief lithic fragments in this rock are gneiss and schist of the Trappman type. This fact indicates, perhaps, that little sedimentary rock of Paleozoic age was encountered by this tuff during its ascent through the crust. The chief lithic fragments in dikes of rhyodacite, exposed near Triangle Mountain about 7 miles northeast of Trappman Hills, are also gneiss and schist of the Trappman type.

The thinness or absence of Paleozoic strata suggested by these data indicates either that prior to Tertiary volcanic eruptions the area stood as a topographic high for a long period during which the Paleozoic rocks were stripped away or that the crystalline rocks at Trappman Hills have been thrust over the Paleozoic rocks. Data on this point are sparse. The gravity high over the hills seemingly is low for basement rocks, because higher anomalies were obtained over Paleozoic and Tertiary rocks in the mapped area. This relatively low anomaly, however, probably reflects only the low density of the quartz monzonite gneiss.

MOUNT HELEN

Mount Helen is a volcano and lava pile that lies at the center of a structural dome which, in turn, lies near the center of a collapsed area or caldera that is 9 miles wide measured east to west (sections *A–A′* and *B–B′*, pl. 1). The structure on the north and south is covered by younger volcanic rocks and alluvium. In the center of the 9-mile-wide zone of collapse (section *A–A′*, pl. 1), an additional collapse zone or graben, which is about 4 miles wide, occurs. This zone contains rocks that are younger than the lava pile; these include the tuff of Tolicha Peak, and lacustrine and fluvial sedimentary rocks totaling more than 2,000 feet in thickness. The graben is inferred to be part of a caldera that formed during the eruption of the tuff of Tolicha Peak.

The lavas at Mount Helen are radially distributed around a large feeder neck that is exposed at the south end of the mountain. The neck is a composite mass composed of an older quartz latite that forms a peripheral zone in the neck and a younger quartz latite that fills the central part. The neck is at least three-fourths of a mile in diameter, but the exact dimensions are unknown because on the northwest and north the rocks grade laterally to lava flows. The feeder may actually be elongate north to south and could underlie the entire length of the mountain (this possibility is not inferred, however, in section *A–A′*, pl. 1).

The andesitic basalt that underlies the quartz latite is not found in the feeder neck, but was undoubtedly fed from the same locality as indicated by several radial dikes that are exposed south and west of the mountain.

SEQUENCE OF EVENTS

The volcanic and structural history of Mount Helen is long and varied, and deciphering the early history is hampered by the occurrence of alluvium and young volcanic rocks that not only mask large parts of the 9-mile-wide structure but also cover vast areas beyond. Little is known, therefore, of the distribution of the older tuffs that can reasonably be inferred to have been extruded from the Mount Helen volcanic center and that caused the initial collapse. Mount Helen possibly lies in a large rift zone which is bounded on the east by crystalline basement rocks of Precambrian age and on the west by sedimentary rocks of early Paleozoic age. The rift may have controlled the location of the Cactus Range, Black Mountain, and Timber Mountain centers as well as Mount Helen.

Whether or not such a rift zone exists, evidence is good that tuffs were extruded from the Mount Helen center prior to the lava eruptions and that these extrusions caused collapse across a broad area. Two ash-flow–tuff cooling units, which have not been positively identified elsewhere crop out on both the east and west flanks of the graben. They probably are radially distributed around the mountain at depth. These ash-flow tuffs were called tuff of Mount Helen and are shown separately on a map covering the north half of the Black Mountain quadrangle by Rogers, Ekren, Noble, and Weir (1968). On plate 1 the two units are included with the tuffs of Antelope Springs. (See p. 29.) They probably are at least 1,500 feet thick. That a topographic and presumably a structural depression existed at Mount Helen after the tuffs were extruded is indicated by the occurrence of coarse fluvial conglomerate, sandstone, and lacustrine siltstone and shale above the tuffs and beneath the lava pile. These rocks are poorly exposed and, although their average thickness is only 100–200 feet, they are widespread, occurring both inside and outside the inner graben.

After the deposition of the sedimentary rocks, lavas ranging in composition from andesitic basalt to quartz latite were erupted from Mount Helen; a long period of erosion then ensued. The lavas from Mount Helen were deeply eroded, at least on the south and southeast flanks, and the volcanic neck was exhumed. In places some of the underlying bedded sedimentary rocks and older welded tuffs were exposed at the surface before the basal member of the tuff of Tolicha Peak was deposited. This tuff locally rests on prelava rocks and locally fills deep gullies cut into the lavas. It seems certain that the tuff lapped up against the feeder neck itself. At the base the tuff contains abundant boulders and cobbles of quartz latite and basalt, but 20 feet above the base and upward it is virtually free of lithic fragments. It is overlain by thin beds of ash-fall tuff, cross-bedded sandstone, lacustrine siltstone, and thin-bedded limestone. The occurrence of lacustrine strata almost directly above the ash-flow tuff indicates that a peripheral low area, which might have existed prior to the ash-flow eruption, was not filled with tuff or that collapse immediately followed the extrusion of the basal member.

