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STRATIGRAPHY, STRUCTURE, AND GEOLOGIC HISTORY OF THE LUNAR LAKE CALDERA OF NORTHERN NYE COUNTY, NEVADA

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Abstract.—The Lunar Lake caldera is in northern Nye County, Nev., about 70 mi (110 km) east-northeast of Tonopah. It is the youngest caldera in the central Nevada multiple-caldron complex and the source of the tuff of Lunar Cuesta, a multiple-flow simple cooling unit of quartz latitic welded tuff that is about 25 m.y. old. The tuff was distributed over an area of nearly 3,000 mi² (7,770 km²) and has a volume of approximately 90 mi³ (375 km³). The Lunar Lake caldera is the site of the Lunar Crater basalt field which contains basalts of Pleistocene and probably Holocene age. These basalts were fed from northeast-trending fissures that had much earlier served as vents for ash-flow tuffs and lavas, possibly including the tuff of Lunar Cuesta.

U.S. Geological Survey investigations in central Nevada on behalf of the U.S. Atomic Energy Commission have led to the recognition of a multiple-caldron complex (U.S. Geological Survey, 1970, p. A39–A40). The boundaries of this caldron complex have been delineated by a combination of geological and geophysical (gravity, aeromagnetic, reflection seismograph) techniques and information from several deep drill holes. Ash-flow tuffs that can reasonably be inferred to have been extruded from the caldron complex include the Windous Butte Formation (Cook, 1965), which is the most widespread and possibly the oldest (30.7 m.y., according to Grommé and others, 1972), and the tuff of Lunar Cuesta, which is about 25 m.y. old and one of the youngest. This report is concerned primarily with the tuff of Lunar Cuesta, whose extrusion resulted in the formation of the present-day topographically expressed Lunar Lake caldera. Rock units that are closely related to the tuff of Lunar Cuesta in time and space are also discussed.

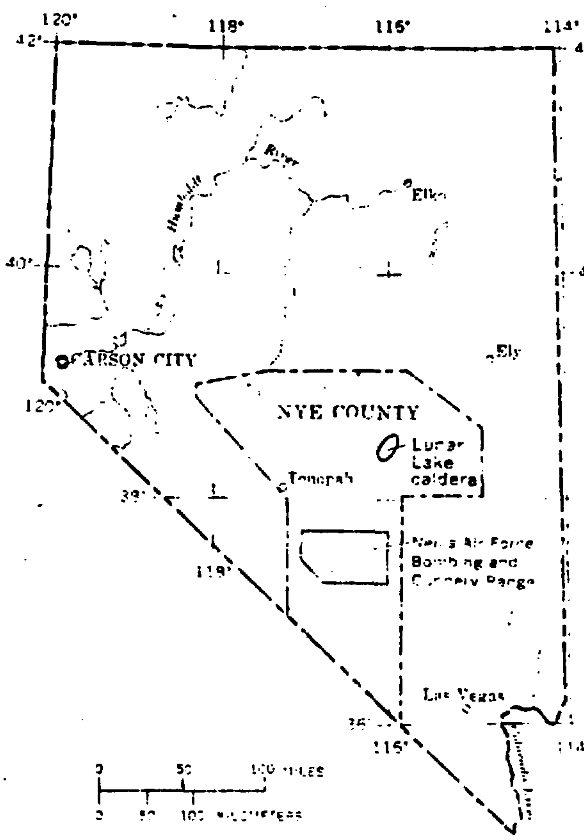


Figure 1.—Map of Nevada showing location of Lunar Lake caldera.

GEOLOGIC SETTING

The Lunar Lake caldera (fig. 1) is in northern Nye County, Nev., approximately 70 mi (110 km) east-northeast of Tonopah. It lies in the southeastern part of the central Nevada multiple-caldron complex (fig. 2), within which ash-flow tuffs and genetically related lavas probably average at least 7,000 ft (2,130 m) in thickness. Drill hole UTH-3, for example, in the central part of the complex (fig. 2) collared in the tuff of Williams Ridge and Morey Peak (Ekren, Hinrichs, and others, 1974) and bottomed in the same unit at a depth of 6,000 ft (1,830 m). We have inferred (U.S. Geological Survey, 1970, p. A39–A40) that this tuff is genetically related to the Windous Butte Formation, and recent paleomagnetic studies suggest that it may be coextensive with the upper part of the Windous Butte.

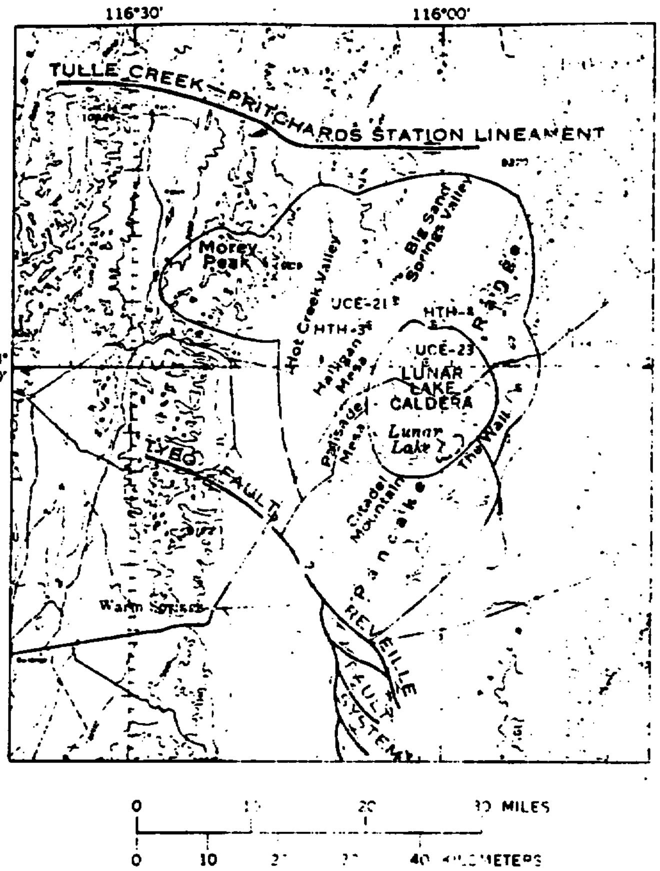


Figure 2.—Map showing location of Lunar Lake caldera with respect to the central Nevada caldron complex, the Tybo and Reveille strike-slip faults, and the Tulle Creek-Pritchards Station lineament. ⊕, Drill hole. Base from U.S. Coast and Geodetic Survey Reno Sectional Aeronautical Chart, 1:500,000, 1958–65.

Except for the strata exposed in the southern Pancake Range in and adjacent to the Lunar Lake caldera, all rocks in the area of the multiple-caldron complex are intensely faulted and fractured, and every drill hole within the complex (see geologic map of the Moores Station quadrangle, by Ekren, Hinrichs, and others, 1974) penetrated highly fractured and faulted rocks. The complex is bounded on the north by the east-trending Tulle Creek–Pritchards Station aeromagnetic lineament along which some left-lateral strike-slip movement has been inferred by Ekren, Bath, Dixon, Healey, and Quinlivan (1974). The complex is inferred to have been cut on the south and southwest by the northwest-trending left-lateral Tybo and Reveille strike-slip faults (Quinlivan and Rogers, 1974; Ekren, Rogers, and Dixon, 1974).

