Geology of Bullfrog Quadrangle and Ore Deposits Related to Bullfrog Hills Caldera, Nye County, Nevada and Inyo County, California

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ABSTRACT

The Bullfrog quadrangle in southern Nye County, Nev., and eastern Inyo County, Calif., east of Death Valley, is underlain by Tertiary volcanic rocks, mainly in the northern part, and by Paleozoic sedimentary rocks, mainly in the southwestern part.

The volcanic rocks are believed to have been derived from a caldera, measuring 10 by 13 miles, that covers the northern half of the quadrangle. Rhyolitic ash flows (welded tuffs) and air-fall tuffs predominate in the volcanic sequence, which also includes extrusions and intrusions of rhyolite, latite, basalt, and basanite. The volume of ash flows (85 cubic miles) is roughly equal to the estimated subsidence in the caldera, and it is probable that the violent eruption of these rocks resulted in the subsidence of the caldera because the eruption removed magma from an underlying chamber. A grabenlike structure extends northeast tangentially from the south rim of the caldera and may also have resulted from subjacent removal of magma during the volcanic activity.

The older rocks range from Precambrian through Mississippian; the section is fragmentary because of poor exposures and intense deformation. These rocks have been folded and intensely faulted, mainly by bedding-plane thrusts that moved northeast or southwest. This deformation is considered to be related to the development of the Las Vegas Valley shear zone, which probably passes diagonally across the center of the quadrangle from southeast to northwest. Monolithologic breccia of dolomite and limestone in the southwestern part of the quadrangle probably formed by landslide off the front of the main thrust. Tertiary to Recent basin-range faults have moderately disrupted the rocks.

Ore mineralization appears to be concentrated near the margins of the subsidence structures. The three known most promising gold-silver deposits are located on the east rim of the Bullfrog Hills caldera. A substantial fluorspar deposit and a small mercury deposit are just south of the grabenlike structure extending east from the caldera across the north end of Bare Mountain. A small bentonite deposit is also just south of this structure near the caldera. The ore deposits are in fracture zones, which probably served as channels for emanations from underlying magma bodies.

INTRODUCTION

The Bullfrog quadrangle is in southern Nye County, Nev., and eastern Inyo County, Calif. (fig. 11). The Bullfrog Hills are in the northern half of the quadrangle. The Grapevine and Funeral Mountains, separated by Boundary Canyon, occupy the southwestern quarter; the town of Beatty is at the eastern edge. The geology of this quadrangle was mapped in cooperation with the Nevada Bureau of Mines during the period 1958–61. The Bare Mountain quadrangle, which adjoins the Bullfrog on the east, was also mapped by the present authors (Cornwall and Kleinhampl, 1960a, b; 1961b).

Published references to the geology of the Bullfrog quadrangle include an areal reconnaissance by Ball (1907), a detailed study of the geology and ore deposits of the Bullfrog district by Ransome and others (1910), and a description of mammal-bearing sedimentary beds of early Oligocene age by Stock and Bode (1935).

Members of the U.S. Geological Survey identified fossils collected by the authors during fieldwork. Cambrian faunas were identified by Helen Duncan, C. A. Nelson, and A. R. Palmer; Ordovician, by R. J. Ross, Jr.; Oligocene, by D. W. Taylor.

PRECAMBRIAN ROCKS

Rocks of older Precambrian age crop out in a small area near the center of the quadrangle (pl. 1) in sec 13, T. 12 S., R. 45 E. Quartz-muscovite-feldspar gneiss and quartz-muscovite-biotite schist have been intruded by irregular bodies of gneissic pegmatitic granite. The gneiss is light gray and is composed mainly of quartz and feldspar, whereas the schist is nearly black and contains abundant biotite and muscovite with lesser amounts of quartz and a little feldspar. The granite is nearly white, very coarse grained, and consists mainly of quartz and feldspar with minor muscovite.

PALEOZOIC ROCKS

Cambrian rocks crop out in the southwestern part of the Bullfrog quadrangle in the Grapevine and Funeral Mountains (pl. 1). Smaller exposures of these and other Paleozoic rocks occur near the middle, northeast corner, and east-central margin of the quadrangle. Most or all of the Paleozoic rocks identified on Bare Mountain (Cornwall and Kleinhampl, 1961b), except for the Fluorspar Canyon Formation of Devonian age, have been found in the Bullfrog quadrangle, but due to the limited exposures and complex deformation, the section revealed here is fragmentary and far from complete. The section that was measured on Bare Mountain (Cornwall and Kleinhampl, 1961b) is shown on plate 2. Detailed descriptions of the Paleozoic rocks will not be given here except where they differ from the section already described on Bare Mountain (Cornwall and Kleinhampl, 1961b).

DAYLIGHT FORMATION

The Daylight Formation crops out over a wide area in the southwestern part of the Bullfrog quadrangle, and also near the east-central and northeast margins. The formation is here named for the extensive exposures of it in the southwestern part, where Daylight Pass is located (sec. 36, T. 13 S., R. 46 E.). A typical section of the Daylight Formation measured on Bare Mountain is shown on plate 2. This formation was first studied on Bare Mountain and was originally considered to be a part of the Johnnie(?) Formation (Cornwall and Kleinhampl, 1960b, 1961a, b); but more recent investigations by the present writers and C. A. Nelson, A. R. Palmer, and J. H. Stewart indicate that a correlation with the Wood Canyon Formation is more probable. This problem will be discussed below.

The Daylight Formation consists predominantly of clastic rocks. Micaceous shale and siltstone are most abundant, but interbedded quartzitic sandstone beds are common. Limestone and dolomite beds as thick as 50 feet occur at intervals in the formation, particularly in the upper and lower parts, and an arkosic conglomeratic quartzite as thick as 300 feet occurs near the middle of the formation.

The shale and siltstone range in color from olive gray to various shades of green and brown. These rocks are commonly schistose with wavy parallel, laminated to very thin bedded stratification, and platy splitting. Cleavage may be parallel to the stratification, but quite commonly it is not. The quartzitic sandstone and conglomerate range in color from almost white to gray and brown and have differing degrees of purity and induration. Stratification is both parallel and cross stratified, laminated to thin bedded, with platy to slabby splitting. As a group these rocks are commonly fine grained and poorly sorted with moderately well rounded quartz grains and a silty matrix of quartz, sericite, biotite, calcite, and dolomite.

Limestone and dolomite beds in the Daylight Formation are light to moderate brown and grayish yellow or orange. The beds commonly have a clastic texture and may grade laterally or vertically into quartzose sandstone. In the upper part of the Daylight Formation are one to three closely spaced beds of yellow to brown, oolitic to pisolitic limestone and dolomite. The coarser grained oolitic and pisolitic beds commonly contain abundant archaeocyathids and pelmatozoan debris. The oolitic limestone or dolomite is a persistent marker zone; it occurs about 800 feet below the top of the Daylight Formation in the unfaulted Bare Mountain section, but in the Bullfrog quadrangle the overlying Corkscrew Quartzite (see below) is faulted over the Daylight Formation and most of or all the shale and siltstone above the oolite may be missing (pl. 1). The oolite is distinguished by a separate pattern on plate 1.

Another unit in the Daylight Formation that is distinguished on plate 1 is the light-gray conglomeratic arkosic quartzite, roughly 300 feet thick, which occurs near the middle of the formation (pl. 2). This is a persistent unit and it, like the oolitic limestone higher up in the section, has served as a reliable marker in working out the structural complexities of the area.

In the upper 500 feet of the Daylight Formation are quartzitic sandstone beds interbedded with siltstone, and some of the sandstone beds contain vertical rods, perpendicular to the bedding, that have been identified as *Scolithus*.

AGE AND CORRELATION

At Daylight Pass the oolitic limestone shown on the map has yellowish-gray to green shale units as thick as 30 feet above and below it, and these contain the olenellid trilobites *Nevadia* and *Nevadella*, which are indicative of Early Cambrian age (C. A. Nelson and A. R. Palmer, written communications, 1959, 1960). Similar fossil-bearing shales border the oolite in the exposures west of Daylight Pass at least as far as the edge of the quadrangle, but southeastward the shale pinches out within a mile and the oolite is bordered by nonfossiliferous siltstone. At Bare Mountain the beds bordering the oolite are siltstone and nearly barren of fossils, although C. W. Merriam (oral communication, 1960) has found a few fragments tentatively identified as olenellid trilobites.

The oolitic limestone contains, as was mentioned above, sparse to abundant archaeocyathids and pelmatozoan debris. A few of the larger fragments were identified by Helen Duncan (written communication, 1959) as *Ethmophyllum* sp., and some of the smaller debris was probably derived from such archaeocyathids as *Archaeocyathus* or *Protopharetra*. Cystid plates were identified in the pelmatozoan debris. Some small algal masses were also seen.

This sequence of clastic rocks, here designated the Daylight Formation, was originally correlated by the present writers (Cornwall and Kleinhampl, 1960b, 1961a, b) with the Johnnie Formation because of its close lithologic resemblance to that formation in the type locality in the northern Spring Mountains (Nolan 1929, p. 461–463; B. C. Burchfiel [1]) and elsewhere. The Daylight Formation is also similar lithologically to the upper part of the Wood Canyon Formation (Nolan, 1929, p. 463–464), but the middle and lower parts of the Wood Canyon Formation tend to be coarser grained than comparable parts of the Daylight Formation. According to Nelson and Palmer (written communication, 1961), *Nevadia*, which occurs in the upper part of the Daylight Formation, has also been found in the upper part of the Wood Canyon Formation in the Nopah Range, 75 miles southeast of the Bullfrog quadrangle; in the Desert Range, 80 miles to the east; and in the Spring Mountains, 50 miles to the southeast.

Oolitic limestone and dolomite beds in the upper part of the Wood Canyon Formation (A. R. Palmer, written communication, 1961) contain archaeocyathids and pelmatozoan debris as do similar beds in the Daylight Formation. Oolite beds in the upper part of the Johnnie Formation, on the other hand, do not contain such organic debris. More work will have to be done to determine whether the Daylight Formation is correlative with the Johnnie or Wood Canyon Formation, but present indications favor a correlation with the Wood Canyon.

CORKSCREW QUARTZITE

The Corkscrew Quartzite forms the major unit in a thrust plate that has overridden the Daylight Formation in the southwestern part of the Bullfrog quadrangle at the south end of the Grapevine Mountains. Corkscrew Quartzite is also thrust over the Daylight Formation in the northeastern corner of the quadrangle, and a small exposure occurs near the middle of the quadrangle on the west edge of Bullfrog Mountain.

The Corkscrew Quartzite is here named for exposures on the east flank of Corkscrew Peak (secs. 5 and 8, T. 14 S., R. 46 E.) in the southwestern corner of the Bullfrog quadrangle. About 1,200 feet of the quartzite are exposed there (sec. *A–A′*, pl. 1). On Bare Mountain an unfaulted section of the quartzite has a measured thickness of 1,140 feet (pl. 2). The Corkscrew Quartzite is a vitreous, pure quartzite that weathers to gray, pink, and reddish or purplish brown. It is fine to medium grained, and locally conglomeratic, containing quartz and sparse red jasper pebbles. The rock is poorly to moderately well sorted, thinly laminated to thin bedded, and exhibits a slabby to massive splitting. Crossbedding is conspicuous in the lower part; stratification in the upper part tends to be obscure. Adjacent to the thrust fault that underlies the Corkscrew Quartzite in the Bullfrog quadrangle, the quartzite is brecciated; this zone, as much as 30 feet thick, is commonly nearly white, in contrast to the typical pink or reddish color of the normal rock, probably due to bleaching by aqueous solutions that moved along the permeable zone. A similar zone of brecciation and bleaching of the basal part of the Stirling Quartzite above the Johnnie thrust in the northern Spring Mountains has been described by Nolan (1929, p. 466–467).

AGE AND CORRELATION

No fossils have been found in the Corkscrew Quartzite in the Bare Mountain or Bullfrog quadrangles, but trilobites indicative of an Early Cambrian age (C. A. Nelson and A. R. Palmer, written communications, 1959, 1960; Cornwall and Kleinhampl, this paper and 1961b) have been found in the underlying Daylight and overlying Carrara Formations. Thus, the quartzite itself must be Lower Cambrian.

The Corkscrew Quartzite in the Bare Mountain and Bullfrog quadrangles was earlier correlated tentatively with the Stirling Quartzite (named by Nolan, 1929, p. 463) by the present writers (Cornwall and Kleinhampl, 1960b, 1961a, b). This correlation was based on the fact that it, like the type Stirling, is a thick quartzite overlying what was then considered to be typical Johnnie Formation. The character of the Corkscrew Quartzite is also rather similar to at least the upper part of the Stirling Quartzite. Much of the lower part of the Stirling Quartzite, however, is coarser grained and more conglomeratic than the Corkscrew Quartzite.

As was discussed above, the Daylight Formation underlying the Corkscrew Quartzite is now considered by the present writers as probably correlative with the Wood Canyon Formation (Nolan, 1929, p. 463–464). The Wood Canyon Formation, as designated by Nolan in the type area in the Spring Mountains, has a quartzite approximately 20 feet thick overlying it. In the Nopah and Resting Springs ranges Hazzard (1937, p. 309) included a correlative quartzite, which is 160 feet thick there, in the upper part of the Wood Canyon Formation and named it the Zabriskie quartzite member. If, as the present writers are now inclined to believe, the Daylight Formation is indeed equivalent to the Wood Canyon Formation as defined by Nolan, then the Corkscrew Quartzite may be a considerably thickened section of the Zabriskie quartzite member of Hazzard. This correlation was first suggested by A. R. Palmer (written communication, 1959). The

[1] Burchfiel, B. C., 1961, Structure and stratigraphy of the Spectre Range quadrangle, Nye County, Nevada: New Haven, Conn., Yale University, Ph. D. thesis, p. 25–30.

Corkscrew Quartzite is 1,000 to 1,200 feet thick, whereas the maximum thickness of definitely known Zabriskie is less than 200 feet except at Eagle Mountain, 50 miles southeast of the Bullfrog quadrangle, where a thickness of 420 feet was measured (J. H. Stewart, oral communication, 1961).

