Rocks, Structure, and Geologic History of Steamboat Springs Thermal Area, Washoe County Nevada

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By DONALD E. WHITE, G. A. THOMPSON, *and* C. H. SANDBERG

GEOLOGY AND GEOCHEMISTRY OF THE STEAMBOAT SPRINGS AREA, NEVADA

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ROCKS, STRUCTURE, AND GEOLOGIC HISTORY OF STEAMBOAT SPRINGS THERMAL AREA, WASHOE COUNTY, NEVADA

By DONALD E. WHITE, G. A. THOMPSON, and C. H. SANDBERG

ABSTRACT

Steamboat Springs has been the site of intense thermal activity through all or most of the Quaternary. The springs emerge near the northeast end of Steamboat Hills, a northeast-trending range transverse to the dominant regional trends; the hills are near the axis of a chain of basins that lies between the north-trending Virginia and Carson Ranges.

For nearly a hundred years the springs have been noted for transport and deposition of mercury and antimony, as well as other ore and gangue minerals. This report, one of a series, concerns the general geology of a small area of current thermal activity that also contains evidence of very extensive activity in the past.

Pre-Tertiary metamorphic and granitic rocks form the basement. Middle and late Tertiary volcanic rocks are abundant in the surrounding area but are notably scarce in the thermal area, where the most widespread Tertiary volcanic rock is a characteristic soda trachyte of the Alta Formation. Dikes and extrusive rocks of the younger Kate Peak Formation also occur, particularly at depth below younger rocks. A basaltic andesite flow of the Lousetown Formation and possibly a concealed shallow intrusion of the Steamboat Hills Rhyolite are early Quaternary in age and constitute the latest volcanic outbreaks that approached the surface.

Experimental geochemistry on the granite system and proportions of feldspars to quartz in the norms of the analyzed rocks of the Steamboat Hills Rhyolite indicate that the magma evolved during the late stages of the total volcanic activity in an environment where the water-vapor pressure was probably between 2,000 and 3,000 bars, the water content was 6 to 8 percent, and the temperature immediately prior to eruption was close to 675°C. A minimum depth of burial of 6 to 9 km for the magma chamber is indicated from these data.

A complex history of erosion alternating with alluviation throughout the Quaternary is revealed from the surface mapping and subsurface drill-hole data. In general, the hot-spring deposits were formed as local facies of the sedimentary formations during periods of alluviation, each of which may correlate with a Sierran glaciation. The oldest hot-spring deposits antedate the local lava flows of the Lousetown Formation, and thermal activity may have been continuous for most or all of the Quaternary. The record is reasonably good in indicating continuous thermal activity since a glaciation correlated with the Sherwin, or third youngest stage of Pleistocene age. During periods of deep erosion and low water table, springs did not always emerge at the surface, but for at least parts of these periods thermal waters continued to circulate below the surface, exsolving H_2S that oxidized to H_2SO_4 and attacked surficial rocks.

The hot-spring deposits consist almost entirely of siliceous sinter and very small amounts of calcium carbonate. The large accumulations around structurally favorable outlets are called hot-spring terraces. Sinter deposits found at Steamboat Springs are classified genetically into two major groups and nine main subdivisions. All primary or single-stage types consist of opal. After burial and prolonged contact with hot silica-bearing waters, most of the older spring deposits were reconstituted into chalcedonic sinter of relatively high density. Some chalcedonic sinter contains notable quantities of HgS.

A violent mud-volcano eruption occurred in the northwestern part of the thermal area, probably slightly earlier than the Tahoe Glaciation. This eruption may have been similar to the eruption of Lake City Hot Springs in northeastern California in 1951. The energy for eruption was stored in the upper part of the hydrothermal system, and no new magma was directly involved.

The report includes logs of wells and diamond drill holes that yielded cuttings or core that could be studied in detail. These data have contributed much to our understanding of relations at depth. Veins and hydrothermal mineral assemblages of each drill hole are described. Relict textures are commonly preserved in rocks completely replaced by new hydrothermal minerals; these textures have proved invaluable in recognizing the nature of the original rocks and in reconstructing the geologic history.

Ancestral Steamboat Hills was a topographic and probably also a structural high prior to Kate Peak volcanism. The major structural relief was largely attained prior to the local eruptions of the Lousetown Formation.

Three well-defined systems of faults have been recognized in the thermal area. An east-northeast system is parallel to the axis of Steamboat Hills and is largely but perhaps not entirely restricted to Lousetown lava flows and older rocks; most of this system is antithetic, with downdropped sides toward the structural axis of the hills. Post-Lousetown movement is as much as 100 feet, but pre-Lousetown movement may be considerably greater.

Northwest-striking faults control Pine Basin in the west-central part of the thermal area, and are approximately contemporaneous with the east-northeast system.

The most numerous faults of the thermal area strike nearly north, and many are antithetic. Some of these faults are relatively old but many displace pre-Lake Lahontan alluvium and sinter of middle Pleistocene age and are the youngest faults of the area. No fault displacement is clearly younger than the Lake Lahontan and Recent sediments.

A system of faults of the north-striking group called the Steamboat Springs fault system provides the structural control for the Low and Main Terraces. Although some evidence suggests west-dipping reverse or thrust movement for the system, the favored interpretation is that of east-dipping normal faults. Total movement may exceed 1,000 feet, nearly all of which was earlier than pre-Lousetown pedimentation and later than the Alta and Kate Peak Formations. Fractures cut the opaline hot-spring deposits but movement on the fractures is negligible. Open fissures in the Main Terrace form from enlargement of fractures by acid leaching of opaline sinter, and not by physical separation of the walls as formerly supposed.

Throughout late Tertiary and Quaternary time, the thermal area has been rather delicately balanced between structural uplift and erosion on the one hand and inundation by volcanic products, hot-spring deposits, and alluvium on the other. At least two cycles of deep entrenchment, alluviation, and pedimentation have occurred. The balance between erosion and burial of the thermal area must have resulted at least in part from coincidence, because the local base level for erosion (Steamboat Creek) has been controlled at least since late Tertiary time by an interplay of influences, including subsidence of the basin of Truckee Meadows, uplift of the Virginia Range, and entrenchment of the Truckee River through this range.

The Steamboat thermal area and its deposits exist because of a combination of favorable circumstances. These include a long history of volcanism in the area; a large magma chamber of at least 50 km^3 that has evolved heat, water, and mineral matter for at least 100,000 years; favorable topographic and water-table relations; and a balance between structural uplift and erosion on the one hand and inundation by volcanic products and alluvium on the other, which has favored preservation of evidence of the complex history.

INTRODUCTION

LOCATION

The Steamboat Springs area is in southern Washoe County near the west border of Nevada (fig. 1). The most intense thermal activity at the present time and throughout most of the Quaternary is localized in an area of about 4 square miles (fig. 2) that straddles the common boundary of the Virginia City and Mount Rose quadrangles (Thompson and White, 1964). The largest part of this area is immediately west of Steamboat Creek, a tributary of the Truckee River that heads in Washoe Lake to the south.

The springs emerge near the northeast end of Steamboat Hills, a northeast-trending range transverse to the dominant regional trends; the hills lie near the axis of a chain of basins between the north-trending Virginia and Carson Ranges. These ranges are offshoots of the northwest-trending Sierra Nevada Range, whose main crest lies 20 miles west of the Carson Range at the latitude of the hot springs.

PURPOSE AND SCOPE

Steamboat Springs has provided an opportunity for fundamental research on processes related to ore transport, ore deposition (rev. by White, 1955a), and geothermal processes in general under natural conditions that cannot be duplicated in the laboratory. Spring systems of this type are a phase of volcanism in which the cooling of a magma body of probable batholithic proportions (White, 1957a, p. 1642) is accompanied by separation of a vapor phase at high temperature and pressure. Most studies of ore deposits concern processes that occurred millions of years ago; most studies of igneous rocks concern either volcanic rocks of appreciable age or active volcanism at the earth's surface. Experimental geochemistry has greatly aided investigation of these natural processes, but it is limited to simple chemical systems and rapidly occurring reactions.

The regional geologic setting of Steamboat Springs is presented by Thompson and White (1964). The present report concerns the rocks, structure, and geologic history of the thermal area. Discussion of the thermal activity and geochemistry of the waters and altered rocks is reserved largely for later reports.

FIELDWORK AND ACKNOWLEDGMENTS

Fieldwork was carried on from 1945 to 1952. The thermal area (pls. 1 and 2) was mapped on a scale of 1 inch =250 feet and detailed maps of the spring terraces (reserved for later reports) were mapped on a scale of 1 inch =50 feet. The topographic mapping was done by Robert G. Reeves and Hale C. Tognoni. The detailed geology was mapped by White, assisted at different times by Douglas Baker, William Ebert, Robert Horton, William Reinken, James Scott, R. K. Vassar, and Reeves and Tognoni. Contributions by P. F. Fix during early stages of the study are specially acknowledged.

The geophysical survey conducted by C. H. Sandberg has added greatly to an understanding of the subsurface geology. Results of the gravity surveying have been published separately (Thompson and Sandberg, 1958), and results of all geophysical work are incorporated in this report where particularly pertinent, and are also summarized in a separate section.

Diamond drilling with scientific objectives was carried on from June 1950 to February 1951. Eight holes were drilled to depths ranging from 130 to 684 feet; total depth of the eight holes was 3,307 feet. The success that may be claimed for the whole study is due in large measure to this drilling program, which provided drill-core and physical data concerning the structure, rocks, temperatures, and geochemical relations at depth. Drilling was also done by private interests during the study, and much useful information has been acquired through cooperation with the individuals involved, including B. C. McCabe of Magma Power Co. Special mention should be made of the helpful cooperation given by Mrs. Edna J. Carver,

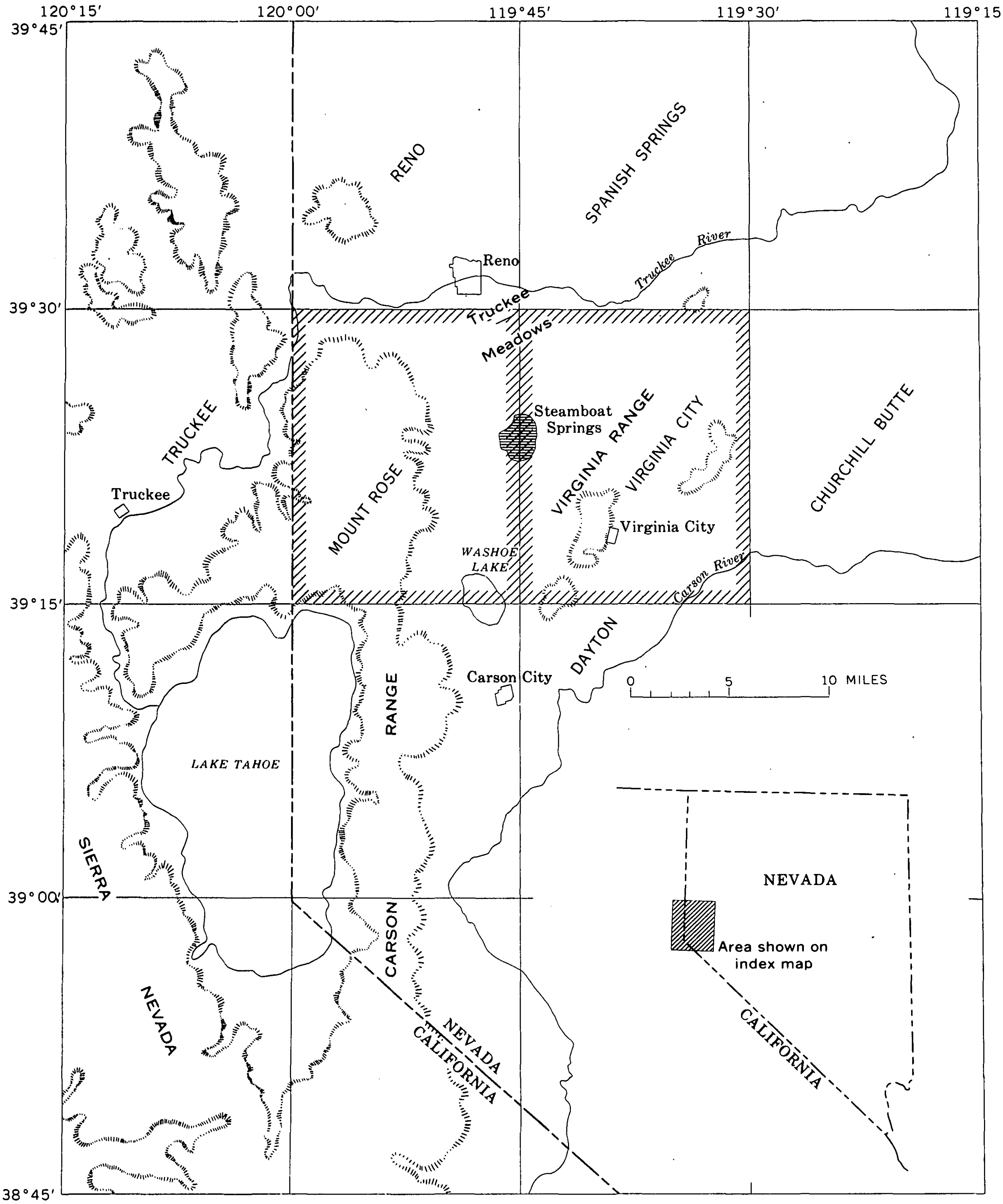

FIGURE 1.—Index map showing location of Steamboat Springs thermal area in relation to the Mount Rose and Virginia City quadrangles and geographic features. Areas outlined by hachures represent mountain ranges higher than 7,000 feet.

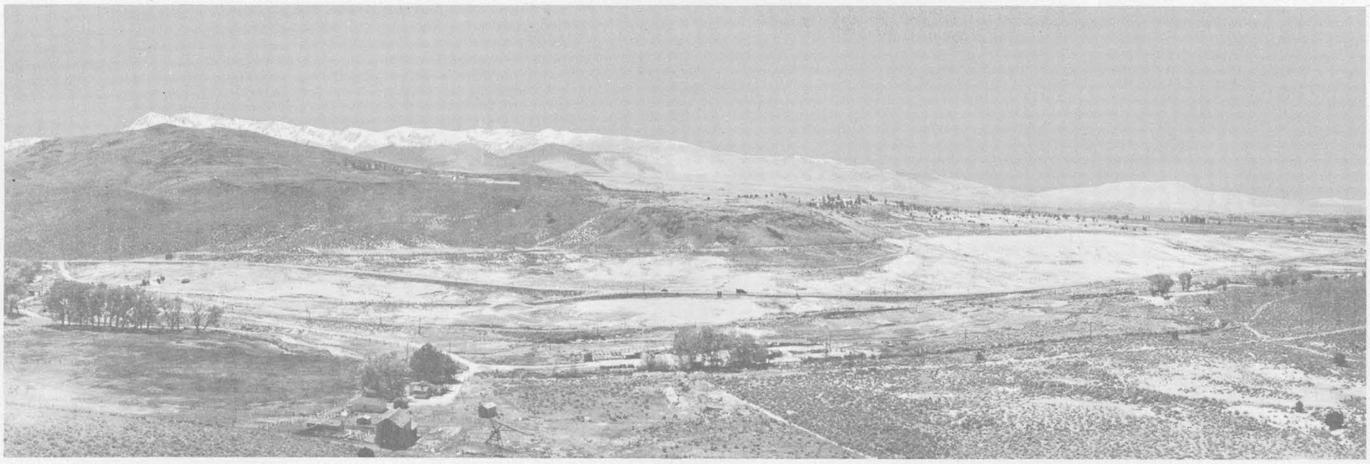

FIGURE 2.—Panorama of the Steamboat Springs thermal area looking west and northwest across the valley of Steamboat Creek. Light-colored areas in middle distance are sinter deposits of Low and Main Terraces. A lava-capped ridge of Steamboat Hills is at the left and center, and the Carson Range is in the background.

owner of the Steamboat Resort during the early years of study.

We are particularly indebted to Vincent P. Gianella, Professor Emeritus of the University of Nevada, who contributed most generously of his time and of his many years of familiarity with the springs and the geology of the region.

PREVIOUS WORK

The earliest reference to Steamboat Springs in geological literature is by Laur (1863), who called attention to the unusual character of the springs and the gold and other metals that were being deposited; he cited the springs as an example of an ore deposit being formed. LeConte (1883), in a brief and excellent summary of many aspects of the activity of the springs, recognized that mercury minerals were being deposited. The springs are particularly well known from studies by Becker (1888, 1889) and by one of his first assistants, Lindgren (1903, 1905). Becker's work is notable for laboratory experiments with mercury; he also found antimony in the fine-grained spring deposits. Lindgren proved that crystals of stibnite and pyrite had been deposited on pebbles he found in a prospect shaft 30 feet deep near the Steamboat Resort. Jones (1912, 1914) found tiny acicular crystals of stibnite in a spring pool, and also verified the existence of metastibnite that had first been reported by Becker. Gianella (1939) found that some wells drilled for hot water erupted stibnite and metastibnite from depth.

Some aspects of the present studies that have already been published include a summary of early results (Brannock and others, 1948); sources of heat and water supply (White and Brannock, 1960; White, 1957a); geochemistry of silica in the waters (White and others, 1956); geochemistry of isotopes of the waters (Craig and others, 1956); utilization of the hot-spring water and heat (White and others, 1953; White, 1961); the ore and gangue minerals (White, 1955a, p. 104, 113); hydrothermal alteration (White, 1955a, p. 104, 111–112; Sigvaldason and White, 1961, 1962); and the geologic setting of the area (Thompson, 1956; Thompson and Sandberg, 1958; Thompson and White, 1964).

SUMMARY OF REGIONAL GEOLOGY

The geology of the region and of specific nearby areas has been summarized by Gianella (1936), Calkins (1944), Calkins and Thayer 1945), and Thompson (1956). The most recent synthesis (Thompson and White, 1964) has provided the geologic setting for the detailed studies contained in this report, and is here summarized:

The rocks consist of a deeply eroded basement overlain by voluminous Cenozoic volcanic rocks and thick sedimentary deposits of lakes and streams. The basement rocks are regionally and thermally metamorphosed volcanic and sedimentary rocks, probably Mesozoic in age, that are intruded by granitic rocks of Cretaceous age. After deep erosion that exposed the granitic rocks, sporadic Cenozoic volcanism over a long time produced, in the Virginia City and Mount Rose quadrangles, more than a hundred cubic miles of lava flows and tuff-breccias, most of which is andesitic in petrographic character but is probably not far from granodiorite in average chemical composition. The earliest Cenozoic eruptives were volcanics of the Hartford Hill Rhyolite Tuff, which may have been deposited in the thermal area but are now absent. Deposition of this tuff was followed by eruption of andesite flows and tuff-breccias of the Alta Formation, only one phase of which has been recognized in Steamboat Hills. A plutonic rock, the

Davidson Granodiorite, intruded the Alta Formation in the Virginia City quadrangle. Next, the voluminous and widespread andesitic flows and tuff-breccias of the Kate Peak Formation of Miocene or Pliocene age were erupted from many vents, localized largely in the Virginia and Carson Ranges.

During and after these eruptions, sandstone, diatomaceous shale, and other fresh-water sedimentary rocks of the Truckee Formation of Pliocene age accumulated in structural basins between hills of volcanic rock; basaltic lava and rhyolitic pumice were also erupted locally and interfinger with other deposits of the Truckee Formation. The Truckee was deformed and tilted 30° or more in many places, after which, in late Pliocene and early Pleistocene time, basaltic andesites and basalts of the Lousetown Formation were erupted from many vents. Scattered domes of pumiceous rhyolite of the Steamboat Hills Rhyolite were implaced locally at about the same time as the youngest eruptions of the Lousetown, in the Pleistocene. Still later, Pleistocene andesite and olivine basalt were erupted in the Virginia City quadrangle.

Repeated glaciations, probably at least four, occurred in the larger drainage basins of the Carson Range. Alluvium, landslide debris, and hot-spring deposits also formed repeatedly over a span of time comparable to that of the glaciations.

Hydrothermal alteration, generally resulting in formation of some of the minerals epidote, albite, potassium feldspar, chlorite, clays, zeolites, calcite, and pyrite, was most widespread and intense prior to the deposition of the Truckee Formation, but alteration is still going on at Steamboat Springs. Where the altered rocks contain pyrite, or where H_2S is released by thermal activity, sulfuric acid is formed near the surface and the rocks are thoroughly bleached.

Intense pre-Cenozoic folding and faulting left the metamorphic rocks dipping 45° to 90° in most places and commonly striking between northeast and northwest. Block faulting and warping, which together with erosion shaped the present mountainous topography, were underway before Pliocene time and continued through Pleistocene. The northern part of the Carson Range was uplifted principally by doming, whereas farther south, near Slide Mountain the range rose as a normal-fault block. Many faults along the east front of the Carson Range and west front of the Virginia Range are antithetic; their downdropped sides are toward the ranges. The trough between the Carson and Virginia Ranges contains a chain of basins that are generally oval and are separated by transverse ridges. The major Cenozoic deformation of which we have a record took place after deposition of the Truckee Formation and prior to eruption of the Lousetown Formation, but the Lousetown also was deformed, imposing several hundred feet of additional structural relief.

Erosion has left a subdued topography in the upland, precipitous slopes on the mountain fronts, and locally, broad pediments around the mountains. Deposition continues in some of the basins.

GEOLOGY OF THE STEAMBOAT SPRINGS THERMAL AREA

PRE-TERTIARY ROCKS

Pre-Tertiary metamorphic and granitic rocks crop out in both the Mount Rose and Virginia City quadrangles (Thompson and White, 1964) but are in part concealed within the thermal area by younger volcanic and sedimentary rocks.

METAMORPHIC ROCKS

Metamorphosed sedimentary rocks make up much of the southeast flank and some of the core of Steamboat Hills, and extend northeast to the southern border of the thermal area, where they are intruded by granodiorite. The intrusive contact is poorly exposed for a distance of several thousand feet; its general trend is northwest, nearly at right angles to the strike of the metamorphic rocks. Farther to the west, the contact passes beneath Steamboat basaltic andesite flows of the Lousetown Formation, and is probably not more than 1,000 feet south of the silica pit.

The rocks are largely metamorphosed stream-deposited volcanic tuffs, interbedded with some sandstone, conglomerate, and lenticular, impure limestone. The metatuffs that locally constitute most of the formation are generally light gray green on weathered surfaces and gray green to black where fresh. Relict tuffaceous texture is apparent in some places but for the most part is obscured by metamorphism.

Slopes underlain by the metamorphic rocks are generally smooth and lacking in prominent outcrops. In many places the rocks are relatively homogeneous, and though they are marked by closely spaced joints, noticeable bedding or foliation is lacking. More commonly, however, bedding can be distinguished. Schistosity is generally absent, except locally near contacts with granodiorite; elsewhere, in the absence of schistosity, the rocks are hornfels. Where bedding and schistosity can be distinguished, they are usually parallel. The metamorphic rocks immediately southwest of the Low Terrace (pl. 1) strike N. 30°–45° E. and dip steeply east or west; they may be isoclinally folded but recognizable key beds are lacking.

The metatuffs consist of plagioclase, biotite, muscovite, chlorite, and quartz. Analysis 1 (W421, table 1)

TABLE 1.—*Chemical and normative analyses of rocks from the Steamboat*

[Analysts (U.S. Geol. Survey): Leonard Shapiro (1-5, 7-9, 13, 15a, 15-19, 22-28), S. M. Berthold and E. A. Nygaard (1-8, 10-13, 15-20, 26-28); H. F. Phillips (6, 9-12, 15a, 20, L. M. Kehl (H_2O^+, H_2O^-, CO_2, Cl, F, S); P. R. Barnett (B);

	Metamorphic rock	Granitic rocks				Alta Formation			Kate Peak Formation				Lousetown Formation	
	Metatuff	Granodiorite			Inclusion	Andesite	Soda trachyte		Lava flow	Andesitic scoria	Lava flow	Tuff-breccia	Upper flows	Steam-boat flows
Analysis	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Field No.	W421	A-17	W419	W420a	W420b	48	W355	W422a	W236b	W442b	W445	66	A-7	W1280
Lab. No.	51-1448CW	51-1466CW	51-1445CW	51-1446CW	51-1447CW	52-860CW	51-1432CW	51-1449CW	53-636C	52-909CW	52-910CW	52-863CW	51-1456CW	Report IWC-9
Location	Pleasant Valley	SW. Washoe City [1]	Steamboat Low Terrace [2]	Steamboat near Low Terrace [3]		⅔ mi E. of Low Terrace	½ mi E. of Low Terrace	Steamboat Hills	Steamboat thermal area	Steamboat Hills		Washoe Summit	Near Lousetown	Steamboat thermal area [4]
CHEMICAL ANALYSIS [Weight percents]														
SiO_2	61.1	65.4	65.6	65.9	57.5	57.0	64.6	65.0	56.0	54.6	59.3	55.4	51.8	54.38
Al_2O_3	21.1	16.2	16.5	16.7	17.6	18.1	18.0	18.6	16.4	17.0	16.8	19.1	16.8	17.83
Fe_2O_3	2.1	1.8	2.2	.60	2.8	2.7	3.5	1.5	4.4	7.0	3.6	4.8	3.8	2.57
FeO	3.2	2.4	2.1	2.2	3.9	4.2	.33	2.0	1.6	1.4	2.4	2.2	4.4	4.97
MgO	1.5	1.6	1.7	1.5	4.0	2.2	.15	.74	2.2	1.8	3.0	3.0	7.3	4.12
CaO	1.6	5.2	3.2	3.8	5.0	4.2	1.3	3.1	6.8	5.6	6.7	6.2	10.9	6.58
Na_2O	3.2	3.7	3.6	3.6	4.3	3.9	5.5	5.0	4.0	4.0	3.6	3.1	2.8	4.03
K_2O	2.3	3.5	2.9	2.8	1.6	2.6	3.9	3.2	3.0	3.5	2.2	.96	.96	2.50
TiO_2	.72	.58	.55	.52	.76	.84	.45	.46	1.4	1.4	.62	.70	1.0	1.89
P_2O_5	.16	.14	.15	.15	.20	.48	.35	.21	.46	.44	.16	.11	.34	.57
MnO	.07	.07	.06	.16	.18	.50	.15	.14	.08	.06	.20	.10	.17	.11
H_2O	[8] 2.9	[1] .44	[2] .55	[8] .67	[8] .93	[8] 3.5	[8] 1.4	[8] .25	[8] 2.2	[8] 2.6	[8] .90	[8] 4.6	[8] .85	[4] .28
FeS_2 [10]	---	.00	---	---	---	---	---	---	---	---	---	.00	---	.01
SO_3	---	---	.00	---	---	---	---	---	---	---	---	---	---	---
CO_2	---	.00	.09	---	---	---	---	---	---	---	---	.01	---	.01
Total	99	101	99	99	99	100	100	100	99	99	99	100	101	100
Powder gr	2.73	2.70	2.69	2.68	2.78	2.72	2.66	2.58	2.68	2.72	2.76	2.58	2.87	2.80
Bulk gr	2.66	2.62	2.62	2.62	2.66	2.60	2.54	2.52	2.50	2.38	2.54	1.93	2.76	2.59
NORMS [Volume percents]														
Q	26.9	20.6	24.0	22.9	8.5	11.0	15.5	15.4	7.3	5.8	13.6	16.0	1.6	1.9
or	13.3	20.6	17.2	16.7	9.5	15.6	22.8	18.9	17.8	20.6	12.8	6.1	5.6	15.0
ab	27.3	30.4	30.4	30.4	36.2	33.0	46.6	42.4	34.1	34.1	30.4	26.2	23.6	34.1
an	7.2	17.5	15.0	18.1	23.9	17.5	[11] 4.7	14.5	17.8	18.1	23.4	30.0	30.6	23.1
ne	---	---	---	---	---	---	---	---	---	---	---	---	---	---
C	10.7	---	1.9	1.1	---	2.3	3.0	1.5	---	---	---	1.8	---	---
hy	6.8	.6	5.3	6.6	13.8	10.5	.4	3.8	0.7	1.9	4.8	7.5	13.4	11.9
di	---	5.4	---	---	---	---		---	11.5	5.6	7.2	---	17.4	5.2
O	---	---	---	---	---	---	---	---	---	---	---	---	---	---
mt	3.0	2.5	3.2	.9	4.2	3.9	.2	2.1	1.2	0.5	5.3	5.3	5.6	3.7
il	1.4	1.1	1.0	1.1	1.5	1.5	.9	.9	2.7	2.7	1.2	1.4	2.0	3.6
hm	---	---	---	---	---	---	[11] 3.4	---	3.7	6.7	---	1.1	---	---
ap	.3	.3	.3	.3	.3	1.3	.7	.3	1.0	1.0	.3	.3	.7	1.3
Normative plagioclase	An_{20}	An_{35}	An_{32}	An_{36}	An_{38}	An_{33}	[11] An_9	An_{24}	An_{33}	An_{33}	An_{42}	An_{52}	An_{55}	An_{39}

[1] Includes H_2O^+, 0.40; H_2O^-, 0.04. Also determined: Cl, 0.04; F, 0.05; by quant. spectro. analysis: B, 0.002; Cu, 0.002; Pb, 0.002; Co, 0.001; Ni, 0.0007; Ga, 0.001; Cr, 0.002; V, 0.01; Sc, 0.0006; Y, 0.003; Zr, 0.01; Be, 0.0008; Sr, 0.01; Ba, 0.1; Li, 0.006; Rb, 0.03; Cs, 0.002.

[2] Includes H_2O^+, 0.50, H_2O^-, 0.05. Also determined: Cl, 0.02; F, 0.03; by quant. spectro. analyses: B, 0.002; Cu, 0.003; Hg, 0.00002(?); Pb, 0.001; Co, 0.001; Ni, 0.0009; Ga, 0.001; Cr, 0.002; V, 0.01; Sc, 0.0006; Y, 0.002; Zr, 0.006; Sr, 0.02; Ba, 0.2; Li, 0.0007; Rb, 0.02.

[3] By quant. spectro. analysis: Cu, 0.002; Pb, 0.001; Co, 0.001; Ni, 0.001; Ga, 0.0009; Cr, 0.002; V, 0.01; Sc, 0.0004; Y, 0.002; Zr, 0.008; Sr, 0.01; Ba, 0.2; B, 0.002; Li, 0.002; Rb, 0.03; Cs, 0.0009.

[4] Includes H_2O^+, 0.16, H_2O^-, 0.12. Also determined: Cl, 0.01; F, 0.06; by quant. spectro. analyses: B, 0.001; Cu, 0.004; Pb, 0.002; Co, 0.002; Ni, 0.005; Ga, 0.001; Cr, 0.004; V, 0.02; Sc, 0.001; Y, 0.004; La, 0.01; Zr, 0.008; Sr, 0.01; Ba, 0.2; Li, 0.002; Rb, 0.03; Cs, 0.0009.

is typical of many of these rocks. Some of the quartz and plagioclase grains have relict clastic shapes, but the original lithic fragments have been completely reconstituted. The plagioclase is oligoclase to sodic andesine and the normative plagioclase is An_{20}. Biotite and muscovite are common as small crystals and shreds and show a more pronounced orientation in thin section than is indicated by the poorly developed schistosity. Quartz is rather abundant. Chlorite is in part an alteration of biotite, and is in part concentrated in "spots," perhaps from retrograde metamorphism or replacement of cordierite. The excess alumina indicated by the relatively high normative corundum (10.7 percent in sample W421, table 1) suggests that the micas and chlorite are high-alumina varieties.

Relict tuffaceous or volcanic texture is not apparent in the analyzed rock, but is characteristic of other similar metamorphic rocks of the area. The analysis in table 1 indicates an andesitic character for the original lithic clastic fragments. The excess of Na_2O over K_2O dis-

Springs thermal area and vicinity, Washoe County, Nev.

22-25); C. C. Alexander (6, 10-12, 20); K. E. White (9, 15a, 22-25); preceding analyses by rapid methods unless footnoted below; W. W. Brannock (14, 21; by standard methods); H. J. Rose (spectro. analyses listed in footnotes)]

Lousetown Formation—Continued		Steamboat Hills Rhyolite				McClellan Peak Olivine Basalt	Hot-spring sinter							
Vent	Truckee River flows	Pumiceous rhyolite	Perlitic rhyolite	Pumiceous rhyolite	Marekanite obsidian "marble"	Vent	Chalcedonic sinter (QTs)	Chalcedonic sinter (Qs_1)		Chalcedony-opal sinter (Qs_1)	Chalcedony (opal) sinter (Qs_1)	Dark opaline sinter (Qs_2)	Opaline sinter (Qs_2)	Opaline sinter with calcite (Qs_2)
15 W415a 51-1443	15a 485 53-634C	16 A-15 51-1464	17 A-16 51-1465	18 W-413 51-1442CW	19 W-416 51-1444CW	20 155 52-870CW	21 W 128-8 Report IWC-9	22 GS-6-2 53-2440C	23 GS-2-28 53-576C	24 GS-6-6 53-612C	25 GS-5-84 53-605C	26 GS-5-19 51-1481CW	27 W 226 51-1431CW	28 W 128-9 51-1429
E. Truckee Meadows	Cinder cone SW. of Boca Truckee quad., Calif.	Dome in Steamboat Hills [5]	Dome, E. Truckee Meadows [6]	Truckee Meadows—⅔ mi NE. of thermal area	2 mi NE. of thermal area	Mount McClellan	SW. slope of Sinter Hill [7]	Sinter Hill	High Terrace	Sinter Hill		Main Terrace		

CHEMICAL ANALYSES

[Weight percents]

54.8	53.5	75.5	75.8	74.9	76.3	48.6	97.72	97.9	98.6	96.4	96.3	91.9	90.0	84.8
17.1	16.6	12.6	12.7	12.7	13.8	15.2	.14	.06	.58	.30	.72	.11	1.4	.46
4.4	4.0	.36	.25	.32	.40	3.1	1.43	.12	<.10	.08	.02	.00	.11	.02
3.0	2.9	.13	.25	.20	.38	6.4	---	.0	.13	.0	.16	.00	.00	.35
2.7	5.2	.13	.20	.76(?)	.15	10.2	None	.00	.00	.01	.02	.00	.52	.50
7.2	6.0	.85	.85	.79	.77	9.2	None	.00	.06	.14	.26	.70	.46	3.0
4.8	4.4	3.8	3.8	3.4	3.7	3.0	.03	.22	.22	.20	.24	.26	.26	.50
1.5	3.0	4.6	4.5	4.3	4.8	1.7	.02	.10	.09	.10	.16	.18	.16	.30
1.0	1.6	.13	.11	.10	.09	2.0	.10	.00	.04	.00	.16	.06	.01	.07
.40	.82	.01	.09	.03	.01	.50	---	.00	.01	.00	.00	.01	.01	.02
.14	.10	.05	.10	.09	.09	.14	---	.00	.00	.00	.00	.01	.02	.05
[8]1.7	[8].50	[5]2.37	[6]2.41	[8]3.9	[8,9].37	[8].6	[7].35	[8]1.1	[8]1.0	[8]2.8	[8]1.6	[8]6.6	8.5	6.7
---	---	.00	.00	---	---	---	---	.02	.06	.02	.52	.11	---	---
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
---	---	.02	.00	---	---	---	None	<.05	<.05	<.05	<.05	<.05	<.05	1.9
99	99	101	101	101	101	101	99.8	100	101	100	100	100	101	99
2.72	2.80	2.38	2.40	2.33	2.34	2.94	2.64	2.59	2.60	2.26	2.40	2.06	2.01	2.06
2.66	2.50	1.84	2.22	1.65	2.36	2.70	2.56	2.36	2.45	1.80	2.07	1.92	1.71	1.32

NORMS

[Volume percents]

6.9	---	33.9	34.6	35.6	34.3	---	---	---	---	---	---	---	---	---
8.9	17.8	27.2	26.7	25.6	28.4	10.0	---	---	---	---	---	---	---	---
40.4	37.2	32.0	32.0	28.9	31.4	24.1	---	---	---	---	---	---	---	---
20.9	16.7	3.9	3.3	3.9	3.9	23.1	---	---	---	---	---	---	---	---
---	---	---	---	---	---	.6	---	---	---	---	---	---	---	---
---	---	---	.4	1.0	1.0	---	---	---	---	---	---	---	---	---
2.5	9.1	.3	.8	2.0	.8	---	---	---	---	---	---	---	---	---
9.8	6.3	.2	---	---	---	15.2	---	---	---	---	---	---	---	---
---	.7	---	---	---	---	17.4	---	---	---	---	---	---	---	---
6.5	4.9	.2	.5	.5	.7	4.4	---	---	---	---	---	---	---	---
2.0	3.0	.1	.1	.1	.1	3.8	---	---	---	---	---	---	---	---
---	.6	.3	---	---	---	---	---	---	---	---	---	---	---	---
1.0	2.0	---	.3	---	---	1.3	---	---	---	---	---	---	---	---
An_{33}	An_{30}	$An_{10.3}$	$An_{9.0}$	$An_{11.3}$	$An_{10.4}$	An_{47}	---	---	---	---	---	---	---	---

[5] Includes H_2O^+, 2.31; H_2O^-, 0.06. Also determined: Cl, 0.03; F, 0.06; by quant. spectro. analysis: B, 0.006; Cu, 0.0005; Pb, 0.005; Ga, 0.001; Cr, 0.0003; Sc, 0.0002; Y, 0.003; Zr, 0.01; Be, 0.002; Ba, 0.004; Li, 0.008; Rb, 0.03; Cs, 0.0009.

