Post-Lake Lahontan deposits in the Carson Desert, near Fallon, Nev.—Continued

	Maximum thickness (feet)
Post-Lake Lahontan soil:	
A submature Gray Desert soil	1.5
Turupah formation:	
Eolian sand and local alluvium, to lowest parts of basin floor	30.
Disconformity, recording widespread deflation, to lowest parts of basin floor.	
Sehoo formation (younger sediments of Lake Lahontan):	
Lacustrine sand, clay, and tufa in basin interior; gravel, sand, and tufa in highlands; extends as high as 510 feet above lowest part of basin floor	96

The Sehoo formation is inferred to record the final lake cycles of Lake Lahontan. The overlying disconformity, Turupah formation, and post-Lake Lahontan soil record a long interval of generally complete desiccation of the Carson Desert, that is correlated with the altithermal age of Antevs (1948, 1952, 1955). The Fallon formation records 5 post-Lahontan shallow-lake cycles, that rose successively about 90, 70, 57, 40, and 30 feet above the lowest part of the Carson Sink. During the intervening lake recessions the basin became nearly or entirely dry. The longest and most pronounced desiccation was between the first and second lake cycles, when the only discernible (albeit very weak) soil development in Fallon time took place.

In the author's opinion the Carson Desert should be designated as a type area for Recent (Holocene) deposits of the Great Basin, and the Pleistocene-Recent boundary (the Pleistocene-Holocene boundary of European usage) should be placed at the top of the post-Lake Lahontan soil. This soil not only is the most distinctive and widely traceable stratigraphic unit in the Recent deposits of the Lake Lahontan area, but its correlative soils in the alluvial, eolian, and glacial deposits of the Great Basin and adjoining areas (for example, the Sierra Nevada and Wasatch-Rocky Mountains) are similarly distinctive. The post-Lake Lahontan soil and its correlatives are known, from archaeologic and radiocarbon dating, to have formed within a span of probably less than 1,000 years in later altithermal time.

This soil-forming interval was induced by a climatic change that probably was essentially synchronous over the entire Great Basin region. Thus, the post-Lake Lahontan soil is assumed to be nearly time-parallel over this region. Also, because it formed during a comparatively brief interval, it is a relatively precise time-stratigraphic marker—more so than any of the younger sedimentary units or unconformities known in the region (other than a few ash beds that occur only locally).

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331. HYDROTHERMAL ALTERATION OF ROCKS IN TWO DRILL HOLES AT STEAMBOAT SPRINGS, WASHOE COUNTY, NEVADA

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Steamboat Springs, in southern Washoe County, Nev., has been well known to economic geologists since the early studies on the metal-bearing spring deposits by Le Conte (1883) and Becker (1888, p. 331–351). The geology of Steamboat Springs has been reviewed by Brannock and others (1948, p. 211–216) and the thermal activity and hydrothermal alteration have been summarized by White (1955, p. 103–104, 110–113; 1957, p. 1639–1647). This report contains results of X-ray and other mineralogical studies of hydrothermally altered rocks found in two drill holes at Steamboat Springs.

DRILL-HOLE GS–1

Drill-hole GS–1 is on the active Low Terrace of Steamboat Springs near the southern end of the thermal area. Some data concerning the hole are shown on figure 331.1, and chemical compositions of fresh and altered rocks are shown by table 331.1.

The degree of alteration in drill-hole GS–1 is determined by depth, original rock type, and relation to permeable channels. The mineral most generally altered is hornblende, followed by biotite and calcic plagioclase. Quartz remains unaffected and K-feldspar and sodic plagioclase appear to be metastable under all the conditions affecting the rocks drilled. Some nearly fresh grandodiorite occurs near the surface. Andesitic tuff breccia, originally consisting entirely of susceptible ferromagnesian minerals, calcic plagioclase, and glass, has undergone complete alteration. The most intensely altered granodiorite lies immediately below a dike of andesitic tuff breccia and near faults and fractures at depths of 270 and 364 feet.

Estimated mineralogical composition is shown graphically on figure 331.1. Straight lines connect points where the mineralogy was determined; however, actual mineral compositions between points of obser-

vation are known to differ greatly from compositions implied by these lines. Small quantities of pyrite, pyrrhotite, stibnite, and calcite are not plotted.