The two quartzites are very similar lithologically; they are pure, vitreous, generally fine to medium grained, but locally conglomeratic. Another striking similarity is that both have prominent *Scolithus* either in or near the base. *Scolithus* occurs in the basal part of the Zabriskie, but it occurs below the main body of the Corkscrew in quartzitic beds in the upper part of the Daylight Formation.

CARRARA FORMATION

The Carrara Formation crops out only in the southwest and northeast corners of the Bullfrog quadrangle, where it conformably overlies the Corkscrew Quartzite. The upper contact is not exposed and complex faulting precludes measurement of a reliable section. The rocks are, for the most part, similar to the formation at the type locality on Bare Mountain (pl. 2; Cornwall and Kleinhampl, 1961b).

The formation consists of interstratified shale and limestone with minor amounts of sandstone and siltstone. Shale predominates in the lower part of the formation and limestone in the upper part. The total thickness measured on Bare Mountain is 1,785 feet, and most of the major units occurring there are present in the two areas of outcrop in the Bullfrog quadrangle. The base of the formation is an abrupt transition from the underlying Corkscrew Quartzite; it consists of alternating beds of sandstone, siltstone, shale, and limestone. Above this are several hundred feet of greenish-, yellowish-, to brownish-gray shale with interbeds of gray and orange limestone, at the top of which is a massive, cliff-forming, dark-gray algal (*Girvanella*) limestone bed, commonly over 100 feet thick. Above the limestone are approximately 400 feet of gray to brown shale and siltstone, and these are overlain by 500 to 1,000 feet of brightly colored, alternating white, pink, orange, and brown limestone. The colored limestones are somewhat clayey or silty.

The age of the lower part of the Carrara Formation has been well established in the Bare Mountain quadrangle. According to Palmer (written communications, 1959, 1962) and Nelson (written communication, 1960), the trilobites *Bristolia* and *Paedumias* were found below the massive limestone containing *Girvanella;* and *Fremontia*, *Olenellus*, and *Paedumias* were found above it. *Fremontia* and *Bristolia* (Nelson, written communication, 1960) were also found in a small outcrop of the Carrara Formation in the southwestern part of the Bullfrog quadrangle. These fossils indicate a late Early Cambrian age for the lower part of the formation. The upper part of the formation is Early or Middle Cambrian. The Carrara Formation correlates in faunal and general lithologic character with the sequence of Latham Shale, Chambless Limestone, and Cadiz Formation in the Providence Mountains described by Hazzard (1954, p. 30–32), and in the Nevada Test Site (according to the revised nomenclature of Barnes and Palmer, 1961). The Carrara Formation is also approximately equivalent to the Bright Angel Shale as defined by Nolan (1929, p. 464) in the northern Spring Mountains, Nev. James McAllister (written communication, 1961) has extended the Carrara Formation southward into an area in the Resting Spring Range.

NOPAH FORMATION

At Bare Mountain the Nopah Formation of Late Cambrian age overlies the Bonanza King Formation and has a thickness of about 1,900 feet (pl. 2 and fig. 1; Cornwall and Kleinhampl, 1961b) and consists predominantly of gray dolomite but also has a 100-foot basal shale member and locally a dark-gray limestone member that overlies the shale. In the Bullfrog quadrangle the Bonanza King Formation is absent and the Nopah Formation crops out only in one small area, 1,000 feet across, 2 miles northwest of Bullfrog Mountain. The rock is entirely dolomite, which is broadly banded light and dark gray. The dolomite

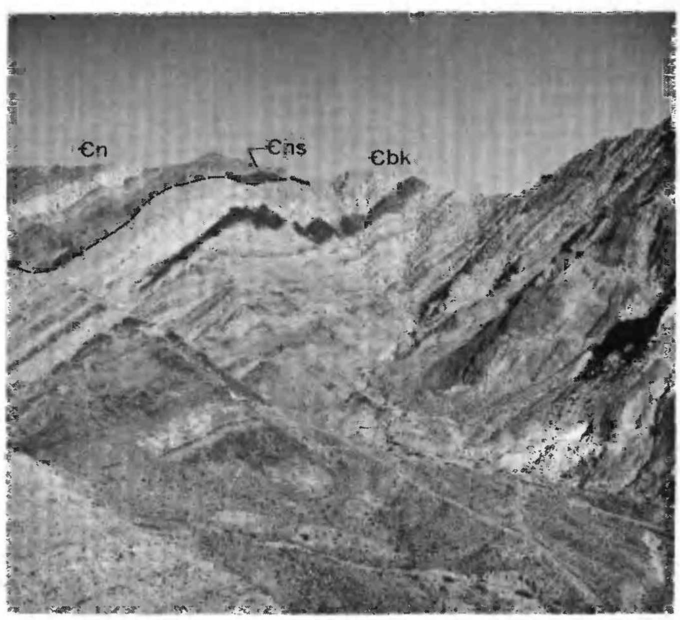

FIGURE 1.—Bonanza King (Ꞓbk) and Nopah (Ꞓn and Ꞓns, the latter is shale member) Formations, view eastward, Carrara Canyon, Bare Mountain, Nev.; sequence is continuous along skyline but faulted toward observer.

contains some chert in nodules and thin lenses and also has zones in which the dolomite has partly recrystallized as coarse-grained, white to yellowish-gray flecks, stringers, and irregular masses.

POGONIP GROUP

The Pogonip Group has a measured thickness on Bare Mountain of 1,375 feet (pl. 2; Cornwall and Kleinhampl, 1961b) and consists of silty and cherty limestone with interbeds of shale and pure limestone. Diagnostic fossils, including the spongelike form *Receptaculites*, the brachiopod *Orthidiella*, and the gastropods *Palliseria* and *Maclurites*, indicate Early and Middle Ordovician age. In the Bullfrog quadrangle, small outcrops exposing partial sections, mostly of the upper part of the Pogonip Group, occur south, southeast, and northwest of Bullfrog Mountain (pl. 1). The rock is aphanitic to medium grained, gray, yellow, and brown silty and shaly limestone. *Orthidiella*, *Palliseria, and Maclurites* (R. J. Ross, written communication, 1960) were found in the limestone. A prominent white limestone bioherm (Ross and Cornwall, 1961) was found in the Pogonip Group at Bare Mountain, but none were seen in the Bullfrog quadrangle.

EUREKA QUARTZITE

A section of the Eureka Quartzite measured at the north end of Bare Mountain on Meiklejohn Peak (pls. 1, 2; fig. 2) was found to be 360 feet thick, and a complete section that crops out in a small area 1 mile northwest of Bullfrog Mountain in the Bullfrog quadrangle has approximately the same thickness. The quartzite has thin units of sandstone at top and bottom, but it is chiefly a vitreous, fine-grained quartzite with well-rounded and well-sorted grains. Bedding tends to be indistinct, very thin to thick bedded; the color is white to grayish orange or brown. No fossils occur in the Eureka Quartzite in this area but it is considered to be Middle Ordovician on the basis of diagnostic fauna found in the underlying and overlying formations here and elsewhere. Figure 2 shows the Eureka Quartzite and overlying formations as they occur on Bare Mountain.

ELY SPRINGS DOLOMITE

The Ely Springs Dolomite overlies the Eureka Quartzite; on Bare Mountain its thickness is 300 feet (pl. 2; fig. 2). In the Bullfrog quadrangle it crops out 1 mile northwest of Bullfrog Mountain in the same locality as the Eureka Quartzite, described above, and the thickness there is about 200 feet. It is a dark-gray aphanitic to very fine grained laminated to thin-bedded cherty dolomite. The chert, as anastamosing

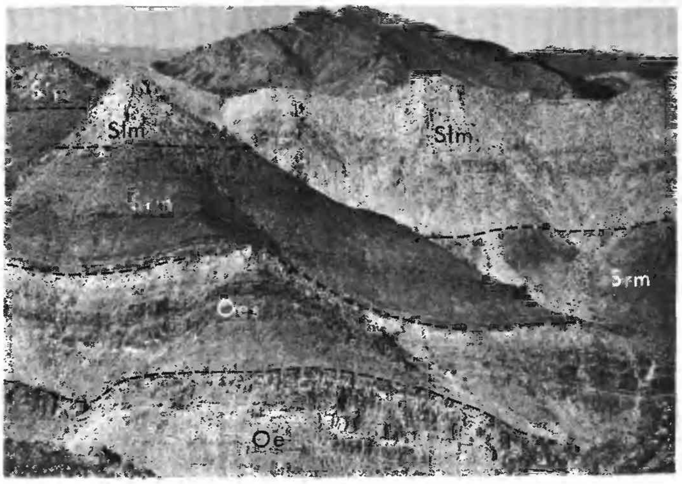

FIGURE 2.—Eureka Quartzite (Oe), Ely Springs Dolomite (Oes), Roberts Mountains Formation (Srm), and Lone Mountain Dolomite (Slm), looking north, Chuckwalla Canyon, Bare Mountain, Nev.

lenses, composes 10 percent of the formation and is locally even more abundant. Diagnostic fossils were not found in the Ely Springs Dolomite in the Bullfrog quadrangle but paleontologic evidence elsewhere indicates a Late Ordovician age.

ROBERTS MOUNTAINS FORMATION

A complete section of the Roberts Mountains Formation, 800 to 900 feet thick, crops out in the small area 1 mile northwest of Bullfrog Mountain and is very similar in general lithology to exposures of the same formation on Bare Mountain (pl. 2; fig. 2; Cornwall and Kleinhampl, 1961b). The formation consists of laminated to thin-bedded dolomite and limestone. The lower 200 feet of the formation is dark-gray cherty dolomite; above this is approximately 400 feet of dark-gray platy limestone; and at the top is roughly 200 feet of dark-gray dolomite, which grades upward into light-gray dolomite. Pentameroid brachiopods and corals, collected from the upper dolomite, are similar to fauna from the type locality (Merriam and Anderson, 1942, p. 1687), which date the formation as Middle Silurian.

LONE MOUNTAIN DOLOMITE

Overlying the Roberts Mountains Formation in the area of Paleozoic rocks 1 mile northwest of Bullfrog Mountain is a partial section of the Lone Mountain Dolomite. The dolomite is homogeneous, light gray, pitted, fine to medium grained. The rock is indistinctly stratified and massive. No fossils were found in the formation in this area, but similar lithology and stratigraphic position indicate a correlation with the Lone Mountain Dolomite at Bare Mountain (pl. 2; fig. 2; Cornwall and Kleinhampl, 1961b) and else-

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where (Nolan and others, 1956, p. 39, 41) where the age is considered to be Late Silurian and Early Devonian.

OTHER PALEOZOIC ROCKS

The Fluorspar Canyon Formation, of Devonian age, which overlies the Lone Mountain Dolomite at Bare Mountain (pl. 2; Cornwall and Kleinhampl, 1961b) and correlates with the Nevada Formation (Merriam, 1940, p. 14–16, 22–25; Nolan and others, 1956, p. 42–48), is not exposed in the Bullfrog quadrangle. The overlying Meiklejohn Formation (pl. 2; Cornwall and Kleinhampl, 1961b), however, crops out 1½ miles west of Bullfrog Mountain in an area shown as undifferentiated Paleozoic rocks. The exposures consist mainly of brown to black silty claystone and shale with interbeds of black chert and dark-gray fossiliferous dolomite. Fossils consisting of Foraminifera and conodonts collected at the type locality on Bare Mountain indicate a Late Mississippian age, and the formation correlates both faunally and lithologically with the Chainman Shale and Diamond Peak Formation near Eureka, Nev. (Nolan and others, 1956, p. 56–61) and in part with the Eleana Formation at the Nevada Test Site (Johnson and Hibbard, 1957, p. 357–360).

In addition to the formations described above, dolomite fragments of the Bonanza King Formation of Middle and Late Cambrian age constitute an important part of the monolithologic breccia described below.

Small areas of limestones whose true identity is uncertain are shown on plate 1 as undifferentiated Paleozoic rocks in the SE¼ sec. 12, T. 12 S., R. 45 E., and in the NE¼ sec. 24, T. 12 S., R. 46 E. In addition, three patches of quartzite that extend to the south margin of the quadrangle in the southwestern part, as well as one in the NW¼ sec. 6, T. 30 N., R. 1 E., are also shown as undifferentiated Paleozoic rocks because of uncertain identity.

CENOZOIC ROCKS AND VOLCANISM

The Cenozoic rocks in the Bullfrog quadrangle range in age from early Tertiary to Quaternary. Most of the rocks are Tertiary and consist of terrestrial sedimentary rocks of the Titus Canyon Formation of Stock and Bode (1935) overlain by tuffs, welded tuffs, and other volcanic rocks derived from the Bullfrog Hills caldera. Monolithologic breccia of early Paleozoic carbonate rocks underlies the Titus Canyon Formation and younger volcanic rocks and is probably early Tertiary but possibly partly Mesozoic in age. Overlying the volcanic sequence are Quaternary older gravels in dissected fans and in terraces found high in present canyons and Recent alluvium in the valleys.

MONOLITHOLOGIC BRECCIA

Monolithologic breccia masses, consisting almost entirely of limestone and dolomite of the Carrara and Bonanza King Formations, respectively, overlie the Daylight Formation in several areas in the southwestern corner of the quadrangle (fig. 3); one of these masses, near the south edge of the quadrangle, is overlain with a sedimentary contact by the Titus Canyon Formation. Other similar breccias occur in scattered outcrops north of the area mentioned above, and these breccia masses are overlain by Tertiary tuff and basalt flows. Two small masses of similar carbonate breccia are interbedded in the tuffs and welded tuffs of the Bullfrog Hills caldera sequence just west of the center of the quadrangle (secs. 15 and 22, T. 12 S., R. 45 E.).