[6] Includes H_2O^+, 2.36; H_2O^-, 0.05. Also determined: Cl, 0.02; F, 0.05; by quant. spectro. analysis: B, 0.006; Cu, 0.0003; Pb, 0.002; Ga, 0.001; Cr, 0.0003; Sc, 0.0002; Y, 0.003; Zr, 0.01; Be, 0.002; Ba, 0.002; Li, 0.008; Rb, 0.04; Cs, 0.001.

[7] Includes H_2O^+, 0.22; H_2O^-, 0.13. Also determined: Sb_2S_3, 0.002; Hg, 0.013; As, none.

[8] Reported ignition loss corrected for gain due to oxidation of FeO; also corrected for CO_2 and SO_3 if reported separately.

[9] H_2O also determined by Irving Friedman as 0.25 percent, with D/H—8.0 percent relative to Lake Michigan water.

[10] Sulfur reported as FeS_2 and iron corrected.

[11] Suggests some hydrothermal alteration or weathering.

tinguishes the rock from normal fine-grained clastic sediments. The abundance of free quartz suggests intermixture of some nonandesitic debris. The relatively high percentage of normative corundum suggests that clay minerals were formed by partial weathering of the tuffs, or that clastic clays derived from other rocks were mixed with volcanic debris.

The metamorphic rocks are older than the granitic rocks to be described and are probably Triassic in age (Thompson and White, 1964).

GRANODIORITE AND RELATED ROCKS

Granodiorite is one of the most abundantly exposed rocks of the Steamboat thermal area. It crops out in many places in the southern half of the area west of Steamboat Creek (pl. 1, tables 1 and 2) and it underlies Steamboat basaltic andesite flows of the Lousetown Formation at depths that probably are rarely more than 50 feet. North of its principal outcrops, granodiorite underlies alluvium and hot-spring sinter. Drill holes and wells in the area (table 3) indicate increasingly

TABLE 2.—*Modal analyses of rocks from the Steamboat Springs thermal area and vicinity*

	Granitic rocks					Rhyolite domes				Pyroclastic rhyolite fragments					
	Granodiorite			Inclusion in W420a	Basaltic andesite of Lousetown Formation	Steamboat Hills Rhyolite	Perlite, NE. dome	Middle dome	Inclusion in A-15	Pumice fragment	Fragment in gravels of pre-Lousetown alluvium		Fragment on basalt andesite flow of Lousetown Formation	Maremkanite "marble," NE. dome	Fragment in pre-Lousetown alluvium
Analysis [1]	2	3	4	5	14	16	17	18	--------	--------	--------	--------	--------	19	--------
Field No.	A-17	W419	W420a	W420b	W128-0	A-15	A-16	W413	W266	W434	W476a	W476b	W374	W416	W129-29c
Location	SW. of Washoe City	Low Terrace	Near Low Terrace		Near silica pit	Western Steamboat Hills	Truckee Meadows		Western Steamboat Hills	½ mi E. of A-15	NW. of silica pit		Traverse 1, 34W	Near A-16	South Steamboat well, 205± ft depth
Mineral (or phenocrysts [2] of volcanic rocks):															
Quartz	22.0	30.1	26.6	19.0	--------	0.7	1.1	1.1	1.2	1.3	1.4	1.6	1.7	0.0	2.9
Potassium feldspar	20.0	9.6	14.4	3.8	--------	2.0	2.5	1.4	1.5	1.5	2.4	.8	1.7	.0	2.2
Plagioclase	45.8	47.0	43.9	54.9	--------	.9	1.5	.6	.6	.5	1.1	.4	.4	.0	.3
Large phenocrysts	--------	--------	--------	--------	[3] 5.6	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
Medium phenocrysts	--------	--------	--------	--------	[4] 20.4	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
Biotite	5.5	6.6	9.4	10.0	--------	.3	.2	.1	.0	.1	.1	.1	.1	.1	.2
Hornblende	4.6	5.3	3.6	10.3	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
Olivine	--------	--------	--------	--------	3.3	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
Accessories	1.9	1.5	2.1	1.9	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
(Total phenocrysts)	--------	--------	--------	--------	(29.3)	(3.9)	(5.3)	(3.2)	(3.3)	(3.4)	(5.0)	(2.9)	(3.9)	(.1)	(5.6)
Groundmass:															
Glass or small crystals	--------	--------	--------	--------	[5] 70.7	89.0	92.9	96.5	[6] 92.3	[6] 94.4	[6] 92.5	[6] 96.4	93.1	[7] 98.9	[6] 89.1
Spherulites	--------	--------	--------	--------	--------	7.1	1.8	.3	4.4	2.2	2.4	.8	3.0	.0	5.4
(Vesicles, not included in total)	--------	--------	--------	--------	--------	(23)	(7.5)	(29)	(10±)	(20±)	(5±)	(25±)	(15±)	0	(<5)
Modal plagioclase	An_{20-45}	An_{15-45}	An_{20-45}	An_{28-45}	[8] An_{15-60}	An_{17}±	An_{16-18}	An_{14-18}	An_{18}±	An_{13}±	An_{14}±	An_{17}±	An_{14}±	--------	An_{10-15}
Index of glass	--------	--------	--------	--------	--------	1.495±	1.496±	1.496±	Devitrified	Devitrified	Devitrified	1.497±	1.494±	1.487±	Devitrified

[1] Analysis numbers correspond to those in table 1.
[2] Phenocrysts in rhyolite >0.1 mm width except for biotite; potassium feldspar is sanidine.
[3] Large phenocrysts, >0.2 mm width; 3.4 percent have grained cores, 2.2 percent not grained (see text).
[4] Phenocrysts >0.5 mm width, <0.2 mm.
[5] Includes 48.2 percent small plagioclase crystals and 22.5 percent miscellaneous, mostly small pyroxene crystals <0.05 mm width.
[6] Devitrified or largely devitrified; W476b only partly devitrified.
[7] Includes 1 percent inclusion of metamorphic rock.
[8] Plagioclase of borders of phenocrysts and of groundmass is probably high potassium oligoclase (see text).

greater depths to granodiorite bedrock toward the north. In GS-2 drill hole on the High Terrace, for example (pl. 2 and table 3), the depth to granodiorite is 351 feet.

TABLE 3.—*Logs of wells, drill holes, and auger holes*

South Steamboat well

[Determined from study of cuttings and from observations by driller, John Czykowsky. Drilled by cable-tool rig, 485 ft E., traverse 5; land-surface alt, 4,611.7 ft]

	Depth (*ft*)
Pre-Lake Lahontan alluvium:	
Silt, sand, and gravel angular, light-brown to brown. Dominantly granitic debris, minor diatoms and andesite of the Kate Peak Formation. Slightly cemented with clay and calcite; water level at about 7 ft	0–8
Gravel to silt, angular to rounded, light brown-gray. Granitic debris and minor Kate Peak andesite, diatoms, and possibly opaline sinter. Cemented by calcite, some clay; silicate minerals unaltered	8–10
Sand and fine gravel, angular to subrounded, brown-gray. Uncemented, requires casing	10–14
Calcite-cemented sand and gravel containing pebbles as large as 5 cm interbedded with slightly cemented blue-gray to brown-gray clay, silt, and sand. Dominantly granitic debris with minor Kate Peak andesite, Steamboat basaltic andesite of the Lousetown Formation; some silicate minerals altered. Diatoms relatively abundant, 27 species, with 25 living elsewhere today and 4 characteristic of hot springs (USGS diatom loc. 4182; identifications by K. E. Lohman)	14–18

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

South Steamboat well—Con.

	Depth (*ft*)
Pre-Lake Lahonton alluvium—Continued	
Clay, silt, and sand, angular green-gray to brown-gray. Dominantly granitic, some Kate Peak andesite, rare metamorphic rock fragments, and diatoms. Silicate minerals and volcanic glass partly altered to argillic minerals, principally chlorite, but some are fresh with hornblende in part unaltered; tiny cubes and spherules of pyrite, largely oxidized. Hard stratum at 26 ft (opal cement) remainder soft (clay cement)	18–38
Sand and fine gravel, angular, green-brown. Granitic debris, minor Kate Peak andesite, rare diatoms. Hard, opal cemented, permeable. Most silicates altered to clay minerals; rare hypersthene is the only unaltered ferromagnesian mineral; all pyrite oxidized	38–39
Silt, sand, and gravel, angular, green-gray to green-brown, but brown at base. Fragments granitic, minor Kate Peak andesite and metamorphic rocks. Some hydrothermal clays, principally chlorite; pyrite largely oxidized	39–63

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

South Steamboat well—Con.

	Depth (ft)
Fault or disconformity; a permeable aquifer?	
Pre-Lousetown alluvium:	
Granitic debris, green-gray, green-brown to brown depending on pyrite and extent of oxidation; pyrite generally cubic, minor pyritohedral. Hydrothermal clay minerals rare to abundant, consisting mostly of illite-montmorillonite and chlorite. All hornblende, most biotite, some plagioclase altered. No fragments of rocks other than granite detected, even in thin sections prepared from drill cuttings	63–114
Fault or permeable aquifer.	
Sand and gravel, green-brown to brown, angular. Dominantly granitic, some metamorphic fragments, minor Kate Peak andesite. Less intense alteration than above, some fresh biotite, largely argillized, and a very little fresh hornblende; chlorite is the most abundant hydrothermal clay mineral. Most pyrite (cubic) oxidized	114–117
Silt, sand, and fine gravel, angular, mostly gray to green-gray. Dominantly granitic, some fragments of metamorphic rocks and Kate Peak andesite. Much plagioclase, most ferromagnesian minerals (except some biotite) argillized to chlorite, illite-montmorillonite, and kaolinite. Pyrite (cubic) fresh except near top and bottom. Siderite near 145 ft	117–156
Silt and sand, angular, brown in central part grading to buff and brown-gray at top and bottom, depending on oxidation of pyrite (cubic, minor octahedral). Dominantly granitic, minor metamorphic rock debris. Fault zone or permeable stratum?	156–175
Clay, silt, and sand, angular, white to light-gray. Arkose, with most plagioclase and all ferromagnesian minerals altered to clay minerals; pyrite fresh, cubic, minor pyritohedral	175–190
Silt, sand, and gravel, largely angular, as large as 2 cm, gray to brown-gray. Dominantly granitic but metamorphic and volcanic (Kate Peak) fragments increase downward. One Kate Peak fragment similar to Steamboat basaltic andesite of Lousetown Formation except for few crystals of hornblende; devitrified rhyolite fragment near 200 ft. Abundant montmorillonite, illite, and chlorite, probably of clastic origin; no hydrothermal alteration or pyrite except at top	190–275

H. Herz 1 well

[Determined from study of cuttings and from observations by driller, H. Herz. Drilled by cable-tool rig about 4,000 ft NW. of Main Terrace, near 150 ft W., traverse 14; land-surface alt, 4,605 ft]

	Depth (ft)
Pre-Lake Lahontan alluvium:	
Surface strewn with large boulders, largely andesite of the Kate Peak Formation. Below surface, clay, sand, gravel as large as 10 cm, subrounded, brown; granitic and Kate Peak rock fragments, unaltered	0–2
Silt, sand, and gravel as large as 1 cm, some rounded. Light-brown "hardpan" with opal(?), clay cement, minor carbonate. Granitic and Kate Peak rock fragments, unaltered	2–4

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

H. Herz 1 well—Con.

	Depth (ft)
Pre-Lake Lahontan alluvium—Con.	
Same as above but more clay and silt, fewer pebbles, uncemented	4–10
Clay to fine gravel as large as 5 mm, gray-brown to brown, angular to subrounded. Dominantly granitic but Kate Peak andesite common, very rare rhyolite, opaline sinter. Silicate minerals and glass of andesite generally fresh but some hydrothermal clay and oxidized octahedral pyrite below zone of "hardpan" at 33 ft	10–52
Clay, sand, gravel pebbles as large as 15 mm, some rounded or subrounded, light-brown to greenish-brown. Debris dominantly granitic but Kate Peak andesite common, very rare andesite (not Steamboat basaltic andesite) of the Lousetown Formation. Two species of freshwater diatoms, living elsewhere today (USGS diatom loc. 4190; identifications by K. E. Lohman). Ferromagnesian minerals still fresh. Minor opal(?) cement, no pyrite. Water level at about 56 ft	52–57
Clay, sand, fine gravel as large as 4 mm, angular to subrounded, light greenish-brown. Granitic and andesitic fragments; hydrothermal clay more common but still some fresh green hornblende, hypersthene, augite; pyrite oxidized to hematite	54–74
Disconformity(?).	
Pre-Lousetown alluvium:	
Clay, silt, coarse sand as large as 2 mm, light brown-gray. Granitic debris dominant, poorly cemented by hydrothermal clay and calcite; all pyrite oxidized	74–100
Clay, silt, and sand as large as 1.5 mm, angular to rounded, blue-gray to light brown-gray. Rounded quartz grains frosted and windblown? Kate Peak andesite nearly equal to granitic debris. Ferromagnesian minerals completely argillized except near top, most plagioclase fresh, all pyrite oxidized. Cement is clay, minor calcite near top	100–130
Clay, silt, and sand as large as 2 mm, angular to subrounded light blue-gray; granitic debris in excess of andesite. Most silicates argillized except for potassium feldspar and some plagioclase. Pyrite common, as large as 0.05 mm, with combined cubic-octahedral-pyritohedral forms, none oxidized	130–155

Steamboat well 4

[At Steamboat Resort. Determined from study of cuttings and from observations by driller, John Czykowsky. Drilled by cable-tool rig near 8 E., traverse 2; land-surface alt, 4,612.8 ft]

	Depth (ft)
Pre-Lake Lahontan alluvium and opaline sinter:	
Fill	0–2
Opaline sinter	2–5
Clay, silt, and sand, light blue-gray. Silicate minerals largely argillized, with fine-grained pyrite. Water level at about 14 ft	5–24
Opaline sinter containing hot-spring diatoms, some debris from granitic and metamorphic rocks, may have been previously acid altered in part	24–29

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

Steamboat well 4—Con.

	Depth (*ft*)
Pre-Lake Lahontan alluvium and opaline sinter—Con.	
Opaline sinter interbedded with sand and gravel, some diatoms. Clastic debris largely granitic, some andesite and soda trachyte. Silicate minerals largely argillized but some fresh plagioclase, green hornblende. Hydrothermal clay abundant, some stibnite, globular pyrite	29–38
Layers of opaline sinter about 6 in. thick alternating with open spaces 1 ft thick, probably originally sand and gravel erupted into adjacent wells	38–45
Sand and gravel, light-gray, largely granitic, some andesitic debris, and rare fragments that may be Steamboat basaltic andesite	45–49
Layers of opaline sinter, containing hot-spring diatoms, hydrothermal stibnite, and pyritohedral pyrite, interbedded with argillized blue-gray clay and sand. Stibnite to 52 ft, none recognized below. Clastic debris is granitic, andesitic, and metamorphic, possibly with Steamboat basaltic andesite. Some open spaces, probably originally clastic sediments erupted into adjacent wells	49–68
Disconformity (?).	
Pre-Lousetown alluvium:	
Strata of clay and sand as large as 2 mm, blue-gray, mostly granitic debris alternating with some open spaces; some calcite, pyritohedral pyrite	68–74
Clay, sand, and fine gravel as large as 4 mm, blue-gray, argillized, dominantly granitic but some fragments of metamorphic rocks. Most ferromagnesian minerals and plagioclase argillized; pyritohedral pyrite	74–82
Clay, silt, and sand, blue-gray, with pyrite	82–92
Clay, sand, and gravel as large as 2 in., rounded to subrounded. Granitic, metamorphic, and andesitic debris. Large rock fragments only partly argillized on borders; pyritohedral pyrite common, minor calcite	92–101
Principal aquifer, mostly sand, minor silt, from granodiorite; blue gray, argillized but permeable; some pyrite	101–108
Clay, sand, and fine gravel as large as 5 mm, blue-gray, mostly from granodiorite, andesite, well-cemented, largely by clay minerals. All silicates argillized except potassium feldspar, some plagioclase; pyrite common, with pyritohedral and octahedral forms, considerable calcite	108–147
Clay, silt, and sand, as large as 2 mm, light blue-gray, angular to subrounded, well-cemented, largely by clay minerals. Fragments mostly from granodiorite, some andesite. Silicates hydrothermally altered; pyrite in pyritohedral and some other forms	147–162
Clay, sand, and gravel as large as 10 mm, light blue-gray, angular to subrounded, largely from granodiorite but abundant andesite and common fragments of metamorphic rock; some fragments amygdular, similar to those of GS–1 drill hole, 129 to 209 ft depth. Well cemented by clay minerals; some plagioclase replaced by potassium feldspar. Pyritohedral pyrite common, some other forms and some marcasite (?); minor clastic garnet. Permeable near 200 ft	162–200
Clay, silt, and sand as large as 2 mm; unstable silicate minerals hydrothermally altered to clay minerals and potassium feldspar; calcite and pyritohedral pyrite	200–225

Rodeo well

[Near crest of Main Terrace. Determined from study of cuttings. Drilled by cable-tool rig to 164-ft depth, then by rotary rig, coring below 180 ft; south of 3 E., traverse 16; land-surface alt, 4,675.7 ft]

	Depth (*ft*)
Pre-Lake Lahontan alluvium and opaline sinter:	
Opaline sinter, some primary but largely fragmental type, nearly white. Minor fragments of clastic granitic rock, some poorly preserved diatoms	0–6
Largely uncemented fragments of opaline sinter, some granitic debris, hot-spring diatoms. Light in color. Depth to water about 9 ft	6–13
Opaline sinter and some granitic debris, nearly white to light-gray	13–13½
Sand and fine gravel, angular, uncemented; largely sinter, some granitic fragments and diatoms. Medium gray, color perhaps from very fine grained pyrite	13½–26
Opaline sinter, very hard drilling, probably because cavities largely filled with opal	26–28
Largely sand, from coarse to fine, angular, gray, uncemented. Sinter fragments dominant, some granitic debris, hot-spring diatoms common. Gray, with rare pyrite, some stibnite. Minor calcite	28–36
Silt and sand, angular to subrounded, black to dark-gray; granitic and sinter fragments abundant, few diatoms, some pyrite. Permeable	36–51
Sand, largely granitic, some sinter fragments, dark-gray, opal-cemented	51–55
Clay, silt, and fine sand, angular, most less than 0.2 mm in diameter. Dark gray, largely granitic but some sinter fragments; abundant well-preserved diatoms; 12 species identified, including 3 characteristic of hot springs, with all still living except possibly 1 new species (USGS diatom loc. 4186; identifications by K. E. Lohman, 1958). Opal (cristobalite), illite-montmorillonite abundant, with rare pyrite	55–60
Interbedded opaline sinter and silt and sand consisting of fragments from granodiorite, opaline and chalcedonic sinter, and some diatoms. Gray, with opal (cristobalite) cement, some calcite at base, minor illite-montmorillonite, common pyrite and stibnite	60–84

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

Rodeo well—Con.

	Depth (ft)
Pre-Lake Lahontan alluvium (or uncemented pre-Lousetown alluvium with detrital pre-Lousetown sinter):	
Arkosic silt, sand, and fine gravel, angular, gray, largely granitic debris but chalcedonic sinter common, some opaline sinter, very few diatoms. Plagioclase largely argillized, pyrite common in lower part, stibnite rare	84–115
Arkosic silt and sand, angular, white, most silicate minerals argillized. Fragments of granitic debris and chalcedonic sinter; some pyrite	115–119
Clay, silt, and sand, red to red-brown, angular fragments of granitic debris and chalcedonic sinter. Silicate minerals largely argillized to chlorite, illite-montmorillonite; much pyrite oxidized to hematite; minor cristobalite. Well first erupted from top of this zone	119–129
Silt, sand as large as ½ mm; fragments angular, gray, largely granitic, some chalcedonic sinter. Diatoms, 142–147 ft (USGS diatom loc. 4187; identification by K. E. Lohman, 1958); 6 living species with 3 characteristic of hot springs. Few thin layers cemented with calcite; most silicate minerals argillized; pyrite common, some globular and pyritohedral; considerable stibnite to 147 ft, none below	129–147
Silt and fine sand, well-sorted, as large as 0.2 mm, red-brown, angular to subrounded; some hydrothermal calcite, but not well cemented. Granitic fragments, abundant opaline and chalcedonic sinter. Silicate minerals largely argillized, most pyrite oxidized	147–156
Silt, sand and gravel as large as 5 mm but largely fine sand, angular to subrounded, red-brown to brown-gray. Fragments are largely from granodiorite, andesite; also a few diatoms, and fragments of chalcedonic and opaline sinter. Silicate minerals in part argillized, but minor fresh hornblende, hypersthene, and volcanic glass; some hydrothermal clay minerals with chlorite dominant; also some calcite, and minor pyrite, largely oxidized	156–164
Silt and sand as large as 0.4 mm, angular, red-brown to brown-gray, derived from granodiorite, some Steamboat(?) basaltic andesite, chalcedonic sinter. Silicate minerals in part fresh, in part argillized; considerable illite-montmorillonite, some chlorite, probably hydrothermal rather than clastic; most pyrite fresh; some calcite	164–166
Unconformity.	
Granodiorite:	
Probably weathered near surface prior to being altered; red brown in color but also contains fresh pyrite. Relatively soft near top, drilled by rock bit to 180 ft, diamond bit below	166–180
Mottled red brown and gray green; some plagioclase and all biotite and hornblende hydrothermally altered, with disseminated pyrite. Calcic cores of plagioclase crystals partly to largely replaced by potassium feldspar, some illite-montmorillonite, chlorite, and carbonate; biotite and hornblende replaced by illite and chlorite. Quartz is red brown, contains tiny inclusions of iron oxide(?)	180–195

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

Rodeo well—Con.

	Depth (ft)
Granodiorite—Con.	
Gray green to gray. Some plagioclase is almost fresh and zoned, with only part of crystal cores replaced by clay minerals, potassium feldspar, and carbonate; hornblende always altered to clay minerals, some biotite fresh. No major veins or crush zones, but local shearing	195–285

Mount Rose (1947) well

3,000 ft N. of Main Terrace; land-surface alt, 4,595 ft]
3,000 ft N. of Main Terrace; land-surface alt, 4.595 ft]

	Depth (ft)
Pre-Lake Lahontan alluvium:	
Surface covered with boulders as much as 1 ft in diameter, largely brown andesite of the Kate Peak Formation, some granodiorite. Below surface, silt, sand, and gravel probably less than 3 in., almost entirely granitic and andesitic, unaltered; here, and at greater depths, no definite Steamboat basaltic andesite found. Some calcite, no pyrite	0–30
Silt and coarse sand as large as 2 mm, angular, brown. Dominantly granodiorite, but common andesite, minor metamorphic rocks. Silicate minerals partly argillized but some fresh brown hornblende and pyroxene. No pyrite. Water level 55 to 60 ft	30–65
Silt, sand, and fine gravel as large as 4 mm, angular to subrounded, brown, largely from granodiorite, some andesite, very rare non-hot-spring diatoms. Hydrothermal clay abundant but some unreplaced green and brown hornblende, hypersthene, and glass of andesite groundmass. Minor hematite after pyrite	65–75
Disconformity(?).	
Pre-Lousetown(?) alluvium:	
Silt to coarse sand as large as 2 mm, angular, brown-green, dominantly granitic but much andesite, minor soda trachyte. Fresh silicate minerals less abundant than above, most argillized, but some fresh plagioclase, a little green and brown hornblende and hypersthene. Clay minerals abundant; some pyrite, cubic-octahedral	75–100
Silt, sand, and gravel as large as 1 in., angular to subrounded, gray. Fragments are from granodiorite, andesite, some soda trachyte. All ferromagnesian minerals and much plagioclase argillized; pyrite common in fine-grained aggregates	100–110
Silt, sand, and gravel as large as 1½ in., angular to subrounded, gray, dominantly granitic, abundant andesite, rare non-hot-spring diatoms. All silicate minerals argillized except orthoclase, some plagioclase. Calcite and pyrite common (poorly developed crystal forms), some stibnite crystals as long as 0.1 mm	110–145

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

Mount Rose (1947) well—Con.

	Depth (ft)
Pre-Lousetown(?) alluvium—Con.	
Silt, sand, and gravel as large as about 1 in., angular to subrounded, gray to brown-gray, dominantly granite and andesite, also some cemented sandstone with root casts. All ferromagnesian minerals replaced by clay minerals, plagioclase largely fresh but minor hydrothermal potassium feldspar, clays; original glassy groundmass of some andesite pebbles in part replaced by zeolite. Pyrite common, generally pyritohedral habit; some stibnite(?)	145–160

GS–1 diamond-drill hole[1]

[Near the south end of the Low Terrace, sta. 0, traverse 19; land-surface alt, 4,622.9 ft]

	Depth (ft)
Opaline sinter:	
Interbedded primary and fragmental types. Some opalized plant remains, abundant hot-spring diatoms, minor angular clastic fragments, little altered, from granodiorite, some andesite and Steamboat basaltic andesite. White to gray and green gray with black stains	0–7
Pre-Lake Lahontan alluvium:	
Silt, sand, and gravel as large as 4 in., poorly bedded, largely granodiorite and andesite, but minor fragments of metamorphic rock and Steamboat basaltic andesite; no sinter	7–13
Unconformity.	
Granodiorite:	
Somewhat weathered, decomposed, and iron stained along fractures, prior(?) to thermal activity. Plagioclase largely fresh, biotite fairly fresh, all hornblende altered but little other evidence of hydrothermal alteration	13–43
Generally little altered near top, well altered at bottom but irregular in progression. Nearly fresh near 63 and 99 ft with only about 25 percent of biotite and 50 percent of hornblende altered, plagioclase almost unaffected. Elsewhere all hornblende, most biotite, and some plagioclase altered, largely to argillic minerals. Veinlets of pyrite, mostly cubic, below 44 ft, pyrrhotite at and below 57 ft, and stibnite from 70 to 114 ft; some opal near 44 ft, minor chalcedony at 110 ft, but no major veins or breccia zones; a little replacement calcite (manganiferous?) at 63 ft and below; vein calcite rare. Minor clinozoisite at 99 ft, not related to present hydrothermal activity(?)	43–129
Fault, dip not evident.	
Kate Peak Formation:	
Intrusive(?) tuff-breccia, with textures and original mineral content similar to andesite of Kate Peak Formation except for few fragments of metamorphic rocks and possibly soda trachyte of Alta Formation near base; no granitic fragments except on brecciated contacts. Volcanic rocks completely argillized to soft incompetent rocks, mostly light gray green but some light to medium gray. Kaolinite and montmorillonite are dominant clay minerals but also considerable chlorite, probably a little illite and celadonite. All fragments less than about 2 in. in diameter, angular to subrounded, unstratified. Relict structures indicate some volcanic fragments dense but many pumiceous (some show flattening or stretching of vesicles); a few were glassy, perlitic. Relict forms of euhedral hornblende, augite, hypersthene, olivine(?), rare biotite, and abundant plagioclase recognized. Cubic pyrite abundant, local pyrrhotite; carbonate minor, some quartz in amygdules, possibly in groundmass	129–209
Fault contact, dips 20° (?).	
Granodiorite:	
Contains some dark inclusions, moderately altered, generally with all biotite and hornblende, much plagioclase altered but near 254 ft most biotite and plagioclase fresh. Some breccia zones 209 to 210, 225 to 226, 230 to 233, 246 to 248, 259 ft, but no major veins. Pryite common, considerable pyrrhotite and chlorite on fractures; a little replacement carbonate	209–263
Kate Peak Formation:	
Intrusive(?) tuff-breccia or fault zone with granitic and andesitic fragments, highly sheared and argillized but several types of texture typical of Kate Peak andesite recognizable, as well as soda trachyte of Alta Formation. Dips 15°	263–264
Granodiorite:	
Altered, with moderately dipping breccia zones cemented in part by chalcedony. Silicate minerals replaced by chlorite and calcite	264–271
Kate Peak Formation:	
Same as 263 to 264 ft except textures of volcanic fragments evident but not as well preserved. Dips 35°	271–272
Granodiorite:	
Generally is moderately argillized. All hornblende, much biotite bleached to light gray green; calcic cores of plagioclase crystals argillized. Somewhat fresher near 285 and between 300 and 325 ft. Some hydrothermal calcite, generally in more thoroughly altered rocks; hydrothermal potassium feldspar rare but observed at 271 and 399 ft. Pyrite disseminated and in some veinlets, pyrrhotite with chlorite in others. No major breccia zones or veins but argillic veinlets not uncommon, many showing slickensides. Hydrothermal quartz, chalcedony, and calcite in veinlets but very rare throughout drill hole in comparison with drill holes of Main and High Terraces	272–399

[1] See Sigvaldason and White (1961, p. D117–D119).

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

GS-2 diamond-drill hole [1]

[Crest of the High Terrace, 26 W., traverse 8; land-surface alt, 4,720.8 ft]

	Depth (ft)
Opaline sinter:	
Fragmental type, with common clastic fragments of chalcedonic sinter, minor quartz; opal cemented, white, porous	0–½
Disconformity.	
Post-Lousetown chalcedonic sinter:	
Chalcedonic sinter, white, light to dark gray except for red or pink HgS near top, stibnite below 28 ft. Originally opaline, completely chalcedonized with much silica added to 30 ft, generally not completely chalcedonized below, but remaining opal is cristobalite by X-ray. A few angular clastic quartz grains, with rare hot-spring diatoms recognizable. Some acid attack, reconversion to opal, especially 7 to 9 ft and 16 to 19 ft. Late opal-cemented breccia near 22 ft	½–39
Sinter, in part completely chalcedonized, white to light-gray (52–54 ft), but most is still partly opal (cristobalite), colored mottled white, light to dark gray. Sinter originally consisted of opaline sinter with previously chalcedonized(?) angular to subrounded sinter fragments, perhaps transported from Sinter Hill, cemented by opal and then all partly chalcedonized. Banded cavity fillings at 52 ft dip 9° parallel to relict bedding, indicating some postchalcedony tilting if drill hole assumed to be vertical. Some stibnite, becoming scarce near bottom; banded chalcedony veins with some cubic pyrite. Calcite and hydrothermal potassium feldspar absent	39–75
Normal(?) contact.	
Pre-Lake Lahontan alluvium and post-Lousetown chalcedonic sinter:	
Silt and sand, generally less than 0.5 mm but some coarse sand and gravel as large as 1 cm. Most grains rounded to subrounded, some as small as 0.04 mm (windblown?); fragments consist of chalcedonic sinter (previously chalcedonized?), opaline sinter, granitic debris, some andesite, and possible Steamboat basaltic andesite. Most crystals of plagioclase and biotite, as well as some hornblende and augite, are fresh. Opal (cristobalite) cement to 82 ft, then opal and chalcedony, with first hydrothermal potassium feldspar at 89 ft, largely as euhedral crystals in open spaces. Steep-dipping banded chalcedony veins very abundant	75–90
Clastic sediments similar to above, and some definite hot-spring sinter deposited in place with plant relicts, hot-spring diatoms. Some opaline (cristobalite) fragments not chalcedonized, some chalcedonized elsewhere(?). Dips as much as 40° but cavity fillings indicate no more than 15° of postchalcedonization tilting, possibly local, rotation between faults(?). Cement is opal (cristobalite), chalcedony, and potassium feldspar; chalcedony veins dominant 90 to 93½ ft (probably 2 ft wide, steep at top, flatten downward), 99 to 102 ft (1½ ft wide, 60° to 90° dip)	94–104

[1] See Sigvaldason and White (1961, p. D119–D121).

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

GS-2 diamond-drill hole—Con.

	Depth (ft)
Erosional disconformity(?).	
Pre-Lousetown(?) alluvium and veins:	
Silt, sand, and gravel as large as 1 in., angular to rounded fragments of granitic and metamorphic rocks, andesite, and minor soda trachyte cemented by opal (cristobalite), chalcedony, and minor adularia with clinoptilolite and diaspore (the latter inherited from previous environment?) at 116 ft. Chalcedony veins dominant 104 to 107, 119 to 122 ft, and about equal to clastic debris elsewhere. Veins generally complex, consisting of medium to dark-gray chalcedony, brecciated and cut by light-gray and white chalcedony, quartz, and very minor calcite (first found at 104 ft)	104–123
Disconformity or unconformity(?).	
Kate Peak Formation (or Truckee Formation?):	
Silt, sand, and gravel as large as 1 in., boulders (rare) as large as 1½ ft (at 296 ft). Light to dark gray, green gray generally angular fragments, but a few subrounded to rounded pebbles near top, bottom, and about 190 to 230 ft. Andesitic rocks typical of the Kate Peak Formation completely dominant, but a little clastic quartz at 141 ft, granitic debris and a few metamorphic fragments from about 190 to 230 ft, and increasingly abundant from 317 ft to base of formation. All silicate minerals hydrothermally altered except for part of plagioclase above 200 ft; dominant hydrothermal mineral is replacement potassium feldspar down to 240 ft, decreasingly abundant below; selective argillic alteration of some fragments or minerals throughout, dominant over potassium feldspar below 270 ft; hydrothermal chlorite (corrensite) relatively abundant from about 230 to 340 ft, mixed-layer illite-montmorillonite dominant below 300 ft; some replacement calcite near 240 ft. Fragments thoroughly cemented by chalcedony, fine-grained quartz and potassium feldspar. Pyrite common throughout, with marked tendency for cubic habit in upper part, pyritohedral habit below 220 ft; marcasite generally present above 240 ft; apatite, probably recrystallized, particularly near middle and bottom. Veins and veinlets very abundant, particularly 150 to 198, 213 to 223, 250 to 267, 322 to 333 ft, and also common elsewhere. Veins are commonly complex, consisting of early gray chalcedony brecciated and cut by white to light-gray veins and veinlets; latter are well defined but commonly ramifying, consisting of white to light-gray chalcedony, fine-grained quartz, and calcite. Calcite increasingly abundant downward to center of formation, with first vein largely calcite at 145 ft; from about 185 to 250 ft, approximately half the vein matter is calcite; at greater depths, veins are less abundant, the proportion of calcite to quartz decreases and calcite is nearly absent below 300 ft. Rocks as-	

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

GS-2 diamond-drill hole—Con.