The dominant hydrothermal minerals are four species of clay. Montmorillonite is most abundant in the altered andesitic dike (fig. 331.1). The spacing of the basal X-ray reflection of this material in air-dried state ranges from 12 to 15 A. The greater spacing results from calcium and magnesium in the interchangeable positions of the montmorillonite lattice, and the lesser spacing from sodium in the interchangeable position.

Kaolinite is the dominant mineral in the most intensely altered and leached parts of the rock penetrated in the drill hole, but is present only in small amounts where alteration is slight. Where kaolinite is a major component, it is usually accompanied by Na-K-montmorillonite; where kaolinite is a minor component, it occurs with Ca-Mg-montmorillonite.

Two types of chlorite were detected. One is a minor component, replacing biotite. The second is abundant in and near fractures at depths of 250 to 300 feet; it does not have X-ray reflections at 14 and 4.7 A as do most chlorites, and its lattice collapses at relatively low temperatures. It is thus similar in some ways to kao-

TABLE 331.1.—*Analyses of hydrothermally altered rocks of drill-hole GS–1 compared to fresh rocks*

[In percent; analyzed by rapid methods by L. Shapiro, H. F. Phillips, K. White, S. M. Berthold, and E. A. Nygaard]

Constituent:	Fresh rocks		Rocks in drill-hole GS–1, and depth, in feet							
	Granodiorite west of Low Terrace	Andesite at Steamboat Hills	Opaline sinter, 2	Granodiorite, 14	Granodiorite, 63	Tuff-breccia, 173	Tuff-breccia, 192	Granodiorite, 259	Granodiorite, 312	Granodiorite, 364
SiO_2	65.6	59.3	92.6	65.4	64.6	57.3	54.7	66.2	67.5	61.6
Al_2O_3	16.5	16.8	1.0	16.2	16.3	17.4	17.3	12.8	16.8	15.6
FeO	2.1	2.4	.14	1.3	2.6	6.5	8.4	8.4	1.8	5.4
Fe_2O_3 [1]	2.2	3.6	.23	3.0	2.2			1.2	1.1	
MgO	1.7	3.0	.07	1.6	1.6	1.3	1.4	1.2	1.1	1.0
CaO	3.2	6.7	.36	4.2	4.4	1.5	1.4	1.0	3.3	2.2
Na_2O	3.6	3.6	.41	3.8	3.6	.41	.58	1.3	3.5	1.2
K_2O	2.9	2.2	.21	2.8	2.9	2.1	1.8	2.4	3.1	3.0
TiO_2	.55	.62	.04	.51	.68	.89	.88	.42	.50	.54
P_2O_5	.15	.16	.02	.14	.34	.24	.25	.14	.14	.11
MnO	.06	.20	.42	.04	.20	.12	.06	.34	.04	.10
CO_2	.09	----------	<.05	<.05	.36	.09	.07	.27	<.05	1.1
S	.00	----------	.00	.01	.02	1.9	4.5	.38	.25	3.0
H_2O+	.50	.60	5.2	1.0	.93	11.7	10.0	4.2	1.2	7.0
H_2O-	.05									
Total as reported	99.2	99.2	100.8	100.1	100.7	101.45	101.34	100.3	100.4	101.9
Less O for S	----------	----------	----------	----------	----------	.95	2.25	.2	.1	1.5
Total	99.2	99.2	100.8	100.1	100.7	100.5	99.1	100.1	100.3	100.4
Specific gravity (powder)	2.69	2.76	2.11	2.72	2.70	2.46	2.49	2.68	2.66	2.62
Specific gravity (lump)	2.62	2.54	1.79	2.59	2.64	1.83	1.90	2.20	2.54	2.12
Prominent hydrothermal minerals	----------	----------	Opal	(Minor clays).	(Minor clays, Mn-calcite).	Kaolinite, montmorillonite, chlorite, pyrite.	Chlorite, kaolinite, montmorillonite, pyrite.	Chlorite, kaolinite, montmorillonite, (pyrrhotite, calcite).	Kaolinite, (chlorite, illite, pyrite).	Kaolinite, montmorillonite, pyrite, (calcite).