Individual breccia masses are as much as 2,000 feet across in longest dimension and as thick as 200 feet, and they consist of angular to subrounded fragments of limestone or dolomite (fig. 3). Most of the fragments are less than 3 feet in diameter, but individual beds in the thoroughly brecciated masses may, in places, be traced without significant offset for 50 feet or more. The matrix consists of finer fragments of the same material. Toward the base of some masses the matrix contains increasing amounts of brown clayey material, and where the breccias overlie the Daylight Formation scattered fragments of quartzite from the Daylight Formation are incorporated in the basal breccia zone.

In considering the origin of the monolithologic breccia, it should be noted that most of the breccia masses occur either as erosional remnants on the Daylight and Crokscrew Formations in the southwestern part of the quadrangle, or along the contact where these early Paleozoic rocks are unconformably over-

FIGURE 3.—Rolling hills underlain by Daylight Formation. Black point near center of photograph is small remnant of dolomitic monolithologic breccia mass. Picture was taken looking east from much larger mass of monolithologic breccia likewise overlying the Daylight Formation near Daylight Pass, Grapevine Mountains, Calif.

lain by the Titus Canyon Formation of Stock and Bode (1935) of Oligocene age.

Recent studies by M. W. Reynolds (oral communication, 1962) in the Grapevine Mountains west of the Bullfrog quadrangle indicate that there the monolithologic breccias are partly interbedded in the Titus Canyon Formation.

The source of the monolithologic breccias was probably a thrust plate (described later) of lower Paleozoic rocks (Corkscrew Quartzite, Carrara, and Bonanza King Formations) that moved northeastward over the Daylight Formation into the southwest corner of the quadrangle. It is believed that most of the monolithologic breccias formed as landslides that slid off the front of the thrust fault either while it was active or later during the long erosion period previous to deposition of the terrestrial fanglomerates of the Titus Canyon Formation. Normal faulting along the east face of the Grapevine Mountains may have also produced scarps from which blocks of carbonate rocks slid off to form monolithologic breccias, but most of these faults in the Bullfrog quadrangle offset, and are thus younger than, the Titus Canyon Formation, whereas most of the monolithologic breccias appear to be as old as or older than that formation.

The thrust fault mentioned above is probably related in age to the major deformation along the Las Vegas Valley shear zone (Cornwall and Kleinhampl, 1960a) to the southeast, which Longwell (1960, p. 197) considers to be Cretaceous or early Tertiary. The landslide breccias must have formed during or following this period. The youngest monolithologic breccias, as was mentioned earlier, are interbedded in and thus contemporaneous with volcanic rocks of the Bullfrog Hills caldera of probable Miocene age.

The interpretation of the monolithologic carbonate breccias as landslide masses agrees with the conclusions of Longwell (1951), Wright (1955), Grose (1959, p. 1535–1537), Kupfer (1960, p. 197–198), and others concerning the origin of similar breccias elsewhere in the Great Basin. These breccias can be distinguished, because of certain significant differences, from tectonic breccias along the soles of thrust faults that are also prominent in the Great Basin (Noble, 1941, p. 963–977; Noble and Wright, 1954, p. 152; Kupfer, 1960, p. 204–206). Kupfer (1960, p. 197–198, 205–206) recognized both types of breccias in the Silurian Hills just south of Death Valley, Calif., and ably described the differences between the two types. The sedimentary breccias tend to have smaller, more angular fragments than tectonic breccias, and the brecciation is more intense. Surfaces of movement are common on blocks in tectonic breccias and rare in sedimentary breccias.

TITUS CANYON FORMATION OF STOCK AND BODE (1935)

The Titus Canyon Formation, first defined and mapped by Stock and Bode (1935), extends southeastward for 30 miles in a narrow, almost continuous belt along the California-Nevada border from the north end of the Grapevine Peak quadrangle to the east edge of the Chloride Cliff quadrangle. These quadrangles adjoin the Bullfrog quadrangle on the west and south respectively, and the Titus Canyon Formation crops out in the southwestern part of the Bullfrog quadrangle along the eastern flank of the Grapevine and Funeral Mountains. Patches of the Titus Canyon Formation, too small to be shown on plate 1, also occur in the northeastern corner of the quadrangle, unconformably overlying the Carrara Formation. In the southwestern part of the quadrangle the Titus Canyon Formation lies unconformably above the Daylight Formation, Corkscrew Quartzite, and Carrara Formation.

The Titus Canyon Formation consists of terrestrial conglomerate with interbedded sandstone, siltstone, mudstone, limestone, and tuff. The formation as a whole is lenticular and changes abruptly in thickness along the strike from 0 to about 3,000 feet. A section (pl. 3; fig. 4) was measured 1 mile southeast of Daylight Pass where the formation is 2,700 feet thick. Conglomerate is predominant in the lower half, whereas arkosic and tuffaceous sandstone and siltstone, and air-fall tuff are increasingly abundant upward above the middle of the formation.

The conglomerate is characteristically reddish brown to brown and contains boulders, cobbles, and pebbles of well-rounded, highly polished black and gray chert, and white and brown quartzite, as well as

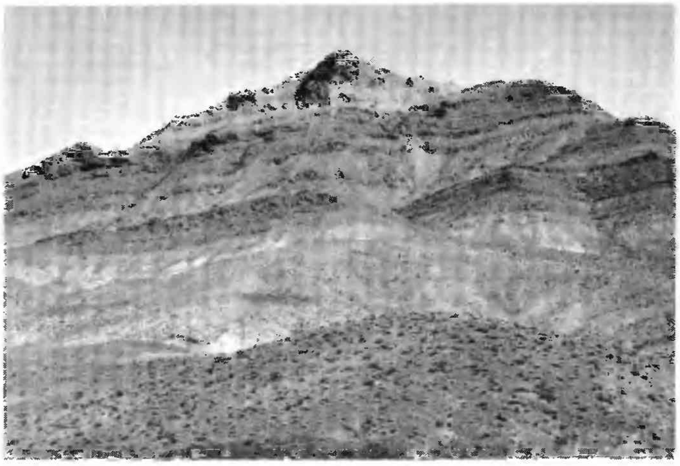


FIGURE 4.—Titus Canyon Formation of Stock and Bode (1935); top of formation is near top of peak where obviously bedded rocks are overlain by massive gray tuff; looking northeast, 1 mile southeast of Daylight Pass, Funeral Mountains, Nev.

some gray to black limestone and dolomite, in an arkosic matrix. A few pebbles of brown stony rhyolite were also found. Lenticular beds, as much as 100 feet thick, of reddish-brown to gray muddy limestone occur near the base, just above the middle, and locally near the top of the Titus Canyon Formation. Some of the limestone beds that occur just above the middle of the formation are algal. The sandstone, siltstone, and mudstone, which are most abundant in the upper half of the formation, are arkosic or tuffaceous, and air-fall tuff beds as much as 50 feet thick are interbedded with them. These rocks are reddish- to yellowish-brown or gray; a few are green. One of the green beds is conspicuous because it contains abundant magnetite crystals.

Stock and Bode (1935, p. 577–578) have dated the Titus Canyon Formation as early Oligocene on the basis of mammalian fossils found in the mudstones in the lower part of the formation. The fauna includes the horse *Mesohippus*, two types of titanotheres, hydracodont rhinoceroses, artiodactyls, and a sciuromorph rodent. The present writers found fresh-water snails, identified by D. W. Taylor (written communication, 1960) as *Valvata* and indeterminate Lymnaeidae, in a limestone bed near the top of the formation, and also a fossil tree truck.

The Titus Canyon Formation is overlain conformably in the Bullfrog quadrangle, but unconformably to the northwest and southeast (Stock and Bode, 1935, p. 577) by tuffs, welded tuffs, lava flows, and sedimentary rocks. The volcanic rocks were probably derived from the Bullfrog Hills caldera.

BULLFROG HILLS CALDERA AND ASSOCIATED ROCKS

The Bullfrog Hills caldera is roughly coextensive with the Bullfrog Hills (pls. 1, 4). It has been described by one of the present writers (Cornwall, 1962). The northern and southern margins of the caldera are covered by alluvium, but the caldera appears to be oval in shape, roughly 13 miles long in a northeasterly direction and 10 miles across. Inside this area volcanic rocks form a broad faulted dome and dip outward. The caldera and its associated volcanic and and minor sedimentary rocks are probably Miocene in age (Stock and Bode, 1935, p. 572–573).

The volcanic rocks are predominantly rhyolitic tuffs and welded tuffs, and it is believed that these rocks were derived from a rather shallow magma chamber, which collapsed following the eruption of the tuffs and welded tuffs to form a caldera. Flows and intrusives of rhyolite, latite, basalt, and basanite are also associated with the caldera. The caldera is delineated by a peripheral fault zone where bedrock is exposed, but the recognition of the structure as a caldera is also based on several features of the volcanic rocks, including their types, relative abundance, distribution, and pattern of deformation. The caldera structures have been partly modified or masked by erosion, deposition of alluvium, and basin-range faulting.

The nomenclature used here in describing the tuffs and welded tuffs is that adopted by R. L. Smith (1960a) in his excellent review article on ash flows. Smith states, "The basic unit of ash-flow deposits is the ash flow that is analogous to, or perhaps the same as, the deposit resulting from the passage of one nuée ardente."

An ash flow may be partly or even completely welded into a cohesive rock, and this is called a welded ash flow or welded tuff. Commonly there will be a zonation from densely welded rock in the interior of an ash-flow sheet (made up of one or more individual ash flows) to nonwelded tuff at the top and bottom, and this is called a cooling unit. In a simple cooling unit cooling was continuous and uninterrupted; in a compound cooling unit abnormal zonation of the welded and nonwelded parts indicates disruption of the cooling gradient by later addition of one or more new hot ash flows.

The central part of the caldera is covered predominantly by ash flows; the margins consist predominantly of younger tuffs with intertonguing rhyolite and latite flows and intrusives. Within the caldera is a northwest-trending dome, measuring roughly 1 by 4 miles, of Precambrian and Paleozoic rocks that were probably pushed up into the volcanics at a late stage by re-entry of magma into the underlying chamber. The domal uplift probably extends 2 miles farther northwest where another block of highly faulted Paleozoic rocks occurs surrounded by pyroclastic rocks of the caldera sequence, and the intervening area consists of older tuffs and interbedded sedimentary lenses, which are also faulted against the surrounding younger ash flows. In these tuffs is an intrusion of rhyolite that may represent a small protrusion of the intrusive body that presumably underlies the dome.

The main fault that marks the rim of the caldera is well exposed on the southeastern rim (pl. 1, sec. *B–B′*). The stratigraphic displacement on this fault and on several parallel faults to the east indicates that the caldera on the west subsided roughly 4,000 feet. Extending northeastward tengentially from the southeast margin of the caldera is a series of normal faults, which have dropped volcanic rocks of the Bullfrog Hills caldera sequence downward successively to the northwest. This foundering is probably related to the caldera subsidence in a manner similar to the graben that extends outward tangentially from the Creede caldera in Colorado (Steven and Ratté, 1960, p. B14–B15).

It is the character and distribution of the rocks as described above that, by analogy with similar relations in more recent unequivocal calderas (see Smith, 1960a, p. 834; Williams, 1941), has led to the conclusion that here, too, is a caldera.

The ash flows and, in part, other flows and tuffs of the Bullfrog Hills caldera extend several miles southwest of the caldera where they overlie the Titus Canyon Formation of Oligocene age. The volcanic rocks also extend several miles east of the caldera, where they are faulted against Paleozoic rocks on the south and are overlain unconformably by alluvium and younger tuffs on the north and east (pl. 4).

A columnar section of the volcanic and minor sedimentary rocks in the Bullfrog Hills caldera is given on plate 5. The thickness of 10,000 feet is probably close to the maximum. A series of ash flows, totaling 6,000 feet, has five distinctive cooling units each of which has nonwelded and densely welded parts, and three of which have prominent basal vitrophyre zones. The remainder of the section consists of airfall tuffs, flows of rhyolite, latite, and basalt, and minor sedimentary lenses. The five cooling units of the ash-flow sequence have also been identified in the structural trough that extends east of the Bullfrog Hills caldera. The easternmost exposure of the cooling units, 6 miles east of the caldera rim (pl. 4), consists of units 4 and 5. Pyroclastic rocks from the Bullfrog Hills caldera in this area are faulted against younger ash flows to the east that were probably derived from the Yucca Mountain caldera. The total volume of ash flows in and around the Bullfrog Hills caldera is estimated to be 85 cubic miles (360 cu km), which is in the range of deposits known to be related to calderas (Smith 1960a, p. 819).

FIGURE 5.—Devitrification zone of an ash flow (welded tuff); oriented, flattened cavities are elongated parallel to the flow plane and represent flattened pumice fragments that have differentially eroded out on the weathering surface. Fluorspar Canyon, north end of Bare Mountain, Nev.

DESCRIPTION OF THE VOLCANIC ROCKS

A brief description will be given here of the flows, intrusives, and tuffs associated with the caldera, and the ash flows will be described in somewhat greater detail.

ASH FLOWS

Plate 5 gives a graphic representation of the ash-flow section, probably at its maximum thickness, within the Bullfrog Hills caldera. It will be noted that there are five cooling units in this pile of ash flows.

Each cooling unit has a densely welded central part and partially welded to nonwelded upper and lower parts. The densely welded part ranges from 100 to 1,300 feet in thickness. There is a zone of vitrophyre as much as 30 feet thick at the base of the densely welded part, overlain by a much thicker zone of devitrification (fig. 5), and, near the top, a zone of vapor phase crystallization. These correspond to the zones in ash flows described by Smith (1960a, p. 830–831). The vitrophyre zones may lens out along the strike to as little as 1 foot and be barely visible, but a glassy transition nevertheless exists between partly welded tuff below and densely welded, devitrified tuff above.

The nonwelded to partially welded zones of the ash flows, which separate the cooling units, range from a few feet to as much as 500 feet thick. The relations in the Bullfrog Hills ash flows are illustrated on plate 5, where four nonwelded zones intervene between five cooling units. It will be noted that the boundaries between cooling units 1 and 2, and between 2 and 3, lie within the nonwelded zone; the boundary is marked by a parting separating two lithologically different tuffs. Between the remaining cooling units the boundary lies either at the top or bottom of the nonwelded zone where basalt flows occur.