	Depth (ft)
Kate Peak Formation (or Truckee Formation?)—Con.	
signed to Kate Peak Formation because of dominance of andesitic fragments, absence of bedding, and scarcity of stream-rounded pebbles, but may be Truckee Formation without good stratification, abundant rounded pebbles, or identifiable diatomite	123–351
Unconformity.	
Granodiorite:	
Contains reddish iron-stained quartz near top and sporadic to 374 ft, remainder mottled light gray to greenish gray without fresh-looking ferromagnesian minerals (some biotite only slightly bleached). Iron staining and more intimate brecciation near top probably from preandesite weathering. Hornblende completely replaced by clay minerals and pyrite, some quartz; biotite converted to hydrobiotite, with a part only slightly bleached below 365 ft; albitic borders of plagioclase unaltered but andesine cores converted to oligoclase (generally albitic), mixed layer illite-montmorillonite, and potassium feldspar; some replacement calcite below 365 ft. Disseminated pyrite common, generally pyritohedral habit but some cubic near top. No major veins or breccia zones but some veinlets of chalcedony and quartz, and a veinlet of coarse calcite at 390 ft	351–398

GS-3 diamond-drill hole

[Near the crest of the Main Terrace, 4 E., traverse 3; land-surface alt, 4,675.7 ft. Minerals identified optically and by D.T.A.; some incomplete X-ray study]

	Depth (ft)
Pre-Lake Lahontan alluvium and opaline sinter:	
Opaline sinter, nearly white to gray, light brown-gray. Some primary sinter but fragmental type dominant, opal cemented in part, but not well cemented from 3 to 12 ft and in some other parts. Silicified plant remains common, also hot-spring diatoms. Minor clastic quartz except near base, where granitic debris is abundant, with some fragments of Steamboat basaltic andesite. Stibnite at 15 ft (partly oxidized) and below, pyrite below 25 ft	0–26
Silt, sand, and gravel as large as 2 in., angular to subrounded, gray with some light-colored fragments. Largely granitic but some Steamboat basaltic andesite, in part previously acid altered(?)	26–28
Disconformity.	
Pre-Lousetown alluvium:	
Silt and sand dominant but gravel as large as 2 in. at 30 to 31, 45 to 47, and 50 to 51 ft. Rocks are white, light gray, some mottled white and greenish gray. Fragments angular to subrounded, largely granitic but some soda trachyte, particularly near base, and minor fragments of metamorphic rocks. Sinter and Steamboat basaltic andesite are absent. Light-colored rocks are acid altered in place to opal, kaolinite, and other to 51 ft. Stibnite and pyrite present, later than clay minerals, most pronounced at top but some acid alteration	28–51
Unconformity.	
Granodiorite:	
Light gray to gray green, partly opalized (early acid alteration) with later mild greenish alteration (illite-montmorillonite?), pyrite. Veinlets of opal, stibnite, and pyrite	51–54
Gray to gray green, generally relatively fresh with considerable unaltered biotite and plagioclase, but all hornblende altered. More intense greenish alteration (chlorite, illite-montmorillonite, minor potassium feldspar, pyrite) adjacent to veinlets, which consist of opal, chalcedony, stibnite, pyrite (some with hematite) as thick as 4 in., and a few earlier veinlets of chalcedony, chlorite, and pyrite as thick as ½ in.; no stibnite found below 130 ft	54–140
Generally more altered than above to gray-green or cream-colored rocks with most original biotite and all hornblende bleached; plagioclase generally greenish in moderately altered rocks (cores of crystals altered to illite-montmorillonite, chlorite, calcite); chalky white where more intensely altered, disintegrating readily, with principal zones 148 to 151 ft (dip 45°?), 209 to 212 ft (70° dip), 375 to 383 ft (70° dip), 473 to 482 ft (steep dip?), 489 to 509 ft (dip unclear), 553 to 570 ft (steep dip?). These bleached zones generally border chalcedony veins but are related to shear zones without veins near 478 and 560 ft and at other depths. Hornblende altered to mosaic of illite-montmorillonite, quartz, pyrite; biotite rarely fresh, generally partly bleached, pseudomorphed by "hydromuscovite" or chlorite; calcic cores of plagioclase to illite-montmorillonite, "sericite," chlorite, minor potassium feldspar, and calcite where moderately altered, with remaining plagioclase commonly "homogenized" to albite or sodic oligoclase; where alteration is most intense (208–211 ft, 475 ft) plagioclase and even potassium feldspar replaced by illite, perhaps with some illite-montmorillonite and chlorite but little or no calcite; sporadic marcasite, generally with pyrite, above 410 ft. Veins as thick as 8 in. consist of quartz, chalcedony, calcite (174–400 ft, rare at greater depth), minor potassium feldspar (142 ft, 243 ft), pyrite, marcasite (142 ft, 285 ft), chlorite (360 ft, 447 ft, 538 ft), illite-montmorillonite (460 ft)	140–580
Similar to above but in general less altered, with fresh biotite common except near the few veins and shear zones. In moderately altered rocks, calcite more abundant and pyrite less abundant than in equivalent rocks above; biotite generally pseudomorphed by green pleochroic chlorite; original magnetite commonly preserved, or partly oxidized to hematite. Veins rare, consisting of quartz and chalcedony, with calcite at 608 ft but not at greater depths	580–686

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

GS-4 diamond-drill hole

[Main Terrace, 7 E., traverse 3; land-surface alt, 4,664.7 ft]

	Depth (ft)
Opaline sinter:	
At top nearly white to gray; below 20 ft, dark gray with some dark, glassy sinter. Largely opal-cemented fragmental type with low initial dips but some primary sinter, generally with abundant plant casts; geyserite near 16 ft; diatoms common in lower part but poorly preserved. Clastic fragments generally rare, but some angular quartz throughout; granitic debris, fragments of andesite, metamorphic rocks, soda trachyte, and probable Steamboat basaltic andesite abundant from 49 to 51 ft; basal layers also include older acid-altered fragments from below contact. Opaline sinter in part chalcedonized below 20 ft, in place(?). Stibnite below 9 ft, some Sb oxides above; pyrite below 16 ft	0–51
Disconformity or slight unconformity.	
Pre-Lousetown alluvium:	
Dominantly silt, sand, and fine gravel, angular to subrounded, fragments seldom larger than 1 cm above 100 ft in depth but as large as 1½ in. in lower part; dominantly granitic but some soda trachyte throughout, minor metamorphic fragments in upper part, andesite in lower part; Steamboat basaltic andesite not found. Color white to light gray near top from acid leaching earlier than opaline sinter; generally light-gray, greenish-gray, or light mottled colors below. Opal is dominant replacement mineral near upper contact, with increasing kaolinite below, and recognizable acid alteration to about 67 ft. Illite-montmorillonite then becomes dominant clay mineral but most plagioclase unaltered to 95 ft, where hydrothermal potassium feldspar becomes abundant. Pyrite is common throughout, stibnite from upper contact to 90 ft, rare or absent below; veinlet of pyrite of radial habit after marcasite(?) at 67 ft, vein calcite at and below 131 ft (none above), a few white chalcedony veinlets in middle and lower part; no major veins or crush zones. Bedding uncommon but some initial(?) dips as much as 30°	51–149
Unconformity, contact dips 15°.	
Granodiorite:	
Moderately to strongly altered rock, no relatively fresh rock as in GS-3, nor much greenish alteration like the dominant type in GS-3. In most abundant bleached type, plagioclase largely replaced by illite-montmorillonite, chlorite, potassium feldspar, except for soidc rims; below 400 ft, part of plagioclase replaced by illite-montmorillonite, remainder albitized; hornblende and biotite entirely replaced by illite-montmorillonite and chlorite. Hydrothermal pyrite common throughout, replacement calcite rare. Principal zones of intense bleaching and alteration: 192–203 ft (60° dip), 208–221 ft (70°?), 246–263 ft (50° to 60°), 346–374 ft (70°?), 398–403 ft (75°?), 409–413 ft (65°?), 427–452 ft (unclear—10°-60°?), 472–476 ft (60°?). Some bleaching very obviously related to chalcedony-calcite veins but much may be related to shear zones without major veins; principal shear zones near 400, and 430–452 ft. Veins largely white chalcedony, generally containing calcite, rare pyrite at 159-160 ft (70°); 181–185 (50°); 188–190; 198–200; 211–212 (70°); 226–230 (88°); 323–327 (87°); 334–337; 395; 466–467; calcite uncommon near top, most abundant 195–350 ft; veins decrease below 350 ft and are rare below 400 ft; minor hematite and pyrite near top and bottom	149–150

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

GS-5 diamond-drill hole[1]

[Main Terrace, 400 ft N. of GS-4; land-surface alt, 4,661 ft]

	Depth (ft)
Opaline sinter:	
White, gray, and nearly black opaline sinter, in part geyserite and other primary sinter types but much opal-cemented fragmental sinter. With increasing depth the color is generally darker, porosity decreases, chalcedonization of opal increases, and remaining opal gives increasingly sharp X-ray patterns of β-cristobalite. Clastic fragments rare but some angular granitic debris, very rare andesite, soda trachyte(?), and metamorphic fragments; hot-spring diatoms, plant remains generally rare, poorly preserved, but locally common in middle and lower part. Stibnite below 11 ft, chalcedony below 19 ft as cavity fillings and below 28 ft as incipient chalcedonization of opal. Veinlet of opal (β-cristobalite) at 73 ft, minor vein calcite at 84 ft, none above; potassium feldspar absent	0–80
Disconformity(?).	
Chalcedonic sinter:	
Clastic deposits and chalcedonic sinter with silicate minerals and part of chalcedony opalized by acid attack prior to deposition of sinter, originally opaline type but now largely chalcedonized. Remaining opal gives sharp cristobalite X-ray pattern	80–84
Disconformity or unconformity.	
Pre-Lousetown alluvium:	
Dominantly silt, sand, fine gravel but locally gravel up to 15 mm; some drill core shows bedding, dips near 30°; fragments angular to subrounded, dominantly granitic with minor soda trachyte, metamorphic rocks; no recognizable sinter, diatoms, andesite or Steamboat basaltic andesite. Hydrothermally altered but hard, with acid leaching absent at upper contact; chalcedony-adularia cement, considerable replacement of plagioclase by potassium feldspar, some illite-montmorillonite, chlorite; remaining plagioclase altered to albite or sodic oligoclase. First chalcedony vein at 85 ft, none above; calcite is part-	

[1] See Sigvaldason and White (1962).

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

GS-5 diamond-drill hole—Con.

	Depth (ft)
Pre-Lousetown alluvium—Continued	
ly leached at 112 ft, absent above; some stibnite to 94 ft, none seen below. Greenish masses of chalcedony, illite-montmorillonite, pyrite, generally with octahedral(?) habit; marcasite(?) common below 121 ft—probably veins but may be replacement of volcanic rocks with no evident relict textures	84–135
Unconformity(?).	
Kate Peak Formation:	
Andesitic tuff-breccia and possibly flow breccia hydrothermally altered, mottled light reddish-gray; gray and gray-green fragments with green-gray matrix. Original silicate minerals replaced by potassium feldspar, chalcedony, chlorite, illite-montmorillonite, pyrite, some marcasite. Abundant veins at 135–136 ft, 140–152 ft, largely chalcedony, quartz, some calcite, dipping 75°–80°	135–154
Unconformity.	
Granodiorite (and veins):	
Granodiorite at top, largely mottled, reddish, with hematite-stained quartz 154–162 ft, 171–173 ft, and slight staining 167–181 ft, 194–196 ft, 317–319 ft, and a little at other depths. Down to about 200 ft, much granodiorite is green, with chlorite fairly abundant, particularly as replacement of ferromagnesian minerals and as tiny veinlets in feldspar; illite-montmorillonite abundant near unconformity and below 200 ft, where most granodiorite is bleached, generally with light-colored inconspicuous relicts of ferromagnesian minerals, chalky argillized plagioclase (except for albitic borders). Some albitized plagioclase and replacement calcite below 400 ft. Pyrite is common, almost always cubic but some octahedral(?) in upper part. In shear zones, 379–402 ft (dip unclear), and particularly 452–465 ft (65° dip?), most granodiorite is "rotten," disintegrates readily, but some cemented by chalcedony and fine-grained quartz. Veins particularly abundant, dominantly chalcedony near top, calcite abundant below 174 ft; thickest veins at 181–192 ft (5 ft thick, dip 65°±), 324–326 ft (45° dip), 337–354 ft (7–8 ft thick, avg dip 65°), 357–370 ft (dip unclear; probably at least 4 ft thick), 383–388 ft (dip unclear; mostly very coarse-grained calcite), 393–395 ft, 434–436 ft (45° dip). Largest vein quartz crystals of area between 181 and 192 ft, as much as 7 mm in length, 1 mm in diameter, euhedral, rarely with basal pinacoid crystal form; coarsest calcite of area between 357 and 388 ft	154–465
Fault and intrusive contact, dip 65° (?).	
Kate Peak Formation:	
Dike, light-gray to greenish-gray porphyritic volcanic rock, highly argillized with no original minerals remaining. Original plagioclase phenocrysts as much as 5 mm in diameter; relict shapes of biotite, hornblende, and pyroxene also recognized. Hydrothermal minerals include illite-montmorillonite, "sericite" (with optical properties close to muscovite), chlorite, potassium feldspar, and pyrite, generally in well-formed cubes. Original rock was biotite-hornblende-pyroxene andesite dike with a few rounded inclusions. Contact of coarse-grained rock against chilled andesite at 524 ft, dipping 75°	465–525
Fault and intrusive contact, with brecciated granodiorite fragments in breccia zone; dip unclear.	
Alta Formation:	
Nearly white argillized dike or extrusive volcanic rock with relict low-dipping (30°) planar structure resembling that of soda trachyte of Alta Formation. Phenocrysts inconspicuous but recognizable relict forms of plagioclase and hornblende, more abundant than in normal soda trachyte. Hydrothermally altered to illite-montmorillonite, "sericite," albite, quartz, chlorite, cubic pyrite, apatite, and calcite; cut by veinlets of red hematite and of calcite. Basal breccia contains iron-stained quartz	525–546
Fault contact, brecciated, dipping 50°.	
Granodiorite:	
Generally somewhat bleached, hydrothermally altered to illite-montmorillonite, albite, chlorite, calcite, minor pyrite (cubic?), hematite. Freshest granodiorite of hole at 562 ft, with biotite mostly fresh (some altered to chlorite), hornblende entirely argillized, plagioclase partly altered to illite-monmorillonite, "sericite," and calcite. Reddish quartz with hematite in places	546–572
Kate Peak Formation:	
Breccia zone containing fragments of granodiorite and hornblende andesite with texture similar to that at 500 ft, hydrothermally altered to illite-montmorillonite, "sericite," chlorite, albite, calcite, pyrite	572–573
Granodiorite:	
Contains chalky plagioclase and conspicuous ferromagnesian relicts, similar to 546 to 572 ft, with illite-montmorillonite, "sericite," albite, chlorite, calcite, and very minor pyrite (not cubic?)	573–575

GS-6 diamond-drill hole

[Sinter Hill, 10 E., traverse 9 and 0, traverse 24; land-surface alt, 4,837 ft. Minerals identified optically and by D.T.A.; some incomplete X-ray study]

	Depth (ft)
Post-Lousetown chalcedonic sinter:	
Sinter, white to gray, largely low in porosity, chalcedonized; opaline sinter, still porous fragmental type and only partly chalcedonized but remaining opal is cristobalite by X-ray, 4–10 ft, 48–50 ft, and to some extent at other depths. Angular clastic quartz and potassium feldspar grains from granodiorite are rare, no fragments of rocks other than sinter found; some hot-spring dia-	

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

GS–6 diamond-drill hole—Con.

	Depth (ft)
Post-Lousetown chalcedonic sinter—Con.	
toms, poorly preserved. Relict bedding nearly horizontal at top, increasing below to maximum of 15° near 18 ft but gravity-controlled chalcedony fillings indicate initial dips, with no post-chalcedony tilting. Steep-dipping chalcedony veinlets and later dark glassy opal (cristobalite) veinlets common 31–45 ft; minor cinnabar in chalcedony veinlet at 31 ft, none seen at other depths	0–50
Disconformity (?).	
Pre-Lake Lahontan alluvium:	
Silt, sand, and fine gravel, with some pebbles as large as 20 mm near 68 ft and near base, generally angular but some subrounded. Acid altered near top, generally white to cream in color, gray below with some mottling and iron staining in middle part. Faint bedding near top with dips as much as 30°. Recognizable fragments largely granitic but andesite is abundant; some metamorphic rocks and partly chalcedonized sinter, rare soda trachyte; Steamboat basaltic andesite abundant in basal 12 ft; a few fragments of probable petrified wood at top and near 72 ft; fragments of rhyolitic rocks with quartz phenocrysts, probably not from Steamboat rhyolite dome, 72 to 76 ft. Opalized silicate minerals from acid attack pronounced at top, decreasing downward but recognizable to 78 ft, accounting for much of the color variations, with alunite veinlets frequent from 74 to 78 ft. Chalcedony abundant below 70 ft, and adularia, chlorite, celadonite at 80 ft and below; minor relict forms of bladed calcite, now leached, recognized at 88 ft; pyrite and marcasite common in lower part, rare or absent near top	50–91
Contact, gradational in proportion of rock types.	
Steamboat basaltic andesite of Lousetown Formation:	
Lava flow with scoriaceous aa flow top grading down into massive lava with few amygdules below 98 ft. Fragments at top are in matrix of extraneous clastic grains, largely angular quartz less than 0.4 mm in diameter, probably windblown. Lava is light to dark green gray and gray, some is bleached to light green and tan near 111 ft (local acid attack; fig. 17), cut by veinlets, generally with red jaspar, pyrite or marcasite; some opal, pyrite, and stibnite. In thin section, relict textures are those of Steamboat basaltic andesite, although generally almost completely replaced by potassium feldspar (as much as 10.9 percent K_2O in total, fig. 20) with some illite-montmorillonite, chlorite, celadonite, marcasite and pyrite. A zone of acid-alteration with kaolinite, opal, alunite, and illite-montmorillonite locally near 110–113 ft. At 109 ft a zone dipping 45°–60° contains acid altered fragments, largely granitic, but some opaline and chalcedonic sinter, soda trachyte and other clastic fragments; this is probably a fault zone with a clastic dike, but could be clastic sediments between two flows; the absence of adjacent scoriaceous zones makes fault with clastic dike more probable	91–133
Disconformity.	
Pre-Lousetown alluvium:	
Silt, sand, and abundant gravel, largely fine grained to 143 ft but as large as 2 in. at 134 ft and 3 in. between 143 and 150 ft. Fragments largely granitic and soda trachyte but andesite is common, some metamorphic rocks; fragments are angular, rarely subrounded; no apparent bedding. Light gray and tan in color near top and bottom, mottled red, red gray, and gray near middle. Alteration minerals are largely chalcedony, potassium feldspar, illite-montmorillonite, chlorite, celadonite, some pyrite and marcasite	133–160
Unconformity or disconformity.	
Alta Formation:	
Felsitic lava containing a few small relicts of plagioclase laths replaced by potassium feldspar and illite-montmorillonite; faint planar structure dipping about 5°–10°. Colors are gray, green gray, and red gray. Microscopic relict textures of soda trachyte of Alta Formation. Completely altered but hard, replaced by potassium-feldspar (K_2O, 8.7 percent of rock), illite-montmorillonite, and chalcedony, and cut by veinlets of chalcedony and potassium feldspar, with common marcasite and pyrite. Basal foot or more is argillized fine-grained tuff, probably pyroclastic soda trachyte	160–170
Silt, sand, and fine gravel, angular, white, consisting entirely of granitic debris. Hydrothermally altered to illite-montmorillonite, chalcedony, potassium feldspar	170–177
Unconformity.	
Granodiorite:	
"Rotten" near top, with thoroughly argillized plagioclase and hornblende, but generally some nearly fresh biotite, some only slightly bleached. Plagioclase near top replaced by kaolinite, with illite-montmorillonite dominant in middle part and potassium feldspar near bottom. Calcite is absent, chlorite very rare; pyritohedral pyrite rather common but some hematite, unreplaced magnetite. Rare aplite dikes show little or no hydrothermal effects	177–210

GS–7 diamond-drill hole[1]

[Silica pit area south of 49 W., traverse 1; land-surface alt, about 5,025 ft]

	Depth (ft)
Granodiorite:	
Intensely leached by sulfuric acid, leaving white porous residue of original quartz plus opaline relicts of silicate minerals. Porosity is particularly high near top, decreases irregularly down-	

[1] See Sigvaldason and White (1962).

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

GS-7 diamond-drill hole—Con.

	Depth (ft)
Granodiorite—Con.	
ward. Opal is cristobalite by X-ray near top, amorphous below. Minor barite at 20 ft and 111 ft; a little cinnabar at 30–32 ft; cubic pyrite below 55 ft, not disseminated as in most drill core but concentrated in veinlets and pores near veinlets; anatase from original titanium. Relict evidence of former kaolinite and alunite recognized at 68 ft and below, now entirely replaced by opal	0–112
Approximate recently prevailing water level, probably fluctuating.	
Granodiorite:	
Effects of acid alteration and bleaching apparent near top, decreasing downward with argillic alteration below. At 114 ft alunite and nearly all kaolinite were opalized (opal amorphous to X-rays), retaining relict structures and with pyrite largely disseminated in relict ferromagnesian minerals and plagioclase. Opalization becomes negligible near 120 ft, where all silicates including orthoclase and sodic plagioclase replaced by potassium alunite and a little kaolinite. At 127 ft all silicates replaced by potassium alunite except for very minor completely fresh biotite and orthoclase protected as inclusions in quartz. From 130 to 145 ft kaolinite is dominant replacement mineral; no alunite below 133 ft; no montmorillonite above 135 ft. Below 145 ft montmorillonite is the dominant hydrothermal mineral, with some illite, cubic pyrite, and local calcite; relict biotite becomes conspicuous, a little apparently fresh, most somewhat bleached but strongly pleochroic. Most granodiorite disintegrates readily, in contrast to that of other drill holes, because of abundance of montmorillonite and scarcity of illite; no definite evidence that montmorillonite-type alteration orginially extended up to present water table prior to acid alteration	112–253
Intrusive contact.	
Kate Peak Formation:	
Completely argillized volcanic dike containing relicts of hornblende phenocrysts about 2 mm and less in diameter, plagioclase as large as 1½ mm; most is white to light gray, but gray to green gray from 267 to 289 ft. The light phase is almost entirely montmorillonite with rare disseminated pyrite but with quartz and fine-grained potassium feldspar (from devitrification?) in groundmass. The dark phase contains abundant calcite (iron-manganese variety) and chlorite; pyrite is common in and next to veinlets, not much is disseminated. Dark phase also has amygdules, may be borders of multiple intrusions. Abundant relict cubes throughout dike. may be from leached early pyrite; replacement is alunite(?), abundant at 264 ft and some below—if alunite, apparently deep, perhaps unrelated to near-surface acid alteration	253–329
Intrusive contact.	
Granodiorite:	
Most of plagioclase and all hornblende replaced by montmorillonite and some sericite ($n \approx 1.55$) and chlorite; biotite largely replaced by clear blue-green pleochroic chlorite; pyrite rather rare, calcite local, hydrothermal potassium feldspar minor or absent. Relatively fresh granodiorite at 358 ft	329–402

GS-8 diamond-drill hole

[Base of Main Terrace, 10 E., traverse 3; land-surface about 4,606 ft. Minerals identified optically and by D.T.A.; minor X-ray study]

	Depth (ft)
Opaline sinter and pre-Lake Lahontan alluvium:	
Opaline sinter, light-colored, largely fragmental but some primary sinter. Few grains of andesite of the Kate Peak Formation, rare granitic debris, some diatoms, plant casts	0–20
Silt, sand, and gravel at least as large as 3 in. at 21 ft, brown-gray with partly oxidized pyrite to 22 ft and a little to 28 ft; generally green-gray with fresh pyrite in lower part. Fragments largely granitic and Kate Peak andesite but also common metamorphic fragments, opal cemented. Some argillic alteration, particularly of fine clastics, but some fresh augite, hornblende. Some granodiorite fragments altered prior to deposition(?)	20–31
Opaline sinter, largely fragmental but a little primary, with plant casts. Some granitic and andesitic fragments, hot-spring diatoms, minor fresh hypersthene, basaltic hornblende. Some sinter fragments partly chalcedonized	31–40
Silt, sand, and gravel, opal-cemented, mostly fine grained but as large as 1½ in. near central part, generally unstratified but some near top dipping as much as 30°. Color gray green to gray. Fragments angular to subrounded, granitic, andesitic, metamorphic, rare Steamboat basaltic andesite, opaline sinter, diatoms. Ferromagnesian minerals altered except for a little biotite; plagioclase generally fresh except where previously(?) altered. Pyrite rare; a little stibnite on fractures near 60 ft	40–60
Opaline fragmental sinter, gray to greenish-gray, partly chalcedonized in place(?). Fragments of minor granitic and andesitic rocks and hot-spring diatoms. Some stibnite, but pyrite rare or absent	60–62
Silt, sand, and fine gravel, gray-green, fragments largely angular, unsorted; cut by chalcedony-pyrite veinlets, with pyrite of spherulitic habit	62–72
Silt, sand, and gravel as large as 3 in., gray-green to gray, angular to subrounded, largely fragments of scoriaceous Steamboat basaltic andesite, and granitic debris, minor andesite, soda trachyte, metamorphic rocks and non-hot-spring diatoms. Cemented by opal and montmorillonite with some celadonite in amygdules. Silicate minerals argillized except for some feldspar. Pyrite disseminated and in veinlets. Some Steamboat basaltic andesite fragments opalized from previous acid alteration(?)	72–81

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

GS-8 diamond-drill hole—Con.

	Depth (ft)
Disconformity (?).	
Pre-Lousetown (?) alluvium:	
Clay, silt, and sand with some angular to rounded gravel as large as 15 mm near 95 ft, in part well-bedded, yellow-brown to blue-gray, well-cemented by illite-montmorillonite and opal (cristobalite). Largely fragments of andesitic and granitic rocks; a few fragments doubtfully of Steamboat basaltic andesite to 95 ft, none found below. Plagioclase generally fresh but all ferromagnesian minerals argillized, pyrite rare. A few fragments were previously (?) acid altered. A few diatoms at 93 ft; three living species of which one is characteristic of hot springs (USGS diatom loc. 4184; identifications by K. E. Lohman, 1958)	81–95
Dominantly silt and sand, relatively well sorted, uncemented except for some argillic minerals; little core recovered. Granitic fragments recognized; probably some volcanic rocks, completely argillized. Pyrite rare	95–127
Arkosic silt and sand as large as 2 mm, angular, unsorted, tan, poorly cemented by argillic minerals. Fragments dominantly granitic, andesitic, metamorphic, with some soda-trachyte (?). Most plagioclase, all ferromagnesian minerals argillized. Pyrite rare	127–130

Auger hole 1

[3.8 W., traverse 9, Sinter Hill]

	Temp (°C)	Depth (ft)
Thin layer of alluvium underlain by opalized pre-Lousetown alluvium, some residual quartz	76. 1	2. 0
Same, minor HgS	87. 2	4. 0
Same, few crystals native S	93. 1	6. 2
Do	96. 4	8. 0
Too rocky for further drilling	96. 4	8. 8

Auger hole 2

[10 ft SW. of 3W., traverse 9, Sinter Hill]

	Temp (°C)	Depth (ft)
Opalized pre-Lousetown alluvium, some HgS	76. 7	1. 4
Greenish-gray altered fragments, some sinter	94. 2	4. 0
Do	95. 7	5. 9
Same, with black material (carbonized wood?)	95. 9	6. 6

Auger hole 3

[15 E., traverse 3 near Steamboat Creek]

	Temp (°C)	Depth (ft)
Sinter fragments overlying hard opaline sinter	----	1. 1

Auger hole 4

[16 E., traverse 3 near Steamboat Creek]

	Chloride (ppm)	pH	Conductance	Temp (°C)	Depth (ft)
Brown and tan silt and gravel	-----	----	---	----	0–6. 5
Water level, July 7, 1949, in fine black silt	-----	----	---	----	6. 5
Fine brown sand	1, 300	7. 27	455	29. 4	8. 4

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

Auger hole 5

[18 E., traverse 3 near Steamboat Creek]

	Chloride (ppm)	pH	Conductance	Temp. (° C)	Depth (ft)
Well-sorted brown sand	-----	----	---	----	6. 5
Water level, July 7, 1949 in dark coarse sand	-----	----	---	----	7. 75
Fine gravel	-----	----	---	33. 7	8. 4
Sand	1, 164	7. 10	413	34. 4	9. 4

Auger hole 6

[In 5-ft pit, 30 ft SE. of GS-3 drill hole, Main Terrace]

	Chloride (ppm)	pH	Conductance	Temp. (° C)	Depth (ft)
Sinter and uncemented sinter fragments	-----	----	---	----	0–9. 4
Water level, Sept. 22, 1949 (below ground level)	-----	----	---	----	9. 4
Sinter	120	5. 70	87	43. 7	9. 7

Auger hole 7

[500 ft N. of crest of Sinter Hill]

	Chloride (ppm)	pH	Conductance	Temp. (° C)	Depth (ft)
Small basin in chalcedonic sinter overlain by opaline sinter; collapse due to acid leaching at depth(?)	-----	----	---	47. 8	3. 9

Auger hole 8

[100 ft NW. of 51W., traverse 8, NW. of Sinter Hill in old mud-volcano area]

	Soil pH	Temp (° C)	Depth (ft)
Brown silt and sand. Here and below, probably alluvium and mud-volcano breccia, reworked by young mud volcanoes	----	49. 0	1. 0
Red sand, gravel	3. 5	----	2. 0
Cream-colored gravel, sand	----	70. 6	3. 0
White kaolinitic silt, sand	----	----	6. 1
Do	2. 9	----	7. 0
Do	----	93. 3	10. 0
Blue-gray sand and clay with pyrite	3. 4	----	12. 5
Blue-gray clay with pyrite	2. 9	----	13. 5
Do	----	95. 2	14. 0

Auger hole 9

[In depression near 70.5W., traverse 8]

	Soil pH	Temp (° C)	Depth (ft)
Brown clay	----	----	4
Depression fill in sinter (not mapped as distinct unit)	----	28. 0	7. 8
Yellow-brown sandy clay	6. 3	----	10
Pinkish-red sandy clay	5. 8	34. 1	13. 8

Auger hole 10a

[SE. corner of clay quarry]

	Temp (° C)	Depth (ft)
White kaolinite (altered basaltic andesite)	32. 2	1. 3
Yellowish opal and kaolinite	39. 3	2. 2

Auger hole 10b

[8 ft E. of 10a, SE. corner of clay quarry]

	Temp (° C)	Depth (ft)
Yellowish kaolinite and opal (altered basaltic andesite)	40. 1	2. 8
Opal, some clay	51. 6	4. 0

Auger hole 11

[In pit 11½ ft deep, 250 ft N. of 3W., traverse 3]

	Temp (° C)	Depth (ft)
Brown and gray clay, sand, and gravel; pebbles as large as 3 in	----	0–6
Brown sand, clay, and gravel as large as 1 in	----	6–10. 5
Yellowish green arkosic sand, clay, fine gravel; gypsum common	----	10. 5–11. 5
Same but more cemented, gray-green; several pebbles of Steamboat basaltic andesite	----	11. 5–13
Do	25. 3	13

TABLE 3.—*Logs of wells, drill holes, and auger holes*—Con.

Auger hole 12

[In pit 15 ft deep, 75 ft N. of 11]

	Chloride (ppm)	*pH*	*Conductance*	*Temp (° C)*	*Depth (ft)*
Water level Nov. 3, 1949	---	---	---	----	15.4
Red-brown clay, sand, and gravel	---	----	---	28.9	16.5
Do	---	----	---	31.9	17.9
Do	88	6.59	87	32.3	18.4

Auger hole 13

[In trench 5.2 ft deep, 125 ft N. of 1W., traverse 3]

	Chloride (ppm)	*pH*	*Conductance*	*Temp (° C)*	*Depth (ft)*
Brown and tan sand and silt	---	----	---	----	0–2
Yellow-brown and greenish sand and silt	---	----	---	----	2–5
Temp 0.8 ft into wall, bottom of trench	---	----	---	17.9	5.2
Dark greenish-gray silt	---	5.8	---	----	7.0
Do	---	----	---	24.4	7.3
Dark greenish-gray clay	---	5.3	---	----	7.7
Dark greenish-gray gravel, as large as 1 in	---	6.1	---	29.7	8.6
Dark greenish-gray sand	---	7.1	---	----	10.0
Water level Oct. 24, 1949 and Nov. 4, 1949	---	----	---	----	10.2
Gas seeping through water	---	----	---	33.6	10.5
Water sample, Nov. 4, 1949	352	5.78	208	34.6	11.2

The granodiorite is extensively altered and weathered throughout most of the thermal area. The freshest rock is 600 to 1,000 feet northwest of the Steamboat Resort (pl. 1). Here, joints are more widely spaced than usual and hydrothermal alteration is slight. The surface is strewn with huge boulders as much as 20 feet in diameter, which stand above the ground surface because of their resistance to erosion. They are believed to be the cores of huge joint blocks that were formed by weathering controlled by the joint intersections. Where original jointing was closely spaced, boulders are not found and the granodiorite is disintegrated to an average depth of 20 feet or more and is now a coarse arkosic sand.

Granodiorite is hydrothermally altered in most of the drill core obtained from depth (figs. 3 and 4). Near-surface bleaching has resulted from attack by sulfuric acid formed by reaction of atmospheric oxygen with H_2S from the thermal waters. The chemistry of this alteration has been summarized elsewhere (White, 1955a, p. 106–108, 111; 1957a, p. 1651–1652; Sigvaldason and White, 1962). Bleaching and acid attack occur only where the water table is at or below the surface. Areas where the action has been conspicuous are indicated on plate 1 by an overprint pattern. Although this near-surface alteration is by no means confined to granodiorite, bleaching is particularly characteristic of many exposures of this rock. The contrasts in vegetation as related to differences in acidity of the soil are similar to those of the bleached areas of the Virginia Range described by Billings (1950). Other types of alteration have resulted from reaction of thermal waters with granodiorite and other rocks below the water table. All these changes will be considered in detail elsewhere.

As mentioned previously, granodiorite is in contact with older metamorphic rocks southwest of the Steamboat Resort. Although exposures are poor, the contact is relatively sharp; if a gradation exists, it is over a narrow zone of perhaps a few feet. Dark inclusions are more abundant in granodiorite near the contact, and the adjacent metamorphic rocks are at least locally coarser grained than elsewhere.

The general strike of the contact is a little north of west, almost at right angles to relict bedding in the metamorphic rocks. This crosscutting relation and the absence of a marked gradational contact are evidence that granodiorite was very probably intruded into its present position and was not formed by granitization of the metamorphic rocks.

FIGURE 3.—Panorama looking west to north across Pine Basin. On the left basaltic andesite overlying acid-leached granodiorite is displaced by a fault. Sinter Hill on the right is underlain by chalcedonic and opaline sinter. Pine trees grow on areas underlain by a variety of rocks, most of which are leached by sulfuric acid produced by near-surface oxidation of H_2S.

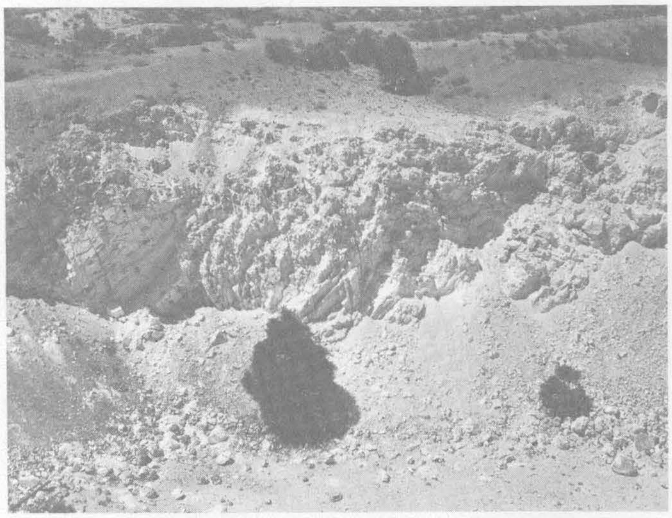

FIGURE 4.—Granodiorite in west wall of silica pit, intensely leached by sulfuric acid produced by oxidation of H_2S. Note perfect preservation of original jointing even though nearly 60 percent of the original mass of the rock has been removed (present bulk specific gravity is about 1.15).

A few dikes of aplite and a very few of pegmatite cut the granodiorite. Most of the dikes are too small to distinguish on the map, but a few are shown (pl. 1). In places the aplite dikes contain a local pegmatitic phase. Aplite is considerably more resistant to weathering than granodiorite. It commonly breaks down into joint blocks, whereas, under similar conditions granodiorite completely disintegrates into arkosic sand. This fact is useful in mapping poorly exposed contacts between granodiorite and basaltic andesite.

Textural and mineralogical characteristics are very useful in studying hydrothermal alteration of the granodiorite. The texture is typical hypidiomorphic granular; much of the biotite and hornblende are euhedral; some plagioclase and a little orthoclase are subhedral, but most feldspar and all quartz are anhedral. Orthoclase is euhedral only in contact with quartz; euhedral borders of plagioclase are common in contact with both orthoclase and quartz. Of the accessory minerals, apatite and zircon are euhedral to subhedral, magnetite is euhedral to anhedral, and sphene, tourmaline, and rare clinozoisite are generally anhedral.

In hand specimen the grain size averages about 2 mm but hornblende needles are as long as 5 mm and white to light-pink orthoclase crystals as long as 1 cm. Under the microscope the grain size has no obvious lower limit; cloudy indeterminate inclusions in plagioclase and other minerals are submicroscopic in size, and small grains of quartz and other minerals are rather commonly distributed along the grain boundaries of larger crystals.

Modal analyses of individual thin sections of three samples of analyzed granodiorite (table 2) show 22 to 30 percent quartz, 10 to 20 percent perthitic orthoclase (in part microcline), 43 to 47 percent plagioclase, 5 to 10 percent biotite, 3 to 6 percent hornblende, and 1½ to 2 percent accessory minerals.