[1] Or total Fe as Fe_2O_3.
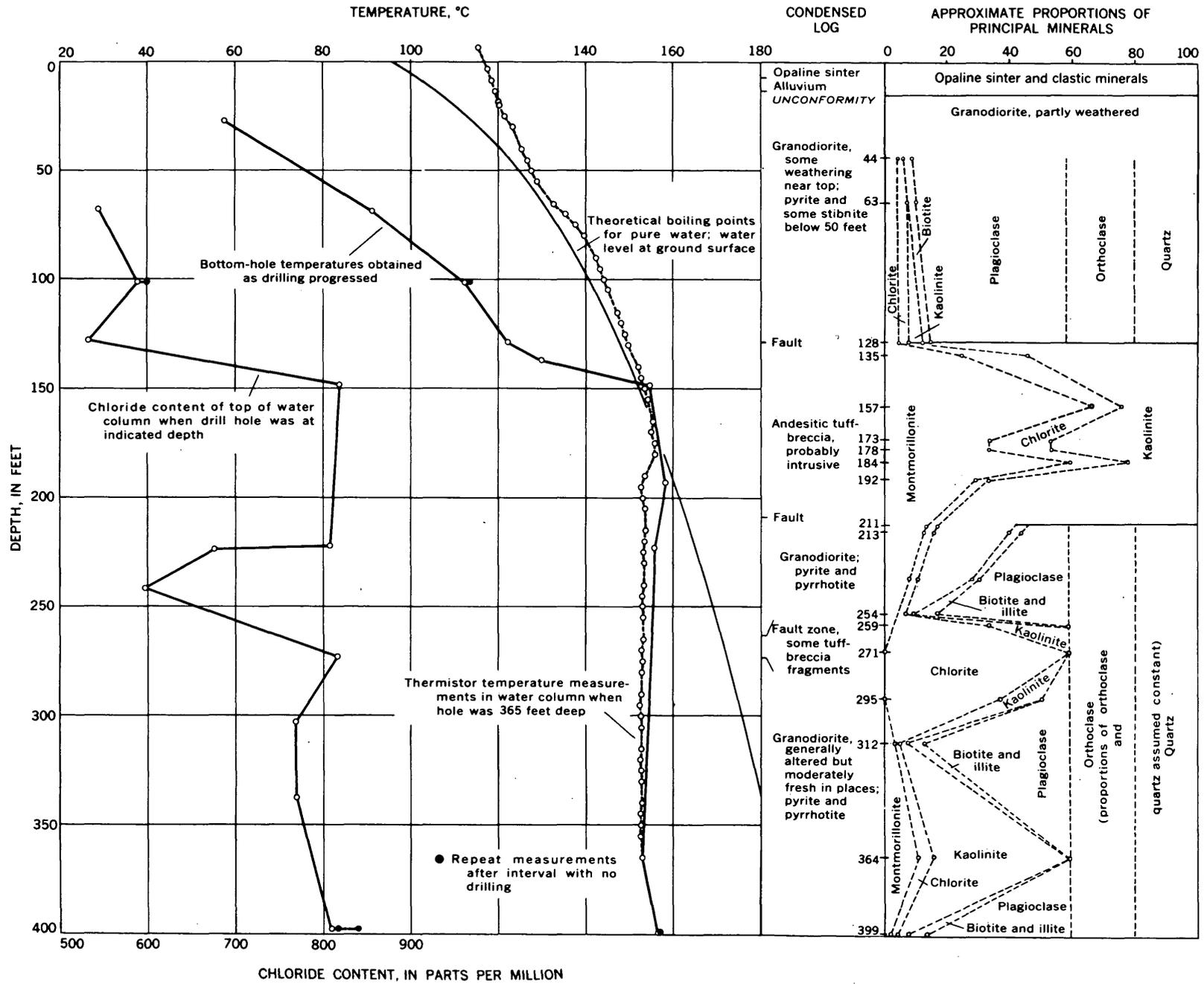
FIGURE 331.1.—Data from drill-hole GS–1, Low Terrace, Steamboat Springs, Nev. Straight lines arbitrarily drawn between points of observation.

linite, but its refractive indices (1.61 to 1.62) and the high content of iron that must be assigned to this mineral (table 331.1, depth 259 feet) support its identification as a chlorite. This mineral is similar to some of the chamosites described by Brindley (1951).