Single cooling units in the ash flows may represent one flow with the zonation expectable in the cooling of a single flow. Figure 5 portrays such a flow. Part of the cooling units, however, in both the Bullfrog Hills and Yucca Mountain ash flows, contain more than one individual flow. In the case of cooling unit 3 of the Bullfrog Hills ash flows, for example, differences in lithology between the lower and upper parts indicate quite certainly that more than one flow is present. The contrast in lithology is illustrated by variations in the mode (table 1, analyses 4–6). Analyses 4 and 5 from the lower part of the unit are similar in their scarcity of phenocrysts, whereas analysis 6, from the upper part, contains nearly 20 percent phenocrysts.

TABLE 1.—*Modal analyses (volume percent) of ash flows in the Bullfrog Hills caldera*

	Cooling unit 1	Cooling unit 2		Cooling unit 3			Cooling unit 4			Cooling unit 5	
	Lithoidal welded tuff	Nonwelded tuff	Lithoidal welded tuff	Nonwelded tuff	Lithoidal welded tuff	Lithoidal welded tuff	Nonwelded tuff	Glass zone of welded tuff	Lithoidal welded tuff	Nonwelded tuff	Lithoidal welded tuff
	1	2	3	4	5	6	7	8	9	10	11
Groundmass	79.3	77.6	79.4	99.0	98.2	81.1	82.4	76.8	76.0	90.6	80.5
Quartz	1.7	2.3	4.8	--------	--------	--------	7.3	12.0	10.9	4.8	5.9
Plagioclase	16.3	6.6	7.0	.6	.5	6.8	3.6	2.8	3.6	1.1	1.8
Sanidine	.9	6.0	7.9	.2	1.1	10.3	4.4	8.0	8.9	3.0	9.2
Magnetite	1.1	.3	.6	.1	.2	.4	.1	.1	.1	--------	.2
Pyroxene	--------	--------	--------	--------	--------	.1	--------	--------	--------	--------	--------
Biotite	.7	.3	.3	.1	--------	1.3	.3	.3	.4	.3	.1
Xenoliths	--------	6.9	--------	--------	--------	--------	1.9	--------	.1	.2	2.3
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Plagioclase composition	An_{10}	An_{25-35}	An_{20}	An_{20}	An_{20}	An_{40}	An_{20}	An_{20}	An_{20}	--------	An_{20}

As indicated in the preceding discussion, variations in the lithology of the ash flows are due to: (a) Variations between individual flows in the proportions of coarse to fine materials, and in the relative proportions of crystals to glass. Accidental lithic fragments also vary from one flow to another. Before welding, the flows were predominantly glass, in the form of shards, pumice, and dust. (b) Variations in the rates of cooling within cooling units. Retention of heat in the interiors of cooling units permitted compaction, welding, deuteric crystallization, and vapor activity. The cooling units are thus zones with variations in density and porosity, degree of flattening of pumice fragments, color, degree of crystallization, and alteration of phenocrysts.

In considering the different original lithologies of individual ash flows, the crystal content is probably the most helpful guide to their identification in the Beatty area. Mackin (1960, p. 90–96) and Williams (1960) have recently correlated a sequence of ash flows over a considerable area elsewhere in the Great Basin on the basis of phenocryst content. All the ash flows studied here contain phenocrysts, partly broken, as much as 3 mm in length. Quartz, oligoclase or andesine, and sanidine are most abundant; biotite and magnetite are quite ubiquitous in smaller amounts and smaller crystals. The phenocryst content of the ash flows ranges from 1 to 25 percent.

The modal analyses in table 1 of the Bullfrog Hills ash flows illustrate differences in crystal content that help to identify individual ash flows. For example, in cooling unit 1 plagioclase is abundant; cooling unit 3 has no quartz; in cooling units 4 and 5 quartz and sanidine are most abundant. Cooling unit 5 is distinguished from cooling unit 4 by its small but widespread content of basalt fragments, which are not found in the other units.

Lithologic characteristics that are related to zonation of cooling units will be described next. Nonwelded tuffs commonly occur at the margins of cooling units but may be absent at either the top or bottom of the unit, as is illustrated in the columnar section on plate 5. The nonwelded tuffs have a relatively low density and high porosity and are light colored—white, gray, or yellowish gray. Undeformed pumice fragments and shards are easily seen (fig. 6*A*). X-ray analysis has shown that in several of the nonwelded tuffs the glass has been partly to largely altered to clinoptilolite (a zeolite), but this is considered to be due to diagenesis that occurred sometime after the emplacement and cooling of the ash flows.

The nonwelded tuffs grade through a zone, normally less than 30 feet thick, of partially welded tuff into the densely welded zone. The partially welded tuffs in the lower parts of cooling units commonly have a pink color that deepens upward toward the densely welded zone, and pumice fragments are increasingly flattened upward (fig. 6*D*).

The densely welded zones of the ash flows are predominantly devitrified lithoidal welded tuff (figs. 5 and 6*C*) with a gray to reddish-brown color. Commonly the rock has a eutaxitic structure with lenticular thin streaks of light brown in darker brown rocks. These lenticles are oriented approximately parallel to the flow plane and represent pumice fragments that have been flattened from several millimeters to one or less. In the upper parts of the densely welded zone, flattening of the pumice fragments is less pronounced. The densely welded zone commonly has a vitrophyre zone as thick as 30 feet at its base. The glass is brown to black in color, partly perlitic, and has black or brown eutaxitic lenticles of collapsed pumice fragments (fig. *6*B).

Devitrification of the densely welded lithoidal zone has resulted in the development of spherulitic or axiolitic intergrowths of cristobalite or quartz, and sanidine (Smith, 1960b, p. 152; Ross and Smith, 1961, p. 36). In addition to devitrification of the glass, vapors escaping upward through the flows have deposited cristobalite, tridymite, and sanidine in pore spaces and have altered the glass and phenocrysts.

The phenocrysts of sanidine tend to have a chatoyant luster in the devitrified zone whereas they are clear in the more quickly chilled glass margins, and biotite that is fresh green or black in the glassy parts has been altered to reddish brown or completely destroyed in the lithoidal parts of the ash flows.

This vapor phase activity, as suggested by Smith (1960a, p. 832), requires a porous matrix and was most intense in the upper part of the densely welded zone.

AIR-FALL TUFFS

Air-fall tuffs are abundant in the lower and upper parts of the pyroclastic sequence of the Bullfrog Hills caldera. The tuffs are predominantly massive but partly bedded and range in color from white to brown or locally green. The tuffs contain fragments as much as 50 mm in diameter of pumice, glass shards, rhyolitic felsite, and locally basalt. They also contain scarce to abundant partly broken crystals, less than 2 mm in longest dimension, of quartz, sanidine, albite, oligoclase, and biotite. The groundmass consists of finely comminuted pumiceous glass and glass shards.

The tuffs are locally intensely silicified, opalized, and argillized probably by thermal springs. The glassy parts of the tuffs are also partly altered to clinoptilolite, probably by diagenesis.

RHYOLITE FLOWS AND INTRUSIVES

Flows and intrusions of rhyolite occur predominantly near what are considered to be the margins of the caldera. The rhyolite bodies are partly vitrophyric and partly felsitic. The color ranges from gray to black in the vitrophyre and gray to reddish brown in the felsite. Most of the vitrophyre is perlitic (fig. 7*A*). The felsite is fine grained to aphanitic (fig. 8*A*) and partly spherulitic (fig. 7*B*). The phenocryst content of the rhyolite bodies is commonly less than 5 percent but may be as much as 15 percent. The phenocrysts, as long as 3 mm, are quartz, sanidine, oligoclase, biotite, magnetite, and hematite. Two intrusive bodies have anorthoclase rather than sanidine.

The vitrophyre tends to occur most abundantly along the margins of the flows and intrusives, and the marginal zones may also be brecciated (fig. 9).

BASALT FLOWS AND INTRUSIVES

Basalt occurs in the Bullfrog Hills in dikes and irregular intrusions, and as flows above cooling units 3, 4, and 5, and near the top of the pyroclastic sequence (pl. 5). Other basalt dikes and flows occur in the pyroclastic rocks several miles east of the Bullfrog Hills caldera. A quartz basalt flow is the youngest unit in the Bullfrog Hills volcanic section (pl. 5), and analcime basanite occurs locally, probably as an alteration facies of the basalt flows above cooling units 3 and 5.

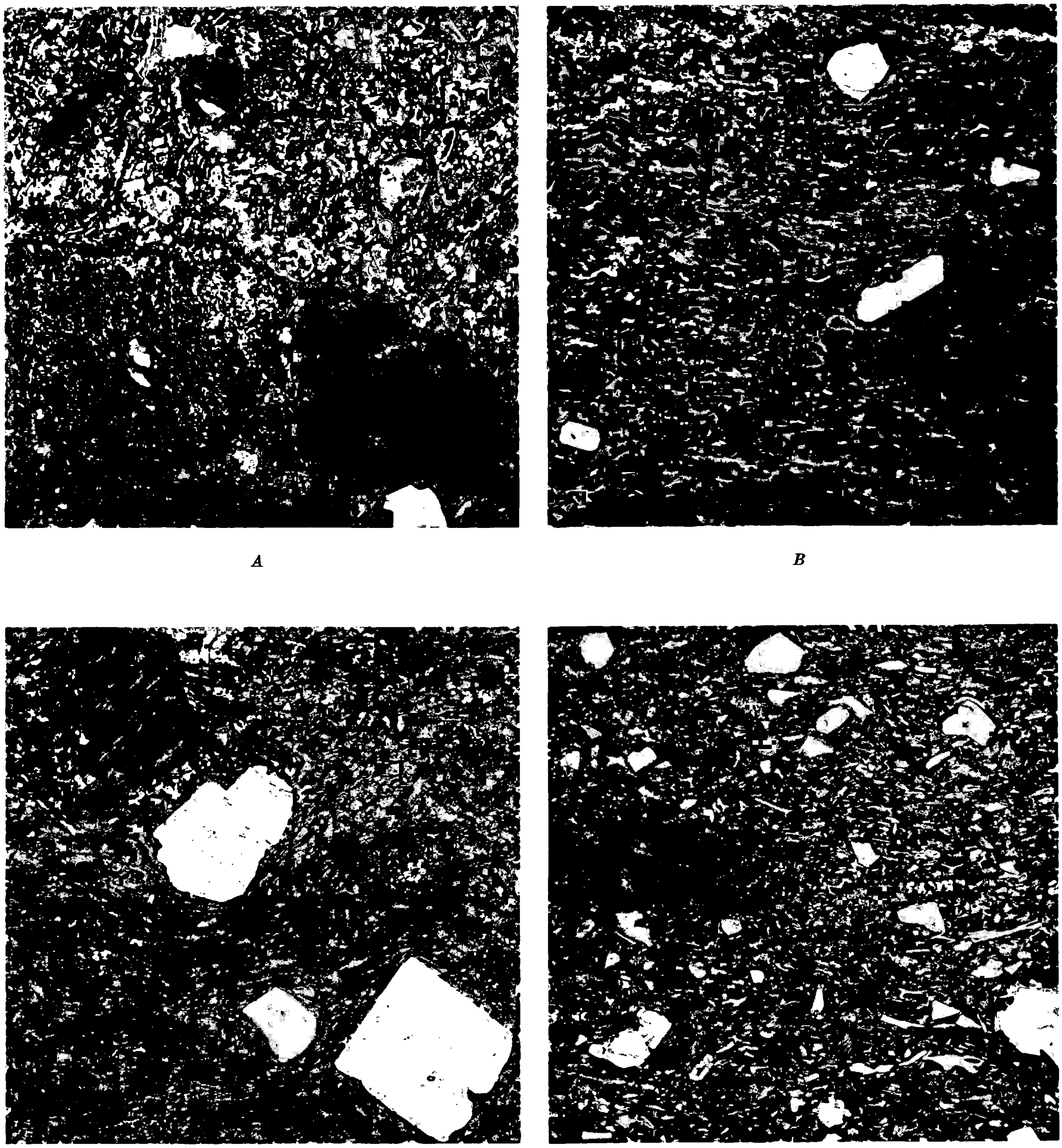
The basalts are dark gray to black, fine grained, and porphyritic; the phenocrysts, as long as 1 mm, are labradorite and olivine partly altered to bowlingite, antigorite, and iddingsite. Analysis 20, table 2, represents one of the basalt flows. The groundmass is an intergrowth of labradorite or andesine, augite, magnetite, hematite, and a little biotite. The groundmass is trachytic in some bodies and is partly brown glass containing skeletal magnetite crystals in others.

The quartz basalt, represented by analysis 19, table 2, contains phenocrysts, as much as 15 mm across, of andesine and quartz in a fine-grained groundmass of labradorite or andesine, quartz, augite, pigeonite, magnetite, hematite, and a little biotite.

The two basalt flows above cooling units 3 and 5 grade abruptly, either horizontally or vertically, into analcime basanite. The basanite (analysis 22, table 2) has phenocrysts, as much as 4 mm across, of olivine, pigeonite, and augite in an aphanitic, nearly black groundmass of analcime, plagioclase (An_{45-60}), pyroxene, magnetite, and a little biotite. The analcime, identified by X-ray, is partly interstitial to the other minerals. The basalt in the flows that contain basanite is very similar texturally and mineralogically to the basanite, including the presence of rather abundant pigeonite as well as augite. The only difference is the absence of analcime. It is not known what caused the local development of analcime, but it may have formed as a late stage primary precipitate, or as a deuteric alteration where volatile constituents locally accumulated.

LATITE FLOWS AND INTRUSIVES

Porphyritic latite was erupted late in the volcanic sequence of the Bullfrog Hills caldera. It forms rather extensive flows as thick as 200 feet near the east rim of the caldera and intrudes the ash flows and tuffs in the western part of the caldera.



A *B* *C* *D*

FIGURE 6.