Chemical analyses and norms of the same three samples, representative of granodiorite of the nearby region, are shown in table 1. The analyses show less variation in bulk chemical composition and mineral proportions than is indicated by the modes, because the mineral distribution is not uniform within individual thin sections, and sufficiently large samples for good modal analyses were not taken. The presence or absence of a single large crystal of orthoclase, for example, can account for most of the differences in the modal analyses. All three of these rocks fall within the range of granodiorite but analysis 4 (W420a), with normative plagioclase nearly three times as abundant as orthoclase, is not far from quartz diorite. This is not surprising in view of the fact that the sample consists of inclusion-free material collected from an outcrop that also contains numerous dark schlieren or inclusions ranging from a few inches up to several feet in length. Analysis 5 (W420b) (tables 1 and 2) is representative of these inclusions, in which biotite, hornblende, and plagioclase are relatively more abundant than in normal granodiorite, and the composition is quartz diorite. Reaction between inclusions and granodiorite may account for the fact that analysis 5 (W420b) approaches the composition of a diorite.

The normative composition of the plagioclase of the inclusion (An_{38}) is significantly different from that of the metatuff (An_{20}) of analysis 1 (W421 table 1). If these analyses are typical of the respective rocks, the inclusions are probably not from granitization of the metamorphic rocks; although their origin is not clear, they may be related to an earlier dioritic phase of the batholithic rocks, perhaps carried up from depth.

The granodiorite and related rocks are very similar, megascopically and also microscopically, to rocks underlying large areas in the Carson Range and in the main Sierra Nevada (Bateman and others, 1963). Structural and stratigraphic relations of the granodiorite to Mesozoic and lower Tertiary rocks are also similar. Granodiorite and related rocks of the Steamboat Springs area are therefore considered to be a part of the series of rocks that are known as the Sierra Nevada batholithic complex, which is Cretaceous in age (Curtis and others, 1958).

TERTIARY ROCKS

Regional study (Thompson and White, 1964) has shown that rhyolitic welded tuffs lie at the base of the Tertiary rocks in and south of the Virginia City quadrangle, but if they were originally present in the Mount Rose quadrangle and Steamboat Hills they have since been removed by erosion. Lying on and intertonguing with the rhyolite tuffs in the Virginia City quadrangle is the thick volcanic complex of the Alta Formation, but the only member of the Alta recognized in or near Steamboat Hills is a soda trachyte. This rock crops out east of the Low Terrace (pl. 1) and has also been identified in drill holes (pl. 2; table 3, GS–6 drill hole; and in the Senges well).

The Kate Peak Formation is the thickest and most extensive volcanic unit of the region. Flows and tuff-breccias are abundant in many places, and are the dominant rocks in the western part of Steamboat Hills. Rocks of the Kate Peak are exceedingly scarce at the surface of the thermal area but dikes and tuff-breccias have been cut at depth in at least four drill holes (pl. 2, and table 3, drill holes GS–1, –2, –5, and –7).

The Truckee Formation, which intertongues regionally with and overlies the Kate Peak, is composed largely of clastic debris from the Kate Peak Formation, and locally contains abundant diatomite. The Truckee is abundant in parts of the region but has not been identified in the thermal area.

ALTA FORMATION

The only rocks exposed in the thermal area that are correlated with the Alta Formation are trachytic lava flows in the hill immediately east of the Low Terrace (pl. 1 and secs. *E–E′* and *F–F′*, pl. 2). These soda trachyte lavas (analysis 7 (W355), table 1) are not similar to any volcanic rocks of the type locality of the Alta but Thompson has mapped them as a phase of the Alta within the limits of the Virginia City quadrangle (Thompson, 1956, p. 51), and they have also been recognized in western Steamboat Hills (Thompson and White, 1964).

Similar trachytic rock was penetrated by GS–6 drill hole (sec. *I–I′*, pl. 2; table 3, GS–6 drill hole) and the Senges well near the east edge of the High Terrace (pl. 1). Core samples from the drill holes indicate extensive hydrothermal alteration, generally with abundant potassium feldspar as a replacement of plagioclase, but relict textures are very similar if not identical to those of the soda trachyte flows that crop out in nearby areas.

The soda trachyte east of the Steamboat Resort is blue gray to purple gray. Megascopically, small white plagioclase laths averaging about 3 mm long in a trachytic groundmass of alined tiny feldspar laths characterize most of the rocks, but are absent in some. Relict outlines of hornblende phenocrysts, marked by abundant tiny magnetite crystals, are distinguishable in some rocks.

The phenocrysts are alined but the resultant flow structure is obscured by prominent platy parting that generally intersects the flow structure at moderate angles. Red iron oxide is commonly concentrated on the fractures that cause the parting. Some rocks show two systems of parting, neither of which is necessarily parallel to the flow structure. Non-porphyritic rocks near the crest of the hill east of the Low Terrace are characterized by fine banding resulting from concentrations of iron oxide in the partings.

The soda trachyte of northwestern Steamboat Hills is generally light to medium purple gray and contains sparse but conspicuous small plagioclase phenocrysts that average about 2 mm in length. A few needles of hornblende with reaction borders, and plates of biotite can usually be distinguished. A single system of thin platy partings characterizes most of the rocks. Upon close inspection, the parting is seen to cut the primary flow structure at angles that average about 45°.

Another phase of the soda trachyte rarely found in place is subvitreous and black except for conspicuous sparse white plagioclase phenocrysts about one half mm long; a few crystals of hornblende and biotite are usually recognizable. The black soda trachyte forms locally where platy parting is not prominent and where the originally glassy groundmass has not been devitrified or oxidized. An analysis of this phase is shown in table 1, analysis 8 (W422a). Chemically, the rock is between rhyodacite and trachyte but this distinctive rock is here called soda trachyte because of its petrographic character and an abundance of sodic plagioclase phenocrysts. This black, subvitreous soda trachyte is highly resistant to chemical and mechanical disintegration and is relatively conspicuous in talus as well as in several of the alluvial formations of the thermal area.

Individual flows of soda trachyte have not been recognized, perhaps because of a lack of diagnostic features such as variation in vesicularity and brecciated tops and bottoms of flows.

In thin section, the dominant phenocrysts of the soda trachyte are plagioclase laths ranging in length from a maximum of about 3 mm to generally less than 2 mm. In composition they are sodic oligoclase to andesine; their cores are more calcic and their borders more sodic. Hornblende is generally present and is commonly but not entirely of the deeply pleochroic oxyhornblende type. Some thin sections contain several flakes of biotite but others contain none. Biotite and hornblende typically show reaction rims rich in magnetite, and in some rocks the biotite and hornblende have been completely destroyed by reaction. Augite and hypersthene also are very scarce components of some rocks. Euhedral magnetite and apatite are generally present. Most of the apatite contains tiny dark inclusions concentrated near the borders of the crystals. Most crystals show a pleochroism similar to that of hypersthene but with a range in intensity that seems related to the dark inclusions.

The sparse phenocrysts are generally well alined in a trachytic groundmass containing abundant tiny plagioclase laths 0.1 to 0.2 mm long in a glassy or, more commonly, a devitrified matrix. Most of the tiny laths are oriented parallel to the phenocrysts, but nearly all thin sections reveal a prominent and intimate system of cross-structures that cut the primary flow structure at angles of as much as 70° and averaging about 45°. The tiny plagioclase laths adjacent to these cross-structures are realined parallel to the structures, and are commonly accompanied by concentrations of iron oxides. These structures are the cause of the platy parting that has been mentioned as characterizing most of the trachyte. The parting as well as the numerous healed fractures revealed under the microscope are best explained by small-scale internal shearing during late stages of movement of the viscous lava flows. The black subvitreous variety without platy parting shows the same cross-structures under the microscope, but the fractures presumably healed and welded at an early stage and did not localize oxidation of iron.

The soda trachyte east of the Low Terrace overlies fine-grained andesite or trachyandesite (analysis 6 (48), table 1), which in turn overlies granodiorite. Each of the two volcanic units is at least two or three hundred feet thick. The soda trachyte appears to be conformable to the underlying andesitic lavas, but individual flows were not distinguished. The rocks are not here associated with other rocks typical of the Alta Formation but Thompson has found such an association east of Steamboat Valley (Thompson, 1956, p. 51).

Within the thermal area, soda trachyte has been tentatively recognized only in GS–6 drill hole on Sinter Hill and in the Senges well about 2,000 feet to the northeast, and is absent in other drill holes, such as GS–2, where it might be expected. In GS–6 drill hole it directly overlies granodiorite and a thin arkosic sandstone (section *I–I′*, pl. 2; table 3, GS–6 drill hole). A few feet of soda trachyte was cored when the Senges well, an old churn drill hole between the Main and High Terraces (fig. 3), was deepened in 1950 to 195 feet. The core in this well is altered soda trachyte that presumably overlies granodiorite.

In GS–5 drill hole, the drill core from 525 to 546 feet in depth immediately below a dike of the Kate Peak Formation (section *B–B′*, pl. 2; table 3, GS–5 drill hole) is different in appearance from the overlying dike. The rock is fine grained and contains only a few phenocrysts. A low-dipping planar structure is present and is cut by reddish veinlets; these characteristics are suggestive of soda trachyte.

Thin sections show this rock to be thoroughly argillized. The larger of the original plagioclase phenocrysts are as long as 1½ mm and are more abundant than is typical of fresh soda trachyte. Hornblende relicts as long as 3 mm are recognizable and are relatively abundant.

Alined relict plagioclase and hornblende crystals about 0.02 mm in diameter are fairly abundant in a fine-grained argillized groundmass. Apatite crystals are as much as 0.08 mm in diameter. Plagioclase is largely argillized but hydrothermal potassium feldspar is present; hornblende is replaced by granular quartz and fine-grained argillic minerals, commonly with some pyrite.

The relative abundance of plagioclase and hornblende phenocrysts suggests that the rock is not typical of most soda trachyte of the area, although it may be a less common phenocryst-rich type. Its association with a dike suggests that it too is a dike and that it could have been a feeder for some of the local soda trachyte lava flows.

Fossil leaves found in the Sutro Member of the Alta Formation in the Comstock district suggest an Oligocene age for that part of the Alta (Axelrod, 1949). Since the Sutro Member is near the lower part of the Alta, the stratigraphically higher soda trachyte of the thermal area may be considerably younger, but conclusive evidence is lacking. Thompson's (1956) age assignment of Oligocene(?) for the Alta Formation is herein retained.

KATE PEAK FORMATION

The regional distribution and characteristics of the Kate Peak Formation have been summarized by Thompson and White (1964). The formation assigned to the Miocene or Pliocene on plate 1, probably has an age span from Miocene to early Pliocene (Axelrod, 1958).

In Steamboat Hills and the Carson Range, volcanic rocks of the Kate Peak Formation are more abundant than any other volcanic rocks (Thompson and White, 1964, pl. 1). In the thermal area, however, outcrops are almost completely absent; the only extrusive rocks appearing at the surface are two small erosion remnants of a lava flow, shown near the center of plate 1.

GS–2 drill hole on the High Terrace penetrated rocks from about 125 to 351 feet in depth that are similar to fine-grained tuff-breccias of the Kate Peak except that these subsurface rocks are highly altered (section *A–A′*, pl. 2, and table 3, GS–2 drill hole; Sigvaldason and White, 1961, p. D119–D121). Similar rocks are not found in other nearby drill holes and wells. The tuff-breccia is probably cut off to the south by an east-trending fault that passes 400 feet south of GS–2 drill hole (pl. 1 and sec. *I–I′*, pl. 2).

GS–1 drill hole on the Low Terrace penetrated highly altered rocks at depth that are correlated with the Kate Peak (section *E–E′*, pl. 2, and table 3, GS–1 drill hole). These rocks are strongly argillized fine-grained tuff-breccia and tuff (Sigvaldason and White, 1961, p. D117–D119) that are interpreted to be an intrusive vent-breccia such as the intrusive tuff-breccias described by Durrell (1944), rather than an extrusive accumulation. The tuff-breccia occurs from 129 to 209 feet and near 264 and 272 feet in the drill hole, and is overlain and underlain by altered granodiorite.

The nearby wells of the Steamboat Resort (table 3, Steamboat well 4) and South Steamboat well (table 3) are churn-drill holes that penetrated Quaternary sedimentary deposits at depth. With a possible exception near 200 feet in Steamboat well 4, no rocks similar to the tuff-breccia were recognized.

Highly argillized dikes with large phenocrysts and a texture more similar to dikes of the Kate Peak Formation than to other known rocks were penetrated by GS–5 drill hole on the Main Terrace and by GS–7 drill hole near the silica pit (sections *B–B′* and *D–D′*, pl. 2; table 3, GS–5, –7 drill holes). After the discovery of the dike in GS–7, a careful search of intensely altered rocks at the surface revealed the outcrop of the dike shown on plate 1. In the earlier mapping this dike had been mistakenly included with bleached rocks of the pre-Lousetown alluvium.

LAVA FLOW OF THE THERMAL AREA

The small erosion remnants of the andesite lava flow shown near the center of plate 1 consist largely of red-brown to purple-brown and dark-gray rocks. Most of the lava is dense and nonvesicular, but the southwestern part of the eastern remnant consists of vesicular and amygdular flow breccia. Tabular plagioclase phenocrysts generally less than 1 mm thick and about 5 mm in diameter characterize all phases of the flow; they are particularly abundant in some breccia fragments that have a dark-gray matrix containing partly altered and bleached plagioclase.

In thin section the plagioclase phenocrysts are strongly zoned; the calcic cores of the larger ones attain an intermediate labradorite composition; the borders are albite to sodic oligoclase. Dark phenocrysts consist of augite as much as 2½ mm in diameter and relicts of olivine about 1 mm in diameter that are completely altered to serpentine minerals.

The source of the lava flow is uncertain. The lava is texturally and mineralogically quite different from the andesite dike of the silica pit, 3,000 feet upslope and southwest of the flow remnants. Kate Peak lavas of very similar petrographic and chemical characteristics (compare analyses 9 (W236b) and 10 (W442b), table 1) occur locally in western Steamboat Hills about 3 miles west-southwest of the High Terrace one-fourth to one-half mile north of the rhyolite dome. Here, the rocks are scoriaceous to dense and are characterized by augite, relicts of olivine, and strongly zoned thin tabular plagioclase phenocrysts. Scoria is abundant and probably indicates the site of an extrusive vent, the topographic form of which is completely destroyed. A local massive phase (analyses 10 (W442b), table 1) represents either a flow or a near-surface intrusion. The scoria is underlain by a thin zone of typical Kate Peak tuff-breccia of heterogeneous composition, which in turn is underlain by soda trachyte. All these rocks are overlain by massive lava flows of the Kate Peak Formation.

The lava flow of the thermal area may have erupted 3 miles to the west in the area that has just been described. The chemical and petrographic characteristics are strikingly similar, but the distance is relatively great and topographic barriers may have intervened.

EXTRUSIVE TUFF-BRECCIAS

GS–2 drill hole penetrated highly altered rocks of the Kate Peak Formation at depths from 123 to 351 feet (table 3, GS–2 drill hole; Sigvaldason and White, 1961, p. D119–D121). In hand specimens the drill core consists of apparently unbedded and unsorted volcanic fragments that, in spite of extensive alteration, contain the numerous large plagioclase phenocrysts that characterize most of the volcanic rocks of the Kate Peak Formation; phenocrysts of ferromagnesian minerals cannot be recognized in hand specimen. Nonvolcanic fragments seem to be lacking except near the basal contact, where fragments of metamorphic rocks and granodiorite may be present. The fragments are thoroughly cemented, and the altered rock is generally hard, unlike the argillic alterations that characterize most of the rocks elsewhere in the thermal area.

The volcanic fragments commonly range from less than 1 inch in diameter to a maximum of about 4 inches; a single exception is a boulder 1½ feet in diameter at a depth of 196 feet. The large boulders typical of most Kate Peak tuff-breccias are almost entirely absent. Most fragments are angular but a few are rounded or subrounded to such a degree that stream abrasion is indicated at least locally. In this respect also, the rocks of the drill hole differ from typical tuff-breccia of the Kate Peak.

Study of thin sections of the tuff-breccias provides evidence of thorough hydrothermal alteration. The most abundant phenocrysts are andesine and labradorite; these have the size, zoning, and composition of phenocrysts in rocks belonging to the Kate Peak. They are partly to almost completely replaced by hydrothermal potassium feldspar in the upper part of the section and by clay minerals and decreasing amounts of potassium feldspar in the lower part (Sigvaldason and White, 1961). Phenocrysts of ferromagnesian minerals are completely altered, generally beyond recognition of original identity. Some rocks contain a few recognizable relict shapes of hornblende, augite, and hypersthene crystals, all of which are characteristic dark phenocrysts of Kate Peak volcanic rocks. No definite olivine relicts were identified. The groundmass of the volcanic rocks as well as the matrix of the fragments consists of a fine-grained mixture of hydrothermal chalcedony and potassium feldspar, some of which has the characteristic crystal habit of adularia.

The presence of metamorphic and granodioritic debris is confirmed near the basal contact of the tuff-breccias, and a little foreign material including clastic quartz occurs at depths from 200 to 230 feet. The striking predominance of volcanic fragments and the complete absence of detrital quartz except for the small amounts mentioned indicate an assemblage that is unlike any of the Quaternary sedimentary deposits known in the region. The absence of similar rocks in the nearby GS–6 drill hole and the Senges well is a puzzling fact that has compounded the problems of correlation.

The absence of coarse fragments and the presence of some stream-rounded pebbles suggest that these rocks may be a phase of the Truckee Formation, not identified with certainty elsewhere in the thermal area. On the other hand, the absence of bedding, abundance of rounded pebbles, and diatomite characteristic of most of the rocks of the Truckee Formation suggest that these rocks are a relatively fine grained phase of Kate Peak tuff-breccia, a small part of which has been transported and deposited by streams.

Hydrothermally altered rocks penetrated by GS–5 drill hole (table 3, p. B16; and section *B–B′*, pl. 2) at depths from 135 to 154 feet may be tuff-breccias of the Kate Peak Formation. Relict textures are very obscure in most of these rocks in contrast to most of the hydrothermally altered rocks of the area. A few textures interpreted to be relicts of plagioclase and hornblende and some recognizable heterogeneity of fragments constitute the evidence for assigning these rocks to the Kate Peak Formation. They are not identical to the altered rocks of GS–2 drill hole that have just been discussed but are grouped with them for convenience.

DIKES

Completely argillized dikes were penetrated by GS–5 drill hole on the Main Terrace at depths from 465 to 525 feet and in GS–7 drill hole in the silica pit area from 253 to 329 feet (table 3, p. B18; sections *B–B′* and *D–D′*, pl. 2).

The rock in GS–5 drill hole from 465 to 525 feet is light colored, moderately soft, and argillized, and it contains large conspicuous altered relicts of phenocrysts of plagioclase as much as 3 or 4 mm in diameter, sparse rounded grains of quartz, and abundant disseminated crystals of pyrite in light-gray to greenish-gray matrix. Rare relicts of biotite that help to distinguish between rocks of the Alta and Kate Peak Formations (Thompson and White, 1964) B18 can be recognized but obvious relicts of other original dark minerals are lacking. A few primary inclusions with fine-grained texture also have been found in some fragments.

In thin sections plagioclase phenocrysts are almost entirely altered to clay minerals, dominantly illite-montmorillonite. Relict phenocrysts of hornblende as much as two thirds mm in diameter are recognizable and relicts of biotite and pyroxene are very rare. Apatite crystals as much as 0.1 and rarely as much as 0.3 mm in diameter seem unaffected by alteration. Most thin sections contain one or two rounded and partly resorbed quartz grains. The phenocrysts are in a fine-grained groundmass consisting of argillic minerals and anhedral quartz grains that are probably secondary.

A dike was also penetrated by GS–7 drill hole in the silica pit area from 253 to 329 feet in depth. The rock is light gray to medium gray green. Relict phenocrysts are generally not conspicuous although pseudomorphs of plagioclase, probable augite, and other ferromagnesian minerals can be identified from crystal forms. The rocks are soft and claylike in appearance but do not swell or disintegrate in water. Pyrite is less abundant than in other hydrothermally altered rocks of the Kate Peak Formation and is largely concentrated in veinlets, but some is disseminated.

In thin sections the rocks are entirely argillized except for some replacement carbonate, quartz, and other secondary minerals. Montmorillonite is the most abundant clay mineral, but kaolinite and illite also are present. Relict plagioclase phenocrysts rarely exceed 1 mm in diameter; relicts of former dark minerals include both augite and hornblende; the original augite and hornblende crystals are as much as 3 mm in diameter. Rocks from depths of 280 to 290 feet near the center of the intrusive mass contain carbonate-filled amygdules, perhaps indicating that the dike is a composite intrusion. No systematic differences, however, were found above and below the amygdular zone.

In the absence of large plagioclase phenocrysts and of other diagnostic features, the dike could be a phase of the Alta Formation, but hornblende is characteristic of so many rocks of the Kate Peak of Steamboat Hills that a relation to the latter seems more probable.

INTRUSIVE TUFF-BRECCIA

Strongly argillized fine-grained tuff-breccia was penetrated at depths of 129 to 209 feet in GS–1 drill hole on the Low Terrace, and locally near 264 and 272 feet (table 3, p. B12, and section *E–E′*, pl. 2; Sigvaldason and White, 1961). The tuff-breccia is underlain and overlain by granodiorite.

In hand specimen the rock is soft and light greenish gray; clay minerals and pyrite are abundant. Some individual fragments as much as 2 inches in diameter can be distinguished in a rather structureless matrix. White argillized phenocrysts from ½ to 2 mm in diameter suggest similarity to the Kate Peak volcanic rocks, but obvious relicts of original dark phenocrysts were not specifically identified. A very few fragments are suggestive of altered metamorphic rocks, but quartz as inclusions or phenocrysts appears to be absent.

The fragments of volcanic rocks seem to be completely unsorted and unbedded. No fragments are definitely stream rounded, although some subrounded fragments do occur.

In thin sections all primary minerals are completely altered but relict textures are generally preserved. Relict plagioclase can generally be recognized with confidence and the relict forms of phenocrysts of original ferromagnesian minerals can usually be identified, but with more difficulty; they generally contain more chlorite, pyrite, and minor accessory minerals than the plagioclase. The specific identity of the original ferromagnesian minerals is commonly doubtful, although some augite, hornblende, and very rare biotite crystals have left recognizable relicts. Olivine and hypersthene relicts have not been identified with certainty. Some relict hornblende has inclusion-filled margins that are probably relicts of the reaction rims that characterize much of the hornblende of the Kate Peak Formation.

An unusual proportion of the fragments has abundant relict vesicles, clearly indicating an original pumiceous or scoriaceous character, with sparse large phenocrysts in a glassy matrix. Other fragments show relict perlitic structure (fig. 5). The abundance of vesicles and the presence of some rocks that originally were largely glass are uncommon features not found elsewhere in the fine-grained phases of the Kate Peak Formation. A few fragments near a depth of 205 feet are altered metamorphic rocks, and several have a relict texture similar to soda trachyte of the Alta Formation. Debris from the granitic rocks is completely absent except adjacent to the contacts.

The tuff-breccia is assigned to the Kate Peak Formation because of the size and original nature of the relict phenocrysts. The restriction of fragment size to less than 2 inches in diameter is not typical of fragmental phases of the Kate Peak that have been studied elsewhere, and the abundance of varieties of volcanic rocks that originally were highly vesicular and glassy is also unlike any other volcanic rocks of intermediate composition known in the region.

The tuff-breccia is interpreted to be intrusive because of the absence elsewhere of thrust or reverse faults required to account for its distribution in the drill hole,

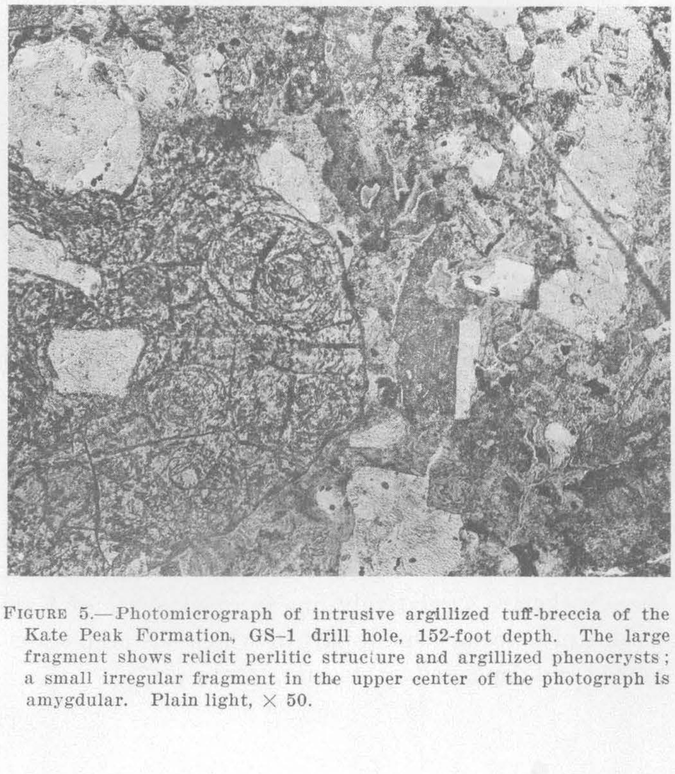

FIGURE 5.—Photomicrograph of intrusive argillized tuff-breccia of the Kate Peak Formation, GS–1 drill hole, 152-foot depth. The large fragment shows relict perlitic structure and argillized phenocrysts; a small irregular fragment in the upper center of the photograph is amygdular. Plain light, × 50.

and also because fragments of tuff-breccia with granodiorite at depths of 264 and 272 feet can be accounted for reasonably as related to offshoots of the main intrusion (indicated thus in section *E–E′*, pl. 2); the coincidence required for repetition by thrust slices seems less probable.

TRUCKEE FORMATION

The thermal area contains no rocks that are clearly related to the Truckee Formation; some poorly exposed siliceous sedimentary rocks about 1,000 feet west of Mill Hill (pl. 1) are herein included with the pre-Lousetown alluvium but could represent diatomite of the Truckee Formation strongly modified by thermal activity. If so, all evidence of diatoms has been destroyed. In addition, as mentioned previously, the altered andesitic rocks of GS–2 drill hole (table 3, p. B13) may also be a facies of the Truckee, although they have been assigned to tuff-breccias of the Kate Peak Formation.

TERTIARY(?) AND QUATERNARY ROCKS

PRE-LOUSETOWN ALLUVIUM

The evidence indicates that prior to eruption of the lavas of the Lousetown Formation, the area was first deeply dissected and was then alluviated to altitudes near 5,000 feet; a stillstand then occurred during which a pediment surface was cut into the bedrock and the pediment gravels were deposited; all these sedimentary deposits are included in the pre-Lousetown alluvium. The older alluvial material is nearly everywhere concealed by younger rocks but is cut by some of the drill holes. Chalcedony-cemented windblown sand, now a quartzite, is a local facies of the alluvium.

Regional relations suggest that the pediment gravels correlate with a boulder-strewn pediment surface along the Truckee River west of Reno, (Thompson and White, 1964) and that the gravels may be outwash of the McGee Glaciation (table 4). If this is so, the gravels are Pleistocene in age.

SILT, SAND, AND GRAVEL

Rocks included in the older part of the pre-Lousetown alluvium have been identified in drill core from GS–3, GS–4, and GS–5 drill holes on the Main Terrace. The logs of these drill holes (table 3, p. B15) describe most of what is known of the detailed lithologic character of the rocks. Cuttings considered to be from this alluvium were also recovered from some wells drilled by cable tools (table 3, South Steamboat well, H. Herz 1 well, Steamboat well 4, and perhaps Mount Rose (1947) well), but detailed relations are obscure.

TABLE 4.—*Tentative correlation of volcanic rocks and sedimentary and hot-spring deposits of the Steamboat Springs thermal area with Sierran glaciations, soils, and Lake Lahontan deposits*

[Symbols shown are those used on the geologic map and sections]

Sierran glaciations and interglaciations	Volcanic rocks	Stream deposits	Hot-spring deposits	Soils[1]	Lacustrine deposits
Recent					
"Little Ice Age" 1750 ± A. D.		Alluvium (Qal_2)	Opaline sinter (Qs_2)	Post-Lake Lahontan and post-Tioga soils; submature	Shallow post-Lake Lahontan lake deposits
Pleistocene					
Tioga Glaciation		Alluvium contemporaneous with Lake Lahontan (Qal_1)	Opaline sinter (Qs_2)	Middle Lake Lahontan soil; mature	Lahontan Valley Group: Sehoo(?) Formation
Interglaciation			(No deposits?)		
Tahoe Glaciation		Alluvium (Qal_1) Mud-volcano breccia (Qmb)	Opaline sinter (Qs_2)	Pre-Lake Lahontan soil; very mature	Lahontan Valley Group: Eetza(?) Formation
Interglaciation			(No deposits?)		
Sherwin Glaciation		Pre-Lake Lahontan alluvium (Qpl) Pediment gravels Early deposits	Opaline sinter (Qs_2)		
Interglaciation	Steamboat Hills Rhyolite (QTr) Steamboat flows of Lousetown Formation (QTl)		Post-Lousetown chalcedonic sinter (Qs_1)		
McGee(?) Glaciation		Pre-Lousetown alluvium (QTa_2)	Pre-Lousetown chalcedonic sinter (QTs)		
?		(QTa_1)			

[1]From Morrison (1961b).

The deposits are moderately fine grained and consist of poorly sorted silt, sand, and fine gravel. Sparse fragments as much as an inch or two in diameter occur at the base of the formation and rarely elsewhere. In most drill core the fragments do not exceed one-fourth inch in diameter. Most grains show little or no rounding. Bedding is rarely apparent in the drill core, although the same rocks if observable in outcrop would probably show some stratification. The few dips that were detected are fairly steep, ranging from 12° to 30°.

Arkosic debris from granodiorite is completely dominant, but a few grains of soda trachyte and metamorphic rocks are generally distinguishable. Fragments of Steamboat basaltic andesite [1] of the Lousetown Formation and hot-springs sinter are notably absent, and fragments of the Kate Peak Formation are very scarce.

The absence of fragments of Steamboat basaltic andesite is the criterion that distinguishes this older alluvium from the several younger alluvial deposits of the area. A total of 23 thin sections of core of these sediments from GS–3, GS–4, and GS–5 drill holes were examined before concluding that fragments of the Steamboat flows are indeed absent. GS–3 and GS–4 drill holes in particular are so located (pl. 1) that the absence of basaltic andesite fragments is unlikely to be explained as a vagary of distribution and drainage. Further evidence supporting the relative age of these rocks is provided by an abundance of soda trachyte fragments and a scarcity of Kate Peak andesite. A similar dominance of soda trachyte over andesite is a characteristic of the younger pre-Lousetown alluvium of the area; as will be seen, the younger alluvium consists of pediment gravels that immediately underlie the basaltic andesite flows. Soda trachyte is also known to underlie basaltic andesite and pediment gravels in GS–6 drill hole (table 3, p. B17), and apparently was abundant at the surface in eastern Steamboat Hills prior to eruption of the local flows of the Lousetown Formation.

QUARTZITE

Quartzite is a local but very distinctive rock found only in a small area northwest of Pine Basin (pl. 1), and is considered to be a facies of the pre-Lousetown alluvium.

The quartzite is massive and generally lacks stratification except in a few places where bedding is indicated by slight variations in grain size. The slopes underlain by quartzite are strewn with irregular blocks, and reliable outcrops are lacking.

[1] Steamboat basaltic andesite is an informal name for the distinctive lava flows included in the Lousetown Formation in Steamboat Hills.

The rocks are composed dominantly of quartz grains generally ranging in size from a fraction of a millimeter to 5 millimeters, with a few larger pebbles. Grains detectable with a hand lens are generally rounded to subrounded, although in some rocks angular grains are dominant. The clastic grains are mostly clear quartz, but a few fragments seem to be siliceous sinter or are indeterminate. The grains are cemented by silica, which in some rocks is clear and not easily distinguished from the clastic quartz but more commonly is translucent and slightly darker in color. In overall appearance most of the rocks range in color from white to light gray; fractures cut across individual quartz grains rather than around them. The rocks are thus similar in general appearance to many quartzites that are much older and have a very different origin.

In thin section, generally less than 5 percent of the clastic grains are not quartz but are probably chalcedonic sinter (described in a later section) derivel from rocks of equivalent age. Rocks from a small area near the center of Pine Basin, which have been included with the quartzite although they are more arkosic, contain original plagioclase largely replaced by opal, probably owing to late acid attack, and biotite replaced by chalcedony and leucoxene.

Although rounded and subrounded grains seem dominant over angular grains in hand specimen, microscopic examination reveals that only 10 to 50 percent are noticeably rounded, and most other grains show little or no rounding (fig. 6). The grains therefore seem to be from different sources, at least some of which were probably nearby. Although in general the largest show the best rounding, this is by no means always true, because some large grains are angular and some grains less than 0.1 mm in diameter are well rounded.

The rounding of small grains is commonly considered to indicate an aeolian origin. Holmes (1921, p. 203) states: "the smallest wind-rounded grains recorded from aeolian deposits have diameters between 0.03 and 0.04 mm, where as no water-rounded grain of diameter less than 0.5 mm has been recorded."

The cement of the clastic grains consists mainly of chalcedony but quartz is minor to locally dominant, and a few rocks show intimate interbanding of chalcedony and opal around individual grains. The cement thus consists of the common silica minerals, but the proportion of these minerals varies. Commonly quartz grains are bordered by a narrow overgrowth of quartz in crystal continuity, but the first zone around the grains in some rocks consists of radically arranged bladed chalcedony with negative elongation and indices of refraction near or less than balsam. In nearly all rocks some

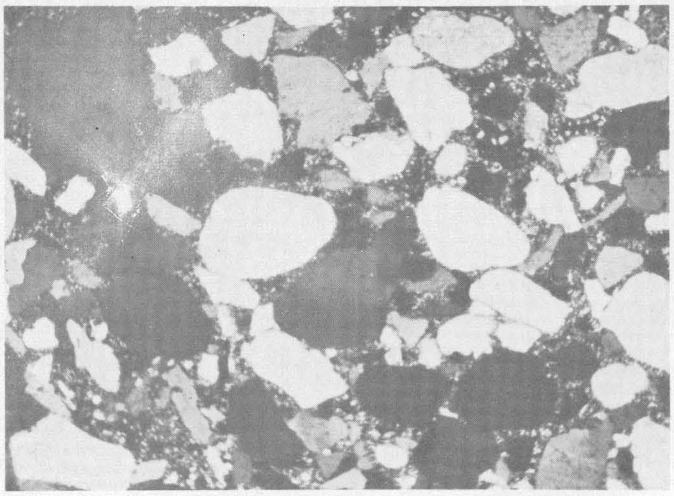

FIGURE 6.—Photomicrograph of quartzite of the pre-Lousetown alluvium. Sample from northwest side of Pine Basin, consists of windblown sand, dominantly quartz, cemented by chalcedony. Some grains as small as 0.1 mm diameter show rounding but many larger grains are angular. Crossed nicols, × 39.

very small open cavities remain that are lined with chalcedony or euhedral crystals of quartz.

The internal structure and contact relations of the quartzite are obscure because of the absence of outcrops that are clearly in place. The quartzite is considered to be a local deposit of windblown sand. The dominance of quartz grains and the abundance of rounded grains as small as 0.1 mm in diameter require the action of wind, probably blowing from the west or southwest over terrane that was almost entirely granitic in nature. The windblown sand presumably accumulated in a gulley on the lee side of, and entrenched into, granitic terrane to the west.

The deposit was cemented by quartz, chalcedony, and opal after the area was buried by younger stream deposits. Hot-spring activity was taking place concurrently, as indicated by sinter that probably underlies the quartzite and is described in a later section.

PEDIMENT GRAVELS

Pediment gravels older than the Lousetown Formation are widely distributed in the thermal area. They are nearly everywhere overlain by lava flows of the Lousetown. In the absence of strong cementation or hydrothermal alteration the gravels are less resistant to erosion and do not crop out; with rare exceptions, the best exposures of the gravels are highly altered (fig. 7).

The pediment gravels were deposited on a fairly evenly sloping, rock-cut surface formed by lateral planation of streams flowing across the eastern and northeastern part of Steamboat Hills after the deeply eroded valley of the area had been partly buried by the older pre-Lousetown alluvium. The higher slopes southwest of the thermal area are relatively steep, with gradients commonly on the order of 10° (see Thompson and White, 1964, pl. 1). These slopes are capped by basaltic andesite with little or no underlying alluvium. Below the 5,200-foot contour, however, the slopes change rather abruptly downward to the north and east to an average gradient of about 3°. These lower slopes are underlain by the pediment-cut surface mantled by gravels and then by the lava flows. In a few places where local topographic highs of granodiorite apparently were not planed off, the gravels are missing.