After the deposition of these sedimentary rocks, the middle member of the tuff of Tolicha Peak was deposited, and collapse certainly occurred. This member south of the mountain is overlain directly by thin beds of limestone and by several tens of feet of finely laminated siltstone, some of which contains fossil plant debris and fish. The collapse associated with the eruption of the second member may have resulted in the burial of the entire mountain, as suggested by the occurrence of finely laminated siltstone near the top of the mountain at the south end. This material is identical with siltstone that crops out around the flanks. The third member of the tuff of Tolicha Peak was then deposited, but whether this unit also gave rise to collapse is uncertain inasmuch as it is almost completely covered by alluvium.

It seems likely that the vent for the tuff of Tolicha Peak was located some distance south of the mountain and that the greatest collapse occurred there, possibly centered on a small gravity low in T. 6 S., R. 47 E. (pl. 1).

After the deposition of the tuff of Tolicha Peak, a dome formed at Mount Helen. Faulting undoubtedly accompanied the doming, and reverse movement probably occurred along faults that formed the earlier graben. Rhyolite dikes that now crop out on the north and northeast flanks probably were intruded during this episode. During a subsequent period of erosion, pediment surfaces were formed radially around the mountain, and the top of the lava pile was exhumed. Porphyritic basalt was extruded from the central feeder zone and also from one arcuate fault on the east side. The eruption of basalt was followed by extensive erosion that removed much of the basalt before the deposition of the Thirsty Canyon Tuff, which lapped onto the flanks of Mount Helen and rests on fanglomerate or other alluvial material containing many large boulders of the Mount Helen porphyritic basalt. Since Thirsty Canyon time, the area has been extensively dissected and most of the Thirsty Canyon adjacent to the mountain has been stripped away.

BLACK MOUNTAIN

The Black Mountain volcano is an excellent example of multiple caldera subsidence uncomplicated by either penecontemporaneous radial faulting or subsequent basin-and-range normal faulting.

The main collapse, which formed an elliptical depression 7 miles in average diameter centered on the summit of Black Mountain, took place after the deposition of the Spearhead Member of the Thirsty Canyon Tuff. A smaller collapse caldera formed within the post-Spearhead caldera immediately west of Black Mountain after the deposition of the Gold Flat Member. Another caldera probably formed within the area of post-Spearhead collapse after the eruption of the Trail Ridge Member. These calderas, however, if they existed, have been completely obliterated by the rhyolite of Pillar Spring.

The cycle of (1) eruption of ash-flow tuff, (2) caldera subsidence, and (3) partial or complete filling of the caldera by lavas has been repeated several times in the Black Mountain center. Thus the trachytes of Yellow Cleft and the trachytes of Hidden Cliff partially filled the post-Spearhead and post-Gold Flat calderas, respectively. The lower and middle units of the rhyolite of Pillar Spring, emplaced after the deposition of the Trail Ridge Members, are probably closely related to the inferred post-Trail Ridge caldera.

Almost all the lavas that erupted after the deposition of the Spearhead Member seem to have been derived from from central vents located within collapsed calderas. In only one place were lavas erupted from the marginal fractures of the post-Spearhead, and those lavas were in very small amounts.

PAHUTE MESA

Pahute Mesa is a broad elevated plateau of relatively gentle relief measuring approximately 20 miles east to west and about 10 miles north to south. On the south, adjacent to the moat area of the Timber Mountain caldera, the mesa is bounded by steep slopes with total maximum relief of about 1,700 feet; on the west it abuts Black Mountain; on the northwest it slopes gently into Gold Flat; and on the north and east it joins the southern extensions of the Kawich and Belted Ranges. The mesa is unique in the Nevada Test Site area in that it is a broad area of gently dipping strata not broken by large fault-controlled basins. Gravity data (pl. 1) indicate that the mesa overlies a deep structural basin, and recent drill-hole data indicate that the volcanic strata are at least 13,000 feet thick in the basin. This structural basin, with its great thicknesses of many different volcanic strata, has been interpreted by geologists working in the Nevada Test Site (Orkild and others, 1968; Noble and others, 1968) to be a large caldera that gave rise to the Belted Range Tuff and related lavas and tuffs.

Most of the faults on Pahute Mesa strike dominantly north, and the strata are downthrown mostly on the west. Vertical displacements average less than 100 feet but range from a few feet to as much as 600 feet. Most of the faults are of post-Thirsty Canyon (early Pliocene) age; a few are older, and some are recurrent, showing greater displacements in pre-Thirsty Canyon strata than in Thirsty Canyon. The faults are inferred to be basin-range structures wholly unrelated to the volcanotectonic basin that underlies the mesa.

MINES AND MINING

The principal mining areas in and adjacent to the project area are at Gold Reed and Silverbow in the Kawich Range; Antelope Springs, Cactus Spring, and Wellington Hills in the Cactus Range; Gold Crater northwest of Mount Helen; at Wilsons Camp; and in the Trappman Hills. These mining areas and others in Nye County have been briefly described by Kral (1951). Prospect pits and exploratory shafts also are abundant in other areas but only in the above listed areas is it apparent that ore was actually shipped. All areas are abandoned, but the Silverbow mining area, just north of the mapped area, enjoyed limited exploration activity during the present field study.

ANTELOPE SPRINGS DISTRICT

The Antelope Springs mining district covers a rectangular area measuring 12 miles northward and 10½ miles eastward, with Antelope Springs in the Cactus Range at the approximate center (Schrader, 1913). It includes scattered mines and prospects at Antelope Springs and Wilsons Camp and in the Wellington Hills.