The Lunar Lake caldera is the site of the Lunar Crater basalt field. According to Scott and Trask (1971) the basaltic rocks include subalkaline, alkaline, and basanitoid types and contain a variety of xenoliths, some of which are inferred to have been derived from the upper mantle. The basalt lavas and pyroclastic ejecta were vented from a series of northeast-trending fissures (fig. 3). Chains of cinder cones that overlie the fissure zones are confined to the larger caldron complex but breach the Lunar Lake caldera on the northeast and southwest sides. The northeast-trending fissure zones were also the vents for several of the pre-basalt volcanic units, possibly including the tuff of Lunar Cuesta.

STRATIGRAPHY

The Tertiary volcanic units of the Lunar Lake caldera area (fig. 3) have been described in detail on the geologic maps of the Lunar Crater quadrangle (Snyder and others, 1972) and The Wall quadrangle (Ekren, Hinrichs, and Dixon, 1973). All units will be very briefly described herein. With the exception of the Shingle Pass Tuff whose source is inferred to have been outside the central Nevada caldron complex (Sargent and Houser, 1970), the units are typically calc-alkaline and are petrographically and chemically extremely similar.

Rocks older than the tuff of Lunar Cuesta

Rocks older than the tuff of Lunar Cuesta form the layer-cake stratigraphy of Palisade and Halligan Mesas (fig. 3), and the beautiful stratiform exposures of these rocks are primarily responsible for the name "Pancake Range." They include at the base of the exposure the tuff of Williams Ridge and Morey Peak, which consists of two lithologically identical cooling units in drill hole HTH-3 and in the vicinity of Black Rock Summit (figs. 3, 5). Both are multiple-flow compound cooling units of phenocryst-rich quartz latite (table 1, samples 12, 13). This tuff apparently underlies much of the central Nevada caldron complex (fig. 2), where it has great thickness, and is inferred to have been erupted concurrently with caldera subsidence after the main extrusions of the Windous Butte Formation (table 1, samples 14, 15) had ceased.

The tuff of Williams Ridge and Morey Peak is overlain on Halligan and Palisade Mesas (fig. 3) by the tuff of Halligan Mesa and in the vicinity of Black Rock Summit by the tuff of Black Rock Summit. The tuff of Halligan Mesa is 500–600 ft (150–180 m) thick; it is a multiple-flow compound cooling unit of moderately phenocryst-rich rhyolite which is characterized by a high percentage of quartz that is amethyst to dark smoky, bipyramidal in habit, and as much as 5 mm in diameter (table 1, sample 10). The unit is nearly completely free of lithic fragments. The tuff of Black Rock Summit, on the other hand, contains only 12–25 percent phenocrysts of plagioclase, biotite, and pseudomorphs after hornblende and pyroxene. Despite its basic suite of phenocrysts the tuff is rhyolitic in composition (table 1, sample 11). In exposures south of U.S. Highway 6 the tuff of Black Rock Summit is conspicuously flow layered and laminated. The laminar flowage structures are so well developed that the rock is unrecognizable as a tuff except in the basal 50–100 ft (15–30 m). The tuff at the top of the exposures has ramp structures similar in all respects to structures at the top of lava flows. The tuff is overlain without an obvious cooling break by flow breccia and lava having the same phenocryst mineralogy as the tuff. These features strongly suggest extrusion of both lava and tuff from the general vicinity of Black Rock Summit, and it is inferred that the laminar flowage structures developed as a result of faulting that probably occurred concurrently with tuff eruption. This inference is made because the tuff of Black Rock Summit does not seem to be the type of tuff that would flow under stable conditions. The tuff is chemically unlike ash-flow tuffs that flow on very gentle slopes under small static load conditions, such as the Grouse Canyon Member of Belted Range Tuff in southern Nevada (Hoover, 1964), the tuff of Wagontire Mountain in Oregon (Walker and Swanson, 1968), and the Precambrian tuffs of southeastern Missouri (Anderson, 1970). All these tuffs are characterized by low Al_2O_3 and by high Na_2O and total-iron contents, unlike the tuff of Black Rock Summit (table 1, sample 11).

Overlying the tuff of Halligan Mesa is the tuff of Palisade Mesa, a multiple-flow compound cooling unit of phenocryst-rich rhyolite and quartz latite (table 1, sample 9). This unit is conspicuously columnar jointed where it is 400–500 ft (122–152 m) thick on Palisade Mesa and it is overlain by the Monotony Tuff (Ekren and others, 1971). The tuff of Williams Ridge and Morey Peak and the tuffs of Halligan and Palisade Mesas appear to have been erupted in rapid succession without long erosional intervals between eruptions; at least, we know of no unconformities or pronounced disconformities between these units, all of which are thought to be genetically related. The Monotony Tuff (Ekren and others, 1971), in contrast, has a pronounced angular unconformity in places at its base, and locally it is separated from older units by coarse gravels. The Monotony, however, on the basis of similarity with older and younger units (table 1, sample 8) and its areal distribution, is inferred to have its source in the central Nevada multiple-caldron complex, and its caldera, as will be discussed later in this report, is overlapped and truncated by the Lunar Lake caldera.

The tuff of Big Round Valley (Quinlivan and others, 1974) crops out over several square miles north of Black Rock Summit and northeast of the Lunar Lake caldera. The tuff consists of two cogenetic multiple-flow compound cooling units that have an aggregate thickness of 700 ft (210 m), both of which resemble the tuffs of Halligan and Palisade Mesas in composition and phenocryst mineralogy. The tuff of Big Round Valley is not believed correlative with them, however, as it is nearly everywhere separated from the tuff of Williams Ridge and Morey Peak by the tuff of Black Rock Summit, which was faulted before emplacement of the tuff of Big Round Valley and is overlain conformably by the Monotony Tuff. An eruptive center for the tuff of Big Round Valley has not been identified.

Rocks younger than the tuff of Lunar Cuesta

Rocks younger than the tuff of Lunar Cuesta from oldest to youngest are the rhyolite of Big Sand Springs Valley, the tuff of Buckskin Point, quartz latite and andesite lavas, tuff of Buckwheat Rim, tuff of Black Beauty Mesa, and a tuff referred to informally as "granite-weathering tuff." With the exception of the last named, all units were extruded from the Lunar Lake area, but these extrusions did not give rise to calderas. All but the rhyolite lavas are thickest in the vicinity of Citadel Mountain, and they are inferred to have been extruded from a southwestward extension of the same northeast-trending faults that later served as conduits for the rising basalts. The rhyolite lavas (rhyolite of Big Sand Springs Valley, fig. 3) were erupted from multiple vents in caldron ring-fracture zones along the southeastern and northern sides of the caldera. At localities A and B (fig. 3) the rhyolite filled two sharp scallops that formed during collapse of the caldera. The rhyolite in these scallops obviously was erupted very shortly after the tuff of Lunar Cuesta was extruded, as indicated by the preservation of the vapor-phase top of the tuff of Lunar Cuesta in these areas. Along the northern flank, however, the rhyolite lavas rest on older strata. Either this northern area underwent extremely rapid erosion after the eruption of the tuff of Lunar Cuesta or the tuff was never deposited there because of high paleotopography. The rhyolite is nearly aphyric and contains no more than 1 percent tiny phenocrysts of quartz, feldspar, and biotite (table 1, sample 4).