The gravels vary greatly in thickness, appearance, and composition from place to place. As mentioned, the unit is absent in places and has a maximum measured thickness of 27 feet in GS–6 drill hole (table 3, p. B17). In the main excavation of the silica pit (pl. 1 and fig. 7), hydrothermally altered alluvium and Steamboat basaltic andesite flows dip about 15° N.; the thickness of the alluvium ranges from about 10 feet near the floor of the pit to about 6 feet near the original land surface entrenched by the pit. With exceptions that have been noted, this is probably the usual order of thickness.

In appearance the unit ranges from a predominating dark color where fresh volcanic rocks are abundant to glaring white where all silicate minerals have been attacked by sulfuric acid and replaced by opal as in the

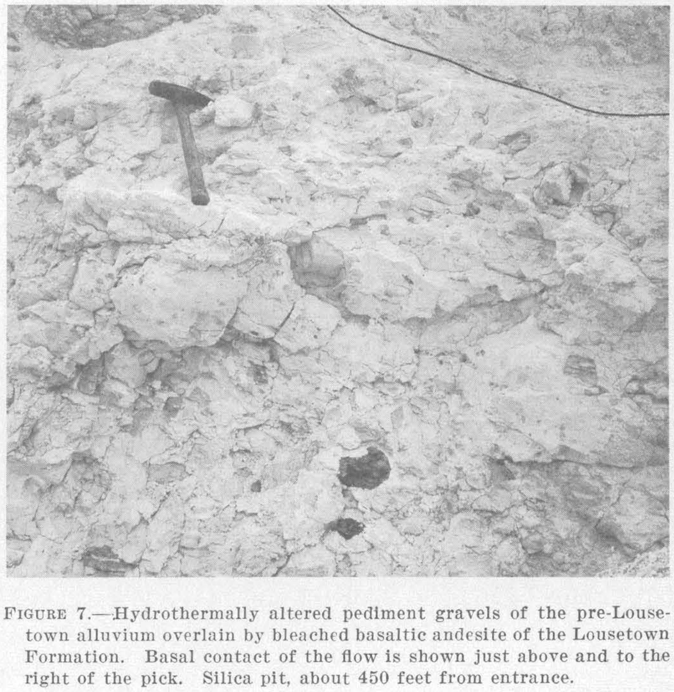

FIGURE 7.—Hydrothermally altered pediment gravels of the pre-Lousetown alluvium overlain by bleached basaltic andesite of the Lousetown Formation. Basal contact of the flow is shown just above and to the right of the pick. Silica pit, about 450 feet from entrance.

silica pit (fig. 7); incomplete removal of iron in places has produced various shade of red and brown.

Most fragments show little or no rounding. The maximum size of fragments differs from place to place. South of the Main Terrace, where the deposit is probably thin and only a few recognizable pebbles are in talus below the basaltic andesite flow, the largest pebbles are 1 to 2 inches in diameter. Elsewhere, fragments as much as 4 inches in diameter are not uncommon, and a few cobbles as much as 6 inches in diameter have been found in the silica pit and southeast of Pine Basin.

The composition of the fragments is not uniform from place to place. In general, where the sequence can be determined, the basal strata are dominantly arkosic and are commonly somewhat finer grained. Where nongranitic fragments are rare or absent, the arkose is similar in appearance to the underlying granodiorite. Elsewhere the unit commonly consists dominantly of granitic debris with some soda trachyte of the Alta Formation and metamorphic rocks. Other components show considerable differences from place to place.

About 1,000 feet northwest of the silica pit the gravels contain abundant fragments of pumiceous rhyolite that are generally but not everywhere devitrified, and common fragments of soda trachyte. Hot-spring sinter and fragments of Kate Peak volcanic rocks apparently are absent. As discussed elsewhere, the pumice seems to be related to pyroclastic eruptions that preceded extrusion of the rhyolite dome of western Steamboat Hills, thus indicating that the first activity near the present dome preceded extrusion of the Steamboat basaltic andesite flows of the Lousetown Formation.

Relatively coarse gravels, whose composition is of critical importance, underlie the small basalt-capped knob a few hundred feet southeast of Pine Basin (pl. 1 and section *H–H′*, pl. 2). In addition to granitic debris, the relatively abundant components are soda trachyte, metamorphic rocks, and vein quartz. Notable but rare are quicksilver-bearing chalcedonic sinter (especially significant in regard to the age of the thermal-spring system), opalized granodiorite from an earlier acid alteration, and petrified wood; Kate Peak volcanic debris is absent. Boulders are as much as 6 inches in diameter.

Pediment gravels that crop out immediately south and southeast of the crest of Mill Hill consist entirely of cemented arkose at the base of the unit but a few feet above the base they consist almost entirely of fragments of light purple to dark purple-gray soda trachyte in tabular blocks as long as 6 inches. A very local source is thus indicated for the soda trachyte, presumably to the southwest or west. The nearest existing outcrop in these directions is 2 miles to the west in northwestern Steamboat Hills. The source of the fragments at Mill Hill must have been nearby and is now either removed by erosion or is concealed by younger rocks. A few fragments that may be Kate Peak andesite were also found.

The small basin immediately southwest of the crest of Sinter Hill is largely underlain by highly altered pediment gravels. Where relict textures are preserved, Kate Peak fragments are recognized to be abundant and in places are the dominant component of the gravels, but soda trachyte and granitic debris are also common.

GS–6 drill hole on Sinter Hill penetrated gravels from 133 to 160 feet below the surface (table 3, p. B17). The alluvium is overlain by Steamboat basaltic andesite and is underlain by soda trachyte. The most abundant components are granitic debris and soda trachyte, but Kate Peak rocks are common and metamorphic rocks also occur.

In summary, details of the character of the pediment gravels differ considerably from place to place. Alluvium in the southern part of the thermal area was probably derived from the southwest. Local sources of soda trachyte and chalcedonic sinter are indicated; these sources were either removed by erosion or more probably are now buried by basaltic andesite flows. Rocks of the Kate Peak Formation were very scarce in the source areas of these sediments. In contrast, the gravels of the northern part of the area contain common to abundant debris from the Kate Peak. These gravels were probably deposited by east-flowing streams that were supplying Kate Peak debris from western Steamboat Hills or from the Carson Range. The boundary between the two stream systems was near the present northeast-trending drainage from Pine Basin. A similar drainage boundary now exists about one-third of a mile north of the one that existed when the pediment gravels were being deposited.

THE OLDEST HOT-SPRING DEPOSITS

DEFINITION AND CLASSIFICATION OF HOT-SPRING SINTERS

In this report, the term "sinter" is restricted to deposits consisting dominantly of one or more of the silica minerals and formed at the surface, at least originally, by deposition from thermal waters. Spring deposits consisting dominantly of one or more of the carbonate minerals are called travertine.

The hot-spring deposits of the Steamboat Springs thermal area are all sinters, with only minor exceptions. A few springs that eject water vigorously as spouters or geysers undergo a strong pH increase because of loss of CO_2 (White and others, 1953, p. 496–498). Such springs deposit layers that are dominantly carbonate, perhaps with some silica (analysis 28 (W128–9), table 1).

The thickest carbonate layer that has been observed was less than one-half of an inch, and it was underlain by much thicker layers of sinter. Even these thin carbonate layers apparently have only a temporary existence at Steamboat Springs for similar bands have not been observed in drill core from the older sinters. Reasons for the scarcity or absence of carbonate are the slow rate of deposition of sinter, resulting in extended exposure of any carbonate layers to weathering; the dissolution of $CaCO_3$ by sulfuric acid which commonly formed at and near the surface from oxidation of H_2S; and the fact that the Steamboat waters are normally undersaturated in calcium carbonate through intermediate depth zones (unpublished geochemical data not discussed here). The geochemistry of silica in these hot-spring waters has been considered elsewhere (White and others, 1956).

The following types of sinter have been recognized at Steamboat Springs, and are likely to include most types found elsewhere:

A. *Single-stage or primary sinters*

1. Thin-bedded opaline sinter considered to be primary deposition of silica on broad discharge aprons. High contents of dissolved silica, high rates of evaporation, and rapid cooling of water discharged at temperatures near boiling are required. This type of sinter has rarely formed in recent years at Steamboat Springs but it has been common in the past (fig. 8).
2. Geyserite, or microbanded opaline sinter of colloform, botryoidal, or "knobby" habit. Hot-spring sinters of many different types are commonly and improperly called geyserite. In sinter deposits of the world, even where geysers are most prominent, true geyserite constitutes only a small part of the total deposits. Of all the types at Steamboat, this is most likely to be interbedded with travertine layers. It is most abundant on sinter cones, and is deposited either by geysers or by vigorously spouting springs called perpetual spouters. Water with a high silica content at or above the surface boiling temperature is ejected and cools and evaporates rapidly, precipitating silica that was probably monomeric or "soluble" rather than colloidal at the moment of precipitation (White and others, 1956, p. 53). Geyserite should be distinguished from other types of sinter because of its usefulness in recognizing proximity to former spring vents and fissures.
3. Bedded opaline sinter with abundant casts of plant roots and stems, commonly of salt grass (fig. 9). This type may not be forming at Steamboat at the present time. It is, however, one of the most common types of opaline sinter, and is particularly abundant near the crest of Sinter Hill. Many of the plant casts lie parallel to the bedding, indicating that the plants were already dead when incorporated in the sinter. In many places, however, the casts or molds are perpendicular to the

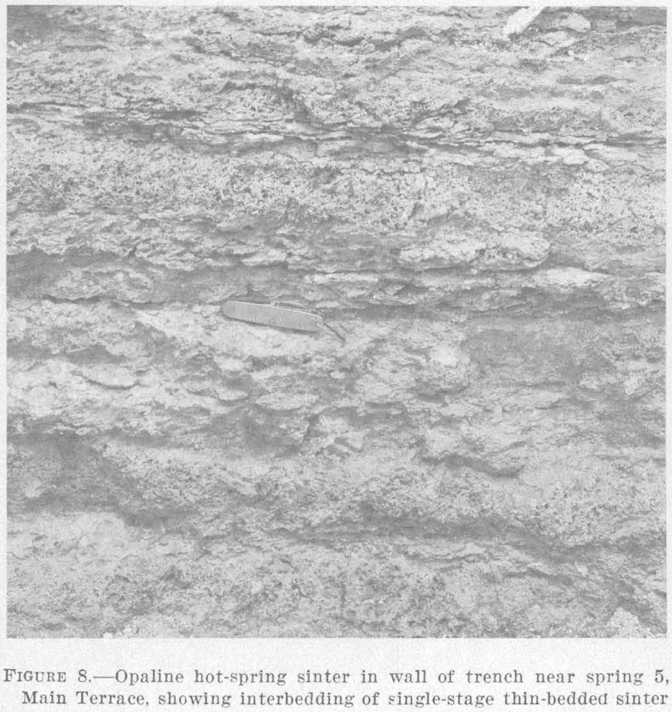

FIGURE 8.—Opaline hot-spring sinter in wall of trench near spring 5, Main Terrace, showing interbedding of single-stage thin-bedded sinter with multiple-stage fragmental sinter (see text).

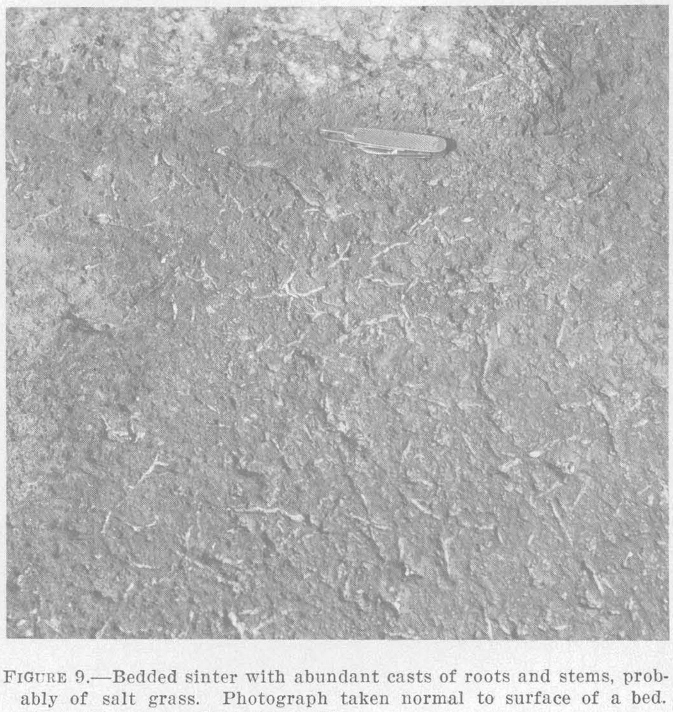

FIGURE 9.—Bedded sinter with abundant casts of roots and stems, probably of salt grass. Photograph taken normal to surface of a bed. Most casts are parallel to the bedding.

bedding; the individual casts have been traced through a thickness of at least 2 inches of sinter, indicating that they were either continuing to grow as the silica accumulated, or they were silicified and remained standing in pools of water, thereby maintaining an upright position perhaps for many years (fig. 10). In either event, the water temperatures must normally have been fairly low. Diatoms of long-ranging species particularly characteristic of hot springs are commonly abundant in type A–3 and in the following type, A–4. The most common hot-spring species have been identified by K. E. Lohman of the Geological Survey (written commun. 1958 and 1962) as *Denticula thermalis* Kützing, *Pinnularia borealis* Ehrengerg, and *Rhopalodia gibberula* (Ehrenberg) Wm. Smith.

4. Cellular opaline sinter is forming at the present time on algae-covered discharge aprons of active springs. The rounded or oval-shaped cells seem to result from accumlations of gas evolved by algae or other organisms. Prolific growth of algae is restricted to parts of discharge aprons where water temperatures are between 75° and 30°C, and where diurnal or other short-term changes in temperature are not much above or below these limits. The cellular type of sinter therefore formed within this range in temperature. When discharge ceases at a spring vent and an area of algal growth dries up, the deposit normally becomes very friable and disintegrates to pulverulent dust. The cellular type, therefore, is not commonly preserved in the older deposits, but under some conditions of wetting and drying not yet well understood, cementation and hardening occur. Some other sinter shows relict structures that may be from algal colonies or from stringy sulfur-depositing bacteria (?), which have been observed to grow at temperatures as high as 87° C (fig. 11).
5. Flocculated silica occurs in some spring pools and discharge aprons (White and others, 1956, p. 39, 53). Such deposits normally dry up, become soft and pulverulent, and are easily eroded. Lithification into hard opaline sinter has not been observed, although under conditions not well understood, lithification occurs. A relation is suspected between this type and the bedded sinter containing abundant plant casts (A–3).

B. *Multiple-stage sinters*

1. A type of sinter here defined as fragmental sinter is perhaps the most common of the opaline types. All the single-stage types of sinter, with the common exception of A–2 and possibly A–3, readily break down into fragments when the deposits become desiccated owing to shifting activity and are exposed to weathering and frost action. The fragments may remain in place, or more commonly may be transported at least locally by wind or water. If at

FIGURE 10.—Bedded sinter with stem molds perpendicular to the bedding. Photograph taken normal to bedding surface, showing molds as round or oval holes.

FIGURE 11.—Relict structures of algae or stringy sulfur-depositing bacteria (?) in sinter, Main Terrace near spring vent 38.

a later time hot-spring waters again flow over or through them, the fragments may become cemented (fig. 8).

2. Opaline sinter of all the previously described types decreases in porosity after burial by deposition of opal from percolating thermal water. In some sinters this process occurs to such an extent that nearly all the pore space is filled, and the rock consists of massive rather glassy opal (fig. 12).
3. Chalcedonic sinter is the most abundant type in the older sinter deposits (figs. 12–14); it has resulted from processes similar to those described under B–2, except that chalcedony and quartz were deposited during late-stage reworking rather than opal, and previously formed opal was at least partly reconstituted into chalcedony and quartz (White and others, 1956, p. 54–56). Incipient chalcedonization is shown in figure 12.
4. Sinter-cemented alluvium is intermediate between normal clastic sediments and sinter. Most sinter contains at least a few clastic grains of quartz and other minerals that have been transported by wind or water. In many places hot-spring waters flowed out over alluvial deposits, so that true sinter is underlain by or is incorporated in clastic sediments. Elsewhere sinter interfingers with sediments that were apparently deposited contemporaneously by streams. Such an origin is indicated for silica-cemented sediments containing hot-spring diatoms or casts of plant roots and stems.

FIGURE 12.—Photomicrograph of fragmental opaline sinter showing partial chalcedonization in the irregular clear area on lower left side of photograph, and banded gravity-controlled filling of cavities by opal in middle and right side. From trench about 200 feet southeast of GS–2 drill hole, High Terrace. Plain light, × 42.

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Other deposits not properly considered as sinter were cemented after burial by silica from percolating hot water. An absence of associated sinter, plant casts, or hot-spring diatoms is interpreted as favorable to such an origin, although negative evidence admittedly is not very reliable. The cement ordinarily is opal, although the pre-Lousetown quartzite previously described consists of windblown sand cemented mostly by chalcedony and quartz.

PRE-LOUSETOWN CHALCEDONIC HOT-SPRING SINTER

Most of the hot-spring deposits of the thermal area are clearly Quaternary in age; however, rather conclusive evidence indicates that at least some sinter is older than the Steamboat flows of the Lousetown Formation but is probably early Quaternary in age. The former existence of moderately widespread old sinter deposits is indicated by pebbles and cobbles of mercury-bearing sinter in pre-Lousetown pediment gravels that must have been derived from the southwestern part of the thermal area (described p. B30).

Thompson and White (1964, pl. 1) have described remnants of siliceous spring deposits on the east flank of Steamboat Hills about a mile south of the silica pit. These deposits are now at an altitude of about 5,050 feet, or 400 feet above Steamboat Valley, and lie on an extension of the pediment surface upon which the Steamboat flows of the Lousetown Formation were erupted. The pediment here slopes gently to the east but is incised as much as 200 feet by the present drainage. The existing topographic situation of this sinter is unfavorable for sinter-depositing types of hot springs because discharge is required at an altitude far above the surrounding water table. The environment for discharge was much more favorable at the time of and soon after the cutting of the pediment surface, when the local water table must have been very near the existing ground surface.

The small mass of sinter mapped on the northwest margin of Pine Basin (pl. 1) consists in part of several closely spaced blocks of sinter surrounded by quartzite. The sinter is white, light gray, or pink; it shows rather prominent vertical banding that is relict bedding, and it consists largely of chalcedony with some included grains of clastic quartz. Elongated irregular cavities that are the principal cause of the prominent banding are in part filled with late quartz and chalcedony.

The much larger mass of sinter immediately north of Pine Basin is also included with the pre-Lousetown spring deposits, although the evidence for this assignment is not conclusive. The physical and mineralogical characteristics of this sinter are virtually identical to those of small mass just described, as well as to those

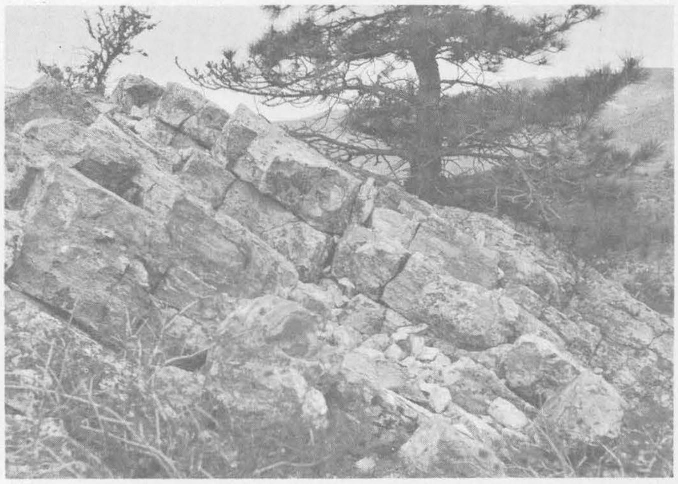

FIGURE 13.—Pre-Lousetown chalcedonic sinter on southeast slope of Sinter Hill. Present dips average 42° SE.; gravity-influenced microbanding in cavities indicate initial dips of about 12°, with structural tilting of 30° SE. since chalcedonization of sinter.

of the post-Lousetown chalcedonic sinter considered in a later section. The only significant difference is that sinters considered to be pre-Lousetown in age have been structurally tilted since they were deposited and after they were reconstituted from opal to chalcedony.

The large body of sinter here considered is very massive and highly resistant to erosion. Individual beds generally range from 6 inches to 2 feet in thickness (fig. 13), but some sinter is more thinly bedded. Relict stratification is observable in individual beds, although the rock generally does not break readily along stratification planes in beds (fig. 14).

The dominant type is chalcedonic sinter containing little or no opal. Fine-grained quartz in cavities is commonly detectable with a hand lens, and is rather abundant in thin section. Most chalcedonic sinter has a dull luster similar to that of unglazed porcelain but some has a resinous appearance and is in part translucent. Fresh surfaces range in color from white to light gray and are commonly streaked or mottled pink or red. Some of the more highly colored rocks are dark gray on weathered surfaces. On freshly broken surfaces their color changes inward within a fraction of an inch to pink or red. These color changes are due to very fine grained disseminated cinnabar that blackens in sunlight (Dreyer, 1939), but the analysis of such a rock (21 (W128–8), table 1) indicates that iron in addition to cinnabar is present.

The porosity of the chalcedonic sinter is generally low in comparison to that of other hot-spring deposits; it ranges from almost zero to 20 percent or more and probably averages 5 to 8 percent. The porosity is largely due to irregular open spaces that are commonly elongated and in part are interconnected parallel to the bedding (fig. 14). These alined pores also partly account for the appearance of internal stratification in individual beds. The remainder is relict primary stratification of other types.

The origin of chalcedonic sinter has been discussed briefly by White and others (1956, p. 54). In summary, the pre-Lousetown chalcedonic sinter deposits were at one time highly porous opaline sinter, commonly of the fragmental type (B–1), that has been changed to its present form by reconstitution of much or all of the opal to chalcedony, and by partial filling of cavities with chalcedony and quartz.

Streaking and mottling caused by mercury sulfide generally show alinements parallel to the bedding but in part are controlled also by joint surfaces and chalcedony veinlets roughly perpendicular to the bedding. The quicksilver was probably introduced when the original opaline sinter was reconstituted to the chalcedonic type. Needles and clusters of stibnite crystals as long as 5 mm occur in some cavities; stibnite is usually the latest mineral to be deposited.

Some cavities are partly filled with microscopically banded chalcedony and quartz, and perhaps with a little opal. Much of the banding curves around the original surfaces, but in some cavities thicker planar layers were deposited parallel to each other, uninfluenced by irregularities in adjacent cavity walls. In younger chalcedonic sinter that has not been disturbed

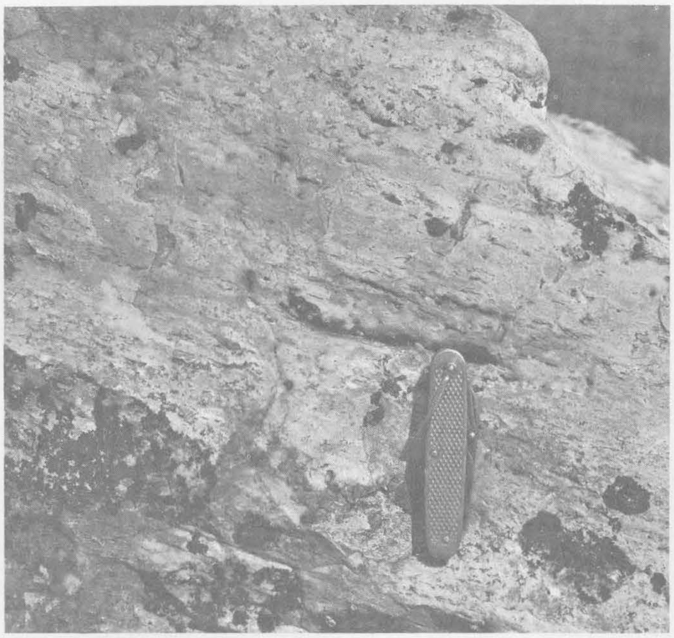

FIGURE 14.—Closeup of chalcedonized sinter of figure 13, showing relict bedding and some unfilled cavities. Gravity-influenced layering can be detected in hand specimen in perhaps 10 percent of the cavities.

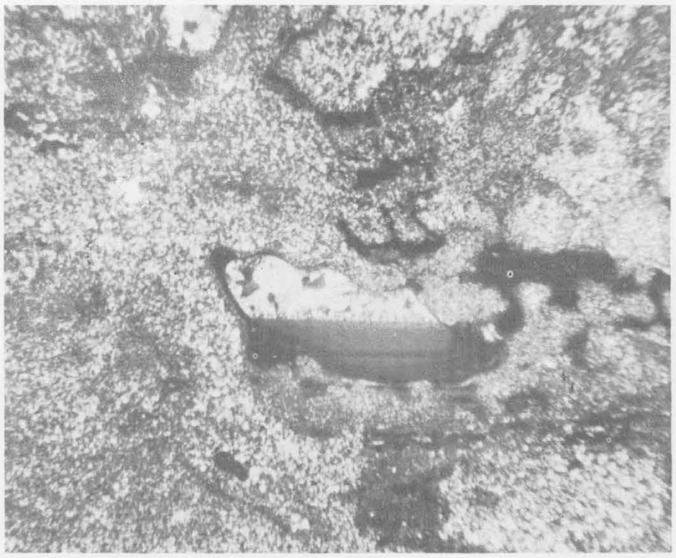

FIGURE 15.—Photomicrograph of gravity-influenced layering in a cavity filling in pre-Lousetown chalcedonic sinter near 3 W., traverse 9. The lower part of the cavity filling is fine-grained chalcedony; the upper and latest part is quartz. The quartz-chalcedony contact is largely parallel to relict bedding of the sinter, and both have been structurally tilted about 40° SE. since chalcedonization. Crossed nicols, × 39.

structurally, the thick planar layers are in the lower parts of individual cavities and are now horizontal. Clearly deposition of silica was controlled to a large extent by gravity (White and others 1956, p. 55). Figure 15 illustrates the characteristics of the fillings; they were first observed in thin section but are also detectable with a hand lens in some rocks.

Steeply dipping massive chalcedonic sinter crops out about 400 feet south of the crest of Sinter Hill (pl. 1). Present dips average a little more than 40° SE. The microbanding in the lower parts of cavities is distinctly not horizontal but dips southeast at somewhat lower angles than the bedding. Five sets of field observations made on the upper beds of the outcrop of figures 13 and 14 yielded the following results: The present dip ranges from 39° to 46° SE. and averages about 42° SE.; approximate determinations on the dip of the microbanding ranged from 24° to 37° and the average was 30° SE. The probable initial dip based on differences between the previous averages was 12°. A more spectacular example of structural tilting exists 400 feet southwest of the crest of Sinter Hill near the base of the exposed sinter. Here, the sinter dips a little more than 40° SE. and the microbanding of the cavities has an equal dip, confirmed microscopically in an oriented specimen. The initial dip of this sinter was probably near zero, and the beds have been tilted 40° SE. since they were chalcedonized. These two examples suggest that the high dips of strata in this part of Sinter Hill resulted largely from structural deformation after the rocks were reconstituted. The indicated low initial dips are consistent with initial dips found elsewhere in siliceous sinter deposits, where very steep initial dips are only local in occurrence and are generally restricted to cones of geysers and spouting springs. Initial dips of more than 20° rarely occur in areas of more than a few square yards. The steepest part of the east-facing slope of the Main Terrace between springs 8 and 13, for example, has an average initial dip of about 15° over a length of 400 feet and a width of 200 feet (pls. 1 and 2). A larger area of comparable initial dips is located on the upper slopes of the Beowawe Geyser Terrace (Nolan and Anderson, 1934). An unpublished topographic map prepared by the present writers indicates that a part of this terrace, for a length of nearly 3,000 feet and a width of 250 feet, has an average initial dip of about 12°, with small parts locally exceeding 15°. Similar areas of steeper initial dips have not been described elsewhere in the United States, Iceland, or New Zealand.

LOUSETOWN FORMATION

The name Lousetown Formation was first applied by Thayer (1937, p. 1648) to rocks north of Virginia City; the formation has been identified and described in the surrounding region by Thompson and White (1964, pls. 1 and 2). Most of the rocks are basalts and basaltic andesites exhibiting conspicuous platy parting and containing small sparse phenocrysts of plagioclase, pyroxene, and olivine.

In the eastern part of Steamboat Hills and in the thermal area (fig. 2, and pl. 1) dark lava flows of basaltic aspect possessing a characteristic texture distinguishable from the Lousetown elsewhere are herein informally referred to as the Steamboat basaltic andesite. Although included in the Lousetown Formation, they are thought to be intermediate in age between lava flows at the type locality of the Lousetown and the McClellan Peak Olivine Basalt (Pleistocene) of the Virginia City quadrangle (Thompson, 1956, p. 59–60). The Steamboat basaltic andesite lacks the platy parting of typical Lousetown flows and contains olivine and plagioclase phenocrysts to the almost complete exclusion of pyroxene (Thompson and White, 1964), and also contains some partly resorbed quartz grains, probably as foreign inclusions. In chemical composition the Lousetown flows are generally close to the boundary between basalt and andesite. Some of the later flows, including those in Steamboat Hills, are high in K_2O and TiO_2 and show chemical affinities to the McClellan Peak Olivine Basalt. (See analyses 13 (A–7), 14 (W128–0), 15a (485), and 20 (155), table 1.)

More than half of the southern and southwestern area in plate 1 is covered by basaltic andesite that is now as thick as 80 feet. The lava was extruded largely if not entirely from somewhat obscure vents one-half to three-quarters of a mile southwest of the silica pit near the east crest of Steamboat Hills. The vents are near the remnants of a cinder cone. Other lava vents may have existed farther from the cinder cone.

The original extent of the flows is not known. They probably moved to the east and northeast over increasing thicknesses of alluvium to ancestral Steamboat Creek, which probably was near the present creek and perhaps a hundred feet higher in altitude. The present limits of the lava flows are probably determined to a considerable extent by the limits of the earlier rock-cut pediment surface that now underlies the pre-Lousetown pediment gravels in most places. The lava flows were easily sapped by erosion where they overlay thick fine-grained alluvium, but the rate of erosion probably was much less where lavas were underlain by coarse gravels and granodiorite.

The Steamboat basaltic andesite is typically a dark-gray rock of basaltic habit. The only phenocrysts identifiable in hand specimen are plagioclase and olivine. Where exposed, the centers of the flows are massive and almost nonvesicular except for a few large smooth-walled vesicles stretched in the direction of movement, and some tiny spherical vesicles. Much of the surface now underlain by the lavas consists of vesicular to highly scoriaceous rock that is in part an agglutinated breccia. Some of the scoria is red and dark brown. These phases are parts of the original tops (or bottoms) of the lava flows.

In most places only a single flow was distinguished. In the trench leading southwest into the largest excavation of the silica pit, however, a highly altered and iron-stained vesicular zone of lava in the west wall of the trench lies between glaringly white, bleached, flow-banded lavas dipping about 10° NW. The vesicular zone, located about 175 feet southwest of the portal of the trench, is the top of the lower of two flows, perhaps including some breccia from the base of the upper flow. The lower flow is about 50 feet thick, but only about 30 feet of the upper flow is locally preserved.

In GS–6 drill hole basaltic andesite altered principally to potassium feldspar was penetrated between depths of 91 and 133 feet (table 3, p. B17). The upper 7 feet consists of scoriaceous breccia typical of an aa lava flow. The open spaces between breccia fragments are largely filled by clastic debris from the overlying pre-Lake Lahontan alluvium. The remainder of the section consists of massive basaltic andesite, probably constituting only a single flow, with relatively few amygdules except at the base (see table 3, p. B17, for details).

The Steamboat flows are highly altered at several places in the thermal area. In the trench leading into the silica pit, previously mentioned, fresh black basaltic andesite of the upper flow grades continuously into a bleached soft rock with mottled iron staining that marks the scoriaceous zone between two flows. Farther southwest the lower flow is glaringly white because all the original silicate minerals are replaced by opal (fig. 7). Acid leaching here has been so intense very near the surface that most of the original texture has been destroyed. Near the floor of the trench and elsewhere, petrographic characteristics of the fresh Steamboat flows are essential in identifying these same rocks where hydrothermal alteration has preserved the texture, or where the identity of clastic fragments is important. As discussed earlier, the presence or absence of fragments with the unique petrographic characteristics of the Steamboat flows is diagnostic in distinguishing the different alluvial deposits of the area. Outstanding characteristics are:

1. The rocks have an intergranular and rarely an intersertal texture, with negligible to abundant vesicles.
2. Three to six percent of the rock consists of plagioclase phenocrysts more than 0.2 mm wide but rarely exceeding 1.0 mm (table 2). Nearly half of these phenocrysts are roughly equidimensional with length less than twice the width. Feldspar phenocrysts of most other volcanic rocks of the region are distinctly more elongate, as are the remaining half of the plagioclase phenocrysts in the Steamboat flows.
3. Most of the equidimensional and some of the elongated feldspar phenocrysts contain cores or intermediate zones showing rounded resorption boundaries and a conspicuous grained texture caused by foreign inclusions and perhaps by intergrowths of plagioclase of two slightly different compositions (fig 16). These phenocrysts are very similar to those described and illustrated by Larsen and others (1938, p. 230–233, 251–257). The grained texture is remarkably well preserved in most of the intensely altered Steamboat rocks. The cores are calcic oligoclase (An_{26-30}) but the overgrowths are andesine to labradorite (An_{42-62}); zoning is much less pronounced in the cores than in other plagioclase phenocrysts.
4. About 20 percent of the rock consists of tabular plagioclase phenocrysts of intermediate size, ranging

from about 0.05 to 0.2 mm in width and seemingly grading into the tiny crystals of the groundmass.

5. Three to four percent of the rock consists of small olivine phenocrysts from about 0.05 to 0.2 mm in width. Many crystals resemble dumbbells in being slightly wider near their ends than in their central part.
6. Augite or pigeonite are almost completely absent as phenocrysts, but small pyroxene crystals and ilmenite are abundant in the intergranular groundmass.
7. The former presence of scarce crystals of hornblende is suggested by patches of fine-grained magnetite and pyroxene; relicts of these patches have been recognized in some altered basaltic andesites.
8. A typical thin section contains one or two rounded grains of quartz showing resorbed borders.

The plagioclase of the groundmass is also of interest but is of little value in distinguishing altered rocks. This inclusion-filled feldspar, commonly in optical continuity with the outermost zones of the plagioclase phenocrysts, has indices of refraction near those of albite with $n\alpha=1.530$ and $n\gamma=1.538$ (± 0.002). This feldspar, however, is definitely not pure albite because the normative composition of the rock (table 1) includes about 15 percent of orthoclase not otherwise occurring as a distinct mineral or as glass. The low-index feldspar is probably an isomorphous mixture of sodium, potassium, and some calcium feldspar preserved as a solid solution because of the rapid cooling and crystallization of the lava. Macdonald (1942) has described Hawaiian lavas that contain plagioclase whose indices of refraction are of oligoclase or andesine but that contain much potassium.

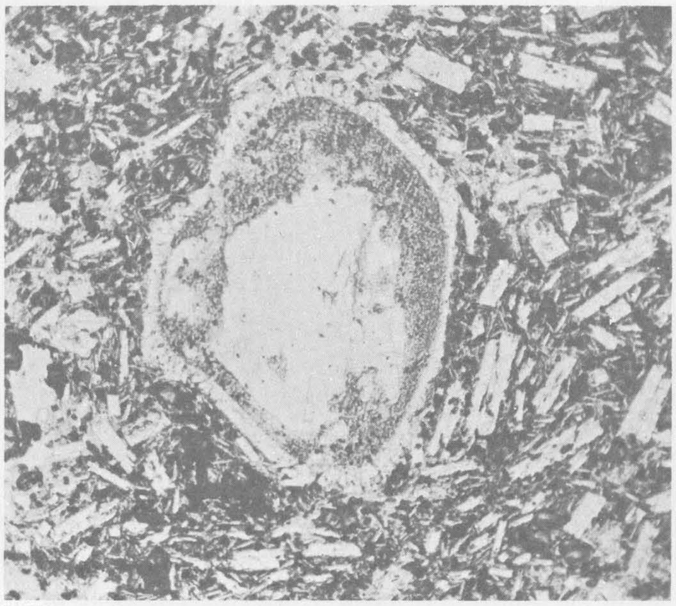

FIGURE 16.—Photomicrograph of almost fresh Steamboat basaltic andesite flow of the Lousetown Formation, showing large-grained plagioclase phenocryst of the type commonly recognizable as relicts in hydrothermally altered basaltic andesite. Dark crystals are dominantly olivine and ilmenite. Near entrance to silica pit. Plain light, × 39.