At Antelope Springs several shafts were sunk along north-trending faults that drop the strata down to the west. The mineralized fault zone along which most of the mines are located dips about 30° W. and displaces the upper part of the tuff of Antelope Springs at least 1,000 feet down to the west. This fault is cut by several west- and northwest-trending faults of small displacement. Drifts in the mines follow both the main fault zone and the west-trending minor faults. The tuffs are propylitically altered throughout the area, and adjacent to ore-bearing veins they are either intensely silicified or argillized and are bleached to light greenish gray and light gray. Schrader (1913), who studied the district in 1912 when the mines were in full operation, noted that sericite, calcite, chlorite, alunite, and hydrous iron oxide, in addition to secondary clay and silica, are common gangue minerals. Development at that time was restricted to the oxidized zone, which yielded cerargyrite and argentite as the chief ore minerals with a silver-gold ratio of 4:1. At the old sulfide prospect

2½ miles south of Antelope Springs (Schrader, 1913, p. 14), the lower part of a 120-foot-deep shaft penetrated the sulfide zone. According to Horton, Bonham, and Longwill (1962a, b), the Antelope Springs mines produced at least 10,000 ounces of silver. The mines are filled with water to very shallow depths, and the good pay zones apparently were below the present water level.

At Wilsons Camp the mines are along a fault zone trending N. 60° E. that drops the strata down on the northwest side. Most of the fractures in the fault zone are filled with quartz, but many are open and contain cavities as much as 6 inches wide that are lined with dogtooth crystals of quartz and minor calcite. Pyrite and hydrous iron oxides are locally abundant. The rocks in the mine are dacitic lavas and welded tuffs of Antelope Springs that have been silicified and argillized. The welded tuffs occur principally in the upthrown block and the lavas, in the downthrown. According to Ball (1907, p. 139), the ore averaged 1 ounce of gold to 5 or 6 ounces of silver. These mines were worked also in the late 1930's and very early in the 1940's. Total production is unknown.

In the Wellington Hills and in the low areas east of them, altered Monotony Tuff, tuffs of Antelope Springs, and intrusive masses of intermediate to rhyolitic composition form most of the weakly mineralized outcrops. Hydrothermal alteration was locally intense along numerous faults in this area. One mine shaft follows a high-angle fault in fine-grained melanodiorite, and numerous shafts and prospect pits are located in country rock adjacent to intrusive masses and along faults some distance from the intrusives. There is, however, no apparent genetic relation between mineralized rock and the intrusion of the various masses; the period of hydrothermal alteration and mineralization postdates intrusive activity.

Several small mines that were being worked during 1905 (Ball, 1907, p. 95) are located south of Wellington Hills and north of Gold Crater in a small patch of brecciated and altered tuff or rhyolite.

Other mines, located 3 miles northwest of Mount Helen near the old townsite of Jamestown (Schrader, 1913, pl. 1), are in altered dacite and andesite that intrudes(?) tuffaceous sediment. At the surface the rocks are brecciated and highly silicified or argillized, and along fault zones they contain barren vein quartz. Hydrothermal alteration occurred in the rocks throughout the area, but most intensely in rocks along faults. Silicification is most intense near the surface and gives way at depth to predominantly argillic alteration; this distribution suggests silica enrichment during weathering. The mine dumps at three of the four main shafts in this area contain both oxidized and unoxidized minerals. The occurrence of oxidized minerals indicates that the workings penetrated the unoxidized zone where primary pyrite and chalcopyrite occur in veinlets a few millimeters wide and as disseminated grains. The rock was mined for silver and gold associated with the sulfide minerals.

TRAPPMAN HILLS

The workings in the Trappman Hills consist of two shafts sunk into Precambrian strata near the south end of the hills. One shaft is sunk in a north-trending quartz vein about 60 feet thick; the other is in a pyritized fault zone that trends north-northeast and dips 60°–70° W. Ball (1907) visited these workings shortly after they were opened in June 1905 and recognized three distinct periods of quartz vein formation. The earliest is pegmatitic, and the associated veins are apparently all barren except where they are brecciated and stained by limonite. In the two youngser sets of veins, which carried the principal ores, Ball (1907, p. 139) recognized minor amounts of native silver, galena, and horn silver. Ball reported that the ratio of gold to silver was 1:4.

GOLD CRATER

Gold Crater consists of a few small hills and knobs of pre-Thirsty Canyon rock surrounded by Thirsty Canyon Tuff, the edge of which forms a discontinuous subcircular rim resembling a crater rim. Here, as in other mining areas in the region, the hydrothermal alteration predates the Thirsty Canyon Tuff. The alteration and associated mineralization were most intense in the north half of the "crater," where most of the mines and prospects are located. Several different lithologies can be recognized in the northern "crater" area, but the chief rock is quartz latite lava of the Mount Helen type. Alteration is predominantly argillic and is most intense along faults. Most of the mining was restricted to the oxidized zone, where the rocks show no visible minerals other than limonite and hematite. Rocks in the mine dump at one of the deeper shafts contain pyrite, indicating penetration below the oxidized zone. Altered rocks, possibly mineralized, probably extend beneath the Thirsty Canyon Tuff adjacent to the mining area.