South of the Lunar Lake caldera, the tuff of Lunar Cuesta is overlain by the tuff of Buckskin Point, a multiple-flow compound cooling unit as much as 250 ft (75 m) thick that consists of phenocryst-poor dark-gray rhyodacite (table 1, sample 1) at the base and phenocryst-rich light-gray quartz latite at the top. On the south flank of Citadel Mountain the tuff of Buckskin Point is overlain, without a cooling break, by quartz latitic vent breccia that grades upward into lithic-free, coarse-grained, phenocryst-rich quartz latite lava (fig. 3). The tuff of Buckskin Point is magnetically reversed.

The tuff of Buckskin Point and the local quartz latite lava are overlain by andesite lavas and flow breccias that are dark brownish gray to black and contain 8–30 percent phenocrysts of plagioclase and clinopyroxene and orthopyroxene (table 1, sample 3). These lavas are 1,200 ft (366 m) thick on Citadel Mountain, and, like the tuffs, they thin abruptly to the northwest and southeast. In the vicinity of Buckskin Point (fig. 3), lavas and flow breccias cropping out between the quartz latite and andesite are dacitic and rhyodacitic in composition, indicative of a gradual change in composition from quartz latite to andesite as lava eruptions proceeded.

The andesite lavas are overlain by the tuff of Buckwheat Rim, a multiple-flow compound cooling unit (possibly two

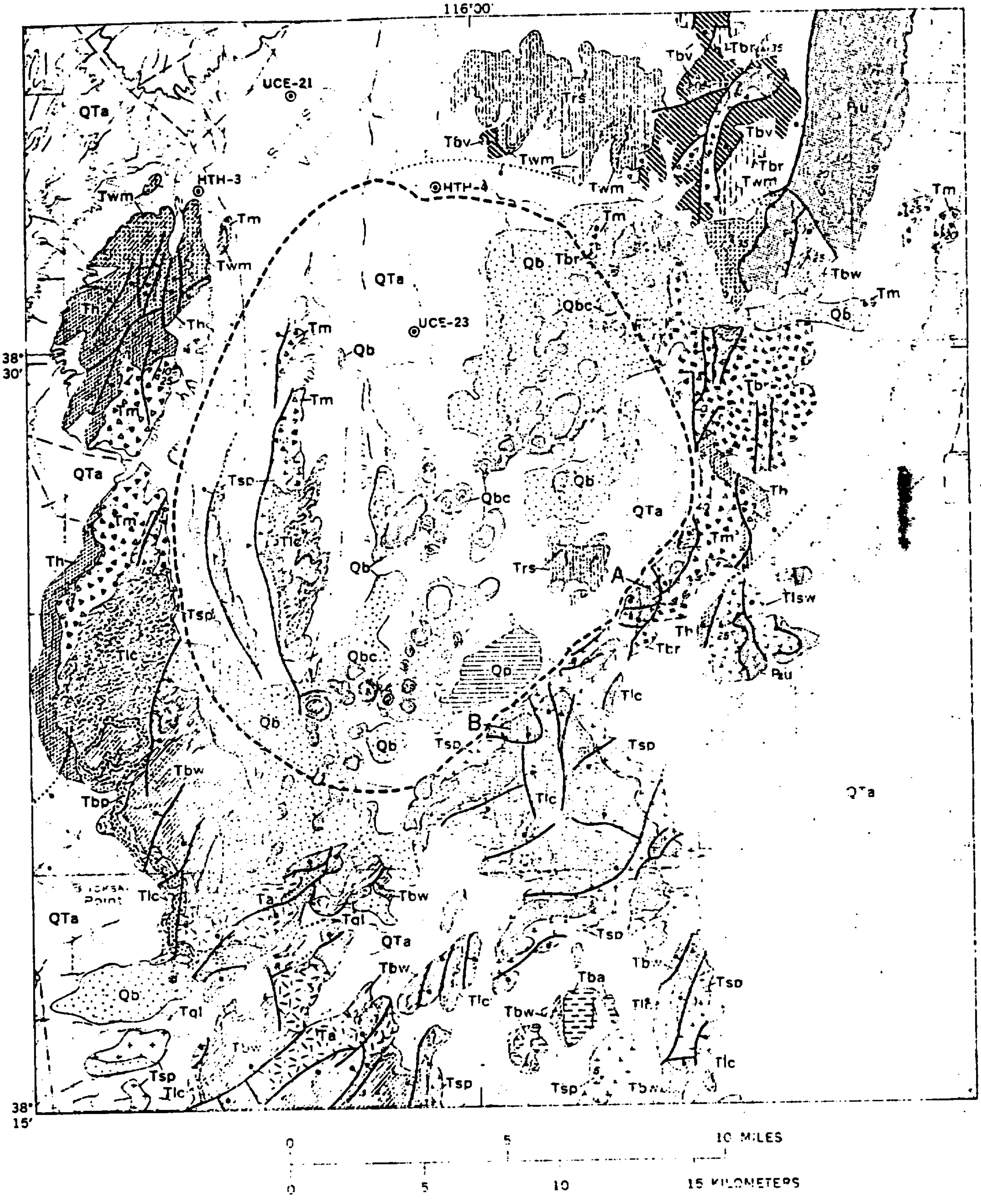
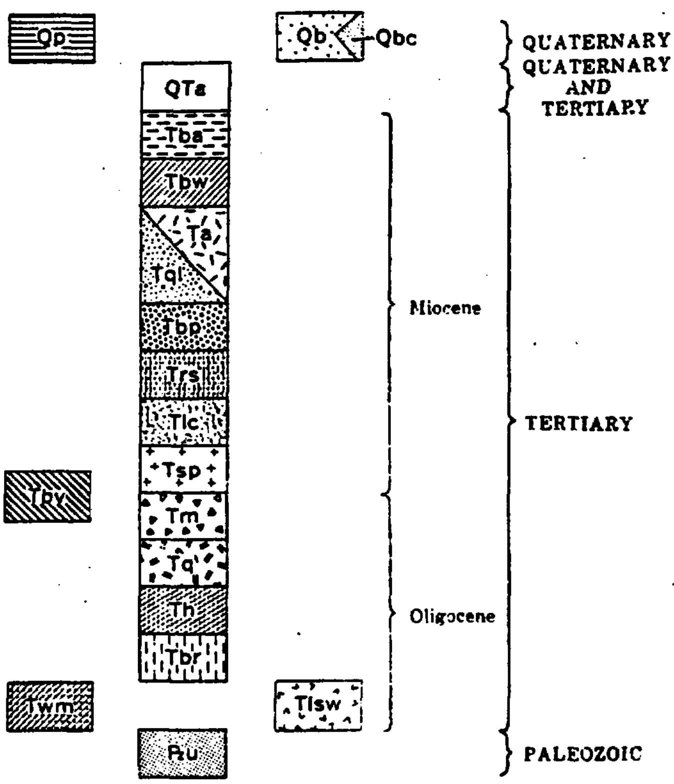


Figure 3.–Geologic map of the Lunar Lake area. Base from U.S. Geological Survey quadrangle maps, 1:250,000 (Tonopah, 1956–62, and Lund, 1956–70).