Thompson and White (1964) concluded that the age of the Lousetown Formation was late Pliocene to early Pleistocene. The Steamboat flows, which are a little younger than most of the Lousetown Formation, are older than the Sherwin Glaciation (Blackwelder, 1931; and table 4); the Sherwin is older than the Tioga and Tahoe but younger than the McGee Glaciation (table 4). The age of the Steamboat flows is now considered to be Pleistocene.

STEAMBOAT HILLS RHYOLITE

The Steamboat thermal area, as first recognized by P. F. Fix (Brannock and others, 1948, p. 216; Thompson and White, 1964, pls. 1 and 2), lies approximately on a line connecting four or five rhyolite domes in and near the southern part of Truckee Meadows. The largest dome lies 2 miles southwest of the springs in western Steamboat Hills and is the type locality of the Steamboat Hills Rhyolite (Thompson, 1956, p. 58–59). A small group of domes, perhaps erupted from as many as four separate but closely spaced vents, lies from 1 to 3 miles northeast of the Main Terrace and immediately west and on the front of the Virginia Range.

The western dome is the only one in the region that was preceded and followed by pyroclastic eruptions (Thompson and White, 1964). Fragments of rhyolitic pumice are so abundant south, southwest, and north of this dome that the underlying bedrock is concealed. Some foreign blocks of metamorphic rocks as well as debris from the Kate Peak Formation also were ejected with the pumice.

Most of the pumice of western Steamboat Hills seems to be related to violent explosive activity that proceeded extrusion of the rhyolite dome. A large crater about half a mile in diameter was formed by the early activity but was partly breached on the southwest side. The dome was then extruded into the crater, nearly filling it. The final episode was marked by relatively mild explosive activity, which resulted in formation of a small asymmetrical crater near the crest of the dome. The total quantity of late-stage pumice probably was small, and no means has been found in western Steamboat Hills to distinguish it from the earlier pumice. It probably was deposited as a relatively thin mantle that has since been removed by erosion or has been incorporated in the earlier pumice that contains foreign inclusions of bedrock.

No evidence was found in western Steamboat Hills to suggest that the three aforementioned stages of activity were separated by more than brief intervals of time. Evidence from the Steamboat thermal area is discussed in the following paragraphs.

Massive rhyolite equivalent to the extrusive domes has not been found in the thermal area; however, a shallow intrusive dome of rhyolite is suggested in section *H–H′* of plate 2. No direct evidence for such an intrusion has been found but by hypothesizing its presence, an explanation is offered for the strong local post-depositional tilting to the southeast of pre-Lousetown chalcedonic sinter (discussed on p. B35). In addition, Steamboat basaltic andesite immediately to the north has probably been tilted in the opposite direction (section *H–H′*, pl. 2). Permission could not be obtained from the landowner to test this hypothesis by drilling.

As previously mentioned, pumice fragments as much as 2 inches in diameter are an abundant component of pre-Lousetown pediment gravels in a small area about 1,000 feet northwest of the silica pit (pl. 1). The pumice is found in talus on both sides of a northeast-trending drainage from the 5,050-foot contour up to the basal contact of the Steamboat basaltic andesite. Some of the pumice fragments are completely devitrified but others contain considerable glass. Specimens W476a and W476b of table 2 are from this locality. Modal analyses of the fragments are very similar to those of rhyolites of the domes and to that of the abundant pyroclastic pumice near the western dome (table 2). The evidence suggests that the strong pyroclastic activity that preceded extrusion of the western dome was slightly earlier than extrusion of the Steamboat basaltic andesite.

The absence or great scarcity of pumice fragments in pre-Lousetown pediment gravels elsewhere in the thermal area is unexplained. None were found immediately east of the above-mentioned locality below the 5,050-foot contour, where the drainage steepens to the east and where pumice was expected in the gravels.

Small pumice fragments were also found on top of Steamboat basaltic andesite in a number of localities. Specific places where the possibility of derivation by downslope creep from pediment gravels seems to be eliminated are near 34W. on traverse 1 (pl. 1) and near 55W. on the same traverse. These fragments are glassy and are only slightly devitrified, and are as much as 1 inch in diameter. Specimen W374 of table 2 is representative of the post-Lousetown pumice. This fragment cannot be distinguished from most other pyroclastic fragments or from the pumiceous glass of the domes of the area by either differences in mineral composition or significant differences in mineral proportions (table 2). The similarities are strengthened by the fact that the plagioclase phenocrysts of all these rocks have an average modal anorthite content of 14 to 18 percent, and the undevitrified glasses have indices of refraction near 1.495. The only exception is the marekanite or obsidian "marble" found on the surface of the dome that is situated about 2⅓ miles northeast of the Main Terrace (19 (W416), tables 1 and 2). This rock is almost devoid of large phenocrysts, and the index of refraction of its glass is approximately 1.487. The low index is clearly related to the low water content of this obsidian, and the known tendency of index of refraction of glasses to increase with water content.

A few fragments of rhyolite have also been found in pre-Lake Lahontan alluvium of GS–6 drill hole (see table 3, p. B17) and in a small outcrop at the northeast end of Sinter Hill (pl. 1). In both localities the alluvium has been thoroughly altered, but original identity of the fragments is revealed by slightly embayed euhedral phenocrysts of quartz that resisted alteration. A single fragment of devitrified rhyolite was also found in pre-Lousetown alluvium near the bottom of the South Steamboat well (table 3, p. B9; and W129–29c, table 2). This rhyolite contains more phenocrysts of quartz and generally more spherulites than other rhyolites of table 2 but the fragment is only half an inch in diameter and the indicated difference may not be significant. The fragment came from about 300 feet below the original top of the pre-Lousetown alluvium, and is probably unrelated to the domes.

Most of the evidence indicates that the Steamboat Hills Rhyolite dome is virtually contemporaneous with and slightly younger than the Steamboat basaltic andesite flows of the Lousetown Formation. The rhyolite is older than pre-Lake Lahontan alluvium that probably correlates with the Sherwin glaciation in the Sierras (table 4); the Steamboat Hills rhyolite is now considered to be probably early Pleistocene in age.

DEPTH OF DIFFERENTIATION OF THE RHYOLITIC MAGMA

The depth of differentiation (or formation by melting) of a rhyolitic magma just saturated with quartz and feldspars can be estimated from published data on binary and ternary systems containing H_2O, SiO_2, $NaAlSi_3O_8$, $KAlSi_3O_8$, and $CaAl_2Si_2O_8$ (Tuttle and Bowen, 1958, p. 31–80; Stewart, 1957, 1958). Stewart (1958) was apparently the first to suggest that the three feldspars-silica-water system could be used as a geological barometer for water pressure. The ratio of a silica polymorph to feldspar crystallizing simultaneously varies with the water pressure, increasing with the water pressure to about 500 bars, and then decreasing at higher water pressures.

Bateman and others (1963) have shown that in late silicic Sierran granitic rocks, quartz crystallized simultaneously with potassium feldspar and plagioclase. A water-vapor pressure on the order of 5,000 bars is indicated by the quartz-feldspar proportions in these late differentiates, assuming that experimentally determined points of equal pressure on the faces of the quartz-albite-anorthite-orthoclase tetrahedron are connected by straight lines through the body of the tetrahedron. A depth of crystallization of at least 15 kilometers is thus indicated. The depth was even greater if the magmas were not water saturated, or water-vapor pressure was less than load pressure.

The depth of crystallization of the Steamboat Hills Rhyolite is readily obtainable by application of this geologic barometer because the rock is composed almost entirely of glass in which quartz and feldspars had just begun to crystallize (3.2 to 5.3 percent phenocrysts in the four analyses of table 2), and 94 to 98 percent of the normative compositions (table 1) are components of the tetrahedron. Under these conditions the water content and pressure, and therefore the minimum depth, can be estimated directly from the chemical composition of the rock, using the diagrams and assumptions of Bateman and others (1963).

All four analyses of Steamboat Hills Rhyolite (table 1) indicate water pressures between 2,000 and 3,000 bars. If this approach is valid and is not affected greatly by other components such as CO_2, Mg, and Fe, or by the assumed straight-line projection of pressures through the body of the tetrahedron, the indicated water content is close to the 6 to 8 percent determined for the ternary minimum in the quartz-albite-orthoclase system (Tuttle and Bowen, 1958, p. 58); indicated temperature of the magma was close to 675°C. If water pressure was equal to load pressure, the rhyolite differentiated at a depth of 6 to 9 km immediately prior to eruption; if load pressure exceeded the indicated water pressure, the depth of differentiation was greater than 9 km.

QUATERNARY DEPOSITS

PRE-LAKE LAHONTAN ALLUVIUM

The pre-Lake Lahontan alluvial deposits have proved to be very significant in unravelling the history of thermal activity in the area. The formation is considered to include all alluvium in the area that is younger than the volcanic rocks of the Lousetown Formation and older than deposits equivalent in age to Lake Lahontan, which in turn are equivalent to the Tahoe and Tioga Glaciations (table 4).

Thompson and White (1964) state:

> The [deposits] antedate the Tahoe and Tioga Tills and the late Pleistocene deposits of Lake Lahontan. The largest expanses are stream gravels capping the extensive lower pediments in the northern part of the [Mount Rose] quadrangle, and sands and gravels northwest of Steamboat Hills. Throughout most of the later area, very coarse boulder gravel covers the surface; the boulders range up to 12 feet or more in diameter and are commonly 3 to 5 feet. In a few roadcuts and gravel pits, the boulder-strewn surface is underlain by coarse bouldery deposits, but elsewhere the underlying deposits range up to cobbles in size and large boulders are absent. Wells drilled on the boulder-strewn surface north of Steamboat Hills and in the thermal area have demonstrated a general absence of boulders at depth; relatively fine clastic sediments correlated with older pre-Lake Lahontan alluvium extend down at least 100 feet below the bouldery surface. Evidently the underlying material was laid down under very different conditions from the upper few feet of boulders.
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> The correlation and comparative dating of the pre-Lake Lahontan deposits is based largely on weathering and soil development. Also important are topographic position, structural deformation, amount of erosion, and stratigraphic relations. The soil is characteristically much deeper than on younger deposits in the same area; it is comparable to or even greater than on the third from youngest Pleistocene glacial till, correlated with the Sherwin Glaciation of the Sierras [table 4, this report]. The soil horizon equivalent to the (B) horizon of Morrison (1961a, p. D111) is 2 to 4 feet thick where fully preserved and is reddish brown and clayey. Buried granodiorite boulders in this zone are thoroughly rotted and andesitic boulders less so, although boulders lying on the surface remain fresh and sound. The underlying light colored horizon equivalent to Morrison's (Cca) horizon is from 4 to at least 10 feet thick; typically it is characterized by veinlets of clay or silica with little or no carbonate.
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> * * * * *
>
> The relatively mature soil has the essential characteristics of the pre-Lake Lahontan and equivalent pre-Tahoe soils recognized by Morrison (1961a, 1961b) in the Carson Desert and Sierra Nevada, and marks the deposits as pre-Tahoe and presumably middle Pleistocene in age.

Pre-Lake Lahontan alluvium underlies a large part of the mapped limits of the thermal area (pl. 1). It extends for a few miles east, north, and northwest of the most intense thermal activity (Thompson and White, 1964, pls. 1 and 2). In places the alluvium is in direct contact with hot-spring deposits, particularly on the flanks of Sinter Hill and the High Terrace but also locally east and west of Mill Hill and adjacent to the Low and Main Terraces. Near the hot-spring terraces the alluvium is commonly cemented by opal where the sediments are older than nearby hot-spring deposits. Where the alluvium is later than nearby spring deposits, it is generally not cemented.

Very large boulders are generally limited to the upper few feet of the formation and are not known to occur at depths greater than 10 feet. In some places boulders lie on the surface but do not extend much below the surface. Elsewhere no boulders larger than about 6 inches were found, presumably because the layers containing the largest boulders have been removed by erosion.

In the near-surface deposits granitic debris is dominant near and west of Steamboat Creek, followed in relative abundance by andesite, basaltic andesite, soda trachyte, and metamorphic rocks. Near the thermal area debris from hot-spring deposits and acid-altered rocks is found. Steamboat basaltic andesite is generally a component near the northeastern part of Steamboat Hills. East of Steamboat Creek, the alluvium has been derived from the Virginia Range instead of from the Carson Range. Fresh and altered Tertiary andesitic rocks are dominant and granitic and metamorphic rocks are rare.

In a few places boulders of the alluvium are included in opaline sinter as, for example, at the north end of the High Terrace. The opal-cemented alluvium is distinguished separately on plate 1, indicating that deposition of alluvium was followed by hot-spring activity. North of Sinter Hill and on both sides of the High Terrace, however, uncemented pre-Lake Lahontan alluvium lies on and is later than nearby chalcedonic sinter. The deeper and older part of deposits included in the pre-Lake Lahontan alluvium is known only from drill holes. The most reliable information was obtained from cemented alluvium in drill core from GS–1, GS–2, GS–3, GS–6, and GS–8 (table 3). Cuttings from wells drilled by cable tools have also been studied in detail; much less can be learned from them but some useful information has been obtained (table 3, p. B8–B11). A common problem is that of distinguishing pre-Lousetown alluvium from pre-Lake Lahontan alluvium; the only reliable criterion is the absence or presence of recognizable fragments of Steamboat basaltic andesite of the Lousetown Formation. Satisfactory recognition becomes less probable with distance and unfavorable direction from source areas of the basaltic andesite, and with decrease in size of clastic fragments.

In and close to the principal centers of hot-spring activity the pre-Lake Lahontan alluvium can be divided satisfactorily into an older part interbedded with post-Lousetown chalcedonic sinter and a younger part interbedded with opaline hot-spring sinter. The two sinter formations are separated, at least near the crest of the High Terrace, by a distinct disconformity. This fact suggests but does not prove that a significant break also occurred during deposition of sediments here included in the pre-Lake Lahontan alluvium. A disconformity has not been recognized in alluvium in any of the drill holes of the area. Alluvium equivalent in age to opaline hot-spring sinter should contain fragments of older chalcedonic sinter, but recognizable fragments are very scarce or absent in some deposits that are clearly young enough to contain such fragments. Unfortunately the physical change from relatively fine clastics to deposits characterized by a dominance of cobbles and boulders does not coincide with first deposition of still-preserved opaline sinter, but apparently came after much opaline sinter had been deposited.

We suspect that we have unravelled only part of a more complex history of interrelated hot-spring activity, clastic sedimentation, and erosion that occurred between the times of Lousetown volcanism and Tioga Glaciation (table 4).

Several lines of evidence indicate that the alluvium was once considerably thicker than it now is in most places, and that former higher level deposits were removed by erosion of unconsolidated material.

1. Southwest of the Low Terrace (pl. 1) the gravels extend up to an altitude of about 4,710 feet, or about 110 feet above present Steamboat Creek. East of the Main Terrace and at a similar distance from the creek, the surface of pre-Lake Lahontan alluvium is only about 70 feet above the creek.
2. Immediately east of the mapped area of plate 1 (Thompson and White, 1964, pl. 1), a knob of boulder gravels rises approximately 60 feet above the general surface underlain by alluvium. The knob contains cobbles that generally are as much as 6 inches in diameter, but some boulders from 12 to 18 inches are near the crest of the knob. Alluvium of the knob and of the surrounding lower deposits seems to be identical. The knob is on the west or lee side of a bedrock hill that could have served to protect the higher alluvium from erosion by streams from the Virginia Range.
3. Cobbles from several inches to about 12 inches in diameter are sparsely distributed over much of the surface of Sinter Hill up to to an altitude of at least 4,860 feet, or 80 feet above the alluvial surface to the northwest. The cobbles consist almost entirely of the most resistant rock types normally found in the alluvium; andesite of the Kate Peak Formation is dominant but Steamboat basaltic andesite, black subvitreous soda trachyte of the Alta Formation, and metamorphic rocks are present; granitic fragments are virtually absent. The cobbles are particularly abundant where the surface is underlain by chalcedonic sinter but a few are also found on opaline sinter. In spite of the fact that no mappable concentration of cobbles remains on Sinter Hill, the hill at one time must have been almost buried by alluvium that has since been stripped away. The cobbles are too

abundant and random in distribution to be accounted for by activity of Indians. The rough surface and highly resistant nature of the chalcedonic sinter favored retention of a few of the more resistant cobbles.

4. In some places large boulders are concentrated on the surface of the pre-Lake Lahontan alluvium but are immediately underlain by finer clastic sediments. This relation is probably not a coincidence but is best explained as a residual concentration of boulders originally deposited with overlying finer clastic debris that has since been removed by erosion.
5. About a mile due west of the thermal area (Thompson and White, 1964, pl. 1) boulder gravels cap a bedrock hill that is surrounded by alluvium of similar appearance. The high gravels are 40 or 50 feet above the surrounding alluvium and apparently are an erosion remnant of strata that have since been stripped elsewhere by erosion.

Structural deformation possibly may account for anomalous positions of some of the boulder gravels. However, described in preceding paragraphs are several widely separated localities where boulder gravels strikingly similar to the pre-Lake Lahontan alluvium occur at altitudes ranging from 40 to nearly 100 feet above the surrounding alluvium-floored surface. All these are best explained as erosion remnants of boulder alluvium that was once more extensive and thicker than at present. Several of the higher remnants may involve a combination of structural uplift and erosion.

Pre-Lake Lahontan deposits probably extended as high as 4,700 feet along the axis of Steamboat Creek, and they occur below the surface down to an altitude of about 4,500 feet (pl. 2). The maximum thickness of the formation was therefore about 200 feet, but more than 100 feet is seldom preserved in one place.

POST-LOUSETOWN CHALCEDONIC HOT-SPRING SINTER

Sinter that is younger than the Lousetown Formation and older than deposits of Lake Lahontan constitutes a large part of Sinter Hill; it crops out over a large part of that hill (pl. 1) and underlies younger deposits elsewhere. In contrast to most other spring deposits of the area, Sinter Hill does not now have the usual topographic form of a hot-spring terrace, and the existing form is not clearly related to spring vents or fissures. If a terrace form ever existed, it has since been modified greatly by structural deformation and erosion.

Post-Lousetown chalcedonic sinter also crops out on and near the crest of the High Terrace and constitutes the major part of the volume of this terrace (section *A–A′*, pl. 2). The same type of sinter also underlies a considerable area farther west, and at least a small part of the Main Terrace (table 3, GS–5 drill hole; and section *B–B′*, pl. 2). It had been expected in drill holes on the Main Terrace but was found only in GS–5 drill hole at depths from 80 to 84 feet, and in the dump of an old adit driven into the terrace from near its base to the east (pl. 1).

Much of the post-Lousetown sinter is identical in appearance and in most other characteristics to the pre-Lousetown chalcedonic sinter previously described.

Much of the post-Lousetown sinter is gradational between chalcedonic sinter and fragmental opaline sinter. The latter consists in part of recognizable light-colored fragments of previously formed sinter (fragmental sinter, type B–1), but in irregularly bounded zones the fragment outlines are either indistinguishable or vague. Waxy to dull chalcedony, commonly somewhat translucent, is characteristic of irregular zones and of cavity fillings between recognizable fragments. Sinter with these gradational characteristics has been recognized in a trench about 200 feet southeast of GS–2 drill hole on the High Terrace (pl. 1 and fig. 12); 100 feet north of station 43 W., traverse 8, north of Sinter Hill; and in GS–6 drill hole (table 3, p. B17; and analysis 24 GS–6–6), table 1).

Incompletely chalcedonized sinter is rare or absent near the crests of the High Terrace and Sinter Hill. The amount of sinter with unreconstituted opal seems to increase downslope from the main fissures that controlled upward movement of hot water.

Another type of sinter of different appearance containing both chalcedony and opal has also been included in the post-Lousetown chalcedonic sinter. This type is generally characterized by a fragmental texture, with dark-colored fragments not found in the other types, by lower bulk density than pure chalcedonic sinter, by lower porosity than is typical of most of the younger opaline sinters, and by a waxy luster over much of a fresh surface. In thin sections opal is abundant but much is chalcedonized. This type of sinter is common in GS–2 drill hole (table 3) below 40 feet, in GS–5 drill hole at a depth of 84 feet (table 3, and analysis 25 (GS–5–84) table 1), and in old shafts on the High Terrace.

Some chalcedonic sinter on the east slope of Sinter Hill is pink and does not darken in sunlight as does the mercury-bearing chalcedonic sinter of the area (analysis 21 (W128–8), table 1). The pink color is attributed to disseminated iron oxide.

Chalcedonic sinter of the High Terrace has thus far been considered largely equivalent in age to the post-Lousetown chalcedonic sinter of Sinter Hill. However, two lines of evidence, outlined below, suggest that the sinter of the High Terrace may be largely or entirely younger than that of Sinter Hill.

1. The High Terrace has the topographic form of hot-spring deposits with still-preserved fissures from which the thermal waters discharged, but Sinter Hill shows no similar relations, and controlling structures have not been recognized.
2. Core from GS-2 drill hole on the High Terrace (table 3, p. B13) from depths of 39 to 104 feet contains abundant clastic fragments of sinter that appear to have been chalcedonized prior to cementation. Some opaline fragments appear to have been partly chalcedonized in place but other rounded to subrounded fragments consist entirely of chalcedony in a matrix of opal and chalcedony. The pre-Lousetown chalcedonic sinter previously described is a possible source, but the post-Lousetown sinter deposits of the northeastern part of Sinter Hill seem even more likely. The history of thermal activity in the High Terrace and Sinter Hill areas is probably considerably more complicated that can be deciphered from present evidence.

The maximum verified thickness of post-Lousetown chalcedonic sinter is in GS-2 drill hole, where approximately 85 feet of the upper 104 feet of the drill hole consists of sinter (table 3, p. B13), and the associated clastic sediments are dominated by sinter fragments.

Post-Lousetown chalcedonic sinter is interbedded with and commonly lies on older alluvium included in the pre-Lake Lahontan alluvium, as indicated in tables 3 (GS-2, -6 drill holes) and 4, and in sections *A-A′* and *I-I′* of plate 2. In GS-5 drill hole (table 3, p. B13; and section *B-B′* pl. 2) the sinter lies directly on pre-Lousetown alluvium.

The upper contact of the post-Lousetown chalcedonic sinter is a disconformity near the crest of the High Terrace and on some of the lower slopes of Sinter Hill. The relations are best seen about 50 feet southwest of GS-2 drill hole (pl. 1) where, in the exposed east wall of a fissure, 6 inches to 1 foot of horizontally bedded opaline sinter lies on and also includes blocks of horizontally bedded chalcedonic sinter. The thickness of chalcedonic sinter removed during the erosion interval is not known but probably is small.

Opaline sinter deposits are probably unconformable on post-Lousetown chalcedonic sinter on the upper slopes of Sinter Hill, and perhaps elsewhere.

The age of the post-Lousetown sinter is not known precisely but in general is equivalent to pre-Lake Lahontan alluvium (table 4), which, as previously discussed, is older than the Tahoe and Tioga Glaciations and is tentatively assigned to the middle Pleistocene.

OPALINE HOT-SPRING SINTER

Opaline hot-spring sinter with little or no chalcedony is exposed extensively at the surface on the Low and Main Terraces and in the High Terrace-Sinter Hill area. Deposits included in this formation range from possibly middle Pleistocene to Recent in age. The oldest is probably on Sinter Hill, where cobbles of pre-Lake Lahontan alluvium are strewn upon the surface. An east-trending belt of sinter that extends from the north base of Mill Hill may be of similar age. Next youngest is the opaline-sinter capping of the High Terrace, which incorporates boulder gravels of the pre-Lake Lahontan alluvium on the northern and western parts of the terrace and thus is younger than the alluvium. Sinter of the Low and Main Terraces and that of isolated patches northwest of the Main Terrace was formed in the recent past and is still being deposited in some places. A satisfactory subdivision into two or three units by relative age was made on original outcrop maps of the thermal area, but no reliable basis was found for correlating these units in drill holes or on structure sections. The several different types of opaline sinter are more related to local spring activity and environment than to age. Opaline sinter in the Main Terrace, for example, is probably equivalent in age to all the opaline deposits mentioned above. All sinters consisting dominantly of opal have therefore been included in the same formation. Thermal activity seems to have been virtually continuous somewhere within the area from the time of Sherwin Glaciation up to the present (table 4), although rate of deposition of sinter and the loci of activity have shifted greatly with time and with base level for the water table.

Opaline sinters range in color from white to light gray, tan, and light brown. They consist almost entirely of opal but some contain a little chalcedony, commonly recognized only in thin section. The deposits are nearly everywhere distinctly bedded on a scale that ranges from microscopic laminations to beds 6 inches to 1 foot in thickness.

The most abundant opaline sinter is the fragmental type (classified as B-1). Individual beds are more coarsely stratified than in most primary sinters; they range from about ½ inch to 6 inches or more in thickness (fig. 8). Individual fragments in beds are generally tabular and are oriented parallel to the bedding. Thin-bedded primary sinter (type A-1) is abundant in places (fig. 8). Bedded opaline sinter containing plant casts (type A-3 and fig. 9) is locally abundant near the crest of Sinter Hill, in the isolated outcrops immediately west of the Main Terrace (pl. 1), and in outcrops east of Steamboat Creek. Geyserite (type A–2) is locally abundant in many spring mounds and along some fissures of the Main and Low Terraces, but is very rare elsewhere.

The porosity of newly formed sinter generally is high; it ordinarily ranges from 20 to 50 percent in most types except for primary types A–1 and A–2. When porous sinter is buried by later deposits, thermal water commonly percolates downslope from the principal fissures through the more permeable strata. Silica from this water is deposited in pores of previously formed sinter as the water cools, decreasing the porosity of the original sinter, commonly to 5 to 20 percent.

Most of the added silica is deposited as opal but chalcedony is common in the Main Terrace immediately adjacent to fissures at depths of a few feet. Some representative depths to prominent chalcedony on the Main Terrace are, from north to south (pl. 1): vent 21–n, 8 feet; 100 feet south of vent 36, 1.2 feet; and vent 40, 2.3 feet. In most other vents chalcedony is not accessible. Chalcedony is increasingly abundant with increasing depth below 25 feet in the drill holes near the crest of the Main Terrace, but except from 80 to 84 feet in GS–5 (table 3, p. B15), it is everywhere greatly exceeded in abundance by opal. Chalcedonization of opaline sinter has been controlled in part by depth and age and in part by proximity to fissures from which the hottest thermal waters migrated. The relatively sharp contact several feet below the surface near the south end of the Main Terrace may have resulted from the selective action of the chalcedonizing waters. Similar selectivity is shown in post-Lousetown chalcedonic sinter of GS–2 and GS–6 drill holes (table 3, p. B13, B17), where degree of chalcedonization is clearly not related to depth alone. In these sinters probably at least a minimum depth was essential (White and others, 1956, p. 53–55), but permeability and probably also difference in impurities to stabilize the opal may also have been important factors.

With increasing depth, opal not yet reconstituted to chalcedony generally has the X-ray pattern of cristobalite (Sigvaldason and White, 1962).

The relations between the opaline hot-spring sinter deposits and pre-Lake Lahontan alluvium have already been considered, but in summary the older sinter deposits in the formation are local hot-spring facies of the younger sediments included in pre-Lake Lahontan alluvium (table 4). Interbedding of the two formations is evident in GS–8 drill hole (table 3, p. B18), in Rodeo well (table 3, p. B10), and in Steamboat well 4 (table 3, p. B9). Exposed contacts exist north of Sinter Hill and on the margins of the High Terrace. At the north end and locally on the west side of the High Terrace opaline sinter definitely includes and cements pre-Lake Lahontan alluvium. Elsewhere at the surface the alluvium is apparently later than the sinter. In several places east and west of Mill Hill, alluvium included with pre-Lake Lahontan alluvium is earlier than and is in part cemented by opaline sinter.

Opaline sinter of the Low, Main, and High Terraces was deposited from springs emerging from fissures and vents of the same general system that exists now and is shown on plate 1 (also on detailed maps of the Low and Main Terraces to be included in later reports). Other opaline sinter, however, is not clearly related to recognized fissures, faults, or specific vents. This is particularly evident on Sinter Hill and east of Mill Hill. The absence of clear structural controls for Sinter Hill is particularly puzzling. A similar situation has been mentioned in regard to the earlier chalcedonic sinters.

MUD-VOLCANO BRECCIA

Deposits here called mud-volcano breccia have been recognized and mapped only in a relatively small area, 1,100 feet long and from 100 to 800 feet wide, northwest of Sinter Hill (pl. 1; and sections *A–A′* and *H–H′*, pl. 2).

The characteristics and probable origin of these deposits were discussed briefly by White (1955b, p. 1129) as a possible prehistoric example of a violent mud-volcano eruption similar to the one that occurred at Lake City Hot Springs, Calif., in 1951. At Steamboat Springs, debris containing bleached and iron-stained boulders and fragments of Tertiary volcanic rocks, opaline and chalcedonic sinter, and disintegrated granitic debris occurs on both sides of a north-trending fault. This debris was first considered to be a local phase of pre-Lake Lahontan alluvium that was bleached and hydrothermally altered in place by sulfuric acid. Evidence that definitely disproved this hypothesis was found when the Steamboat ditch from the Truckee River was extended into the area in 1947, and a trench was cut through the low mound west of the fault (pl. 1). The exposed section in the basal part consists of pre-Lake Lahontan alluvium, with numerous pebbles and boulders as much as 1 foot in diameter and a single large boulder 10 feet in diameter. Sinter and hydrothermally altered rocks are completely absent. The upper 2 to 5 feet of the section, however, is very different, consisting of iron-stained debris that is unbedded except in the basal 6 inches. The debris contains chalcedonic and partly chalcedonized sinter and isolated rock fragments that must have been bleached by acid attack prior to transport to present position. Outcrops of such rocks do not occur west of and upslope from the cut. The only local source for many of the breccia fragments is in and near the fault zone east of the cut; the breccia fragments must have been ejected into their present position by a violent hydrothermal eruption.

Similar eruptions have also occurred at Waiotapu, New Zealand (Lloyd, 1959), about 900 years ago, and perhaps in Jigokudani Valley, Hokkaido, Japan (Fukutomi and Fujiki, 1953) in 1951 and 1952. As in the Lake City Hot Springs, the energy for eruption seems to have been stored in the hydrothermal system from an ultimate volcanic source, but there is no evidence for direct involvement of new magma in these eruptions. A hydrothermal system with temperatures at depth close to the boiling points for prevailing hydrostatic pressures is unstable and contains stored energy wholly adequate for a geyser eruption. As stated by White (1955b, p. 1127)

> If material is suddenly removed at the top of the system, the pressure is lowered throughout. Each point at depth, formerly just at its boiling point, is now above its boiling point. Boiling then starts throughout the column, or if mild boiling had previously existed, the rate (and total depth range) of boiling rapidly increases. In competent fractured rock, water is displaced upward and out of the system by expanding gas bubbles, decreasing the hydrostatic pressure on the system and setting off a chain reaction that results in geyser action.

White also pointed out that all recorded mud-volcano eruptions in areas containing nearly neutral chloride waters involved fine-grained clastic sediments with no near-surface competent rocks. Such incompetent material has little strength to resist long applied stresses. The load pressure of the plastic sediments is effective in restricting or closing channels of water movement. The pressure on the water can then be significantly higher than the hydrostatic pressures of water in fractured competent rocks near the surface, and is likely to approach load pressure. Under these conditions of higher pressure, temperatures may be much higher than in a water system under hydrostatic pressure alone. The higher permissible temperatures in incompetent materials are accompanied by higher stored energy and even greater instability than in geyser systems.

The actual triggering mechanism is not clearly understood but several possibilities have been discussed by White (1955b, p. 1127–1128) and Lloyd (1959, p. 174–175). A local earthquake that forces a large volume of water to rise rapidly into lower pressure environments where boiling points are exceeded is a plausible explanation, but no evidence of an earthquake was found for the 1951 eruption of Lake City Hot Springs. Another possibility involves a rapid lowering of barometric pressure, which would increase the rate of boiling in the upper part of the system.

The hydrothermal eruption hypothesized for the mud-volcano breccia of Steamboat Springs occurred after the pre-Lake Lahontan alluvium was deposited, and perhaps before deposition of the alluvium contemporaneous with Lake Lahontan (table 4). Definite evidence for the latter is lacking but the Steamboat ditch exposure previously described includes a small north-striking normal fault (pl. 1) dipping steeply toward the probable source area of mud-volcano breccia. The base of the breccia is faulted downward about 3 feet to the east, but the time since eruption and faulting has been sufficiently long for erosion to remove all evidence of the fault scarp. Numerous preserved fault scarps in the Truckee Meadows area are younger than the pre-Lake Lahontan alluvium but none clearly displaces Lake Lahontan sediments. The mud-volcano breccia is therefore considered to be slightly older than Lake Lahontan and Tahoe Glaciation.

A small mud pot or mud volcano was active in recent time where auger hole 8 was bored 100 feet northwest of 51W., traverse 8 (table 3, p. B19). A low mud cone still exists, and a temperature of 95.2°C, which is nearly boiling for this altitude, was measured in the hole at a depth of 14 feet.

ALLUVIUM CONTEMPORANEOUS WITH LAKE LAHONTAN

Lake and stream deposits of late Pleistocene age are recognized in many places throughout the surrounding region and are particularly common in Truckee Meadows north and northeast of the thermal area (Thompson and White, 1964, pls. 1 and 2). In the quadrangle maps, deposits of Lake Lahontan are distinguished from contemporaneous stream deposits, but post-Lake Lahontan deposits were not mapped separately because they are so insignificant in quantity.

In the Steamboat thermal area (pl. 1), stream deposits probably equivalent in age to deposits of Lake Lahontan are herein referred to informally as Lahontan alluvium. These deposits are generally near Steamboat Creek, but they also crop out in a broad area west of the Main Terrace and in Pine Basin. Alluvial deposits in small undrained or poorly drained basins in the northwestern part of the thermal area are mapped as Recent alluvium, but they could almost equally well be considered as Lahontan alluvium.

Lahontan alluvium consists mostly of fine-grained clastic sediments but include some gravel and boulders, which, in the thermal area, were probably derived very locally from pre-Lake Lahontan boulder gravels. Where well exposed, the Lahontan alluvium generally shows better stratification and sorting than the pre-Lake Lahontan deposits but few fragments are well rounded.

Near Steamboat Creek the formation is clearly related to the present drainage. It occurs in terraces graded to a former creek level that was in general about 10 feet above the present level. Internally, these terraces are composed entirely of Lahontan alluvium down to the level of the creek and perhaps even to greater depths. Pre-Lake Lahontan alluvium, therefore, was entrenched at least down to and perhaps below the present creek level prior to deposition of Lahontan alluvium.

West of the Main Terrace local base levels controlled deposition to a greater degree than did Steamboat Creek. The Main Terrace has been effective in damming or diverting drainage from the central part of the thermal area.

Lahontan alluvium and much of the younger deposits included in the opaline hot-spring sinter show complete intergradations of two different types. One is illustrated by the contact between the two formations along the east base of the Main Terrace (pl. 1). The flank of the terrace consists mostly of the fragmental type of sinter cemented by opal. The degree of cementation decreases to the east and the proportion of nonsinter clastic debris increases. The contact was mapped primarily on the basis of degree of cementation; east of the contact uncemented fragments consisting largely of sinter extend in places to the creek. An unmapped mantle of disintegrated sinter also covers a considerable part of the Main Terrace, but the fragments lie on firm sinter at slight depths.

A complete gradation also exists between sinter and silica-cemented foreign clastic sediments, as discussed previously in classification of sinters. Even the purest primary sinter contains some foreign fragments incorporated in the hot-spring deposits by action of either wind or water. Most sinter probably contains a few percent of foreign material, but some contains abundant non-hot-spring debris. In areas where foreign fragments are dominant, the cemented material is shown on plate 1 as silica-cemented silt and sand. These areas contain two subtypes not distinguished on the maps. Some opal-cemented alluvium is interbedded with definite sinter containing hot-spring diatoms or silicified casts of plants, and deposited at the surface on spring aprons encroaching on clastic sediments. Elsewhere, alluvium is cemented by opal without diagnostic properties to indicate time of cementation. As discussed in classification of sinter, cementation probably often occurred below the surface from percolating thermal waters. Most of the mapped cemented alluvium is of the type without diagnostic characteristics.

Soil profiles on Lahontan alluvium (Thompson and White, 1964) are weakly developed and are similar to those of the post-Lake Lahontan soil commonly formed on lake deposits, as described by Morrison (1961a, p. D112).

RECENT ALLUVIUM

Recent alluvium is found only near present drainage channels and in undrained or poorly drained basins. In most gulleys and streambeds in the thermal area, the unit is not distinguished from Lahontan alluvium, but in the central and northern parts of Steamboat Creek and in several basins of the northwestern part of the thermal area (pl. 1) a thin mantle of Recent alluvium overlies older clastic deposits.