GOLD REED (KAWICH)

The Gold Reed (originally Gold Reef or Kawich) mining area lies 6 miles northwest of Kawich playa on the east side of the Kawich Range. The first locations were made in December 1904, and 10 miners were at work in August 1905 after a rush of several hundred men in the spring of 1905 (Ball, 1907, p. 111).

The principal mines are located along a northwest-trending silicified horst along which the strata have been dropped both to the northeast and southwest. The silicified zone forms a reeflike ridge; hence, the original name Gold Reef. It is not known when or how the original name was corrupted to Gold Reed.

None of the major mines are accessible at present; however, all the deep shafts are sunk in porphyritic dacite which seems to be the principal ore bearer. The dacite is bleached to light gray and pastel shades of yellow and pink. The gold is not visible to the eye but apparently is associated with iron oxide and pyrite. According to Ball (1907, p. 111–112), some of the limonite-stained casts of phenocrysts contained visible plates of hackly gold, but these relatively rich oxidized zones apparently were restricted to shallow depth and have been mined out.

The amount of gold ore produced at Gold Reed is unknown. Data compiled by Horton, Bonham, and Longwill (1962b) indicate only that the Kawich (Gold Reed) area produced an estimated total of between 0 and 1,000 ounces of silver.

SILVERBOW (TICKABO) MINES

The Silverbow (Tickabo) mines are located half a mile north of the mapped area, in T. 1 N., R. 49 E., along the west flank of the Kawich Range northeast of Mellan; only a few minor prospects are in the project area. The mines were operated intermittently during 1904–40, and they produced at least 10,000 ounces of silver and 1,000 ounces of gold (Horton and others, 1962a, b).

The mines are along several northwest- and west-trending faults that drop the Fraction Tuff and dacite lavas down on the west and south against the tuff of White Blotch Spring and older tuffs; mines are also in and adjacent to rhyolite plugs. Horn silver is concentrated locally in thin veinlets, and in places it is disseminated in the country rock. Secondary copper minerals occur locally; Ball (1907, p. 109) reported that specks of stephanite and "ruby silver" occur and that gold occurs free in some of the veins but that silver was the predominant metal.

The authors visited the Silverbow mines in April 1964 and were guided through the area by Mr. Dan Sheek of Tickabo Mining and Milling Co. At that time the company was in the process of reopening many of the mines and was building a small concentration mill. (The reactivation was short lived; by 1967 all activity had ceased.) Several of the prospects controlled by the Tickabo Mining and Milling Co. are in Fraction Tuff. Inasmuch as the lavas of intermediate composition are the principal ore bearers in adjacent areas, especially at Tonopah where they also underlie the Fraction Tuff, those lavas possibly are mineralized at depth along the west flank of the range in the Silverbow area. The Fraction has been pervasively altered in much of the Silverbow area, but in most places the alteration and associated mineralization were restricted to the lower part of the tuff except where faults or open fractures cut the tuff. Where the rock is unfractured, the hydrothermal solutions apparently were unable to penetrate above a densely welded impermeable zone in the tuff. The altered rock beneath the impermeable zone is moderately to densely welded in most exposures, but it weathers easily and closely resembles nonwelded or partially welded tuff.

SUGGESTIONS FOR PROSPECTING

Future mining exploration in and adjacent to the project area, especially in the Silverbow area, should include sampling the lavas of intermediate composition wherever practicable. These rocks are generally the most intensely altered rocks in areas of hydrothermal alteration and, as stated previously, are the chief ore bearers at Goldfield and Tonopah. In the Antelope Springs area the possibility seems good that weakly mineralized welded tuffs at the surface are intruded by dacite and andesite at shallow depths. If the intrusive rocks are present, they may contain ore.

In mineralized areas adjacent to the Thirsty Canyon Tuff or alluvium-filled valleys, the possibility of buried deposits beneath the tuff or alluvium should be considered, inasmuch as these strata postdate most periods of hydrothermal activity (Anderson and others, 1965). The most likely areas for buried deposits appear to be (1) the area north of Stonewall Mountain bordering Stonewall Flat, (2) the area between Stonewall Mountain and Mount Helen, and (3) Stonewall Flat adjacent to the Cactus Range.

POTENTIAL SITES FOR UNDERGROUND NUCLEAR TESTING

The project area, exclusive of Pahute Mesa which is currently being used as a testing area, offers various sites that may be suitable for underground nuclear testing. The sites and the thicknesses and physical properties of available media are discussed below.

ALLUVIUM-FILLED BASINS

Most of the underground nuclear testing at Nevada Test Site has been in alluvium-filled basins. The basins in the area of study are very similar geologically to those in Nevada Test Site and should, therefore, provide suitable environments for testing. Of the four principal basins–Kawich Valley, Gold Flat, Cactus Flat, and Stonewall Flat–the first two appear to be most suitable because they are far removed from population centers and have the thickest deposits of alluvium. Gravity data (Healey and Miller, 1962, p. 20–22; C. H. Miller and D. L. Healey, oral commun., 1968) suggest 4,500 feet of alluvial fill and volcanic rocks in the deepest parts of both valleys and indicate sizable areas where the alluvium and volcanic rocks can be expected to be at least 2,000 feet thick.