PHOTOMICROGRAPHS OF ASH FLOWS

The intrusive latite and the interiors of the flows are massive reddish- to grayish-brown to black rock; the flow tops, as thick as 10 feet, are vesicular and reddish brown; the basal zones of the flows, 10 to 25 feet thick, are commonly brecciated, and locally the flows have a black glass zone, 1 to 5 feet thick at the base. Phenocrysts as much as 3 mm across are commonly arranged in clusters of plagioclase (An_{20-45}), augite, pigeonite, magnetite, and biotite (fig. 8*B*). The groundmass is microcrystalline, partly trachytic, and consists of intergrown sanidine, oligoclase, magnetite, and hematite. Analyses 17 and 18 represent two of the flows.

CHEMICAL COMPOSITION OF THE ROCKS

The volcanic rocks of the Bullfrog Hills caldera range from basanite and basalt to latite, rhyodacite, and rhyolite. The rocks are probably hypabyssal in origin and occur as flows, ash flows (welded tuffs), tuffs, and intrusives. The rhyolitic rocks quantitatively far exceed the other types and include the ash flows, most of the tuffs, and the majority of the flows and intrusives.

Chemical analyses are given in table 2 of 22 volcanic rocks in the Beatty area and of four related tuffs and ash flows from the same pyroclastic field in the Nevada Test Site, 35 miles northeast of Beatty (Wilcox, 1958). Four of the analyses are old and were made in connection with a study of the Bullfrog mining district (Ransome and others, 1910). The remainder are new. All were made by analysts of the U.S. Geological Survey, as were the spectrographic analyses shown in table 2. Norms and modes are also shown for most of the rocks.

The differentiation index of Thornton and Tuttle (1956, 1960) has been calculated from the norms, and the oxides have been plotted against this index in figure 10. A semilogarithmic graph was used and the differentiation index was plotted on the logarithmic coordinate. The graph plotted in this way shows greatest detail in the rhyolitic range, where the majority of the analyses lie, and yet permits inclusion of the basaltic rocks on the same graph in a reasonable space pattern.

The trend lines for the 5,000 analyses in Washington's tables as contoured by Thornton and Tuttle (1960, p. 674–679) are also shown for six of the oxides in figure 10. Where the analyses from the Beatty area have a nearly linear arrangement, they follow the trend lines rather closely. This is true for SiO_2, which increases with increasing D.I. (differentiation index), and also for CaO and MgO, which decrease with increasing D.I. TiO_2 and $FeO+Fe_2O_3$ also follow good trends, decreasing with increasing D.I., whereas Na_2O and K_2O increase as D.I. increases, but with some scattering of points.

It will be noted that the air-fall and nonwelded tuff samples plot more or less as a group and are separated from the other rocks for several of the oxides. The tuffs are markedly low in Na_2O and Al_2O_3 with respect to the trend for the other rocks in the D.I. range in which they lie. The tuffs are also slightly low in $FeO+Fe_2O_3$, CaO, and TiO_2. It was determined by X-ray analysis that the glass in these tuffs has been altered to clinoptilolite. Changes in the bulk composition of the rocks probably occurred during this alteration and may account for their somewhat abnormal composition.

Minor elements.—Quantitative spectrographic analyses were obtained for 18 of the 26 volcanic rocks listed in table 2. Only a brief discussion of the results will be given here. The amounts of the minor elements in each rock have been compared with the estimates of Vinogradov (1956) for the same rock type in the whole earth's crust.

The abundance of the following minor elements in volcanic rocks of the Beatty area is roughly comparable to Vinogradov's estimate: B, Be, Ga, Mo, Nb, Pb, Sc, V. The rocks in the Beatty area are low in Co, Cr, Cu, Li, and Ni, and they are high in La, Y, Yb, and Zr. The La content of the Beatty latite

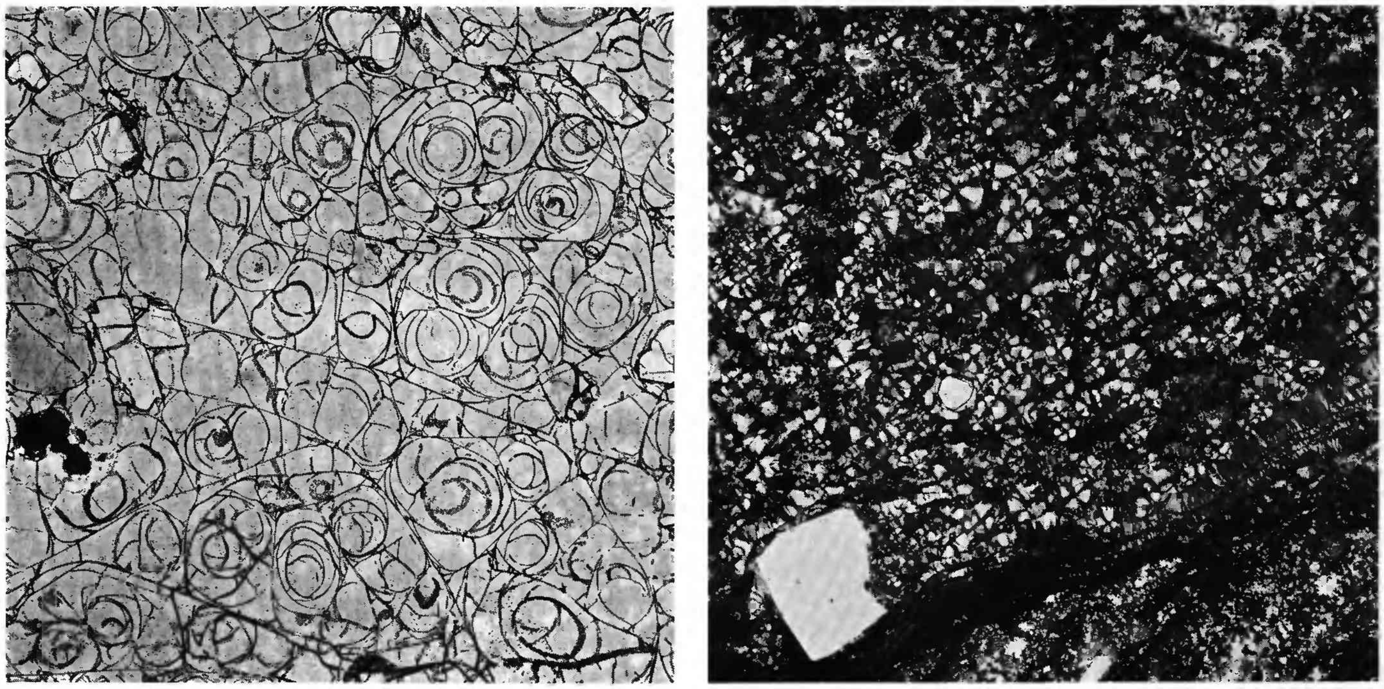
EXPLANATION FOR FIGURE 6

A, Nonwelded basal zone of ash flow. Dark patches are accidental felsite inclusions. The large medium-gray patch is an undeformed pumice fragment. Quartz crystals, partly broken into small fragments, are white. Matrix consists of glass dust and angular shards. Plain light, × 20.

B, Vitrophyre zone that overlies the basal nonwelded zone of *A*. The rock is almost entirely medium- and dark-brown glass with schlieren oriented more or less parallel to the flow plane. One incompletely fused flattened pumice fragment (speckled gray) can be seen near the middle of the picture. Scattered white crystals are sanidine. Plain light, × 20.

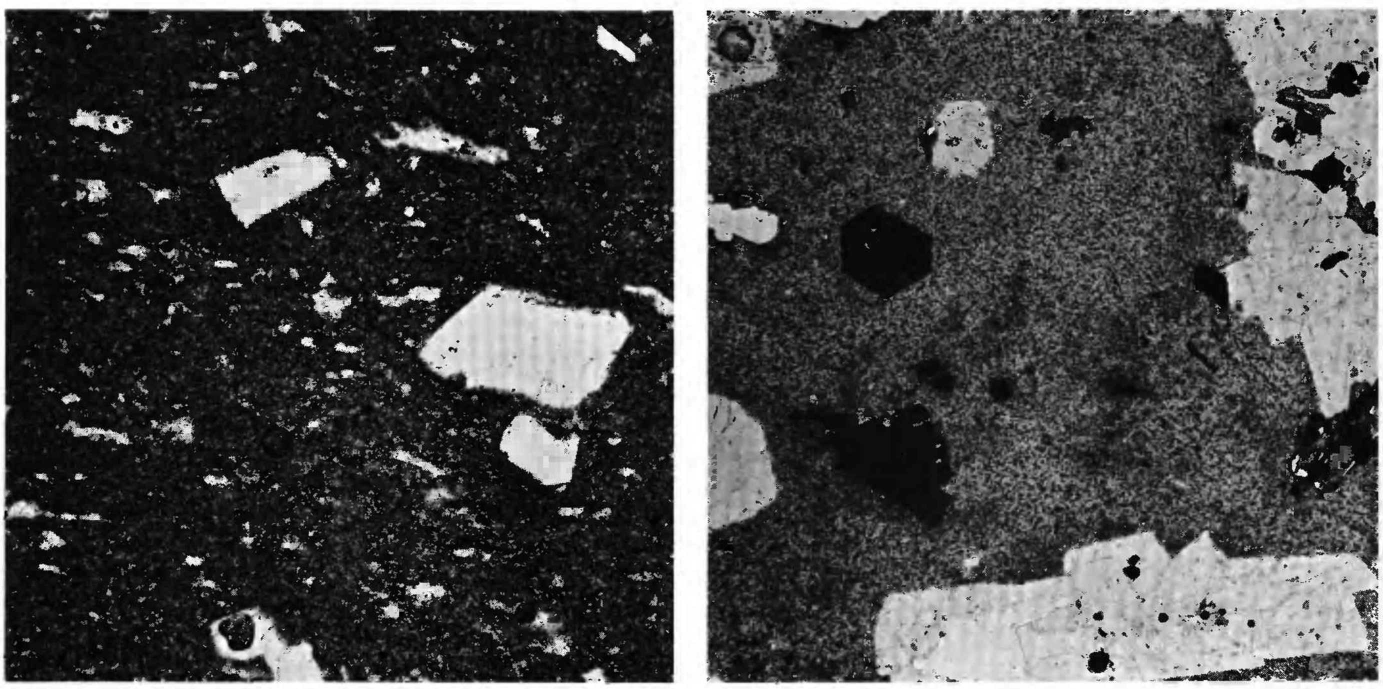
C, Devitrified densely welded lithoidal zone of same ash flow as in *A*. Groundmass of microcrystalline eutaxitic schlieren, elongated more or less parallel to the flow plane, but deflected around crystals and fragments. Dark fragment is glass. White crystals are sanidine and anorthoclase. Plain light, × 20.

D, Partly welded tuff just below the vitrophyre zone of an ash flow. Pumice fragments (speckled gray) are flattened parallel to the flow plane. Groundmass consists of glass dust (black), small pumice fragments (gray), and angular glass shards (white and light gray). Crystals (white) are quartz, plagioclase, and sanidine. Plain light, × 20.



A *B*

FIGURE 7.—Photomicrographs of perlitic and spherulitic rhyolite bodies. *A*, Perlite from the margin of a rhyolite intrusion. Rock is mostly perlitic glass, but it contains several subrounded crystals of quartz (white), plagioclase (white), and sanidine (slightly darker gray than the glass). Plain light, × 16. *B*, Spherulites from the margin of a rhyolite flow. Rock consists of spherulites of various sizes and scattered crystals (white). Large crystal is oligoclase; small crystal is quartz. Crossed nicols, × 20.



A *B*

FIGURE 8.—Photomicrographs of felsitic rocks. *A*, Rhyolite porphyry intrusive. Rectangular white patches are anorthoclase phenocrysts. Small white streaks are miarolitic cavities filled with quartz and anorthoclase. Groundmass (dark gray) consists of a very fine intergrowth of quartz and feldspar speckled with hematite. Plain light, × 15. *B*, Latite porphyry flow. Phenocrysts of oligoclase (white), augite (gray, in or adjacent to oligoclase), and altered biotite (black) tend to be clustered together. The groundmass is very fine grained, slightly trachytic, and consists of intergrown oligoclase, K-feldspar, and magnetite. Plain light, × 15.

FIGURE 9.—Rhyolitic vitrophyre breccia at base of flow in the upper part of the Bullfrog Hills volcanic sequence, Rainbow Mountain, Bullfrog quadrangle, Nevada.

and basalts is 3 to 10 times Vinogradov's figure for the same rocks. Ba and Sr are nearly equal to Vinogradov's figure in the rhyolites, but in the latite and basalts they are 2 to 7 times higher. F is about average in the rhyolites of the Beatty area, but it is 3 times higher than Vinogradov's estimates in the latite and basalt.

OLDER GRAVELS

Older gravels, probably Pleistocene in age and characterized by the variable sorting of the detritus, occur in the south and northeastern parts of the Bullfrog quadrangle. These gravels are old dissected fans, which have been eroded and partly covered by Recent alluvium. These dissected fans consist of relatively fine detritus, cobbles, and boulders. The upper surfaces are strewn with boulders, mostly less than 3 feet across, derived from the various types of bedrock in the adjacent areas. In the south part of the quadrangle, the boulders on the fans are quartzite from the Corkscrew and Daylight Formations, dolomite and limestone from the Bonanza King and Carrara Formations, and welded tuff and basalt from the Tertiary volcanic rocks. In the northeastern part of the quadrangle, the dissected fans are strewn with the same types of boulders, but rhyolite derived from welded tuffs and intrusives predominates.

Two of the dissected fan remnants in the southern part of the quadrangle had been intruded by basalt (pl. 1) prior to dissection and the surfaces adjacent to these areas are strewn with basalt boulders.

RECENT ALLUVIUM

The Amargosa Desert and Sarcobatus Flat in the southeastern and northwestern parts of the quadrangle, respectively, are mostly underlain by Recent alluvium composed of gravel, sand, and silt. The alluvium has encroached on the Funeral and Grapevine Mountains in the southwestern part of the quadrangle, and on the Bullfrog Hills in the northern part. Large areas of the alluvium are covered by smooth desert pavement broken by the gullies of ephemeral streams.