The deposits consist of fine-grained clastic material except locally where gravel and boulders have been derived from pre-Lake Lahontan deposits. Even when Steamboat Creek is in flood stage and overflows its banks, little coarse material is transported. In contrast, some streams in other parts of the region transport boulders during flood stages of discharge (Thompson and White, 1964).

The undrained and poorly drained basins west and northwest of Sinter Hill have been formed by acid leaching and subsequent compaction of rocks above the water table. The process is still continuing (table 3, auger holes 1, 2, and 9) although probably at a slower rate than in the past. Talus and fine sediments are being transported by sheet wash toward the centers of the basins to form Recent alluvium that mantles older clastic deposits.

ALTERED ROCKS

Most of the rocks that have been described are locally changed drastically in appearance and in mineralogy by hydrothermal alteration. These changes have already been described briefly (Brannock and others, 1948, p. 224–225; White, 1955a, p. 110–112; Sigvaldason and White, 1961, 1962) and they will be considered in detail in later reports.

In this report the mineralogy of the altered rocks is indicated in part in the logs of the drill holes (table 3, especially drill holes GS–1 to GS–7), and areas of near-surface acid bleaching are shown by overprint on plate 1. The rocks most drastically affected are granodiorite and basaltic andesite (figs. 3, 4, 7, 17, and 18). As described in previous reports (White and Roberson, 1962; Sigvaldason and White, 1962), in areas locally above the main water table of saline water, H_2S is evolved and is oxidized near the ground surface to sulfuric acid, which then attacks silicate minerals. In places the leaching extends 100 feet or more below the

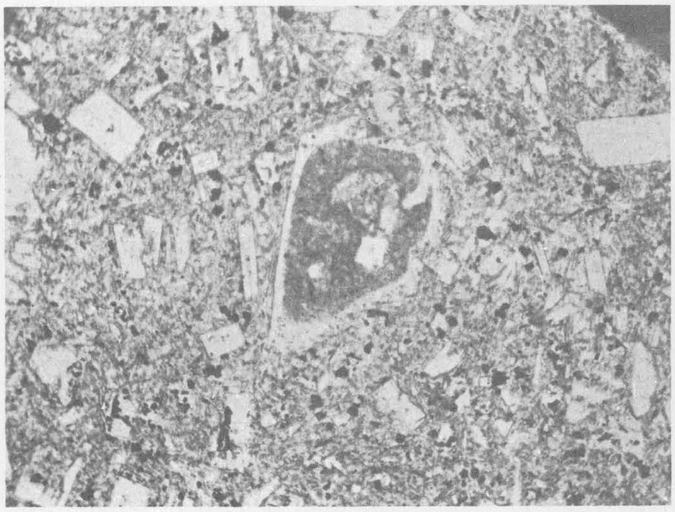

FIGURE 17.—Photomicrograph of basaltic andesite of the Lousetown Formation with relict "grained" plagioclase. Rock now consists of kaolinite and opal resulting from attack by sulfuric acid. GS–6 drill hole, 111-foot depth, eastern part of Sinter Hill. Plain light, × 39.

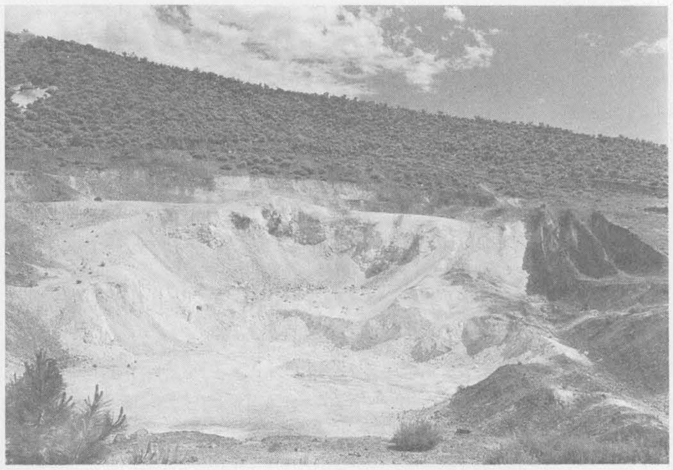

FIGURE 18.—View south toward clay quarry. Most of the bleached rock is basaltic andesite of the Lousetown Formation altered by the action of sulfuric acid to kaolinite with some opal and anatase. Basaltic andesite and talus in trenches on the right are unaltered or iron stained near surface, and overlie bleached basaltic andesite. Floor of quarry is bleached pre-Lousetown alluvium.

surface. Intense attack on granodiorite dissolves all soluble components including some silica and leaves a porous siliceous residue of original quartz, opal (amorphous and cristobalite by X-ray), and anatase, commonly with no change in volume (table 3, GS–7 drill hole; fig. 4; and Sigvaldason and White, 1962).

Acid condensates of steam also attack opaline sinter, causing it to disintegrate and slowly dissolve (fig. 19). Areas of disintegrated sinter are not indicated on plate 1, but are shown on detailed maps of the spring terraces to be included in later reports.

Bleached rocks of similar appearance have been described by Thompson and White (1964) in the surrounding quadrangles, but the sulfuric acid that is the active agent in most of these bleached areas has been derived by oxidation of pyrite from earlier deep alterations. Both in the region and in the thermal area, a characteristic vegetation marks the acid ground (Billings, 1950). Ponderosa pines of the thermal area (figs. 2 and 3) grow in ground that is too acid for normal vegetation. Lack of competition for available moisture enables ponderosa pines to grow here, a thousand feet lower in altitude than their normal lower limit in western Nevada.

All rocks in the thermal area have also been affected at depth near channels of migrating thermal water, and will be described in detail in later reports. Interpretation of their relict textures has been of great significance to the present report. The logs of the drill holes (table 3) incorporate many interpretations, but only a few examples can be illustrated here (figs. 17, and 20).

STRUCTURE

THE REGION AND STEAMBOAT HILLS

The regional structure has been summarized by Thompson and White (1964):

> Intense pre-Cenozoic folding and faulting left the metamorphic rocks dipping 45 to 90 degrees in most places and commonly striking between northeast and northwest. Cenozoic block faulting and warping, which together with erosion shaped the present mountainous topography, were underway before Pliocene time and have continued through Pleistocene. The northern and northeastern part of the Carson Range was principally domed up, while farther south * * * the range rose as a normal-fault block. Many faults along the eastern front of the Carson Range and western front of the Virginia Range are antithetic (with down-faulted sides toward the ranges). The complex trough between the Carson and Virginia Ranges contains a chain of basins, which are oval in general plan and separated by transverse ridges. The major Cenozoic deformation of which we have a record took place after deposition of the Truckee Formation and prior to the lava eruptions of the Lousetown Formation, but the Lousetown was also subjected to deformation that resulted in several hundred feet of additional structural relief.

Thompson and White also state (1964):

> Steamboat Hills is in many ways a miniature replica of the major ranges except that its long axis trends northeast, transverse to the trends of the ranges. The hills have an anticlinal form produced by a combination of warping and tilting of fault blocks (sec. *E–E'*, pl. 2). On the southeast flank of Steamboat Hills north of Pleasant Valley (2 miles southwest of the Springs) basal tuff-breccias of the Kate Peak Formation dip 45° to the southeast under Pleasant Valley and reappear again on the southeast side of the synclinal structure of the valley. Pre-Tertiary rocks crop out in many places near the

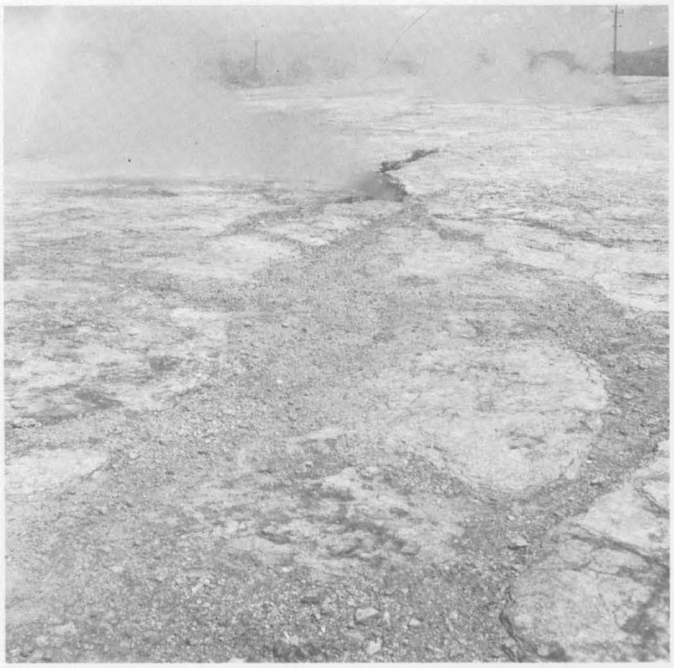

FIGURE 19.—Closed fissures near vent 39 on the crest of the Main Terrace. Fractures in sinter have controlled condensation of steam and oxidation of H_2S resulting in disintegration of opaline sinter adjacent to the fractures.

crestline of the hills and in general decrease in altitude on the flank of the anticlinal structure to the northwest where the older rocks are concealed by volcanic rocks. The structural relief, as in the Carson Range, has been produced by a combination of normal faults dipping away from the hills, and tilting of blocks that more than compensates for antithetic normal faults dipping toward the hills.

At least three systems of normal faults have been recognized in the hills. One major set strikes northeast, parallel to the axis of the hills; many of these are of the antithetic type that has been mentioned. A second set of faults strikes northwest nearly at right angles to the first. The third set strikes nearly north and is particularly prominent near Steamboat Springs; many of this set are also antithetic in that they dip toward the structural crest of Steamboat Hills, but their strikes are not parallel to the axis of the hills. Although faults of the three systems are not of distinctly different ages, those of the north-striking system show evidence of being most active recently, for many of them cut the pediment surface developed on pre-Lahontan deposits. On the other hand, few of those of the northwest and northeast systems cut this surface.

The western bounding fault of Steamboat Hills has been one of the most active in late geologic time. It cuts the alluvium along part of its trace, and in its strike and sense of displacement it obviously belongs to the same extensive system of faults that cuts the pre-Lahontan alluvium west and north of the hills. A fault bounding part of the southeast side of Steamboat Hills at Pleasant Valley must also have moved fairly recently to account for the lack of larger fans where Galena and Steamboat Creeks debouch on the floor of Pleasant Valley.

Ancestral Steamboat Hills was a topographic and perhaps also a structural high prior to Kate Peak volcanism. Soda trachyte lavas of the Alta Formation may have covered the area of the present hills but if so, they were eroded from most of the high parts of the uplift prior to eruption of the Kate Peak rocks.

The structural relief of the hills was largely attained prior to eruption of the Steamboat flows of the Lousetown Formation in the eastern part of the hills. A pre-Lousetown pediment surface upon which some of the lava was erupted has been identified around the northeast end of the hills and south of Steamboat Valley (Thompson and White, 1964). The altitudes of recognized parts of this pediment range from 4,800 to 5,200 feet. The pediment and the later Lousetown lavas are cut by a number of faults, but displacements are generally small. Some of these faults are antithetic, tending to decrease the structural relief, whereas tilting of the fault blocks and displacements on the other faults have tended to increase it.

THERMAL AREA

Throughout late Tertiary and Quaternary time, the Steamboat thermal area has been part of a zone balanced in general between structural uplift and erosion on the one hand and inundation by volcanic products and alluvium on the other. At least six different kinds of extrusive volcanic rocks have been found in the area.

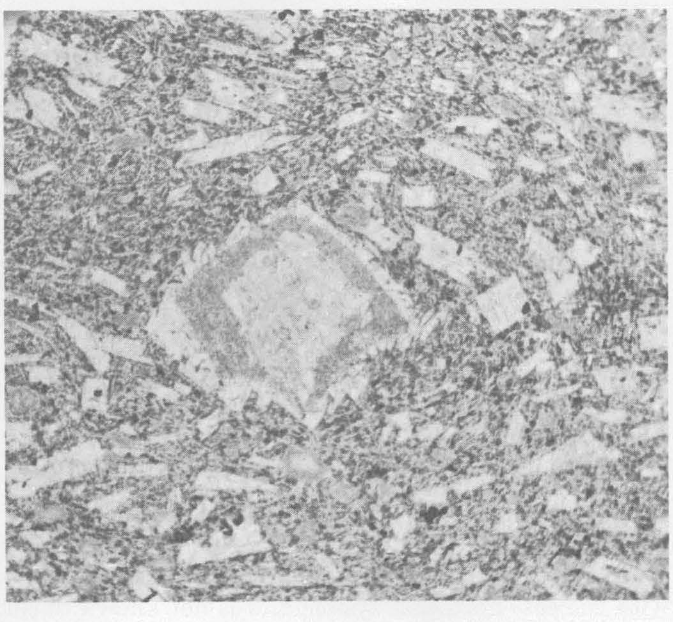

FIGURE 20.—Photomicrograph of rock from same lava flow as figure 17 with relict "grained" plagioclase. Here, the rock is almost completely replaced by potassium feldspar except for original olivine crystals, now largely chlorite. GS–6 drill hole, 100-foot depth. Plain light, × 39.

and three or four different kinds of intrusive rocks may have fed extrusives for which other direct evidence is lacking; in addition, at least two cycles of deep entrenchment and alluviation have occurred.

The balance between structural uplift and burial of the thermal area is at least in part coincidental because the local base level for erosion has been controlled since late Tertiary time by structural events affecting the basin of Truckee Meadows, and by entrenchment of the channel of Truckee River through the structurally positive Virginia Range. We can decipher only in part this complex interplay of factors that have influenced the thermal area.

Faults of the thermal area show a wide range in strike, but three rather well defined fault systems previously mentioned have been recognized in Steamboat Hills (pl. 1). The east-northeast system that parallels the axis of Steamboat Hills is largely but perhaps not entirely restricted to the Lousetown lava flows and older rocks in the western part of the thermal area. An exception is a hypothetical fault in the northern part of the mapped area near the Mount Rose Resort (pl. 1), which seems to displace the erosion surface cut on pre-Lake Lahontan alluvium. Two faults northwest of the silica pit (pl. 1) are antithetic; their scarps face the structural axis of the hills. The northeast-striking faults near the clay quarry are downfaulted to the north and are the only ones that are clearly not antithetic. This fault complex has about 100 feet of post-Lousetown displacement. If it continues below the surface to the northeast as suggested on plate 1 and sections *H–H′* and *I–I′* of plate 2, it is relatively old and large, with at least 200 feet of pre-Lousetown displacement.

The Kate Peak dike that crops out in the silica pit area strikes east-northeast and probably followed an old fault or fracture of the system. No evidence was found for post-Lousetown displacement along this structure.

The northwest-striking fault system in Steamboat Hills is represented in the thermal area by two faults in and near Pine Basin (pl. 1). These faults largely account for the graben structure of the basin. The western fault in particular is anomalous; it drops Steamboat basaltic andesite at least 100 feet downward to the northeast (fig. 3), but it could be traced no more than 1,000 feet from the zone of maximum displacement. This fault system is approximately contemporaneous with the east-northeast system and is not known to cut pre-Lake Lahontan alluvium.

The most numerous faults of the thermal area strike nearly north; strikes range from about N. 25° E. to N. 10° W. Many faults of this system are antithetic in that the downdropped sides are toward the structural crest of Steamboat Hills, but they strike at high angles into the east-northeast structural axis of the hills, which bisects the thermal area (pl. 1). Some of these faults are relatively old but many displace pre-Lake Lahontan alluvium and sinter and are thus the youngest faults of the area. None is known to cut deposits that are late Pleistocene or Recent in age. Old faults of this system have provided the structural control for most of the thermal activity of the area.

MAIN AND LOW TERRACES

Certain faults and fractures of the area have served as channels for upward migration of thermal waters that have at times in the past discharged at the surface, depositing siliceous sinter. The youngest large accumulations of sinter, flat on top but sloping downward on their east sides, are called hot-spring terraces. The name "terrace" is also extended to the High Terrace (pl. 1) because of preservation of its original topographic form even though sinter has accumulated here as a low symmetrical ridge. Older hot-spring deposits whose original topographic forms have been modified greatly by erosion, such as Sinter Hill, are not called terraces.

Subsurface data obtained from drilling, together with geophysical evidence, have shown that the structure of the active spring terraces is considerably more complex than was evident from surface mapping. The fissure systems of the terraces (pl. 1; figs. 19, 21, 22, and 23) were first assumed to be the surface expressions of the principal structural features and early evidence from the South Steamboat well seemed best explained by a west-dipping thrust or reverse fault system (White and

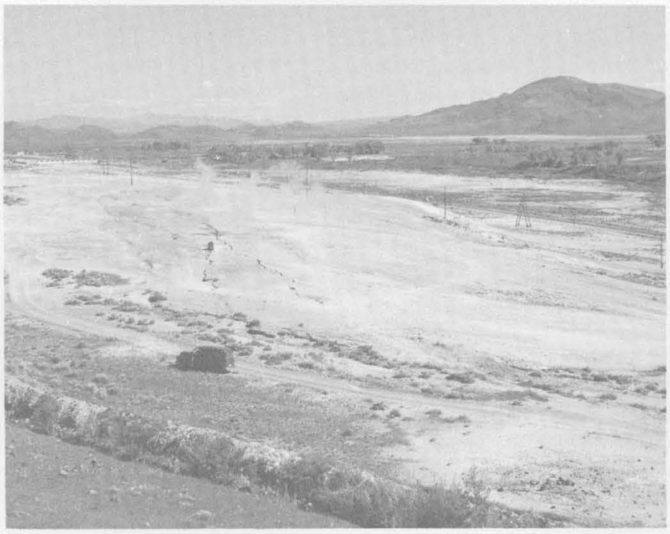

FIGURE 21.—View north along the fissure system and the crest of the Main Terrace.

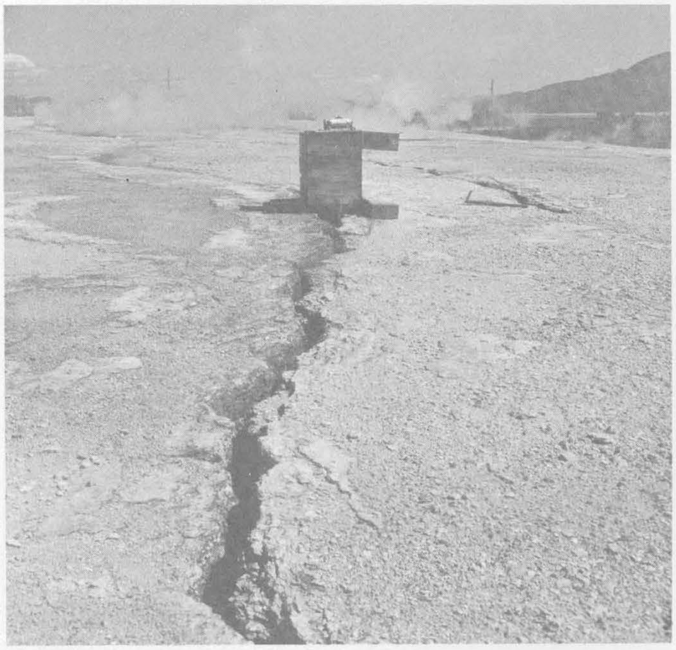

FIGURE 22.—An open fissure near the crest of the Main Terrace; view north toward a water-stage recorder installed at vent 35. The average width of the fissure is about 5 inches.

Brannock, 1950, p. 572–573). Drill cuttings from about 60 to 114 feet in depth in this well (table 3) consisted entirely of granodiorite debris except for a very few fragments that seemed best interpreted as contaminants from higher in the hole.

The first hole drilled by the Geological Survey (table 3, GS–1 drill hole; and Sigvaldason and White, 1961, p. D117–D119) was located from geophysical data (traverse 19, pls. 3–5) on the theory that the principal structural feature was a west-dipping reverse fault that could be intersected at depth by collaring the hole west of the resistivity and magnetic lows. The drill hole penetrated highly altered tuff-breccias with relict textures of Kate Peak volcanic rocks from 129 to 209 feet in depth; granodiorite was penetrated above and below the tuff-breccia. Presumably tuff-breccia of extrusive origin had accumulated on a surface underlain by granodiorite, and granodiorite was later thrust over the younger rocks; the thrust hypothesis seemed to be completely confirmed (later petrographic study revealed two deep narrow breccia zones near depths of 264 and 272 feet that contained some fragments of tuff-breccia, requiring a series of thrust slices, or some other explanation).

GS–3 drill hole (table 3) on the Main Terrace was also located on the basis of the thrust hypothesis, even though here there was little confirming evidence from the geophysical data (pls. 3–5). The hole was first drilled to a depth of 300 feet without finding positive evidence of thrust faulting. In fact, breccia zones and veins were unexpectedly scarce. GS–4 (table 3) was then drilled east of the crest of the terrace. Veins in greater abundance, stronger rock alteration, and somewhat higher temperatures at depth (169°C near 300 ft, as compared to 166°C at the same depth in GS–3) indicated east-dipping structural features, at least in the upper parts of the spring system (section *C–C′*, pl. 2).

GS–5 (table 3; Sigvaldason and White, 1962) was originally to be drilled to a shallow depth, principally in order to find post-Lousetown chalcedonic sinter reportedly found in the old adit 300 feet to the east. Only a few feet of chalcedonic sinter was found, but the discovery of relatively high temperatures (170°C at 300 ft), thick quartz-chalcedony-calcite veins, and extensive alteration encouraged further drilling. A dike of the Kate Peak Formation was penetrated at 465 feet, and thoroughly argillized fine-grained volcanic rock having relict texture similar to soda trachyte of the Alta Formation was penetrated from 525 to 546 feet.

The evidence at this stage seemed reconciled by a deep west-dipping thrust fault whose bedrock trace was near the east borders of the Low and Main Terraces, and whose hanging wall was cut by east-dipping normal faults or fractures. GS–3 drill hole was then deepened to 686 feet but no evidence for a deep thrust fault was found. The maximum temperature in GS–3 is only 169°C near 500 feet and there is a slight temperature reversal to 164°C at the bottom. The intensity of alteration below 580 feet is also somewhat less than at

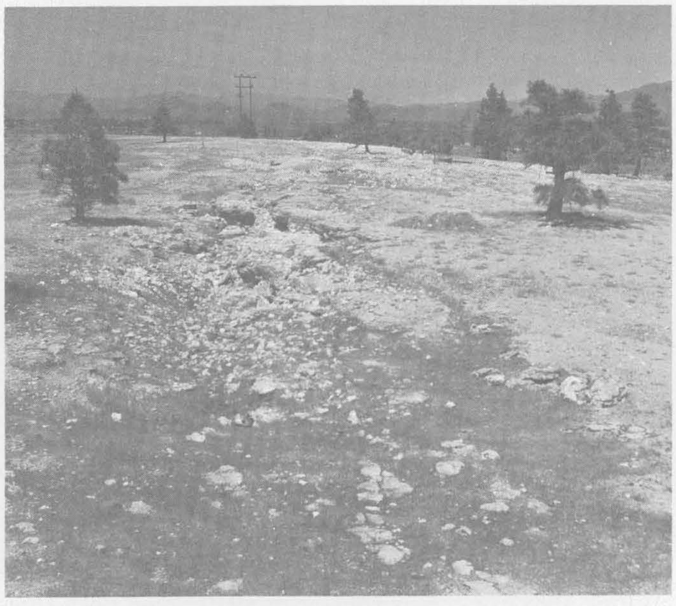

FIGURE 23.—Crest of the High Terrace; view north along the old fissure system and the axis of the terrace. The casing of GS–2 drill hole is indicated by arrow in the middle distance.

higher levels and average alteration is less than in GS-4 and GS-5 drill holes. These facts seem to contradict the thrust hypothesis.

A fault or fault system with a displacement on the order of 500 to 1,000 feet and situated under or near Steamboat Creek is required to account for the fact that soda trachyte of the Alta Formation east of Steamboat Creek (pl. 1) dips west into the pre-Tertiary basement rocks of the thermal area. Confirming evidence for a fault of this magnitude was found in Nevada Thermal Well 1, drilled near Steamboat Creek in 1959 (pl. 1 and section *B–B′* of pl. 2; Nevada Thermal Power Co., written commun. and well log, 1959). Volcanic rock seemingly similar to soda trachyte of the Alta Formation was found from 350 to 550 feet and perhaps deeper. In the log of the well, the rock is described as "andesite, dark red to black, subtrachytic, iron-stained, * * * phenocrysts replaced with clay minerals." Below 550 feet some of the volcanic rocks have larger phenocrysts including "hornblende," and some cuttings are described as tuff-breccias, but many are "trachytic to sub-trachytic." The well reportedly penetrated granodiorite at 1,050 feet, and its total depth is 1,830 feet. The relations shown on section *B–B′* of plate 2 indicates a displacement of probably 1,000 feet or more of the granodiorite contact. Most of the displacement may be on a single fault, or it may be shared by several faults east of GS-5 drill hole, as suggested in section *B–B′*. This fault or faults and associated fractures of the Low and Main Terraces are here called the Steamboat Springs fault zone. The minimum dip of the fault or faults, as indicated by relations in drill holes on section *B–B′*, is 50°. This dip is too steep to be a pre-Alta fault scarp, with soda trachyte of the Alta Formation flowing against the scarp. A part of the movement on the fault could have been earlier than the Alta, but most was more closely related in time to the Kate Peak Formation.

In bedrock 1 to 3 miles southwest of the Low Terrace, a fault of similar or greater magnitude extends northeast toward the springs (Thompson and White, 1964, pls. 1 and 2) and is probably the continuation of the Steamboat Springs fault zone, although a connection beneath alluvium was not shown on the published map. The fault clearly displaces Kate Peak volcanic rocks (Thompson and White, 1964, section *B–B′*, pl. 2) but there has been little or no movement since cutting of the pre-Lousetown pediment surface (Thompson and White, 1964), which is similar in altitude on both sides of the fault. The fault is probably normal rather than reverse, and its dip is steep, as shown by the straightness of the fault trace across topography of considerable relief. No evidence for thrust or reverse faults was found elsewhere in the Mount Rose or Virginia City quadrangles. If the Steamboat Springs fault zone has thrust or reverse movement, it is a unique structure in the area. In view of the probability that this fault system continues south of Steamboat Valley as a normal fault consistent with regional structure, it is probably also normal within the thermal area, and is so interpreted on geologic sections in spite of the fact that some local evidence favors interpretation as a thrust.

A gravity traverse near the south end of the thermal area has provided significant data on the Steamboat Springs fault zone and the structure of the spring terraces (Thompson and Sandberg, 1958, p. 1273–1274). The gravity stations are along a road in the southeast corner of the thermal area (pl. 1), and are projected to traverse 18, plate 4. The line of the traverse extended to bedrock outcrops east and west of the segment of road shown on plate 1, and the reader is referred to the original publication for additional details.

Thompson and Sandberg found that a gravity profile calculated from section *F–F′* of plate 2 was very close to the observed gravity data; no attempt was made to achieve a better fit. Parts of the bedrock surface near the west end of the traverse must dip under alluvium at angles of as much as 60°–70° (op. cit., p. 1273). The steep dip of the bedrock provides strong evidence of a fault scarp, and a thrust hypothesis does not give as satisfactory a fit as that of a normal fault. The gravity profile also indicates a lack of appreciable displacement of the bedrock surface under tthe valley floor.

Gravity data for traverse 3 (pl. 3; Thompson and Sandberg, 1958, p. 1273–1274) and drill-hole data are interpreted in section *C–C′*, plate 2. All available evidence indicates little displacement on the fissure system of the Main Terrace, at least since the time of deposition of pre-Lousetown alluvium. The gravity data also indicate the absence of a pronounced fault scarp east of the main fissure system. The main period of movement on the Steamboat Springs fault system was later than extrusion of the Kate Peak formation and earlier than the cutting of the pre-Lousetown pediment. Geophysical evidence does not exclude the possibility of small-scale later movement and this is indicated in section *B–B′* and *C–C′* of plate 2.

HIGH TERRACE

The dominant structure of the High Terrace seems to be a system of east-dipping fractures (section *A–A′*, pl. 2). GS-2 drill hole (table 3; and Sigvaldason and White, 1961, p. D119–D121) was collared on the east edge of the zone of fissures evident at the surface (pl. 1). These fissures have nearly vertical dips near the surface (fig. 23) and in an old shaft near GS–2, and also in the Main Terrace (fig. 22). Many veins were penetrated by the drill hole, particularly at depths from 100 to 335 feet (table 3, GS–2 drill hole; and section *A–A′*, pl. 2). Although the possibility of west-dipping fractures and "blind" veins cannot be eliminated by data from a single drill hole, the evidence favors a system of east-dipping fractures and veins as indicated in the structure section.

The amount of displacement on the fracture system is not known. If it is similar to that of the Main Terrace, the total displacement is probably small, and is so shown in section *A–A′*.

SINTER HILL

As mentioned previously, little is known about the internal structure of Sinter Hill (pl. 1 and fig. 3) or of the faults and fractures that controlled migrating thermal waters from which the sinters were deposited. No specific vents or fissures related to deposition of sinter have been recognized. The absence of recognizable vents is not too surprising if most of the sinter was originally deposited on broad aprons. The irregular forms of primary geyserite (type A–2 of classification) must have been rare or absent, because this type of sinter should still be recognizable even when chalcedonized. Observed structures indicate a dominance of type A–1 and B–1 prior to chalcedonization.

The general distribution of sinter as well as the topographic form of the hill suggest a control by east-northeast structure, perhaps with less conspicuous control by north-striking structures. Regardless of the nature of the structural control, it is effectively concealed by sinter.

GS–6 drill hole (table 3, p. B17; and section *I–I′*, pl. 2) penetrated granodiorite at an altitude of about 4,660 feet, and granodiorite crops out to the south in the floor of the valley near the line of section at an altitude of 4,740 feet. In the absence of other evidence, the section has been constructed with no major fault between these two localities. A fault does seem to be required, however, between GS–6 and GS–2 drill holes. Granodiorite was penetrated in GS–2 at an altitude of 4,365 feet, and was overlain by 225 feet of Kate Peak tuff-breccia that is entirely missing in GS–6 drill hole. Although the evidence is not conclusive, pre-Lousetown faulting has probably caused displacement of 200 feet or more between the two drill holes. A possible location for such a fault is indicated on plate 1 and sections *H–H′* and *I–I′* of plate 2.

The west part of Sinter Hill is structurally complex and is further complicated by the very thorough hydrothermal alteration of silicate rocks west and southwest of the crest of the hill, where some activity is still continuing (table 3, auger holes 1 and 2). In most places the dips of the sinters of Sinter Hill are gentle to moderate and apparently are initial. In the southwestern part, however, the dips are generally southwest at angles of 30°–45° (fig. 13). As described previously, the gravity-controlled planar banding in cavities indicate tilting of 30°–40° SE. since the rocks were chalcedonized. The deformation is earlier than the opaline hot-spring sinter of Sinter Hill, and presumably earlier than the post-Lousetown chalcedonic hot-spring sinter but later than the Lousetown flows. The dip of the basal contact of the Lousetown flow northwest of the crest of Sinter Hill is about 20° NE. and is opposed to that of the chalcedonic sinter. Positive evidence is lacking for structural tilting of the lava flow, but 20° is considerably steeper than initial dips elsewhere.

No similar deformation has been found in chalcedonic sinter that is definitely post-Lousetown in age; banded cavity fillings in these rocks, wherever noted, are nearly horizontal (table 3, GS–2 and GS–6 drill holes). For this and other reasons already discussed, the sinter in the southwest part of Sinter Hill is considered to be pre-Lousetown in age. The explanation of such local anomalous deformation is a major problem. Section *H–H′* (pl. 2) illustrates one possible interpretation of the relations. The strong tilting of the sinter toward the northeast-trending axis of Steamboat Hills and nearly at right angles to the graben structure of Pine Basin is here assumed to be caused by a shallow domal intrusion that may have broken through to the surface. The time of deformation coincides closely with eruption of the dome of the Steamboat Hills Rhyolite. Although there is no direct evidence for the existence of such an intrusion and permission could not be obtained to drill the ground, this hypothesis does account for the existing strong and apparently local deformation.

PINE BASIN

Pine Basin is a structural depression modified by erosion (pl. 1 and fig. 3); it formed as a graben between two faults of the northwest system. The western fault is a few hundred feet west of the floor of the basin, and drops Steamboat basaltic andesite at least 100 feet down to the east. A peculiar characteristic of this fault is that it cannot be traced more than a few hundred feet from the zone of maximum displacement. This situation is explainable as the effect of (1) very pronounced rotational or hinge movements at both ends and (2) structural extension, the cause of which is unknown. Evidence for northward termination or offset against another fault was sought but not found.

The northeast side of the graben is a fault that passes near the center of Pine Basin; the structural basin has been enlarged to the east by erosion. The eastern fault can be traced about 2,000 feet southeast of the floor of the basin, where it dies out. The vertical displacement of the basal contact of basaltic andesite is 40 feet immediately southeast of the basin; immediately northwest of the basin, basaltic andesite is downfaulted 50–100 feet against pre-Lousetown sinter.

CLAY QUARRY

The clay quarry (fig. 18) is near the junction of a small north-trending fault and a relatively large north-northeast fault. The latter splits westward into two segments near the quarry; the total post-Lousetown displacement is about 75 feet (section *G–G′*, pl. 2). This fault supposedly continues to the northeast under the sinter of Sinter Hill, as indicated on plate 1, with Kate Peak tuff-breccia of GS–2 drill hole downfaulted 200 to 300 feet to the north, thereby preserving the rock, as shown in sections *G–G′* and *H–H′* of plate 2. If this supposition is in accord with fact, the fault is old and there was much movement on it prior to deposition of the Lousetown.

Slight thermal activity still persists in the clay quarry, where gases continue to rise above a water table 60 feet or more below the surface. Temperatures of more than 50°C were recorded in auger holes 10a and 10b (table 3) at a depth of 4 feet, but these holes were bored in or near places where the air was noticeably warm and the ground moist. An old well 1,000 feet west of the clay quarry and near the west edge of plate 1 is 58 feet deep and normally is dry at bottom, where the temperature is 70°C.

Nevada Thermal well 5, located 250 feet east of the clay quarry, was drilled in 1961 to a depth of about 825 feet (Magma Power Co., written commun., 1962). Temperatures were below the boiling-point curve, and a maximum of 175°C was measured at a depth of about 700 feet; depth to water table is probably near 85 feet.

SILICA PIT

Until GS–7 drill hole was bored, the data required for a structural explanation of thermal activity in the silica pit area were lacking (table 3; White, 1955a, p. 111; Sigvaldason and White, 1962). GS–7 penetrated a completely argillized pyroxene andesite dike of the Kate Peak Formation from 253 to 329 feet. Careful search on the surface then revealed a strongly acid leached and opalized dike that previously was included with nearby opalized pre-Lousetown alluvium of similar appearance.

The dike strikes about N. 60° E. and dips 70° SE. (section *G–G′*, pl. 2). It was intruded along a fault or fracture of the system of north-northeast faults parallel to the axis of Steamboat Hills. If there were appreciable pre-Lousetown movement on the fault, the evidence was obscured by pediment cutting before deposition of pre-Lousetown alluvium. There is no evidence of post-Lousetown movement on the fault.

The silica pit fault or fracture probably controlled thermal waters that deposited pre-Lousetown hot-spring sinter somewhere in the immediate vicinity. Boulders of chalcedonic sinter are found in pre-Lousetown alluvium in the lava-capped knob 200 feet east of the floor of Pine Basin (section *H–H′*, pl. 2). This knob is directly down the pediment slope from the silica pit area. No outcrops of sinter have been found nearby, although Becker (1888, Atlas sheet 14) incorrectly mapped opalized residues of intensely altered older rocks as sinter.

The silica pit fault and the pyroxene andesite dike dip under the most intensely altered rocks. Although hot water is no longer discharged from the area, except in minor amounts as vapor, H_2S and other gases separate from water at depth and rise up the fracture into the hanging-wall block. Effects of the near-surface bleaching caused by sulphuric acid from oxidation of H_2S are summarized briefly in table 3 (GS–7 drill hole) but will be treated in more detail in other reports.

HISTORY OF STRUCTURAL FEATURES OF THE THERMAL AREA

PRE-TERTIARY FEATURES

Exposed pre-Tertiary structural features seem to have had little influence on the history of the thermal area. Structural trends in the metamorphic rocks in and southeast of Steamboat Hills range from N. 30° to 50° E. The only similar Cenozoic structural trends are those of the east-northeast fault system and the axis of Steamboat Hills. The contact between granodiorite and metamorphic rocks in the southern part of the thermal area is largely concealed by Steamboat basaltic andesite flows, but the general trend must be nearly due west (Thompson and White, 1964, pl. 1). All late Tertiary and Quaternary structural trends differ markedly from the trend of the intrusive contact.