As of June 1966 no drill holes had penetrated sufficiently deep to determine the thickness of alluvium and volcanic rocks in any of the valleys. The logs of several wells that have been drilled for water (pl. 1) very briefly describe the material penetrated (p. 84). The driller's log of Gold Flat well 1 indicates bedrock at from 400 feet to 486 feet, but this log may be erroneous inasmuch as it conflicts with gravity data and the geologic setting. It seems more likely that the driller reached well-cemented gravel rather than bedrock, but possibly the alluvium in this part of Gold Flat is thin. In general, the greatest thicknesses of alluvium within the valley areas probably occur within or adjacent to the lowest gravity contours along the east flanks of the valleys, but drill-hole data are needed for accurate thickness determination.

NONWELDED AND PARTIALLY WELDED ZEOLITIZED TUFF

Thick zones of nonwelded and partially welded zeolitized tuff have been used for contained explosions for many years at the Nevada Test Site. As much as 800 feet of such tuff (bedded) crops out along the west flank of the Belted Range east of Pahute Mesa in the vicinity of Quartet Dome (Sargent and others, 1966). Here the tuff is capped by 80 feet of the densely welded ash-flow tuff of the Grouse Canyon Member of the Belted Range Tuff. The bedded tuff dips gently to the east, and it may thicken eastward. As much as 1,000 feet of cover could be obtained by driving tunnels 3,000 feet eastward from an elevation of 6,200 feet approximately 2 miles south-southwest of Quartet Dome (K. A. Sargent, written commun., 1963).

Thick sections of zeolitized nonwelded and partially welded tuff have been penetrated by the drill beneath the Timber Mountain Tuff in local areas on Pahute Mesa. The possibility seems good that similar tuff in thinner beds is also present beneath the Timber Mountain Tuff along the south flank of Gold Flat north and northwest of Silent Canyon. In this area, the alluvium probably ranges in thickness from 0 to at least 1,000 feet and, excluding the western part of the flat, the first bedrock is probably either basalt, Thirsty Canyon Tuff, or Timber Mountain Tuff. Along the west and south-west flanks of Gold Flat, lavas and tuffs that are older than the Timber Mountain Tuff crop out. These outcrops indicate that the maximum width of ground that can be inferred to be underlain by Timber Mountain Tuff and thick alluvium in Gold Flat is less than 5 miles measured east to west. Most of the alluvium above the volcanic rocks is probably poorly lithified and rich in boulders; therefore, drill holes will undoubtedly meet with lost circulation zones in the alluvial section. The volcanic rocks beneath the alluvium are probably no more fractured and faulted than those on Pahute Mesa; they should drill easily and provide tight impermeable zones suitable for test media. Drill holes would be required for accurate thicknesses of the total alluvium-volcanic rock section in this area.

WELDED TUFF

Thick sections of densely welded tuff are probably present at various depths in all the basin areas, and in a few areas they may be sufficiently homogeneous and impermeable to be potentially valuable as test media. The most favorable areas for such occurrences appear to be the west flank of Kawich Valley east of Trailer Pass and north of Gold Reed, in Tps. 3 and 4 S., R. 51 E., and in Gold Flat adjacent to the Cathedral Ridge caldera. In both areas several thousand feet of Fraction Tuff probably underlies the sedimentary rocks of Tertiary age and the alluvium of Cenozoic age. Depending on the distance outward from the range, the tuff could be expected to occur at depths from zero to several thousand feet. Drilling would be required to determine the depth to ground water and the occurrence of impermeable zones suitable for test media. Physical properties of Fraction Tuff and of two samples of subjacent lava of intermediate composition are given in table 10.

BASEMENT ROCKS AND GRANITE

The Trappman Hills are a structural horst formed of gneiss and schist of Precambrian age. The gneiss (gneissic quartz monzonite) forms the bulk of the outcrops in the hills and intrudes the schist. Both rock types are well foliated and intensely fractured; locally they are hydrothermally altered. The rocks are cut by numerous quartz, aplite, and pegmatite veins as well as by several rhyolite dikes of Tertiary age. The schist is characterized by abundant femic minerals and relatively high dry bulk density (2.8 grams per cubic centimeter, E. F. Monk, written commun., 1963); the gneissic quartz monzonite is characterized by relatively sparse femic minerals and lower dry bulk density (2.6 g/cc). In several areas gneissic quartz monzonite forms the only visible outcrops and probably forms a homogeneous medium at depth suitable for some types of nuclear tests.

Granite of probable Mesozoic age in T. 3 S., R 46 E., in the Cactus Range along the northeast flank of Stonewall Flat, and southeast of Quartzite Mountain in the southern Kawich Range about 4½ miles west-northwest of the Floyd Lamb water well provides relatively unfractured media similar to the quartz monzonite in the Climax stock at Nevada Test Site.