CORRELATION OF MAP UNITS



LIST OF MAP UNITS

Qp — **Playa deposits** (Quaternary)

Basalt (Quaternary)

Qb — **Lava flows**

Qbc — **Cinder cones**

QTa — **Alluvium and colluvium** (Quaternary and Tertiary)

Tba — **Basaltic andesite** (Miocene)

Tbw — **"Granite-weathering tuff," tuff of Black Beauty Mesa, and tuff of Buckwheat Rim** (Miocene)

Intermediate lavas (Miocene)

Ta — **Andesite**

Tql — **Quartz latite**

Tbp — **Tuff of Buckskin Point** (Miocene)

Trs — **Rhyolite of Big Sand Springs Valley** (Miocene)

Tlc — **Tuff of Lunar Cuesta** (Miocene)

Tsp — **Shingle Pass Tuff** (Miocene)

Tm — **Monotony Tuff** (Oligocene)

Tbv — **Tuff of Big Round Valley** (Miocene and Oligocene) —Age relations uncertain

Tq — **Quartz latite lava** (Oligocene)

Th — **Tuffs of Palisade and Halligan Mesas** (Oligocene)

Tbr — **Tuff of Black Rock Summit** (Oligocene)

Tlsw — **Landslipped welded tuff** (Oligocene)

Twm — **Tuff of Williams Ridge and Morey Peak** (Oligocene)

Pzu — **Paleozoic rocks**

Contact

Fault—Dotted where concealed. Bar and ball on downthrown side

Gravity slide fault—Sawteeth on upper plate

20 **Strike and dip of beds**

20 **Strike and dip of compaction foliation**

Buried boundary of Lunar Lake caldera

UCE-23 **Drill hole**

cooling units) as much as 500 ft (150 m) thick that consists of cliff-forming, moderately welded, mafic-poor rhyolite at the base (one-third of unit) and slope-forming, partially welded mafic-rich quartz latite and rhyodacite (table 1, sample 2) at the top (two-thirds of unit). The tuff of Buckwheat Rim is magnetically reversed. On the southwest flank of Citadel Mountain and on Black Beauty Mesa the tuff of Buckwheat Rim is overlain, without an obvious cooling break, by stratified quartz latitic vent breccia having the same phenocryst mineralogy as the underlying welded tuff.

On Black Beauty Mesa (fig. 3) and on local areas to the south and east, the tuff of Buckwheat Rim is overlain by two thin simple cooling units of rhyodacitic densely welded tuff called the tuff of Black Beauty Mesa. These units are indistinguishable in outcrop and in thin section from the basal rhyodacitic tuff of Buckskin Point, but the tuff of Black Beauty Mesa is magnetically normal.

The "granite-weathering tuff" disconformably overlies the tuff of Black Beauty Mesa and other units in the Lunar Lake area. It is quartz-rich rhyolite and everywhere is characterized by chatoyant alkali feldspar. It is very similar to the tuff of White Blotch Spring in the northern Nellis Air Force Base Bombing and Gunnery Range (Ekren and others, 1971) and we presume that it was vented from a center in or near the bombing and gunnery range.

The tuff of Lunar Cuesta

The tuff of Lunar Cuesta is a multiple-flow simple cooling unit of quartz latite; it is typically densely welded, devitrified,

Table 1.—*Chemical analyses, in percent, of selected volcanic rocks in and around the Lunar Lake caldera*

[Values for sample 11, for SiO_2 and Al_2O_3 by X-ray fluorescence, analyst L. S. Wahlberg; total Fe, MgO, and CaO by atomic absorption, analyst Wayne Mountjoy; Na_2O and K_2O by flame photometer, analyst Wayne Mountjoy; TiO_2 by tiron colorimetry, analyst Claude Huffman, Jr.; P_2O_5 obtained colorimetrically, analyst G. D. Shipley. Values for all other samples by rapid rock analysis; analysts S. D. Botts, P. L. D. Elmore, G. W. Chloe, J. Kelsey, H. Smith, Lowell Artis, and J. L. Glenn]

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Laboratory No.	W178-668	W172-306	W172-302	W172-305	W178-672	W178-676	W178-678	W178-671	W172-139	W172-140	D150-346	W172-143	W172-145	W175-163	W175-164
Field No.	W-68-BE-18	RS-7E	RS-6	RS-5A	WPC-5	SPC-8	RC-9	RC-3	NPC-33	NPC-26	BE-281-66	NPC-2	NPC-15	70FB-83	70FB-84
SiO_2	73.0	65.2	50.00	65.5	69.8	72.2	69.2	68.0	73.2	74.7	75.1	64.5	71.4	77.6	67.8
Al_2O_3	12.9	15.7	17.70	14.4	14.3	12.8	15.3	15.3	13.9	12.2	13.5	15.4	11.1	12.5	15.2
Fe_2O_3	.70	3.9	7.80	3.2	1.6	1.1	1.7	3.2	1.1	.84	1.25	3.7	1.5	.72	1.5
FeO	.78	.60	2.50	2.0	.40	.48	.70	.50	.44	.24		.11	.28	.16	1.9
MgO	.17	1.4	1.00	1.1	.55	.48	1.9	1.1	.37	.37	.37	1.4	.54	.25	1.2
CaO	.82	1.0	8.80	3.3	2.0	2.6	3.1	3.7	1.6	1.6	1.44	3.7	2.0	1.3	3.3
Na_2O	3.5	2.6	2.50	3.2	2.9	3.1	3.2	3.0	3.3	3.0	2.98	2.4	2.8	2.9	2.6
K_2O	5.1	3.6	1.10	3.9	4.6	4.8	1.2	3.5	4.7	4.5	4.41	3.2	1.7	4.6	1.1
H_2O+	.49	.80	2.22	1.5	2.9	.43	1.9	1.2	.84	1.0	......	1.3	1.3	.38	1.9
H_2O-	.19	1.2		.30	.88	.38	.78	1.0	.15	.35	......	2.2	.84	.17	.22
TiO_2	.04	.62	1.90	.93	.20	.15	.26	.42	.20	.13	.21	.64	.27	.06	.55
P_2O_5	....	.22	.69	.38	.08	.06	.10	.11	.08	.08	.19	.15	.03	.02	.13
MnO	.04	.04	.16	.12	.09	.06	.05	.10	.03	.04	......	.03	.03	.00	.00
Co_2	.08	.22	.31	<.05	.02	.49	.08	.04	<.05	.28	......	<.05	<.05	.00	.00
Total	99.81	99.90	99.80	100.03	100.32	99.13	100.07	101.29	99.96	99.34	99.35	99.16	99.84	100.66	100.10