STRUCTURE

The structural features of the rocks in the Bullfrog quadrangle, like those in the Bare Mountain quadrangle, are due both to tectonic deformation and to volcanic activity. The Paleozoic rocks have been intensely folded and faulted by a major tectonic orogeny (Cornwall and Kleinhampl, 1960a), probably in the Cretaceous and early Tertiary, that also produced major thrust faults and right-lateral strike-slip faults in the Las Vegas Valley shear zone (Longwell, 1960) southeast of Bare Mountain. The volcanic rocks in the northern parts of the two quadrangles have been deformed by the catastrophic subsidence (Cornwall, 1962) of the edifices from which these rocks were erupted to form the Bullfrog Hills caldera, probably in the Miocene, and the Yucca Mountain graben, probably in the Pliocene (pl. 4). During the Tertiary and Quaternary the whole region has been subjected to basin-range normal faulting.

TECTONIC DEFORMATION

In the southwestern part of the Bullfrog quadrangle a flat thrust plate of Corkscrew Quartzite and overlying carbonate rocks of the Carrara and Bonanza King Formations moved northeastward over the older Daylight Formation. Erosional remnants of the thrust plate, consisting mostly of Corkscrew Quartzite, are scattered over the area (pl. 1). This is essentially a bedding-plane fault and stratigraphic displacement has for the most part not been great; the sole of the fault lies near the base of the Corkscrew Quartzite, and in most places it overlies the upper part of the Daylight Formation. The Johnnie thrust in the northern Spring Mountains (Nolan, 1929, p. 466–471) shows similar relations. Movement along the fault has been sufficient to thoroughly brecciate the basal 20 to 30 feet of the Corkscrew Quartzite immediately above the fault. Percolating group water has subsequently bleached the normally reddish-brown rock.

Underneath the thrust fault the incompetent Daylight Formation has been folded with axes trending northwest at right angles to the direction of movement of the thrust plate. The Daylight Formation has been rather thoroughly fractured and faulted, and the basal part of the formation is also faulted against a massive quartzite (shown as four patches of Paleozoic rocks, undifferentiated, on pl. 1) near the south boundary of

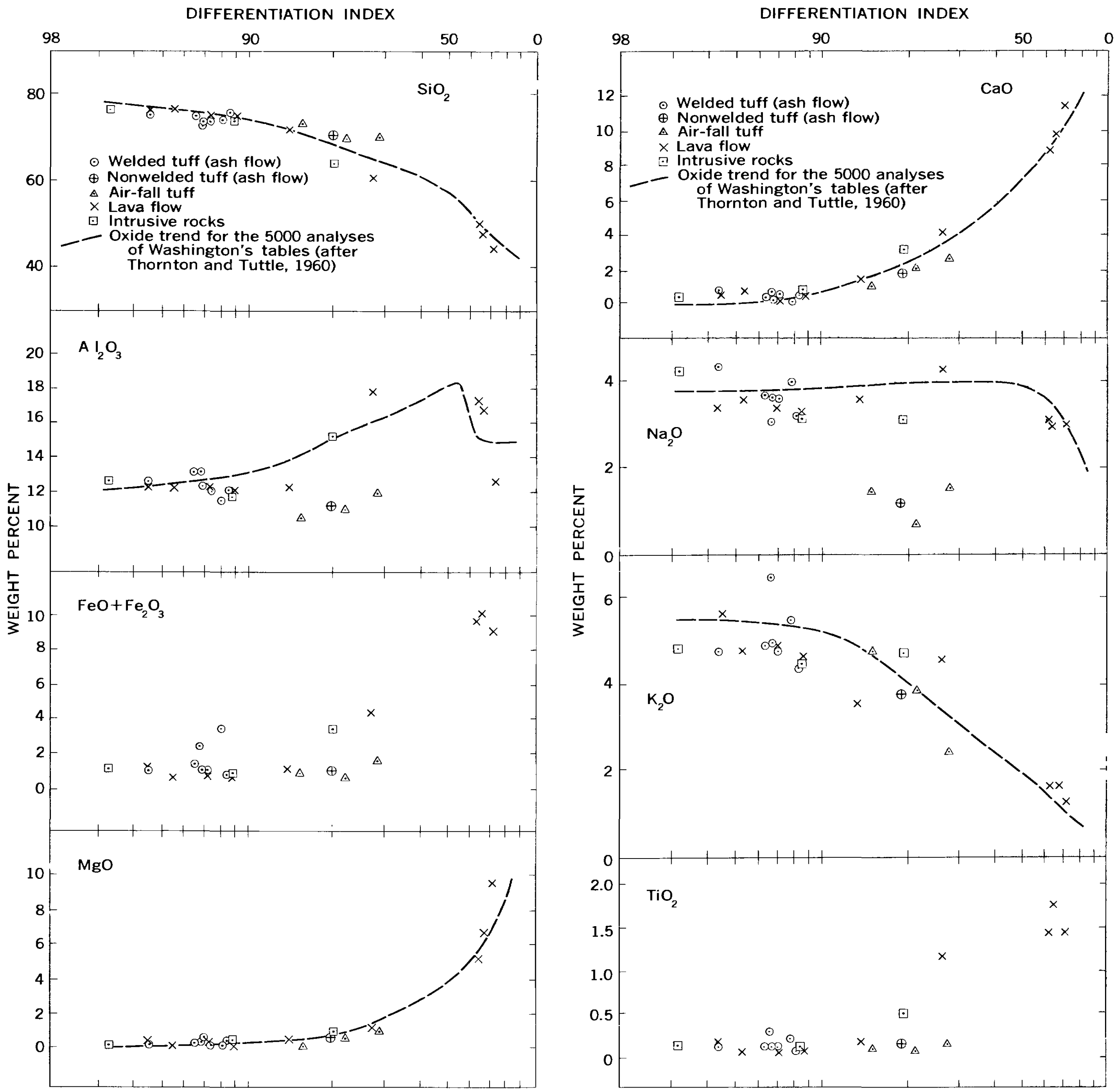


FIGURE 10.—Variation diagrams of oxide versus differentiation index of volcanic rocks in the Beatty area, Nevada.

the quadrangle. This fault, like the thrust fault beneath the Corkscrew Quartzite, is generally rather flat and may also be a thrust fault. Thus the shaly Daylight Formation probably occurs as an incompetent plate between two massive quartzites.

Just east of the Bullfrog quadrangle on Bare Mountain, the Paleozoic rocks have been intensely deformed by flat thrust faults and north-trending right-lateral strike-slip faults (Cornwall and Kleinhampl, 1960 a, b, 1961b). The oldest thrust plates moved southwest, and younger overlying plates moved south or southeast. The rocks on the east sides of the strike-slip faults have moved south relative to those on the west sides.

RELATION TO WALKER LANE AND LAS VEGAS VALLEY SHEAR ZONE

The Las Vegas Valley shear zone, a major transcurrent lineament with right-lateral displacement estimated at about 25 miles (Longwell, 1960, p. 197; B. C. Burchfiel [2] 1961, p. 134–135), has been traced northwest to the west end of the Spectre Range quadrangle (fig. 11). Bare Mountain is only 25 miles northwest of there, and it is most likely that the shear zone passes northwestward near Bare Mountain either on the east in Crater Flat or on the west across the Amargosa Desert. The general east-west strike of the beds on Bare Mountain (Cornwall and Kleinhampl, 1961b) may be due to drag along the shear zone, similar to the situation farther southeast in Las Vegas Valley (fig. 11), and may thus indicate proximity to the shear zone.

Gianella and Callaghan (1934, p. 3, 18–19) suggested that the Las Vegas Valley shear zone may be part of a major lineament that extends 200 miles northwest to the area of Cedar Mountain, Nev., and Locke and others (1940, p. 522–523) named this lineament the Walker Lane for the valley at Goldfield, which was the route used by the explorer Walker. This valley, in which there are indications of a right-lateral shear zone at Goldfield according to Locke, extends south to the Bullfrog quadrangle along Sarcobatus Flat and thence into Amargosa Desert.

Recent mapping by B. C. Burchfiel [2] (1961, pls. 10, 14) indicates that the Las Vegas Valley shear zone strikes nearly due west at the west border of the Spectre Range quadrangle (fig. 11). If this is the case, the shear zone probably passes south of Bare Mountain and thence northwestward across the Amargosa Desert and the Bullfrog Hills in the Bullfrog quadrangle as shown in figure 11. Burchfiel [2] (1961, p. 136–140) further suggests that a major branch of the shear zone may continue northwestward just south of Silver Peak, 60 miles northwest of the Bullfrog quadrangle, and thence into California north of the White Mountains, but geologic mapping in this area, described below, does not favor this interpretation.

J. P. Albers and J. H. Stewart (oral communication, 1962) have recently completed geologic mapping of Esmeralda County, Nev., and their data indicate that the shear zone may extend, as shown in figure 11, northwestward from the Bullfrog quadrangle toward Coaldale and thence northwestward up the Soda Spring Valley, where a right-lateral fault with a displacement of 4 miles has been postulated by Ferguson and Muller (1949, pl. 1 and p. 14, 29). It is now considered more likely (Albers, oral communication, 1963) that the shear zone extends northward up Sarcobatus Flat past Goldfield to connect with the Cedar Mountains fault zone near Tonopah, as suggested by Gianella and Callaghan (1934) and Locke and others (1940).

[2] Burchfiel, B. C., 1961, Structure and stratigraphy of the Spectre Range quadrangle, Nye County, Nevada: New Haven, Conn., Yale University, Ph. D. thesis.

The right-lateral transcurrent fault along the east side of the White Mountains in the valley west of Silver Peak, considered by Burchfiel [2] (1961, p. 136–140) to be a possible extension of the Las Vegas Valley shear zone, has been recently studied by E. H. McKee (oral communication, 1962). According to McKee this fault can be traced southeastward into Death Valley and down the east side of Death Valley where it is known as the Furnace Creek fault (Jennings, 1958).

It thus appears that there are two major right-lateral fault zones in this region (fig. 11). One, the Las Vegas Valley shear zone, extends northwestward past Beatty up Sarcobatus Flat, and possibly into Soda Spring Valley, or to Tonopah and thence northwestward to the Cedar Mountains. The other, the Furnace Creek fault, extends northwestward along Death Valley and thence along the east side of the White Mountains.

BASIN-RANGE FAULTING

Basin-range normal faults have probably been developing in the Bullfrog quadrangle from Tertiary to Recent time. One Recent fault along the east-central border of the quadrangle (pl. 1) and extending into the Bare Mountain quadrangle has displaced Recent alluvial fans by as much as 40 feet, with the west or valley side down.

Older normal faults, trending more or less north-south, have moderately disrupted the Paleozoic and Tertiary rocks in the southwestern part of the quadrangle. One such fault underlies Boundary Canyon and another is in the next canyon to the west that runs south from Willow Spring. A northwest-striking fault has dropped a small graben of Titus Canyon Formation of Stock and Bode (1935) into the older Daylight Formation at the south border of the map, southeast of Boundary Canyon. All of these faults have downward displacement on the west side.

Other normal faults of the basin-range type, due to regional subsidence, may occur in the volcanic rocks of the Bullfrog Hills caldera. The faults there are normal, and due to subsidence, but most of the deformation is probably related to the local collapse of the Bullfrog Hills caldera.

VOLCANIC DEFORMATION

The Bullfrog Hills caldera has been described above (p. J8–J15), and only a brief review of the principal

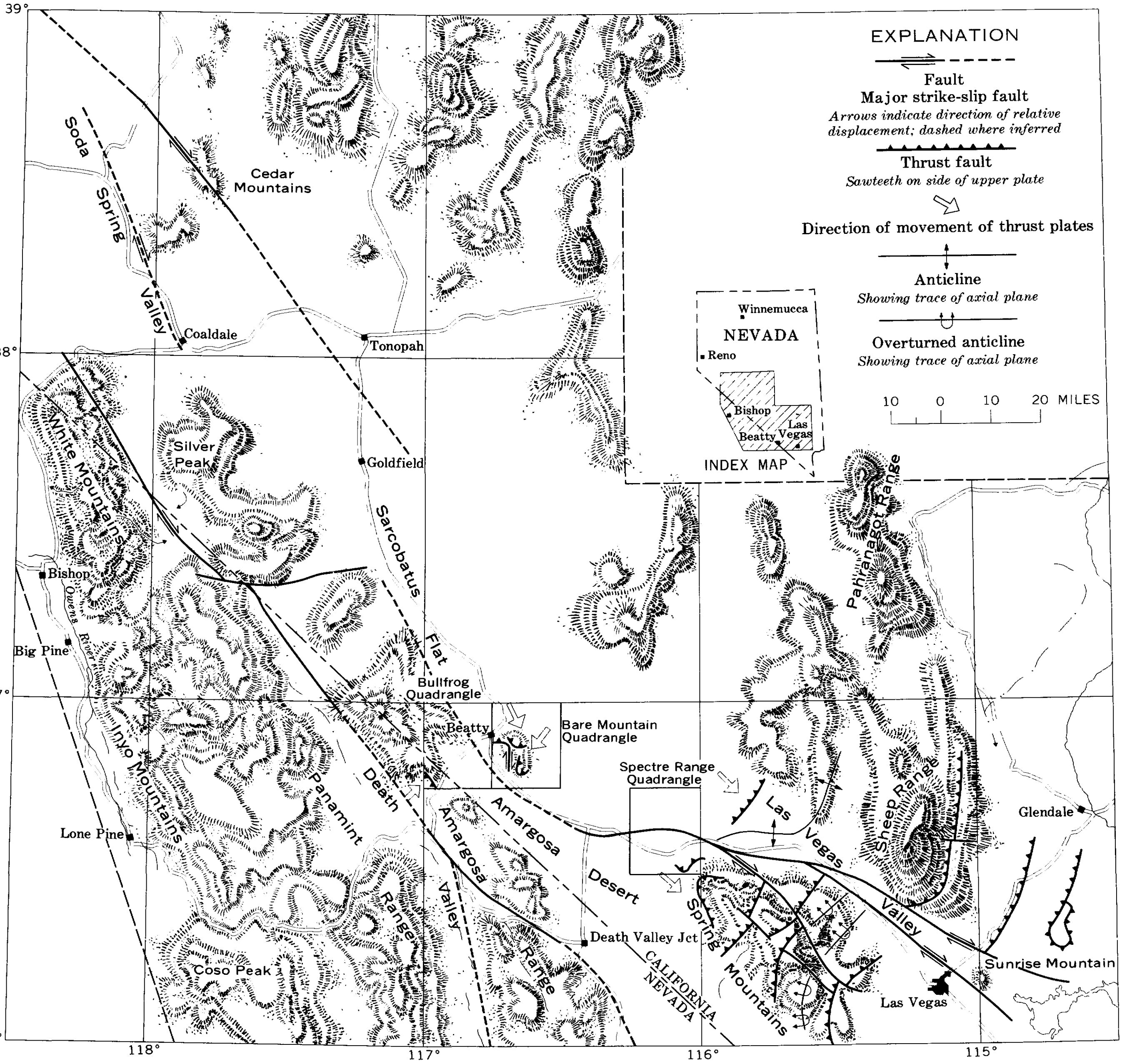


Figure 11.—Map of the major tectonic features of southwestern Nevada. Generalized tectonic features in the Las Vegas Valley from Longwell (1960, p. 194, fig. 2), and in the Spectre Range quadrangle from B. C. Burchfiel (unpublished data). Other data from Gianella and Callaghan (1934, p. 3–5, figs. 1 and 2), Locke and others (1940, pl. 1), Ferguson and Muller (1949), Jennings (1958), J. P. Albers (oral communication, 1962), and E. H. McKee (oral communication, 1962).

structural features will be given here. The caldera measures approximately 10 by 13 miles and is elongated in a northeasterly direction. The rocks in the caldera, mainly ash flows and air-fall tuffs, have the form of an intricately faulted dome, developed subsequent to the initial collapse, with the ash flows and tuffs dipping outward toward the rim and normal faults commonly dipping inward (pl. 4, section *A–A′*).