MEASURED SECTIONS

Tuff of White Blotch Spring

[Outside mapped area, about 1 mile north of White Blotch Spring in NE¼ T. 5 S., R. 53 E., White Blotch Spring quadrangle, Nye County, Nev. Measured by E. B. Ekren, C. L. Rogers, Theodore Botinelly, and J. E. Weir, April 1963]

	Unit thickness (feet)	*Accumulated thickness (feet)*
Top of section is fault contact with younger ash-flow tuff.		
Tuff of White Blotch Spring (incomplete):		
Ash-flow tuff, weathers white; moderately welded. Contains abundant white fiamme as much as 2 in. long, sparse biotite as sole mafite, 30 percent phenocrysts consisting of 40 percent quartz, 40 percent sanidine, and 20 percent andesine. (A comparison of this zone with outcrops where top of White Blotch Spring is preserved indicates no more than a few tens of feet are cut out here by fault.) Forms bench	50	895
Ash-flow tuff, light-gray, densely welded, crumbly weathering; vague flow layering with layers about 3 ft thick. Contains fairly abundant lithic fragments of shard-rich gray welded tuff about 1 in. in diameter, abundant white fiamme, same phenocrysts as above, sparse biotite. Forms bench above cliff. Thickness of unit, approximate	120	845
Ash-flow tuff, medium-gray, weathers brownish gray; otherwise similar to above but fiamme are very sparse and groundmass is mostly vitric. Contains 24 percent phenocrysts consisting of 33 percent quartz, 42 percent sanidine, 24 percent plagioclase, and 1 percent biotite. Forms upper part of cliff	30	725

Tuff of White Blotch Spring—Continued

	Unit thickness (feet)	*Accumulated thickness (feet)*
Ash-flow tuff, light-gray, weathers light reddish brown, densely welded; groundmass partly vitric. Contains small white fiamme and 32 percent phenocrysts consisting of 40 percent quartz, 43 percent sanidine, and 17 percent plagioclase. Forms steep jointed cliff	160	695
Ash-flow tuff, light-gray, weathers light reddish brown. Basal less-welded slope-forming part of same zone as above, but is richer in biotite and plagioclase; no apparent cooling break. Contains sparse small andesite lithic fragments, 34 percent phenocrysts consisting of 36 percent quartz, 20 percent sanidine, 33 percent plagioclase, and 11 percent biotite	30	535
Ash-flow tuff, very light gray, densely welded, fiamme-poor, shard-rich. Groundmass vitric to weakly devitrified. Unit contains 35 percent phenocrysts consisting of 41 percent quartz, 36 percent anidine, 21 percent plagioclase, 2 percent biotite. Forms slope	100	505
Ash-flow tuff, light-gray, weathers to alternating light-, medium-, and dark-brown zones. Pumice lapilli very sparse, eutaxitic structure vague, groundmass vitric to weakly devitrified. Contains 30 percent phenocrysts consisting of 45 percent quartz, 30 percent sanidine, 18 percent plagioclase, 7 percent biotite. Forms cliff that is columnar jointed at base	70	405
Ash-flow tuff, tan, pale-pink, green, and gray, biotite-rich, weakly to moderately welded. Contains abundant light-greenish rhyolite fragments and flattened pumice lapilli and blocks as much as 4 in. long; at about 150 ft above base lithic fragments diminish. Unit forms slope. Mostly covered, thickness approximate	335	335
Total incomplete tuff of White Blotch Spring	895	
Shingle Pass Tuff (incomplete):		
Ash-flow tuff, vitrophyre, black. Contains 23 percent phenocrysts of plagioclase, hornblende, biotite, and magnetite. Unit appears to be vitrophyre at top of flow that is very poorly exposed but may be basal part of flow extending into covered zone above	20	

Fraction Tuff

About 1½ miles south of Trailer Pass in N½ T. 4 S., Rs. 50, 51 E., Quartzite Mountain quardrangle, Nye County, Nev. Measured by E. B. Ekren and C. L. Rogers, May 23, 1963]