1. Rhyolite of Big Sand Springs Valley at lat 38°27′ N., long 115°37′ W. 3.8 percent phenocrysts: quartz 30.9, alkali feldspar 49.1, plagioclase 18.2, biotite 1.8, hornblende tr.
2. Tuff of Buckwheat Rim at lat 38°19′ N., long 116°7 1/2′ W. 40.8 percent phenocrysts: quartz 16.8, alkali feldspar 0.7, plagioclase 49.9, biotite 6.8, opaque minerals 2.1.
3. Andesite lava at lat 38°19′ N., long 116°7 1/2′ W. 25.1 percent phenocrysts: plagioclase 75.7, biotite 1.8, opaque minerals 5.5, clinopyroxene 16.1, hornblende 0.5.
4. Tuff of Buckskin Point at lat 38°17′ N., long 116°7 1/2′ W. 13.5 percent phenocrysts: quartz 4.2, alkali feldspar 0.5, plagioclase 62.1, biotite 8.4, opaque minerals 1.1, hornblende 8.4, pyroxene 1.1, altered mafic minerals 2.1, holes in thin section 6.3.
5. Tuff of Lunar Cuesta at lat 38°24′ N., long 116°11′ W. Modes not counted for samples 5, 6, and 7. Modes of tuff of Lunar Cuesta sampled elsewhere in central Nevada give the following ranges or averages: 20–35 percent phenocrysts: quartz 12–20, alkali feldspar 7–15, plagioclase 45–75, biotite 10–15, hornblende 3, opaque minerals 2.
6. Tuff of Lunar Cuesta at lat 38°14′ N., long 116°3′ W.
7. Tuff of Lunar Cuesta at lat 38°27 1/2′ N., long 116°3′ W.
8. Monotony Tuff at lat 38°28′ N., long 116°7′ W. Mode count for several samples. 25–55 percent phenocrysts: quartz 10–22, alkali feldspar 5–12, plagioclase 46–64, biotite 10–22, hornblende tr–7, clinopyroxene 1–5, orthopyroxene tr, opaque minerals 1–2.
9. Tuff of Palisade Mesa at lat 38°29 1/2′ N., long 116°8′ W. 36.3 percent phenocrysts: quartz 31.4, alkali feldspar 28.1, plagioclase 32.6, biotite 5.1, opaque minerals 1.7, hornblende 1.1.
10. Tuff of Halligan Mesa at lat 38°31′ N., long 116°8′ W. 29.0 percent phenocrysts: quartz 21.1, alkali feldspar 20.5, plagioclase 11.2, biotite 8.8, opaque minerals 0.8, hornblende 2.1.
11. Tuff of Black Rock Summit at lat 38°29 1/2′ N., long 115°51′ W. Mode count for several samples: 12–25 percent phenocrysts: quartz 8–25, alkali feldspar 0–3, plagioclase 65–70, biotite 7–10, hornblende 0–3, clinopyroxene tr, opaque minerals tr–3.
12. Tuff of Williams Ridge and Morey Peak at lat 38°33′ N., long 116°8′ W. 21.4 percent phenocrysts: quartz 27.3, alkali feldspar 1.5, plagioclase 53.4, biotite 6.5, opaque minerals 0.7, hornblende 2.4, altered mafic minerals 7.9, holes in thin section 0.4.
13. Tuff of Williams Ridge and Morey Peak at lat 38°32′ N., long 116°8′ W. 20.2 percent phenocrysts: quartz 27.9, alkali feldspar 21.2, plagioclase 40.4, biotite 1.7, opaque minerals 0.3, hornblende 3.3, holes in thin section 1.[illegible]
14. Windous Butte Formation (tuff) at lat 38°17′ N., long 116°20′ W. 38.9 percent phenocrysts: quartz 10.8, alkali feldspar 18.9, plagioclase [illegible], biotite [illegible], opaque minerals 1.[illegible]
15. Windous Butte Formation (tuff) at lat 38°15′ N., long 116°20′ W. 29.9 percent phenocrysts: quartz 19.4, plagioclase 52.9, biotite 15.2, hornblende 12.2, orthopyroxene 0.7.

and bluish gray, and weathers to brown and buff. In most localities it contains abundant red lithic fragments of Shingle Pass Tuff in its nonwelded to partially welded basal part. It contains 20–35 percent phenocrysts of which quartz constitutes 12–20 percent, alkali feldspar 7–15 percent, plagioclase 45–75 percent, biotite 10–15 percent, hornblende 3 percent, and opaques 2 percent (table 1, samples 5–7). The tuff is everywhere magnetically reversed.

The conclusion that the tuff of Lunar Cuesta was erupted from the Lunar Lake area and that its eruption gave rise to the Lunar Lake caldera is based on three lines of evidence: (1) The thickest known sections of the tuff are adjacent to the Lunar Lake caldera, (2) rhyolite of Big Sand Springs Valley, which is chemically similar to the tuff (fig. 4), rest directly on the tuff of Lunar Cuesta in two sharp scallops (locs. A and B, fig. 3) along the southeastern wall (these rhyolite-scallop-tuff relationships would be extremely unlikely if the caldera formed as a result of either earlier or later tuff eruptions), and (3) the Lunar Lake caldera lies near the center of the area of distribution of the tuff (fig. 5).

The "inferred original" distribution shown in figure 5 encompasses all areas where the tuff is preserved in situ or where its former presence is indicated by erosional rubble. The inferred distribution includes areas that have been either deeply eroded or deeply buried but can reasonably be inferred to have been covered by the tuff. For example, the extension of the tuff eastward into Railroad Valley is recognized on the basis of the large thickness preserved along the west flank of the valley. The extension south of the southern Pancake Range beyond the southernmost outcrops is recognized on the basis of evidence there of extensive removal by erosion prior to the eruption of younger tuffs. Such removal is indicated along the east flank of the Pancake Range in the Reveille quadrangle (Ekren, Rogers, and Dixon,

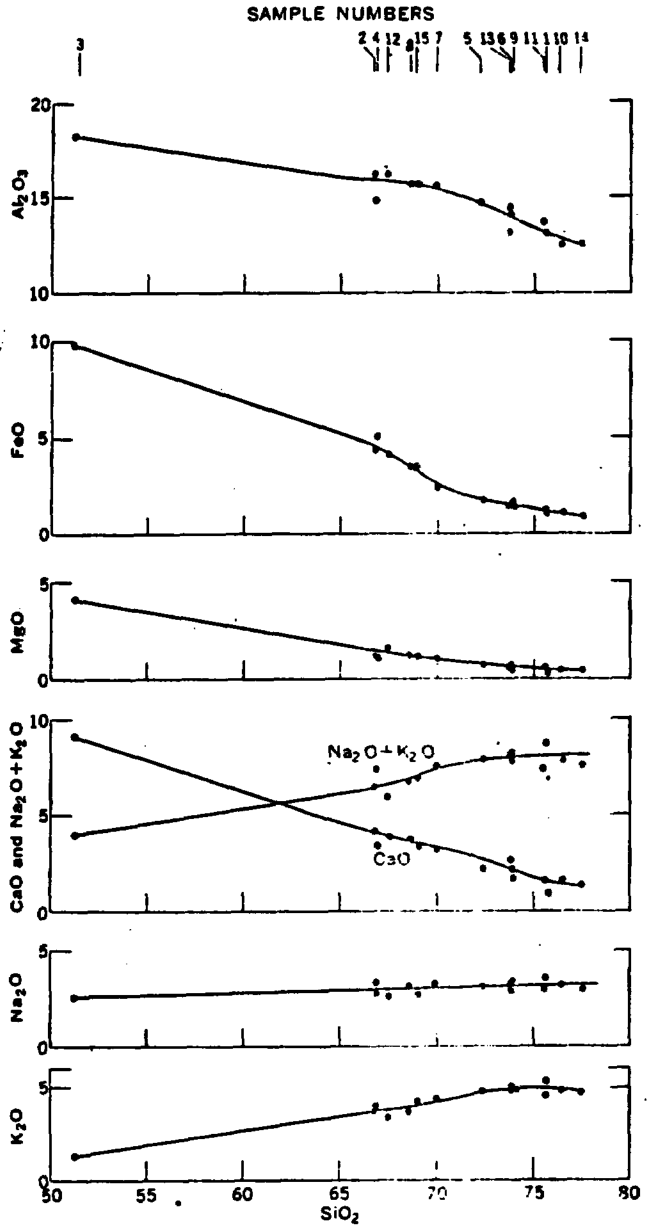


Figure 4.—Variation diagrams for samples listed in table 1. All analyses in weight percent recalculated (minus H_2O and CO_2) to 100 percent.