TERTIARY FEATURES

Little is known about the early Tertiary history of the thermal area. Volcanic rocks of the Hartford Hill and Alta Formations probably covered the area but were removed later by erosion. Probably when soda trachyte of the younger part of the Alta Formation was erupted, and certainly during Kate Peak volcanism, Steamboat Hills was rising intermittently relative to the adjoining basins. The uplift took place partly by faulting and partly by broad warping of the competent basement rocks; the main faults trended east-northeast and a few faults of probably similar age trended northwest. The oldest faults of the north-striking system must also have been active, because a few dikes related to the Alta and Kate Peak Formations were intruded along east-northeast and north-striking fractures. These dikes probably fed lava flows and extrusive tuff-breccias, because the upper surface of granodiorite and probably also the topographic surface were only slightly higher than the present surfaces. This is indicated by small remnants of Kate Peak flows south of Mill Hill (pl. 1) and along the north border of Steamboat Hills. Extrusive tuff-breccias of the Kate Peak Formation in GS–2 and GS–5 drill holes were downfaulted and thus protected from the erosion that presumably stripped late Tertiary volcanic rocks from most of the thermal area.

The structural relief of the hills and the thermal area was largely determined immediately before, during, and soon after Kate Peak volcanism. Deformation was probably going on while Truckee sediments were being deposited elsewhere in the region, but rocks of the Truckee Formation are not recognized with certainty in the thermal area. In this connection, altered siliceous sediments on the lower southeast slope of Sinter Hill are included with the pre-Lousetown alluvium but may be reconstituted diatomite, and the altered volcanic rocks overlying granodiorite in GS–2 drill hole could be unsorted clastic deposits of the Truckee Formation.

The Steamboat Springs fault system that bounds Steamboat Hills on the east is a major system with a total displacement on the order of 1,000 feet, as previously discussed. Most or all of this movement occurred after eruption of the Kate Peak Formation and prior to cutting of the pre-Lousetown pediment surface, which extends across the fault from eastern Steamboat Hills to the south side of Steamboat Valley 2 miles south of the springs (Thompson and White, 1964).

QUATERNARY FEATURES

Following extensive erosion, and then eruption of the local lava flows of the Lousetown Formation, additional movement occurred on some of the old faults, but no displacement of more than 100 feet is evident. A fault cutting basaltic andesite immediately south of the clay quarry has a vertical displacement of about 75 feet, and another southwest of Pine Basin has about 100 feet. Faults of the sinter terraces presumably were active to a slight extent and are so indicated on the structure sections (pl. 2). A scarcity of evidence is to be expected because of concealment by hot-spring deposits, but the evidence from drill holes and detailed gravity measurements in general favors little or no movement.

Many fault scarps are discernible in areas underlain by pre-Lake Lahontan alluvium. Probably all are small, because none has been traced definitely into a fault cutting bedrock. The fault northwest of Sinter Hill that controls Mud Volcano Basin is a possible exception if it curves southeastward into the fault that passes under Pine Basin.

No post-Pleistocene (post-Lake Lahontan) fault scarps have been recognized in the area, despite the fact that local earthquakes are relatively frequent. Fissures controlling the thermal activity are probably maintained as permeable channels by periodic slight movement. No vertical displacement of near-surface sinter has been recognized on any of the fissures. Blake (1864), Phillips (1879), and probably others believed that the open fissures of the Low and Main Terraces (figs. 21 and 22) were caused by deformation or physical separation of the fissure walls. The present study indicates, however, that chemical attack by sulfuric acid and disintegration of sinter adjacent to fractures are the dominant factors in creating and maintaining open fissures near the surface. In many places the walls of a fissure do not match closely; in other places a fissure perhaps 4 to 6 inches wide narrows within a distance of a few inches and continues as a fracture less than half an inch wide (figs. 24 and 25) and bordered by horizontal rather than vertical layering. These facts are not compatible with a structural origin for the open spaces of the fissures, in contrast to an unquestioned structural origin for the original fractures.

PRESENT SEISMIC ACTIVITY

None of the many faults in the Mount Rose and Virginia City quadrangles is known to have been active at the surface since about 1850, when the region was first settled by white men. Probably the nearest faults with historic surface displacements are those of Fort Sage Mountain, 50 miles to the north-northwest (Gianella, 1957), and the Fallon-Stillwater faults of 1954 (Tocher, 1956; Slemmons, 1956). Byerly (1956) has summarized the major historic earthquakes of Nevada, some of which had epicenters in or near Steamboat Springs, and which may have had unrecognized surface displacements. The numerous local earthquakes of the region indicate than many faults are active at depth and possibly even at the surface (table 5). None of the epicenters of these earthquakes is known

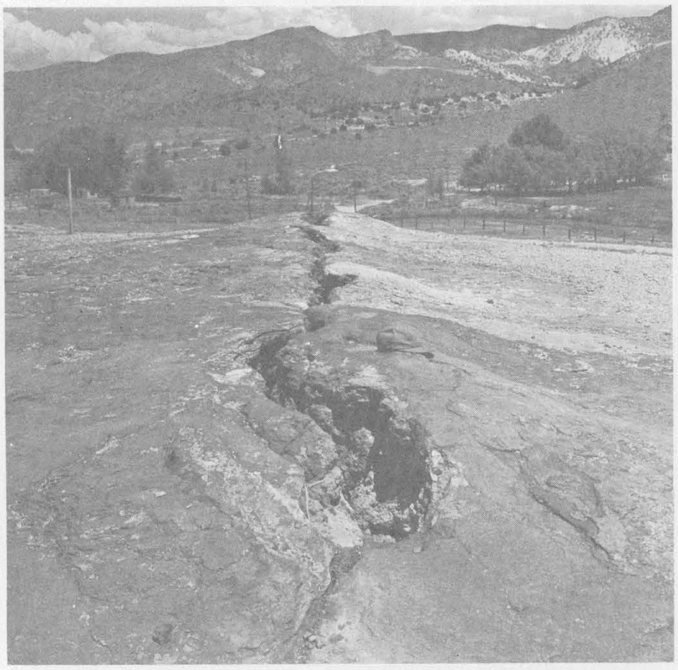

FIGURE 24.—Open fissure of springs 30 and 30–s, Low Terrace, showing mismatching of walls and abrupt transition (at near end) into closed fissure without significant structural separation. Disintegration of previously formed opaline sinter by sulfuric acid at time of low water level is a major factor in creating open fissures from fractures.

to be in the immediate area of the springs, but some may have been, especially the series of September 7, 1947. Between seven and nine separate shocks were felt by residents near Steamboat Springs, but only three or four of the strongest were felt in Reno, 10 miles to the north, and Carson City, 20 miles to the south. These earthquakes had pronounced effects on the hot springs, to be considered in another report. In contrast, the epicenter of the strong earthquake of December 29, 1948 (Gianella, 1949) was near Verdi, about 30 miles from the springs, but the earthquake had no noticeable effect on any springs or vents.

GEOMORPHOLOGY

The geomorphology of the region has been summarized by Thompson and White (1964):

> Former landscapes very different from the present have evolved by continuous modification at variable rates. Relics of certain stages in the evolution are recognizable and partly decipherable, and three of these, the low-relief erosion surface high in the ranges and two broad pediment surfaces around the margins of the ranges, are discussed in some detail. The high surface is no older than Pliocene and probably reached its optimum development in late Pliocene or early Pleistocene time, but it may not represent the landscape at a particular short period of time. The two best developed pediments were possibly cut during the McGee and Sherwin Glaciations.

The high surface is well developed in various parts of the Carson Range at altitudes of 8,000 to 9,000 feet, in the Virginia Range at altitudes about 5,600 to 7,500 feet, and near the crest of Steamboat Hills at about 5,800 feet. Although some geologists have assumed that the surface is older than the basins and ranges, evidence found in the present study indicates instead that the basins and low ancestral ranges were already in existence when the surface was being cut. Differences in altitude of the high erosion surface in the two ranges are then attributable to original differences in what may have been a compound pediment or rolling upland, and to later structural deformation. No completely reliable criteria exist for correlation of the separate topographic remnants. A still higher and older erosion surface may be represented on the summits above 9,000 feet, but no attempt is made here to reconstruct it.

Below the prominent high surface are numerous remnants of erosion surfaces that defy regional correlation, and below these are two main systems of broad pediments. Several low and narrower pediments are so obviously related to terraces along present valleys that they need not be discussed. The higher of the two high pediments on the northern margin of the Carson Range was cut about the same time as the prominent lava-capped pediment in the eastern part of Steamboat Hills. Other remnants to the south and along the Virginia Range show that the higher pediment was widely developed, and during its development the chain of valleys from Washoe Valley to the Truckee River was broader than at present, was filled with alluvium to heights of 200 feet above present base levels, and probably has an axial gradient of less than 50 feet per mile, compared to a slope of about 300 feet per mile of the pediment toward the valleys. Local evidence at Steamboat Springs indicates that the cutting of this high pediment was both preceded and followed by cycles of deep erosion, alluviation, and pedimentation by streams. The first cycle was earlier than basaltic andesite flows of the Lousetown Formation and

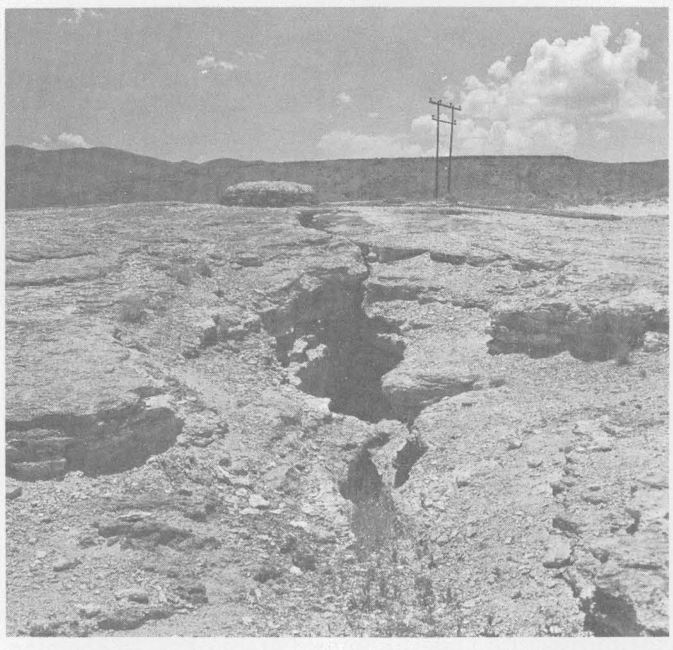

FIGURE 25.—Vent 21–n near the north end of the Main Terrace, showing gross mismatching of walls caused by disintegration of opaline sinter.

the second cycle was later and probably Sherwin in age [table 4, this report]. The lower of the two high pediments in the northern part of the Carson Range was then cut to the same general base level as the broad boulder-strewn surface of pre-Lahontan alluvium southwest of Truckee Meadows. A widely developed pre-Lahontan soil then formed on the pediment surface, which was then displaced by faults with as much as 75 feet of vertical movement. Events contemporaneous with and later than Tahoe and Tioga Glaciations have had relatively minor geomorphic effects.

Many factors have contributed to create the landforms of the thermal area. Erosion, as in most areas, has been a major process. The different rocks present extreme contrasts in their resistance to erosion, ranging from highly resistant chalcedonic sinter and chalcedony-cemented quartzite to easily eroded fine-grained pre-Lousetown alluvium, which was probably stripped from much of the bedrock now exposed at the surface.

Geologic processes that result in topographic highs or constructional landforms are of three types: (1) Structural deformation, consisting here of faulting and broad wraping, is chiefly responsible for Steamboat Hills, with the thermal area at the northeast end. Fault scarps, although generally not prominent, are impor-

TABLE 5.—*Local earthquakes 1947 to 1952 with epicenters near Steamboat Springs*

Date	Pacific standard time	Richter magnitude [1]	Computed location [1]		Reference [2]	Distance from Steamboat Springs (lat 39°23′ N., long 119°44′ W.) and location
			Lat N.	Long W.		
1947						
Sept. 7	21:52	"Moderate"	39.3°	120.2°	17-3-99	32 miles WSW. (or nearer (?)—see text.)
Do	23:13	do	39.3°	120.2°		Do.
Nov. 25	10:09	do	39.3°	119.8°	17-4-146	6 miles SW.; N. end Washoe Valley.
1948						
Mar. 28	10:26	4.6	39.0°	119.9°	18-1-6	28 miles SSW.; near Zephyr Cove, Lake Tahoe.
Dec. 29	4:53	[3] 6.0	39°33′	120°05′	18-4-284	30 miles NW.; NW. of Verdi, W. of Reno.[4]
1949						
July 18	7:31	4.5	39.7°	119.8°	19-3-157	22 miles N.; Hungry Valley.
Nov. 14	2:41	3.5	39°23′	119°42′	19-4-289	2 miles E. of Steamboat.
Dec. 7	10:44	3.8	39.0°	119.8°		26 miles S-SW.; Genoa, W. border Carson Valley.
1950						
May 5	3:01	3.5	39°06′	119°41′	20-2-42	20 miles S.; SE. of Carson City.
June 6	8:34	3.1	39°33′	120°05′	20-2-43	22 miles NW.; W. of Verdi.
Oct. 25	19:18	4.2	39°37′	119°42′	20-4-129	17 miles N.; Spanish Spring Valley. 10 miles NE. of Reno.
Nov. 1	21:07	3.9	39°37′	119°55′		18 miles N-NW.; NE. slope Peavine Peak. 6 miles NW. of Reno.
Nov. 10	9:28	4.0	39°38′	119°41′		18 miles N-NE.; E. side Spanish Spring Valley, 10 miles NE. of Reno.
Dec. 7	4:54	3.3	39°40′	119°44′	20-4-131	20 miles N.; W. side Spanish Spring Valley, 10 miles N. of Reno.
Dec. 14[4]	5:24	5.6	40°05′	120°04′		50 miles N-NW.; Fort Sage Mtn. E. of Doyle, Calif.
1951						
Jan. 2	15:31	4.4	39.9°	119.3°	21-1-4	40 miles N-NE.; W. shore Pyramid Lake.
Jan. 20	22:28	4.1	39°37′	119°48′		17 miles N.; N. of Reno.
Jan. 22	7:14	4.8	39°05′	119°57′		23 miles SW.; Glenbrook, E. shore Lake Tahoe.
Apr. 3	18:46	3.0	39.7°	119.8°	21-2-46	23 miles N.; E. side Lemmon Valley.
Apr. 14	13:59	3.2	39.5°	120.1°		20 miles NW.; W. of Verdi.
May 1	2:13	3.1	39°13′	119°37′		13 miles S-SE.; 1 mile SW. of Dayton.
Do	17:00	3.4	39°17′	119°33′		12 miles SE.; 4 miles NE. of Dayton.
May 8	5:35	3.3	39.4°	119.3°	21-2-47	24 miles E.; 20 miles NE. of Dayton.
June 29	18:54	3.3	39.4°	119.8°	21-2-48	4 miles NW.
July 28	13:34	3.0	39.4°	120.0°	21-3-88	14 miles W-NW.
1952						
May 9	7:31	5.1	39°25′	119°47′	22-2-37	4 miles NW.
May 13	11:17	3.4	39°45′	119°51′		18 miles N-NW.; S. border Lemmon Valley.

[1] Determined without data from Reno prior to Dec. 15, 1948; reliability of data greatly increased after that date by use of a 3-component Sprengnether short-period seismograph at Univ. Nevada.

[2] References are to volume, number, and page, in that order, of California Univ. Seismog. Sta. Bulls.

[3] Probably 6½ or stronger according to Gianella (1949), with epicenter 12-15 miles from Reno.

[4] The only earthquake of the series with proved surface displacement (Gianella, 1957). Fault consists of two segments of about equal length traced for total of 5½ miles; maximum displacement is 8 in., downthrown to the west.

tant elements of the present topography; (2) volcanism, the process directly responsible for the Lousetown lava flows and other volcanic rocks of the area, and which may be an underlying cause of structural uplift of Steamboat Hills; and (3) deposition of silica from discharging hot water, a process ultimately related to volcanism, resulting in formation of hot-spring sinter deposits.

As discussed previously, the geomorphic history of the landforms is complicated by the fact that the local base level, Steamboat Creek, has fluctuated a number of times above and below its present position. An area on the crest of a major range is influenced mostly by erosion, a process which may be complicated by volcanism and periodic structural uplift; an area in the center of a structural basin is likely to be influenced largely by deposition of alluvium and be buried under basin sediments. The Steamboat thermal area, situated on the margin of the minor structurally positive Steamboat Hills, has been affected alternately by the two different trends.

The Truckee River and its outlet through the Virginia Range have been the dominant influence in determining whether Steamboat Creek was aggrading or degrading at any specific time. Climate, of course, has also been important in controlling the creek's discharge, its sediment load, and its equilibrium gradient between the Truckee River and the thermal area.

In general through late Tertiary and Quaternary time the Truckee River has been entrenching its channel through the Virginia Range. The local base level, Steamboat Creek, has not been consistently lowered through the same interval of time relative to bedrock of the thermal area, but has fluctuated above and below its present position. The thermal area has subsided structurally at about the same average rate that the Truckee River has entrenched into the Virginia Range. The thermal area has therefore subsided in relation to the Virginia Range, but has not gone down as rapidly as the basin of Truckee Meadows. Another way of stating this relation is to say that the thermal area has not risen as rapidly as the Virginia Range or as the main part of Steamboat Hills.

SUMMARY OF THE GEOLOGIC HISTORY OF THE THERMAL AREA

The long pre-Tertiary and early Tertiary history of the area is vaguely known. The sequence of middle Tertiary to Quaternary events in or near the thermal area can be deciphered in greater detail:

1. Soda trachyte lava flows of the Alta Formation were extruded, probably in middle Tertiary time.
2. Steamboat Hills was uplifted by faulting and broad warping, contemporaneous with erosion.
3. Largely contemporaneous with but also after this uplift, volcanic rocks of the Kate Peak Formation were intruded as dikes and some were extruded. Near the axis of the hills the extrusive volcanic rocks were thinner and in places were soon stripped off by erosion. At least locally on the flanks of the hills volcanic rocks were downfaulted and preserved from erosion.
4. Sediments of the Truckee Formation were deposited elsewhere in the region but have not been recognized with certainty in the thermal area, although some highly altered rocks may be facies of the Truckee Formation. Steamboat Hills apparently continued to rise and the principal faults were probably most active at this time.
5. The area was deeply eroded as Steamboat Creek became strongly entrenched.
6. Pre-Lousetown alluvium was deposited to depths of as much as 500 feet. This stage may coincide at least in part with the McGee or oldest glaciation recognized for the Pleistocene in the Sierras (table 4).
7. Pre-Lousetown hot-spring sinter was deposited contemporaneously with at least some of the pre-Lousetown alluvium.
8. During a structural stillstand, a pediment was cut by streams on granodiorite and metamorphic rocks around the northeast end of Steamboat Hills and south of Steamboat Valley, and pediment gravels were deposited on the rock-cut surface. The pediment cutting progressed an average distance of about half a mile from the margins of the deep alluvial fill. Remnants of this pediment are largely restricted to present altitudes between 5,000 and 5,200 feet.
9. Pre-Lousetown hot-spring sinter continued to be deposited during the period of pediment cutting, probably on the pediment surface somewhere near the silica pit, and contributed detritus to the pre-Lousetown pediment gravels south and west of Pine Basin. Small patches of chalcedonic and opaline sinter that lie on metamorphic rocks 1 mile south-southeast of the silica pit (Thompson and White, 1964, pl. 1) were probably deposited on the same pediment surface.
10. Rhyolite pumice was erupted and mixed locally with the pre-Lousetown pediment gravels west of

the silica pit. A pyroclastic eruption that preceded extrusion of the Steamboat Hills rhyolite dome from the same vent probably supplied the pumice.

11. At nearly the same time, Steamboat basaltic andesite flows of the Lousetown Formation were erupted early in the Pleistocene near the crest of Steamboat Hills from a volcano that lies nearly a mile southwest of the silica pit on the structural axis of the hills.
12. Also at about the same time or shortly afterward, the Steamboat Hills rhyolite dome was extruded 3 miles southwest of the springs and also on the structural axis of the hills. A final stage of explosive activity ejected pumice that now lies on top of the basaltic andesite flows. Pre-Lousetown sinter on the southwest slope of Sinter Hill and basaltic andesite flows immediately to the north were strongly tilted in opposite directions, perhaps by a shallow intrusion of rhyolite.
13. The area was then eroded about 250 feet below the top of the basaltic andesite flows, and Steamboat Creek attained a relative base level about 100 feet below its present level. Fine-grained sediments of the earlier pre-Lousetown alluvium were being removed rapidly, and older topography that had been buried by the alluvium was largely exhumed, perhaps with little modificaton.
14. Opaline sinter that was later largely chalcedonized was probably being deposited at this time. Pre-Lousetown alluvium along the line of section *C C′* (pl. 2) that had been previously altered hydrothermally below the water table now stood above the local water table and was leached by sulfuric acid derived from oxidation of H_2S from an active thermal system in the Main Terrace. Thermal water was probably emerging elsewhere at lower altitudes and was depositing sinter.
15. Pre-Lake Lahontan alluvium was deposited by streams to depths of nearly 200 feet. Most of the deposits were relatively fine grained but their upper parts contained many boulders. This stage probably correlates with the Sherwin, or second oldest recognized glaciation of the Sierras. Deposition of hot-spring sinter still preserved as opaline sinter began at this time.
16. Faults in the southwestern part of the thermal area were active, and the base of the Steamboat basaltic andesite was vertically displaced as much as 100 feet. None of these faults appears to have been an important control for thermal activity. The older faults of the hot-spring terraces were probably also still active but no displacement exceeded 50 feet.
17. The high surface underlain by pre-Lake Lahontan alluvium was then eroded down nearly to its present position, presumably by pedimentation.
18. An extensive pre-Lake Lahontan soil 10 or more feet deep in places then formed.
19. The erosion surface cut on pre-Lake Lahontan alluvium was displaced by numerous north-striking faults. Most of these faults are of small displacement, and generally do not seem to extend into the exposed bedrock of Steamboat Hills.
20. Thermal activity was possibly continuous from stage 7 and more certainly from stage 14 through stage 24. Near the silica pit and the clay quarry, where the water table was below the surface (after stage 19 and perhaps earlier), the principal activity consisted of oxidation of H_2S and acid leaching of granodiorite and basaltic andesite. Mud-volcano breccia was erupted from one of the younger faults northwest of Sinter Hill. The eruption was almost certainly a hydrothermal phenomenon with no new magma involved, other than heat and some steam of magmatic origin.
21. Pre-Lake Lahontan alluvium was entrenched as much as an additional 50 feet by Steamboat Creek. Water levels of the area were in general lowered by a corresponding amount; discharge of hot water ceased at the surface from the fissure system of the High Terrace, but subsurface discharge continued through available permeable channels. Hot springs continued to discharge on the Low and Main Terraces but at decreased rates because of the lowered base level.
22. Alluvium contemporaneous with Lake Lahontan was deposited to a depth of at least 10 feet in the valley of Steamboat Creek; the thickness of the deposit may have been greater, as it was controlled by the depth of the previous entrenchment. This stage of alluviation probably coincided with the Tahoe and Tioga Glaciations in the Sierras.
23. Lahontan alluvium was then entrenched about 10 feet by Steamboat Creek in the northern part of the thermal area and to lesser depths to the south.
24. Recent alluvium is being deposited locally as thermal activity continues. Occasional local seismic activity is evident, but no fault scarps near the thermal area are known to displace Lake Lahontan or Recent sediments.

EXPLANATION FOR THE LOCALIZED THERMAL ACTIVITY

The location of the Steamboat thermal area has been determined by a combination of circumstances. The first and perhaps most essential is the long history of volcanism through Tertiary and Quaternary time; however, many volcanic areas of similarly long history lack the hydrothermal activity of the Steamboat area. A second factor of perhaps equal importance must be a large magma chamber at a moderate and perhaps a particularly suitable depth that has continued to evolve heat and some water with dissolved chemical substances over a period of at least 100,000 years and possibly a million. The present rate of heat flow, if extended back for 100,000 years, requires the cooling and crystallization of a magma chamber on the order of 50 km^3 (White 1957a, p. 1642). An environment permitting extensive convection in the magma chamber may also be essential for the following reasons: Volcanic steam constitutes less than 5 percent of the total water of this system (Craig and others, 1956) and can therefore supply only a small part of the total heat flow (White, 1957a, p. 1642–1643). The remaining heat must be supplied by conduction, and this in turn requires maintenance of high temperatures in the upper part of the magma chamber in order to provide high rates of heat flow through rocks of low thermal conductance to the channels of circulating meteoric water. If high local temperatures are not maintained, the temperatures in circulating water largely meteoric in origin cannot remain high over a long period of time.

Topography and ground-water relations are critically important in determining the specific location of hot-spring outlets. Almost all hot springs emerge in or near topographic lows, and are very rarely high up in mountain ranges. Deep thermal water (excepting steam) discharges at the ground surface only where the surrounding water table also intersects the surface. Where the water table is well below the surface, as on the margins of many basins, only subsurface circulation can take place. If two otherwise equally favorable channels are available to migrating thermal water, the channel that reaches the surface at the lowest altitude will be the favored one. The Steamboat Springs fault zone is in this way favored over the many other faults to the east and west that might have localized the thermal activity.

Evidence for an exceptionally long history of geothermal activity at Steamboat has been preserved because of the general balance that has prevailed between structural uplift and erosion on the one hand and inundation by volcanic products and alluvium on the other. No other hot-spring area in the world is presently known to have as long and complex a history. Perhaps other areas do have similar histories, but lack environments that favor preservation of the evidence.

SUMMARY OF RESULTS OF GEOPHYSICAL SURVEYS

A summary of the applications and limitations of the various geophysical studies carried out at Steamboat Springs may be of value in geothermal studies elsewhere. The results of the geophysical measurements have been incorporated with other studies in all sections of this report, and in many places where geophysical methods were of value they were not specifically credited.

MAGNETIC SURVEYS

A magnetometer measures differences in the intensity of the earth's magnetic field or one of its components. These differences are largely related to differences in orientation, proportion, and proximity of magnetic minerals in the rocks. The most important magnetic mineral in most rocks is magnetite.

Magnetic surveys have been found useful in the study of thermal areas in New Zealand (Studt, 1959). Some representative ground magnetometer traverses in the Steamboat area are shown on plates 3 and 4; magnetometer readings were made by a Schmidt vertical intensity magnetometer on almost all traverse points shown on plate 1. The magnetic survey was very useful in the eastern part of the thermal area and in some places elsewhere. A contour map of the magnetic anomalies (pl. 5) outlines clearly the integrated effects of near-surface and deep hydrothermal alteration of rocks that normally have only moderate concentrations of magnetite. The central and western parts of traverse 1 (pl. 4) exemplify the local magnetic variation characteristic of unaltered basaltic andesite of the Lousetown Formation. Unaltered granodiorite also is characterized by pronounced local magnetic variation in the "bouldery" area west of the Low Terrace (south of 43S., traverse 6, pl. 4). Elsewhere, the magnetic intensity of unaltered granodiorite apparently is only moderate. Unaltered alluvium normally has little or no magnetic effects, but some of the local small anomalies in the eastern and western parts of traverse 8 (pl. 3) are attributable to concentrations of large near-surface boulders in pre-Lake Lahontan alluvium or to lightning strikes. Broader anomalies like that at 52W. on traverse 8 may possibly have their source in maghemite concentrations in altered rock.

Near-surface acid alteration at Steamboat Springs has completely destroyed the original magnetic minerals; the iron has been removed in solution or redistributed locally as ferric oxides. In deep alteration below the water table, sulfur is introduced to combine with original iron; original magnetic minerals are decomposed and pyrite or marcasite is formed (White, 1955a, p. 111–112; Sigvaldason and White, 1961, 1962).

Hydrothermal alteration of rocks under the Low and Main Terraces has resulted in a magnetic trough localized under the Low Terrace (pl. 5); as mentioned, the granitic rocks in this part of the area were originally more magnetic, and they occur either at the surface or at relatively shallow depths. The position of the keel of the magnetic trough adds some support to the favored hypothesis that the principal structures of the Low and Main Terraces are normal faults dipping eastward rather than reverse faults dipping westward. Effects of the thermal activity clearly decrease rapidly south of GS–1 drill hole (table 3), confirming the evidence from the South Steamboat well (table 3 and temperature data not included with this report); the effects also decrease rapidly north of traverse 16, confirming the evidence of surface distribution of sinter.

Hydrothermal alteration at considerable depth is not detectable with certainty if the original rocks are not moderately or highly magnetic or if they are overlain and hence masked by unaltered magnetic rocks. A probable example of the first situation is illustrated by traverse 8 (pl. 3) near the High Terrace, where no magnetic anomaly related to the known fissure systems and associated alteration is evident.

A detailed magnetic study on Sinter Hill, with numerous short traverses not shown on Plate 1, provided the data for distinguishing a concealed contact of Steamboat basaltic andesite. Exposed lava on the northwest slope of Sinter Hill is generally fresh and highly magnetic, characterized by rapid local changes unpredictable in direction and similar to the parts of traverse 1 (pl. 4) underlain by basaltic andesite. Similar local anomalies extend from exposed basaltic andesite over opaline sinter up to the limits of the concealed contact shown on plate 1; beyond these limits local anomalies are absent. The concealed contact probably delimits fresh or only partly altered basaltic andesite from completely altered lava similar to that of GS–6 drill hole (table 3; figs. 17 and 20).

In an airborne magnetic survey, because of flight height of the instruments, sharp, near-surface anomalies are integrated with effects of larger regional features and are not so evident as in a ground survey.

An airborne magnetic survey of the Truckee Meadows-Washoe Valley area (unpub. map, U.S. Geol. Survey) is not easily interpreted in terms of known near-surface features. Areas underlain by thick lava flows, domes, or intrusive plugs show pronounced anomalies, but these may be either positive or negative. At least some of the negative anomalies are related to reversed magnetic polarization.

The two strongest magnetic highs of the area occur in unexpected positions immediately north and south of Steamboat Hills in basin areas underlain by alluvium. The southern anomaly is centered a few hundred feet south of Little Washoe Lake (Thompson and White, 1964, pl. 1) and the northern one is about 1 mile northwest of the clay quarry; both anomalies have east-west elongations that contrast with most known structural trends of the region with the exception of the intrusive granitic contacts. These magnetic anomalies do not seem to be accompanied by pronounced gravity anomalies (Thompson and Sandberg, 1958, pl. 1); they may be due to irregular distribution of disseminated magnetite near granitic contacts.

The generally higher magnetic measurements in the northern part of the thermal area (pl. 5) are largely due to encroachment up the flank of the northern major eastward-elongated magnetic high found in the airborne survey. The axis of this high passes near the northernmost end of the thermal area as mapped on plate 1; the relatively high temperatures and the hydrothermally altered sediments found in wells of the Reno and Mount Rose Resorts (table 3) and the H. Herz 1 well (table 3) seem to be near-surface phenomena that have not affected the high intensity of magnetization of deeper rocks.

ELECTRICAL RESISTIVITY SURVEYS

An electrical resistivity survey measures the electrical resistance of near-surface materials. A resistivity survey has some degree of depth control approximately proportional to the distance between the electrodes. Magnetic and gravity surveys, on the other hand, incorporate effects from all depths.

Electrical resistivity measurements were made on most of the traverses crossing the Low and Main Terraces and on the single traverse crossing the High Terrace (pls. 3 and 4). Resistivity surveying is relatively expensive and time consuming; it yields very worthwhile results where conditions are favorable but is of less significance elsewhere.

Most rock-forming minerals are chiefly nonconductors. In wet porous rocks, electrical conductivity (the reciprocal of resistivity) increases greatly with increase in temperature and with increase in salinity of interstitial water. This means that resistivities should be very low where temperatures are high, saline ground water is close to the topographic surface, and the rocks are porous or are high in clay content. On the other hand, where near-surface rocks are fresh or consist of siliceous sinters without high porosity, or where they are far above a saline water table even though warm or hot, resistivities are high.

The most useful information was obtained from resistivity measurements near the south end of the Low Terrace (pl. 4), where ground water is near the surface. The succession of traverses from 1 through 23, 19, 5, and 18 (pl. 4) indicate decreasing intensity of thermal activity southward, with increasing resistivities as part of the evidence. Electrode spreads of 200 feet (pl. 4) indicate higher resistivities at depth than near the surface. These results agree completely with measurements made in GS–1 drill hole and South Steamboat well (table 3; Sigvaldason and White, 1961). The South Steamboat well (White and Brannock, 1950, p. 572–573) penetrated a near-surface zone of warm to hot saline water, which apparently was migrating southward in the upper part of the system, and was overlying water of very low salinity (but in part even slightly higher in temperature) below 150 feet; the deeper water has the chemical and isotopic composition of meteoric water (Craig and others, 1956) and is moving northward into the spring system as it becomes heated by conduction.

Traverses 4, 16, and 3 on the Main Terrace (pl. 3) demonstrate a strong influence by siliceous sinter near the surface, particularly where the saline water table is at appreciable depth. On traverse 3, for example, GS–3 drill hole penetrated 26 feet of porous sinter, and the saline water table was at a depth of 10 feet; GS–4 penetrated 51 feet of generally less porous sinter at relatively high temperature, and the water table was only 2 feet below the surface. In spite of higher temperatures and shallower water, the thicker and less porous sinter near GS–4 was more effective in causing higher resistivities there than near GS–3. Resistivities are even higher near GS–8 (table 3), where all near-surface deposits including abundant sinter are porous but dry, and the water table is 27 feet below the surface.

Traverse 8 near the High Terrace (pl. 3) is an example of extremely high resistivity of hot-spring deposits near the surface, more than offsetting high temperatures and high salinity below the water table, which is near 40 feet. The dominant rock type in the upper 100 feet is chalcedonic sinter of low porosity. Resistivity values reached a maximum of 100,000 ohm-centimeters, and the differences were so extreme that the data for this traverse alone were plotted on a logarithmic scale.

Depth profiles were also made at 8 or 10 different points; the electrode spacing was increased from 10 to 300 feet at 10-foot intervals. In a few places changes in the curves could be correlated with depth-related factors such as water table, salinity, or temperature, but the method did not give much information that could be interpreted with confidence in this area.

NATURAL POTENTIAL SURVEY

A natural potential or self-potential survey measures local differences in the earth's electrical potential that result from any cause. Many different sources of electrical potential are described in the literature. Natural potential surveys are most effective where significant potential differences are related to a single identifiable source.

Natural or self-potential readings were made on almost all the geophysical traverse points shown on plate 1. Considerable difficulty was caused by fluctuating conditions, probably related to actual differences in chemical activity, weather, soil moisture, and the porous pot electrodes that were used. These difficulties were obviated largely by devising a system using two reference points rather than the usual one. One of the two was constant in location for the entire survey (near 13S., traverse 6) and the second was located at local spots away from evident chemical or thermal activity.

The measurements indicate areas of high near-surface chemical activity; anomalies are both positive and negative, with no recognized geologic differences to distinguish positive from negative. The smoothed averages over the active thermal areas are generally close to the averages of nearby inactive areas, and no broad-scale trends were found.

Wherever chemical activity was indicated by sharp local variations in natural potential, the activity generally was observable in the form of flowing springs, hot-spring sinter, acid bleaching, or sulfate minerals.

GRAVITY SURVEY

A gravity survey yields information on differences in the bulk density of the earth's crust. Effects from all depths are integrated but are proportional to the square of the distance from the instrument. Very useful information has been obtained from a relatively small investment in gravity work in the area. A North American type gravimeter was used; a light-weight portable instrument would have been even more useful.

The results of the work have been published by Thompson and Sandberg (1958) and have been specifically mentioned at several places in the present text. The work has been particularly useful in distinguishing the general form of sediment-filled basins, and the order of magnitude of thickness of alluvial fill. Gravity has also been critical in detecting buried fault scarps, establishing the absence of pronounced buried scarps, and finding the order of magnitude of displacements on scarps. Much additional detailed work is desirable in the thermal and nearby areas where critical geology is concealed by alluvium.

GEOTHERMAL MEASUREMENTS

The Steamboat Springs project is to a major degree a geothermal survey, whose results will be considered in detail in later reports. Systematic measurements of temperature at a specified depth and in a grid system have been made in Japan (Fukutomi and Fujiki, 1953; Fukutomi, and others, 1956) and New Zealand (Thompson, 1960). A similar survey at Steamboat Springs would certainly yield useful results, but most available resources were used instead for test drilling at a few selected spots. Shallow auger holes were bored at critical spots for data on nature of material, temperatures, or depth to water table (table 3, pl. 1).

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