	Unit thickness (feet)	Accumulated thickness (feet)
Top of section represented by a poorly exposed contact with overlying dacitic debris flow.		
Fraction Tuff:		
Ash-flow tuff, white, weathers white; vitric, weakly welded. Contains phenocrysts of plagioclase, alkali feldspar, quartz, biotite, hornblende, sphene, and magnetite. Gently sloping surface. Generally poorly exposed	1, 300	7, 220
Ash-flow tuff, light-pinkish-gray, weathers brownish gray, vitric, moderately welded. Contains fairly abundant white flattened pumice lapilli, plagioclase, quartz, alkali feldspar, biotite, and abundant hornblende. Weathers to rubbly slope, forms gentle hills. Contact gradational with units above and below	600	5, 920
Ash-flow tuff, dark-brownish-gray at base grading upward to light-pinkish-gray at top; white flattened pumice lapilli, vitric, moderately welded. Plagioclase is dominant phenocryst, quartz and alkali feldspar also present; abundant biotite, very little hornblende, no sphene	700	5, 320
Vitrophyre of ash-flow tuff, brown-black; same mineralogy as unit above	30	4, 620
Ash-flow tuff, brown-gray; same mineralogy as unit above, very rich in lithic fragments, including dacite, schist, and quartzite, the latter in boulders as much as 3 ft in diameter; unit is moderately welded, vitric	300	4, 590
Ash-flow tuff, light-brownish-gray, lithic-rich, weakly welded; approximately equal amounts of plagioclase, alkali feldspar, and quartz, with minor biotite and no hornblende or sphene. Zone of hydrothermal alteration may indicate fault contact with unit above	100	4, 290
Ash-flow tuff, light-brownish-gray, weathers dark brownish gray, moderately welded, lithic-rich; same mineralogy as unit above	800	4, 190
Ash-flow tuff, weathers brown, densely welded. Phenocrysts are quartz, alkali feldspar, plagioclase, abundant biotite, very sparse hornblende. Forms rugged hills above two vitrophyre zones that show as two dark conspicuous bands on arerial photographs	700	3, 390
Ash-flow tuff. Interval includes two vitrophyres about 30 ft thick with about 120 ft of intervening devitrified welded tuff; upper vitrophyre apparently is base of of ash flow described above; lower vitrophyre is base of 150-ft-thick welded tuff. Unit contains abundant biotite; phenocrysts consist of plagioclase (dominant), quartz, and alkali feldspar	180	2, 690
Ash-flow tuff, light-buff, weathers brown, densely welded, partly devitrified. Contains small amount of biotite, no hornblende or sphene; quartz dominant phenocryst, alkali feldspar exceeds plagioclase; contains a few dacite lithic fragments. Forms steep jointed cliffs that weather to spires; columnar jointed at base. Thickness, approximate	1, 100	2, 510
Ash-flow tuff, discontinuous. Basal 35 ft is black vitrophyre; above the vitrophyre the unit is light gray and weathers gray brown. Unit is partly devitrified, forms stepped cliff near base grading upward to slabby- and crumbly-weathering slope former. Same mineralogy as unit above	200	1, 410
Ash-flow tuff, some lenses of vitrophyre at base, light-gray at base, light-violet-gray at top. Crystal rich with same mineralogy as unit above	70	1, 210
Ash-flow tuff, densely welded. At base, black vitrophyre pods, as much as 10 ft thick; above base, unit is gray green and devitrified. Phenocrysts: quartz (dominant), alkali feldspar and plagioclase about equal, small amount of biotite	40	1, 140
Ash-flow tuff. At base, discontinuous dark-brownish-gray to black vitrophyre as much as 40 ft thick; above base, unit is largely devitrified. Unit contains sparse hornblende and biotite, very minor sphene; quartz, plagioclase, and alkali feldspar in about equal amounts, abundant dacite lithic fragments	230	1, 100
Ash-flow tuff, olive-gray, hackly-weathering, densely welded at base of exposure; grades upward within about 20 ft to black vitrophyre as much as 50 ft thick; rock above vitrophyre same lithology as rock below; some biotite, no hornblende, minor sphene; quartz, plagioclase, alkali feldspar; no visible ash fall at base of unit in vicinity of section, but in exposures to north about 50 ft of stratified yellow tuff crops out at base	120	870
Ash-flow tuff, light-red to light-reddish-gray, densely welded, devitrified, irregular slabby weathering. Contains abundant flattened light-gray to yellow-gray pumice; biotite abundant, some hornblende and large sphene; plagioclase, quartz, alkali feldspar. Unit forms gentle slopes and hummocky hills in line of section; to north weathers to small rounded "haystack" hills; lower 5 ft crystal poor and locally silicified	750	75
Total Fraction Tuff	7, 220	
Lavas of intermediate composition (incomplete):		
Latite or rhyodacite, light-gray to yellowish-green, flow-layered, crystal-rich; plagioclase, quartz, biotite, and hornblende. Base not exposed	40	

DRILLERS' LOGS OF WATER WELLS IN MAPPED AREA

Drillers' logs throughout this section are quoted verbatim.

Gold Flat 1

[Well drilled by E. C. Ferguson, Tonopah, Nev. Casing 6 in. in diameter to 390-ft (?) depth]

Material	*Depth (feet)*	*Thickness (feet)*
Gravelly sand	40	40
Whitish soil	200	160
Reddish soil	255	55
Gravelly sand	260	5
Whitish soil	390	130
(Not logged)	400	10
Bedrock	486	86

Gold Flat 2

[Well drilled by E. C. Ferguson, Tonopah, Nev. Casing 5¾ in. in diameter to 290-ft depth, perforated 225–290 ft. Could not lower water level with 5-in.-diameter bailer 20 ft long]

Material	*Depth (feet)*	*Thickness (feet)*
Soft volcanic gravel	90	90
Slightly harder volcanic gravel	200	110
Reddish volcanic gravel, water	250	50
Blackish volcanic gravel	290	40

Sandia 1

[Well drilled by S.R. McKinney and Son, Las Vegas, Nev. Uncased test hole. Bailed 330 gal of water from zone at 45 ft, remainder of well dry]

Material	*Depth (feet)*	*Thickness (feet)*
Loose sand and gravel	3	3
Cement gravel and boulders	28	25
Black, pink, and white cemented gravel	35	7
Granite clay	45	10
Cement gravel with clay	50	5
Cement gravel	55	5
Cement gravel and clay	60	5
Brown cemented gravel	75	15
Black, red, and white cement gravel	100	25
Brown cemented gravel	110	10
Pink, white, and brown cemented gravel	130	20
Gray and white cemented gravel	160	30
Brown cemented gravel and sand	175	15
Gray cemented gravel and sand	220	45
Gray clay and gravel	260	40
Gray clay and sand	325	65
Gray clay	435	110
Gray and green clay	440	5
Green clay	465	25
Gray and green and gray and black shale	470	5
Blue shale	475	5
Blue and green shale	480	5
Gray limestone	485	5
Dark-gray shale	535	50
Brown shale	541	6
Brown and gray shale	548	7
Blue shale	588	40
Blue and brown shale with limestone shelves	593	5
Blue shale	600	7