1974) where the tuff thins from 200+ ft (61+ m) to 0 in a distance of less than 3 mi (4.8 km), and there is no indication of a "lap out" against old topography nor a decrease in the degree of welding. If we use the inferred boundaries shown in figure 5 and assume an average thickness of 200 ft (61 m), the tuff had a volume of approximately 90 mi^3 (370 km^3) and covered nearly 3,000 mi^2 (7,770 km^2).

The tuff of Lunar Cuesta is about 25 m.y. old, on the basis of K-Ar analyses of the tuff itself and of samples from overlying and underlying strata. Samples of tuff of Lunar Cuesta exposed on the wall east of Lunar Lake were analyzed by R. F. Marvin, who reported (written commun., 1970) dates of 25.5±0.8 m.y. on biotite and 22.5±0.7 m.y. on sanidine. The Shingle Pass Tuff, exposed beneath the tuff of Lunar Cuesta on Palisade Mesa, also yielded dates of 25.5±0.8 m.y. on biotite and 22.5±0.7 m.y. on sanidine. The rhyolite of Big Sand Springs Valley above the tuff of Lunar Cuesta yielded a date of 25.8±3 m.y. on a whole-rock sample; and the tuff of Buckskin Point gave a date of 25.4±1.3 m.y. on biotite.

Chemical variations

Chemical analyses of the principal rocks in the Lunar Lake caldera and the central Nevada caldron complex are shown in table 1, and plots of major oxides against percentage of silica are shown in figure 4. These analyses indicate that no systematic chemical variations took place as eruptions proceeded, starting about 30.5 m.y. ago (approximate age of the Windous Butte) and ending about 25 m.y. ago (approximate age of the tuff of Buckskin Point). The youngest rocks are the most basic as well as the most silicic of the suite (fig. 4). The available analyses indicate that the Windous Butte shows more extreme chemical variations within a single cooling unit than any of the other principal units in the area (compare samples 14 and 15, table 1 and fig. 4). The major oxides of the contrasting lithologies in the Windous Butte, however, all plot neatly along the curves defined by the major oxides of the younger rocks (fig. 4). The Windous Butte is characterized by a mafic-poor rhyolitic base (sample 15) and a mafic-rich quartz latitic top (sample 14). This trend is, in fact, shown by most of the ash-flow tuff cooling units in the Lunar Lake area.

The alkali-lime index for the tuffs and lavas of the Lunar Lake area is approximately 62 (fig. 4). This index is well within the calc-alkalic field of Peacock (1931).

Noble (1972) indicated that most of the lower Miocene volcanic rocks of the Great Basin, particularly those 25–22 m.y. in age, closely resemble the highly differentiated rhyolites found in bimodal basalt-rhyolite provinces. The Shingle Pass Tuff, which separates the younger rocks associated with the Lunar Lake caldera from older rocks of the central Nevada caldron complex, was cited as an example of this type of volcanism. We concur in recognition of the distinctive features of the Shingle Pass Tuff, as well as of the Bates Mountain Tuff and New Pass Tuff, also cited by Noble as examples of "early Miocene silicic volcanic rocks that represent a new pulse of magmatism rather than a continuation of Oligocene calc-alkalic volcanism * * *." Of interest is the close bracketing of the Shingle Pass Tuff in the report area by calc-alkalic volcanism that displays no obvious changes in chemistry or mineralogy.

STRUCTURE AND GEOLOGIC HISTORY OF THE LUNAR LAKE CALDERA

The Lunar Lake caldera is expressed as a partially enclosed topographic basin bounded on the east by an arcuate ridge, The Wall (fig. 2), on the west by Palisade and Halligan Mesas,