The main fault on the rim of the caldera is exposed at the Montgomery-Shoshone mine on the southeast rim (pls. 1, 4), where rocks in the caldera on the northwest side have been displaced downward about 3,500 feet with respect to those on the southeast. Additional subsidence of about 500 feet has occurred along several other faults parallel to this fault in a zone about 1 mile wide east of the Montgomery-Shoshone mine (pls. 1, 4).

Extending northeastward from the southeast rim of the caldera into the Bare Mountain quadrangle (Cornwall, 1962) is a series of normal faults that have dropped the volcanic rocks downward successively to the northwest (pl. 4). This subsidence is also probably due to withdrawal of magma from an underlying chamber. These fault blocks are bounded on the south by a north-dipping fault of variable strike and dip along which the volcanic rocks have apparently slid down toward the north across underlying Paleozoic rocks. This fault was earlier considered by the present writers (1961b) to be a thrust fault, before the general pattern of subsidence related to the caldera was recognized. Ransome (Ransome and others, 1910, p. 101–102) favored the interpretation of this fault as a thrust, but he considered that normal movement was also a possibility.

The rocks in the caldera were still further deformed when magma re-entered the underlying magma chamber at a late stage and pushed the basement of Precambrian and Paleozoic rocks up into the volcanic sequence (p. 33; pl. 1, section *B–B′*).

The youngest extrusive rocks of the Bullfrog Hills volcanic sequence are latite and quartz basalt flows, mainly in the eastern part of the caldera. These gently dipping flows in part unconformably overlie the older steeply dipping volcanic rocks (pl. 1, section *B–B′*) but they, too, are deformed, though to a lesser degree, in the same general pattern as the older rocks. It thus appears that the major part of the deformation, owing to the subsidence of the caldera, occurred before the latest volcanic event, namely, the extrusion of the latite flows.

ORE DEPOSITS ASSOCIATED WITH THE CALDERA

The four most prominent known ore deposits in the Bullfrog and Bare Mountain quadrangles, as well as the majority of the smaller deposits, are located along marginal faults of the Bullfrog Hills caldera, or near the related area of subsidence that extends outward from the southeast rim of the caldera (pls. 1, 4). Three of the deposits, the Montgomery-Soshone, Mayflower, and Pioneer (one-half mile north of the Mayflower) gold-silver mines, are on the east rim of the caldera. The fourth, the Daisy fluorspar mine, occurs in Paleozoic rocks adjacent to the southern margin of the subsidence zone that extends tangentially outward from the caldera toward the northeast.

The greatest concentration of mineral prospects, mostly gold-silver, also occur along the east rim of the Bullfrog Hills caldera near the Montgomery-Soshone mine. In addition, several small gold deposits, including the initial discovery of the district, the original Bullfrog mine, occur within the caldera along the north margin of the area of pre-Tertiary basement rocks that have been pushed up into the tuffs and ash flows.

Mineral exploration has been carried on actively in the Bare Mountain and Bullfrog quadrangles since 1904 when gold was discovered at the Original Bullfrog mine (Ransome and others, 1910, p. 12) at the south end of Bullfrog Mountain. The total production of gold-silver ore is valued at nearly $2 million. Most of the ore has come from the Bullfrog district in the Bullfrog Hills west of Beatty and most of the mining was prior to 1910 (Kral, 1951, p. 29).

Fluorspar is the only other mineral commodity that has been produced in significant amounts in the two quadrangles under consideration. Since the discovery of fluorite in 1918, production of somewhat more than 100,000 tons has come mostly from the Daisy mine at the north end of Bare Mountain. In addition to these minerals, a small production of bentonite, mercury, and pumicite has been recorded.

FLUORSPAR

Several fluorspar deposits have been explored in the Paleozoic carbonate rocks of Bare Mountain. These deposits have been briefly described by the present authors elsewhere (Cornwall and Kleinhampl, 1961b); only those at the north end of Bare Mountain near, and possibly related to, the caldera subsidence structure mentioned above will be discussed here. Part of these deposits have been described by Thurston (1949). By far the largest deposit occurs in the Nopah Formation, a dolomite of Late Cambrian age, at the north end of Bare Mountain in Fluorspar Canyon (pl. 4). This deposit, at the Daisy mine, is described in detail below. A small prospect, the Enif, occurs a quarter mile west of the Daisy in the same formation. A shaft was first sunk in the Enif deposit in 1906 in a search for gold; the small amount of fluorite found was not of interest at that time. In 1918 the Continental Fluorspar Company found fluorite on the Daisy claim; 1,300 tons of fluorspar were mined between then and 1922. Another fluorite deposit occurs in limestone of the Carrara Formation (Lower and Middle Cambrian) three-quarters of a mile south of the Daisy mine.

All the fluorite deposits have similar characteristics and are undoubtedly related in origin. They occur in highly deformed and fractured dolomite or limestone near major faults. The fluorite ranges in color from white to yellow, purple, or nearly black, but most of it is purple. It is commonly intergrown with yellow or brown clay from the faults with which the deposits are associated. Really large bodies of nearly pure massive fluorite are known only in the Daisy deposit.

DAISY MINE

The Daisy fluorspar mine is by far the largest of the known fluorspar deposits in the Bare Mountain area. It is located at the north end of Bare Mountain 5 miles east of Beatty in Fluorspar Canyon, in the NW¼, sec. 23, T. 12 S., R. 47 E. As mentioned above, the Daisy mine was one of several fluorspar prospects that were explored during the period 1919–22 by the Continental Fluorspar Company, headed by J. Irving Crowell. In 1927 the claims were acquired by J. Irving Crowell, Jr., and the Daisy mine has been actively operated since that time. The deposit has been developed to a depth of over 500 feet and for a horizontal length of 900 feet in a maze of workings (pl. 6) that includes 14 levels and sublevels.

GEOLOGIC SETTING

The Daisy fluorspar deposit occurs in dolomite of the Nopah Formation of Upper Cambrian age in an area of great structural complexity. The Paleozoic rocks in the area have been intensely deformed by repeated thrust faults, locally to the point of imbrication, and by steeply dipping right-lateral strike-slip faults. Rhyolitic pyroclastic rocks of probable Miocene age are faulted against the deformed Paleozoic rocks less than a quarter of a mile north of the Daisy mine. The Tertiary rocks are also deformed, but the pattern of deformation is quite different from that in the Paleozoic rocks.

As has been discussed earlier (p. J15–J17), the principal deformation of the Paleozoic rocks occurred during a major period of thrusting and right-lateral strike-slip faulting along the Las Vegas Valley shear zone, probably in the Cretaceous. The thrust faults dip gently to moderately north and northeast at the north end of Bare Mountain and the major right-lateral strike-slip faults strike nearly north-south. The Miocene pyroclastic rocks are cut by a series of northeast-trending normal faults which have, for the most part, dropped the rocks successively toward the northwest. This subsidence structure, described above, is bounded on the south by an undulating normal fault, variable both in strike and in dip, that separates pyroclastic rocks from the Paleozoic rocks to the south in which the fluorite deposits occur. This fault was earlier mapped and described as a thrust (reverse) fault by the present writers (Cornwall and Kleinhampl, 1961b) before they recognized evidence of subsidence in the Tertiary volcanic rocks.

STRUCTURE OF THE ORE DEPOSIT

The shape and distribution of ore shoots in the fluorite deposit appear to be controlled in large part by two principal sets of faults. One set strikes roughly northeast and dips vertically to steeply east. The ore shoots extend along and are bounded laterally by faults of this set. In detail the individual faults undulate quite markedly, both in plan and in section, and the fluorite bodies bounded by such faults accordingly range in thickness from less than 1 foot to a maximum of 80 feet. Examples of these patterns are seen both in the plan maps (pls. 7, 8) and in the sections (pl. 9.) Level 3 on plate 7 and the upper four levels on plate 9 are modifications of mapping done by Thurston (1949). The shoot with the maximum horizontal thickness of 80 feet occurs on and adjacent to level 6.

The other set of faults that control the distribution of ore strikes more or less northwest and dips gently to moderately northeast. These faults, like the first set, undulate markedly in strike and dip. There are only a few of these faults, but their control on the distribution of ore appears to be quite fundamental. The three most important of these faults are best seen in the sections (pl. 9), particularly in section *A–A′*. These faults do not bound the ore shoots quite as abruptly as is indicated on the somewhat generalized sections. For example, the fault that limits the base of an ore shoot in the upper four levels and the top of a larger shoot in levels 5 through 8 (pl. 9, section *A–A′*) has some ore below and adjacent to it on level 3 and some above it on level 8. The second of these faults bounds the bottom of the larger shoot on the intermediate levels and also limits the base of another shoot at the southwest end of levels 3 and 5. On levels 5 and 8 a little ore occurs below it. A pipelike shoot extends downward from this fault to level 13 along the south winze (pl. 9, section *A–A′*). It was by following this shoot, in places not much larger than the winze, that the large ore shoot on level 13 was discovered. The third important low-angle fault of this set bounds the top of the shoot on level 13.

These low-angle, northeast-dipping faults definitely cut off the northeast-striking steep faults in places, but elsewhere they appear to bend and branch into the steep faults. It was not possible to determine the direction of displacement along any of the major faults.

The available evidence indicates that most of the faulting occurred before the fluorite mineralization and that the zones of fractured rock along the steep, northeast-trending faults served as channels for the ore solutions. The ore shoots are almost everywhere bounded by gouge zones of faults, and it appears that these impermeable zones restricted the ore solutions to definite channels where the fractured dolomite was almost completely replaced by the fluorite-bearing solutions. As has been indicated by the breccia pattern on the level maps (pls. 7, 8), quite a bit of the ore contains scattered angular fragments, and these fragments are mostly dolomite as much as a foot in diameter but mostly less than 2 inches. Locally the wall rock is limestone or shale and these may also occur as fragments in the ore in such areas. Small fragments of clayey gouge are also sparingly present, and the fluorite itself is locally fragmented. The lower part of the deposit below level 8 contains less fragmental ore than the upper levels. The local presence of fluorite fragments indicates some fault movement during the mineralization process. The matrix of all the brecciated ore is mostly fluorite.

NATURE OF THE ORE

The ore consists mostly of fine-grained purple fluorite with seams, lenses, and layers of yellow clayey gouge. The ore is partly banded parallel to the faults that bound the shoots. The banding is due to the alternation of light-purple fluorite, dark-purple fluorite, and scattered seams and layers of yellow gouge, and also to the alternation of dense and vuggy layers. Most of the fluorite appears aphanitic, but part of it is visibly crystalline. The aphanitic fluorite actually consists of tiny crystals less than 0.1 mm in diameter. In places the fluorite has a comb structure due to the growth of elongated crystals outward from the walls of cavities.

In the lower levels the fluorite is partly to largely white or yellow with a fine granular texture. Locally it tends to be loosely consolidated and may flow like granulated sugar when struck with a pick. Calcite fissures as much as 3 feet wide are rather common in this ore, particularly where the ore pinches out along the strike. These calcite veins are vuggy, even cavernous, and the vugs are lined with yellow or white fluorite, clear calcite, quartz crystals, and locally fine crystals of cinnabar.

X-ray study of the yellow clayey gouge that occurs as seams or layers in the fluorite shows that it is montmorillonite. The shale member of the Nopah Formation that locally is adjacent to ore consists, on the other hand, of illite and very small amounts of montmorillonite and chlorite. The purple and white varieties of fluorite were examined with the X-ray spectrograph and found to be nearly pure except for small amounts of iron in the purple fluorite and a trace of iron in the white fluorite. The iron may be due to small amounts of limonite in the fluorite sample.

The radioactivity of the Daisy fluorspar deposit has been investigated by Chesterman and Main (in Lovering, 1954, p. 91–92). Six channel samples of the purple fluorite ranged from 0.007 to 0.015 percent equivalent uranium, and a sample of mill concentrate ran 0.002 percent. These values, while high enough to merit consideration, are probably not recoverable commercially. For comparison, the fluorspar deposits of the Thomas Range, Utah, which are considered to be high in uranium for this type of deposit, range from 0.003 to 0.33 percent uranium (Staatz and Osterwald, 1956). The highest values are apparently due to secondary enrichment of uranium near the surface.