Sandia 2

[Well drilled by S. R. McKinney and Son, Las Vegas, Nev. Casing 8 in. in diameter to 525-ft depth; perforated 325–485 ft. Well yielded 15 gpm with 142-ft drawdown during a test of unspecified length of time]

Material	*Depth (feet)*	*Thickness (feet)*
Gravel and clay	4	4
Brown cement gravel	20	16
Red, brown, and white cement gravel	35	15
Brown cement gravel	45	10
Brown and white cement gravel	70	25
Brown, red, and white cement gravel	99	29
Brown and gray gravel, hard	110	11
Brown and gray cement gravel	125	15
Brown, gray, and red cement gravel	170	45
Brown, gray, and red cement and sand	215	45
Brown, gray, and white cement gravel	280	65
Brown and white cement gravel	327	47
Brown, white, and pink cement gravel	346	19
Brown, white, and pink cement gravel and sand	357	11
Brown, white, and pink cement gravel and clay	362	5
Cement gravel, water	367	5
Brown, red, and white cement gravel	387	20
Brown, red, and white cement gravel, water	392	5
Brown, red, and white cement gravel	397	5
Cement gravel and clay	407	10
Brown and white cement gravel	417	10
Brown and white cement gravel and clay	437	20
Yellow clay	442	5
Yellow clay and gravel	452	10
Brown cement gravel, hard	455	3
Muddy clay	467	12
Clay and gravel, water	477	10
Gray sand and clay	525	48

Sandia 3

No log available.

Sandia 4

[Well drilled by S. R. McKinney and Son, Las Vegas, Nev. Casing 8 in. in diameter to 580-ft depth, perforated 351–466 ft. Well yielded 6 gpm with 67-ft drawdown during a test of unspecified length of time]

Material	*Depth (feet)*	*Thickness (feet)*
Soil and gravel	5	5
Gravel	15	10
Cement gravel and boulders	65	50
Gravel	74	9
Cement gravel and boulders	81	7
Cement gravel	95	14
Cement gravel and boulders	130	35
Gravel and little clay	134	4
Cement gravel	196	62
Gravel	201	5
Cement gravel	225	24
Gravel and sand	230	5
Cement gravel and sand	260	30
Cemented sand	347	87
Cemented sand and gravel	362	15

Sandia 4—Continued

Material	Depth (feet)	Thickness (feet)
Sand, gravel, and clay; lost mud	367	5
Cemented sand	397	30
Cemented sand, little clay, little water	402	5
Cemented sand, little water	412	10
Cemented sand	422	10
Cemented sand and clay	437	15
Sandy clay, little gravel	442	5
Sandy clay	477	35
Gray sandy clay	497	20
Gray clay, muddy	546	49
Pink clay	580	34

Sandia 5

[Well drilled by Perry Bros., Flagstaff, Ariz.]

Material	Depth (feet)
Sandy clay	0–18
Sand and gravel	19–30
Brown clay	30–36
Fine sand	36–51
Sandy clay and gravel	51–82
Sand and gravel	82–125
Brown sandy clay	125–132
Sandy clay with streaks of semicemented gravel	132–180
Sand and gravel	180–280
Black volcanic rock	280–300

Test pumping results: Pump setting 210 ft to end of suction. At start 11 gpm, water level 210 ft. Surging and backwashing increased yield to 15 gpm. At completion of test, yield had increased to 16 gpm. After setting overnight, well would pump 20 gpm for 10 hours then drop off to 16 gpm. Maximum yield was from 210-ft level.

Sandia 6

[Well drilled by Perry Bros., Flagstaff, Ariz.]

Material	Depth (feet)
Soil	0–2
Boulders	2–34
Large gravel and boulders	34–60
Large loose gravel	60–140
Gravel and brown sandy clay	140–245
Cemented gravel (small)	245–305
Sand and gravel	305–415
Sandy clay with streaks of sand	415–510
Gray clay	510–525
White soapstone	525–568
White and blue shale with limestone streaks	568–620
Green shale with limestone streaks	620–705
White sandy clay	705–755
Dark-gray and black clay	755–790

Test pumping results: Pump setting at 510 ft; water level 351 ft. Ninety gpm resulted in 75-ft drawdown to 426 ft; 70 gpm resulted in 74-ft drawdown to 425 ft. Pumped 48 hours at 90 gpm.

Sandia 7

[Well drilled by Perry Bros., Flagstaff, Ariz.]

Material	Depth (feet)
Blow sand	0–4
Sand and sandy clay	4–110
Sand and large gravel	110–120
Sand and small gravel (water level 137 ft)	120–280
Gravel, sand, and clay	280–305

Test pumping results: Static water level 137 ft; 125 gpm with 23-ft drawdown; 150 gpm with 38-ft drawdown.

Sandia 8

[Well drilled by Perry Bros., Flagstaff, Ariz. Casing 8 in. in diameter to 793-ft depth, perforated 368–773 ft. Well yielded 122 gpm with 100-ft drawdown during test of unspecified length of time]

Material	Depth (feet)	Thickness (feet)
Brown clay with gravel and sand	250	250
Basalt sill or cemented gravel	268	18
Clay, gravel, and sand with basalt stringers	328	60
Sandy clay	483	155
Clay, gravel, and sand	710	227
Sand with clay	793	83

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