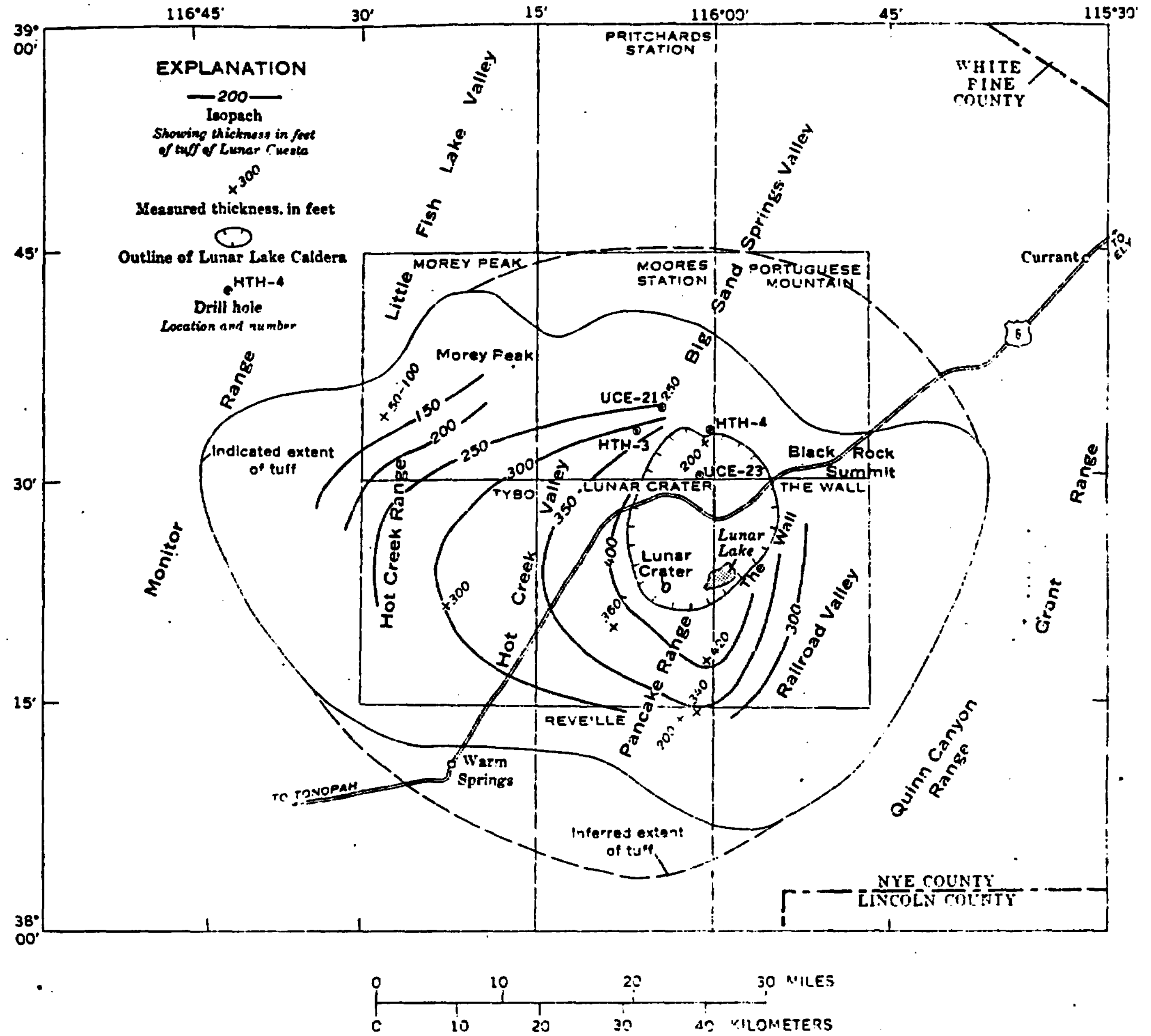


Figure 5.—Sketch map showing quadrangles mapped in central Nevada and showing indicated and inferred original extent of tuff of Lunar Cuesta.

and on the south by Citadel Mountain. On the north side the basin is contiguous with Big Sand Springs Valley. The caldera is best observed from high points along The Wall where a view to the west gives the impression of peering into an enormous kettle filled with bubbling (numerous extinct cinder cones) viscous black liquid (basalt lavas). The boundary of the caldera is well defined only on the eastern and southeastern sides along The Wall. The location of the northern boundary is based on drill-hole and reflection seismic data. The northern boundary was placed south of drill hole HTH-4 (fig. 3) because this drill hole did not penetrate either the tuff of Lunar Cuesta or the Monotony Tuff, which was nearly 1,000 ft (305 m) thick in drill hole UCE-23. Drill hole HTH-4, however, cut several fault zones; drilling operations were extremely difficult and there was a tremendous loss of drilling fluid. Only two cores were obtained, one from 1,166 ft (355 m) and the other from 6,030 ft (1,840 m). Lithologic correlations (Ekren, Hinrichs, and others, 1974) were made principally on the basis of cuttings and geophysical logs. The possibility exists, therefore, that both the tuff of Lunar Cuesta and the Monotony Tuff were faulted out in this drill hole, and it is problematic whether the caldera wall lies north or south of, or, perhaps within the drill-hole location. The occurrence of rhyolite of Big Sand Springs Valley between depths of about 200 and 800 ft (60 and 240 m) indicates that a major fault, probably east-trending, lies between the drill hole and the large rhyolite mass exposed to the northeast (fig. 3). This fault, if it is east-trending as postulated in figure 3, could mark the main caldera boundary or a relatively minor secondary ring-fracture zone.

The presumed location of the caldera boundary between drill holes UCE-21 and UCE-23 is inferred from a reflection seismic survey run on a traverse line southeastward from UCE-21 toward UCE-23. The boundary was placed at a point on the traverse about 2.5 mi (4 km) southeast of UCE-21 at the southeast edge of a zone of no reflections, which was interpreted as a structural high between the Lunar Lake caldera and a deeper, older caldron—the "outer Hot Creek Valley caldron" (Ekren, Hinrichs, and others, 1974). The boundaries of this older caldron are not shown in figure 2.

There is no present-day indication of western and southwestern boundaries to the caldera. This could be due to an original lack of caldera boundary faults along the western half of the Lunar Lake depression. Initially, the western half of the "caldera" simply sagged toward the center of the structure. P. P. Orkild, who mapped part of the Lunar Lake area in 1966, suggested that this type of volcanic depression be termed a "trapdoor caldron" (written commun., 1972). On the other hand, the lack of a discernible boundary today may have resulted from basin-range faulting which effectively lowered the outer rim of the caldera (Palisade Mesa) and raised the interior (Little Lunar Cuesta). We favor the "trapdoor" interpretation. That a structural break of some kind exists in this area is clearly indicated by the marked contrast between the nearly flat-lying broad mesas west of Little Lunar Cuesta and the broad depression broken only by the subdued east-tilted cuestas and the abundant cinder cones east of Palisade Mesa. That this structural break may be arcuate in form is suggested by the curvilinear nature of the Little Lunar Cuesta fault block (fig. 3).

The caldera, as just defined, is semicircular in plan, measuring about 11 mi (18 km) east to west, and 13 mi (21 km) north to south. Owing to the effect of postcaldera basin-and-range faulting, the amount of vertical displacement is difficult to determine in the caldera. Drill hole UCE-23, for example, penetrated the tuff of Lunar Cuesta at a depth of 1,200 ft (365 m) and an elevation of 4,600 ft (1,400 m), which is nearly 2,000 ft (610 m) lower than the top of the tuff in the nearest outcrop outside the caldera. This 2,000 ft (610 m) of structural relief may be due partly to caldera displacement and partly to basin-and-range faulting, or it may constitute the structural relief remaining after the drill-hole area was relatively uplifted by basin-and-range faulting. The first possibility seems more plausible, however, and a minimum of about 1,000 ft (305 m) and a maximum of about 2,000 ft (610 m) of displacement for the central part of the Lunar Lake caldera probably are a reasonable estimate.

Drill hole UCE-23 cut a basalt flow intercalated in alluvium at a depth of 140–175 ft (43–53 m), continued in alluvium to a depth of about 1,100 ft (335 m); from 1,100 ft (335 m) to 1,200 ft (365 m) it cut 100 ft (30 m) of bedded tuff and debris; it penetrated intensely fractured (probably faulted) tuff of Lunar Cuesta between 1,200 and 1,240 ft (365 and 380 m). The total thickness of the tuff of Lunar Cuesta cut by the drill hole, determined from cuttings and geophysical logs, is 200–350 ft (61–105 m), which indicates that the tuff is no thicker in the caldera than outside; conceivably it is thinner. Eruption of the tuff of Lunar Cuesta, therefore, apparently was completed before caldera subsidence began. In this regard, the Lunar Lake caldera is similar to the Valles caldera of New Mexico where the last erupted tuff is no thicker inside the caldera than outside (Smith and Bailey, 1968), and it differs from the Timber Mountain caldera in southern Nevada (Byers and others, 1969) and many other calderas where subsidence and tuff eruptions occurred concurrently.

The relationship of the Lunar Lake caldera with older caldrons within the large multiple-caldron complex (fig. 2) indicates that it was the last caldera to form and, although nested within the central complex, its boundaries overlap and partly coincide with boundaries of older caldrons. The proximity of the buried northern wall to the wall of the "outer Hot Creek Valley caldron" (Ekren, Hinrichs, and others, 1974), as indicated by a reflection seismic survey, has been previously described. That an earlier caldron wall existed approximately at the present-day well-defined eastern wall of the Lunar Lake caldera is strongly suggested by the unconformable relationships of the Monotony Tuff where it rides up against a northeast-trending topographic high formed of pre-Monotony quartz latite lava (loc. A, fig. 3) and against the tuff of Black Rock Summit and the tuff of Palisade Mesa (figs. 3, 5) in exposures south of Black Rock Summit. This older wall could have formed during a period of subsidence related to the extrusion of the tuff of Palisade Mesa or the tuff of Halligan Mesa, or both. If this is so, the data from drill hole UCE-23 indicate that younger rocks, principally the voluminous Monotony Tuff, filled the caldera prior to the eruption of the tuff of Lunar Cuesta. The possibility also exists that the drill hole lies within the caldera which formed as a result of Monotony Tuff eruptions.