The present writers, using a scintillation detector, mapped the distribution of radioactivity throughout the Daisy mine. The fluorite ore has a radioactivity of one to two orders of magnitude greater than the barren dolomite wallrock. The highest values were found in purple ore that contains appreciable clay gouge or occurs adjacent to shale, indicating that the radioactive material is concentrated in the clay.

PRODUCTION

The total production from the Daisy mine, given in table 3, amounts to 118,000 short tons through 1961. Since 1945, production has been at a rate of about 5,000 tons per year. The grade of the ore has ranged between 70 and 80 percent CaF_2 and the average is probably close to 75 percent. The SiO_2 content has averaged less than 2 percent. The remaining material in the ore consists of calcite, dolomite, and clay (fault gouge).

TABLE 3.—*Fluorspar production of the Daisy mine*

Year	*Short tons*
1919	700
1920	632
1921	—
1922	300
1923	—
1924	—
1925	—
1926	—
1927	—
1928	495
1929	757
1930	992
1931	478
1932	175
1933	75
1934	200
1935	250
1936	225
1937	350
1938	775
1939	1, 200
1940	3, 700
1941	5, 000
1942	3, 600
1943	3, 213
1944	2, 400
1945	4, 000
1946	3, 000
1947	4, 000
1948	7, 000
1949	4, 078

TABLE 3.—*Fluorspar production of the Daisy mine*—Continued

Year	*Short tons*
1950	6,321
1951	6,548
1952	6,408
1953	7,066
1954	4,726
1955	5,069
1956	4,807
1957	3,850
1958	4,354
1959	5,600
1960	7,632
1961	7,672
Total	117,648

The largest tonnage of ore occurs in the shoot that has its greatest width and length on levels 6 and 8 and extends downward at the northeast end of the mine to below level 12, but the most promising area for finding new ore is at the southwest end of the mine in the lower levels where a large recently discovered ore shoot is being developed at the present time.

Mr. Crowell, the owner and operator of the Daisy mine, has done a remarkable job of following the irregular, lenticular ore shoots downward, and of finding new shoots. His exploration technique of staying in ore as much as possible has been very successful. In 1945 an exploration was carried out by the Bureau of Mines (Geehan, 1946) in the Daisy mine area. Twelve diamond-drill holes were drilled but no ore was found. The mine workings were mapped geologically by W. R. Thurston (1949) of the U.S. Geological Survey as a part of this exploration program.

ORIGIN OF THE DEPOSIT

The Daisy fluorite depost is believed to be a hydrothermal deposit from ascending solutions that moved along permeable zones in the highly deformed and fractured Paleozoic rocks. The ore channels and sites of deposition were determined by the spatial arrangement of two sets of faults and fissures, one steep and northeastward trending, the other flat and northwestward trending. Impermeable gouge along the more important faults apparently confined the ore solutions to certain zones where the CaF_2 from the solutions almost completely replaced the dolomite and minor limestone. Fluorite was also deposited in cavities that resulted either from brecciation during the deformation or from solution of the carbonate rocks by the migrating hydrothermal solutions. Calcite and small amounts of quartz and cinnabar were also deposited in cavities.

The ore-bearing solutions were probably related to the Tertiary volcanism that erupted large volumes of rhyolite ash flows, tuffs, and flows immediately north of the Daisy mine. The volcanic rocks, as mentioned above, are in an area of subsidence that probably was underlain by a magma chamber from which the ore solutions may have come.

It was noted above that locally fragments of fluorite occur in a fluorite matrix and this indicates deformation during the ore-forming period, but the deformation must have been very minor as the amount of such breccia is small. The principal deformation in the mine area is clearly related to the thrusting and strike-slip faulting elsewhere in the Paleozoic rocks on Bare Mountain and must be pre-Tertiary because the Tertiary rocks were not involved.

GOLD

The early prospectors roamed the Bullfrog Hills and Bare Mountain looking for gold, and it was found in 1904 at the Original Bullfrog mine, 7 miles west of Beatty (Ransome and others, 1910, p. 12; Lincoln, 1923, p. 162; Kral, 1951, p. 28). A rush of prospectors followed and by 1905 a number of claims were being explored. Most of the gold showings were found in the pyroclastic rocks of the Bullfrog Hills, but several prospects were explored in the Paleozoic rocks on Bare Mountain.

Recorded gold and silver production through 1948 amounted to $1,886,000 (Kral, 1951, p. 29). Most of the production came before 1910 and from the Montgomery-Shoshone mine, which yielded 128,980 tons of ore valued at $1,344,000. The total production from Bare Mountain is not known but small.

The gold deposits in the Bullfrog Hills are in fissures and veins related to normal faults. These deposits have been described in detail by Ransome (Ransome and others, 1910, p. 90–125) and will only be briefly described here. Most of the gold-bearing fissures, including the Montgomery-Soshone, are steep and occur at or near the rim of the Bullfrog Hills caldera, and this relationship is probably more than coincidence. Several other deposits, including the Original Bullfrog mine, occur along the north contact of the central domal uplift of basement rocks into the Tertiary pyroclastics. This contact is a low-angle, north-dipping fault.

The mineralogy of the gold fissure deposits is simple and consists of quartz, calcite, and finely disseminated gold-silver in scattered grains of pyrite. Near the surface the pyrite has been altered to limonite. The Original Bullfrog mine also contains a little chalcocite that has been oxidized to malachite and chrysocolla. Cerargyrite has been detected but is apparently not prominent even in rich ore. The production record indicates that for the district as a whole the ratio of silver to gold in the ore is 8 to 1 (Lincoln, 1923, p. 162).

The mined ore averaged about $10 per ton (Kral, 1951, p. 29).

The gold-silver mineralization of most of the fissures is meager, even though hydrothermal alteration of the rhyolite may be pronounced; but in the Montgomery-Soshone mine a sizable body of fractured rhyolite on the footwall (southeast) side of the Montgomery-Soshone fault averaged $10 per ton in gold-silver. This ore body occurred near the surface in a fractured zone near the fault where numerous, nearly vertical, north-striking fissures intersect the northeast-trending fault (Ransome and others, 1910, p. 97). The Montgomery-Soshone fault is a northwest-dipping, steep normal fault with an apparent downward displacement of 3,500 feet on the north side.

Most of the other gold-silver prospects in the Bullfrog Hills are similar to but leaner than the Montgomery-Soshone deposit and occur along steep normal faults near the rim of the caldera. Two of the most promising deposits, other than the Montgomery-Soshone, are the Mayflower and Pioneer mines on the northeast rim of the caldera. The Mayflower deposit occurs along a fissure or fault that strikes N. 50° W. and dips 60° to 65° SW. (Ransome and others, 1910, p. 124). The Pioneer deposit occurs half a mile north of the Mayflower mine (just north of the north border of the Bullfrog quadrangle, which is shown on plate 1) and is said to be "almost identical to the adjoining Mayflower" (Kral, 1951, p. 39).

One of the gold prospects on Bare Mountain is located 2 miles northeast of the Daisy fluorspar mine (pl. 4), near the subsidence feature associated with the Bullfrog Hills caldera described earlier, and may be related to it. This mine, called the Harvey (formerly known as the Telluride), was first prospected for gold in 1905 and later mined for mercury. It will be described under quicksilver.

ORIGIN OF THE DEPOSITS

It has been pointed out that most of the gold deposits in the Bullfrog Hills district occur either along steep normal faults near the rim of the Bullfrog Hills caldera, or near the domal uplift of basement rocks into the Tertiary pyroclastic rocks within the caldera. It is probable that the ore-bearing solutions were derived from the magma chamber that presumably existed beneath the caldera. The mineralization must have occurred late in the period of volcanism after the development of the structures to which the deposits are related. The probable age thus is late Miocene or Pliocene.

BENTONITE

A small bentonite deposit at the Vanderbilt mine has been operated for over 10 years by the Silicates Corporation; it is located 1½ miles south of Beatty (pl. 4). Two bodies of bentonite occur 300 feet apart on the footwall side of a fault that dips 50° W. Most of the production has come from the larger deposit, which is shown in figure 12.

The bentonite was formed by the alteration of densely welded and nonwelded tuff of cooling units Nos. 4 and 5 respectively of the ash-flow sequence in the Bullfrog Hills caldera. The bentonite occurs in a zone of intense fracturing and faulting and apparently resulted from the activity of hydrothermal solutions that migrated through this permeable zone. The deposit occurs at the south edge of the subsidence zone that extends eastward from the Bullfrog Hills caldera.

The high-grade bentonite ore is soft and white and has scattered waxy pink or tan spots which probably represent replaced pumice fragments. The original unaltered rock had rather abundant phenocrysts of quartz, sanidine, oligoclase, and biotite, and these are still present in the bentonite ore but the feldspar and biotite are moderately to intensely altered. In part the contacts between bentontinte ore and unaltered welded or nonwelded tuff are sharp, but elsewhere a zone of moderately altered rock forms a transition. X-ray analysis shows that the bentonitic clay, both the white rock and also the pink fragments, is nearly pure montmorillonite.

QUICKSILVER

Cinnabar (HgS) was discovered in 1908 at the north end of Meiklejohn Peak (NW¼ sec. 18, T. 12 S., R. 48 E., unsurveyed) in the Bare Mountain quadrangle. Quicksilver production from this property, the Harvey mine, was recorded as 72 flasks up to 1943 according to Bailey and Phoenix (1944, p. 142). The deposit was mined again for about a year in 1956, but the amount of production is unknown and probably small. The mercury occurs as cinnabar sparsely disseminated in a lens of chalcedony and opal along a steeply dipping fissure in dolomite of the Fluorspar Canyon Formation of Devonian age.

Another small mercury deposit known as the Tip Top mine, is located 600 feet north of the Harvey mine in the Lone Mountain Dolomite of Silurian age. Production here is reported as possibly about 100 flasks of quicksilver (Bailey and Phoenix, 1944, p. 144). The cinnabar occurs along a southwest-trending, nearly vertical fault and is in 1- to 2-inch veins and also disseminated in the gouge.

PUMICITE

A moderate amount of pumicite was quarried around 1950 from pumiceous tuff located 3 miles northeast of Beatty (SE¼ sec. 28, T. 11 S., R. 47 E.)

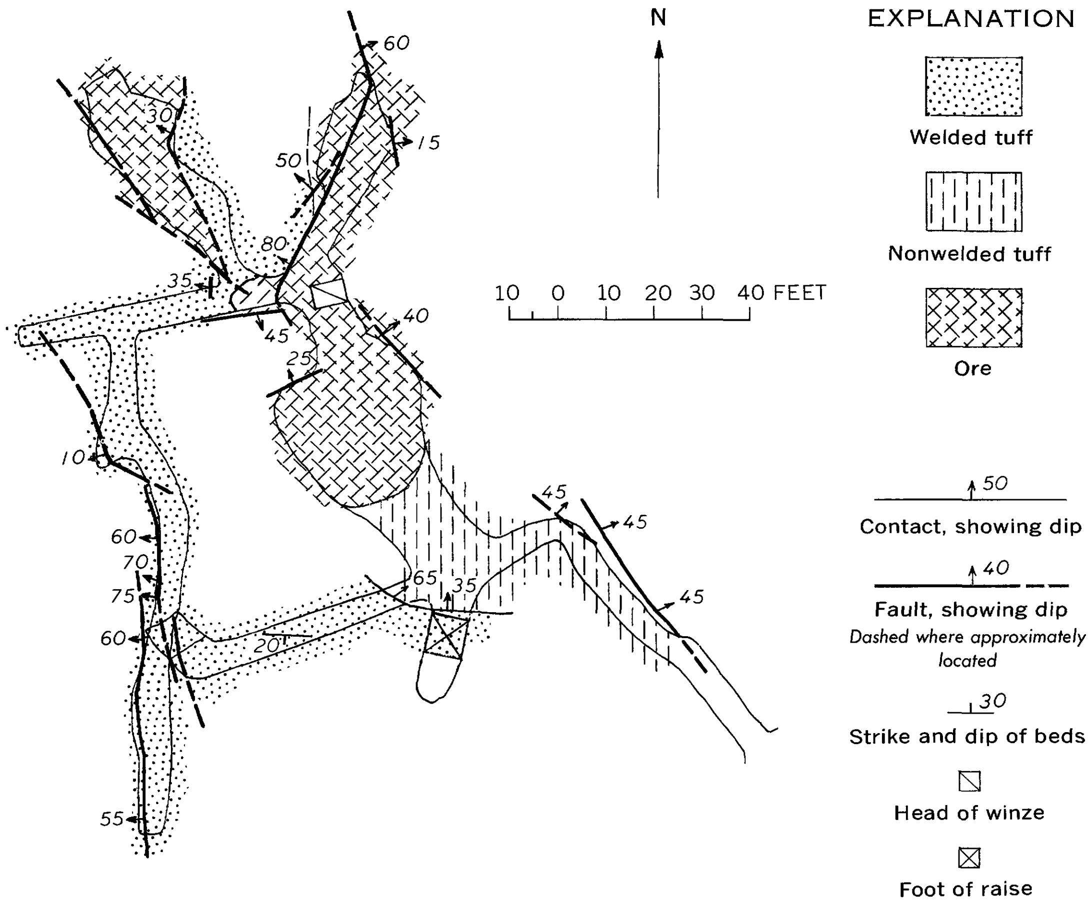


FIGURE 12.—Geologic plan of the Vanderbilt bentonite mine, Nye County, Nev.

near Nevada Highway 95. The pumicite was used to make lightweight aggregate building blocks according to Kral (1951, p. 68).

PERLITE

Several large bodies of perlite have been prospected but no production is reported. One occurs in Beatty Wash (SW¼ sec. 25, T. 11 S., R. 47 E.); another is located in the NE¼ of sec. 10, T. 12 S., R. 47 E. All of these perlite bodies are glassy facies of rhyolite flows or intrusives.

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