On Palisade Mesa, the northeast-trending fault that extends through the mesa (against which the Shingle Pass Tuff was deposited and over which the tuff of Lunar Cuesta was deposited) is inferred to be the western wall or boundary of the caldera that formed as a result of the extrusions of the widespread Monotony Tuff. This caldera is truncated by the Lunar Lake caldera in the vicinity of Lunar Cuesta, and its northern boundary is concealed within the Lunar Lake caldera. Farther south, in the Reveille quadrangle (Ekren, Rogers, and Dixon, 1974), the caldera is cut by a system of northwest-trending left-lateral faults, and the southwestern part of the caldera is strung out as a series of fault slices along splays of the left-lateral system (Ekren, Rogers, and Dixon, 1974).

CHRONOLOGY OF VOLCANIC EVENTS

1. Tuff eruptions and the development of a multiple-caldera complex started in central Nevada about 30–31 m.y. ago with the eruption of the Windous Butte Formation and related rocks.
2. For a period of 3–4 m.y. tuff eruptions continued and numerous calderas were formed within the caldron complex. About 25 m.y. ago the tuff of Lunar Cuesta was erupted from vents located in the southeastern part of the caldron complex. The eruption of this tuff, having a volume of about 90 mi^3 (375 km^3), resulted in the collapse of a semicircular area about 12 mi (19 km) in diameter and possibly 1,000–2,000 ft (305–610 m) deep—the herein-named Lunar Lake caldera.
3. Rhyolite lavas were erupted from the northern and southeastern ring-fracture zones of the Lunar Lake caldera.
4. The tuff of Buckskin Point, quartz latite and andesitic lavas, and the tuffs of Buckwheat Rim and Black Beauty Mesa were erupted from fissures in the vicinity of Citadel Mountain. These eruptions did not result in caldera development.
5. The caldera was broken by basin-and-range faults, and two fault blocks were uplifted relative to the remainder of the caldera to form Lunar and Little Lunar Cuestas.
6. In Quaternary time basalt lavas and pyroclastic debris were erupted from a northeast-trending fissure system that extends through the Lunar Lake caldera and coincides, in part, with the old fissure system that extends through the Citadel Mountain area.

REFERENCES CITED

Anderson, R. E., 1970, Ash-flow tuffs of Precambrian age in southeast Missouri: Missouri Div. Geol. Survey and Water Resources Rept. Inv. 46, 50 p.

Byers, F. M., Jr., Carr, W. J., and Orkild, P. P., 1969, Volcano-tectonic history of southwestern Nevada caldera complex, U.S.A. [abs.] *in* Symposium on volcanoes and their roots: Oxford, England, Internat. Assoc. Volcanology and Chemistry of the Earth's Interior, v. abs., p. 84–86.

Cook, E. F., 1965, Stratigraphy of Tertiary volcanic rocks in eastern Nevada: Nevada Bur. Mines Rept. 11, 61 p.

Ekren, E. B., Anderson, R. E., Rogers, C. L., and Noble, D. C., 1971, Geology of northern Nellis Air Force Base Bombing and Gunnery Range, Nye County, Nevada: U.S. Geol. Survey Prof. Paper 651, 91 p.

Ekren, E. B., Bath, G. D., Dixon, G. L., Healey, D. L., and Quinlivan W. D., 1974, Tertiary history of Little Fish Lake Valley, Ny County, Nevada, and implications as to the origin of the Grea Basin: U.S. Geol. Survey Jour. Research, v. 2, no. 1, p. 105–118.

Ekren, E. B., Hinrichs, E. N., and Dixon, G. L., 1973, Geologic map o The Wall quadrangle, Nye County, Nevada: U.S. Geol. Survey Misc Geol. Inv. Map I-719, scale 1:48,000.

Ekren, E. B., Hinrichs, E. N., Quinlivan, W. D., and Hoover, D. L 1974, Geologic map of the Moores Station quadrangle, Ny County, Nevada: U.S. Geol. Survey Misc. Geol. Inv. Map I-756 scale 1:48,000.

Ekren, E. B., Rogers, C. L., and Dixon, G. L., 1974, Geologic an Bouguer gravity map of the Reveille quadrangle, Nye County Nevada: U.S. Geol. Survey Misc. Geol. Inv. Map I-806, scal 1:48,000. (In press.)

Grommé, C. S., McKee, E. H., and Blake, M. C., Jr., 1972, Paleomagne tic correlations and potassium-argon dating of middle Tertiary ash flow sheets in the eastern Great Basin, Nevada and Utah: Geol. Soc America Bull., v. 83, p. 1619–1638.

Hoover, D. L., 1964, Flow structures in a welded tuff, Nye County Nevada [abs.], *in* Abstracts for 1963: Geol. Soc. America Spec Paper 76, p. 83.

Noble, D. C., 1972, Some observations on the Cenozoic volcano *tectonic evolution of the Great Basin, western United States*: Eart and Planetary Sci. Letters, v. 17, p. 142–150.

Peacock, M. A., 1931, Classification of igneous rock series: Jour Geology, v. 39, no. 1, p. 54–67.

Quinlivan, W. D., and Rogers, C. L., 1974, Geologic map of the Tyb quadrangle, Nye County, Nevada: U.S. Geol. Survey Misc. Geol Inv Map I-821, scale 1:48,000. (In press.)

Quinlivan, W. D., Rogers, C. L., and Dodge, H. W., Jr., 1974, Geologi map of the Portuguese Mountain quadrangle, Nye County, Nevada U.S. Geol. Survey Misc. Geol. Inv. Map I-804, scale 1:48,000. (I press.)

Sargent, K. A., and Houser, F. N., 1970, The Shingle Pass Tuff o central Nevada: Geol. Soc. America Abs. with Program (Cordilleran sec.), v. 2, no. 2, p. 140–141.

Scott, D. H., and Trask, N. J., 1971, Geology of the Lunar Crate volcanic field, Nye County, Nevada: U.S. Geol. Survey Prof. Pape 599-I, 22 p.

Smith, R. L., and Bailey, R. A., 1968, Resurgent cauldrons, *in* Coats, R R., Hay, R. L., and Anderson, C. A., eds., Studies in volcanology memoir in honor of Howel Williams: Geol. Soc. America Mem. 116 p. 613–662.

Snyder, R. P., Ekren, E. B., and Dixon, G. L., 1972, Geologic map o the Lunar Crater quadrangle, Nye County, Nevada: U.S. Geol. Sur vey Misc. Geol. Inv. Map I-700, scale 1:48,000.

U.S. Geological Survey, 1970, Geological Survey research 1970: U.S Geol. Survey Prof. Paper 700-A, 426 p.

Walker, G. W., and Swanson, D. A., 1968, Laminar flowage in Pliocene soda rhyolite ash-flow tuff, Lake and Harney Countie Oregon, *in* Geological Survey research 1968: U.S. Geol. Survey Pro Paper 600-B, p. B37–B47.