Illite seems to be confined to slightly altered granodiorite, where the amount of illite does not exceed the original percentage of biotite in the granodiorite. Illite may be present elsewhere but obscured by other clay minerals.

DRILL-HOLE GS-2

Drill-hole GS-2 is on the High Terrace of Steamboat Springs in the northwestern part of the thermal area 6,400 feet north-northwest of drill-hole GS-1. The High Terrace has had little or no surface discharge since the Pleistocene, but thermal water flows in the system and escapes below the surface. Descriptions of the rocks found in drilling are given on figure 331.2 and in table 331.2.

The assemblage of hydrothermal minerals in hole GS-2 varies considerably with depth and differs from the assemblage in hole GS-1. Beginning at approximately 90 feet, silicates are replaced extensively by K-feldspar. Quartz and K-feldspar are the dominant hydrothermal minerals to a depth of approximately 280 feet, where clay minerals become abundant. The clays are dominant from 288 feet to the basal contact of tuff breccia at 351 feet. From 200 to 240 feet the only identified clay mineral is chlorite-vermiculite(?) with regular mixed layering. The X-ray pattern of the clay shows a basal reflection at approximately 28 A, and an integral series of 9 well-defined higher orders. Upon saturation with ethylene glycol the lattice expands to 31.5 A; heat treatment at 550° C for two hours results in a poorly defined X-ray peak at approximately 23 A, and two higher orders at 12 and 8 A. As defined by Lippmann (1956), this mineral is a corrensite; it was not found below 277 feet.

At about 240 feet chlorite and a random mixed-layer illite-montmorillonite appear. The chlorite is an iron-rich variety, showing a low intensity X-ray peak at 14 A and a strong (002) reflection at 7 A. Chlorite is dominant near 300 feet but is not present at the contact with granodiorite. Below the contact chlorite is abundant again, but as a replacement of biotite.

TABLE 331.2.—*Analyses of hydrothermally altered rocks of drill-hole GS-2*

[In percent; analyzed by rapid methods by L. Shapiro, H. F. Phillips, K. White, S. M. Berthold, and E. A. Nygaard]

	Rocks in GS-2, and depth, in feet									
	Chalcedonic sinter, 28	Tuff-breccia, 125	Tuff-breccia, single pebble, 138	Tuff-breccia, 202	Tuff-breccia, 239	Tuff-breccia, 297	Tuff-breccia, 317	Granodiorite, 355	Granodiorite, 367	Granodiorite, 375
Constituent:										
SiO_2	98.6	75.0	62.5	84.0	79.0	70.2	74.8	75.2	71.2	72.2
Al_2O_3	.58	11.6	18.0	7.8	10.1	12.7	10.0	13.9	15.0	15.0
FeO	.16	2.9	2.2	1.1	.96	3.1	4.2	1.6	1.6	.89
Fe_2O_3 [1]	<.10									.6
MgO	.00	.15	.28	.14	.40	.97	1.3	.15	.30	.44
CaO	.06	1.5	1.1	.18	.44	1.3	.34	.82	1.7	1.3
Na_2O	.22	.91	1.5	.20	.32	.28	.39	1.5	2.9	3.2
K_2O	.09	6.0	10.8	5.8	8.2	8.3	3.6	4.8	5.1	4.6
TiO_2	.04	.54	.58	.22	.30	.46	.40	.40	.86	.32
P_2O_5	.01	.04	.08	.02	.05	.17	.07	.04	.13	.10
MnO	.00	.00	.01	.00	.01	.06	.02	.01	.01	.01
CO_2	<.05	.20	.10	<.05	.25	.77	<.05	<.05	.30	<.05
S	.03	1.9	1.0	.68	.37	.73	1.4	.88	.53	.44
H_2O+	1.1	2.1	2.3	.82	.81	1.7	3.8	2.8	1.5	1.2
H_2O-										
Total as reported	100.9	102.8	100.5	101.0	101.2	100.7	100.3	102.1	101.1	100.3
Less O for S		1.0	.5	.3	.2	.4	.7	.4	.3	.2
Total	100.9	101.8	100.0	100.7	101.0	100.3	99.6	101.7	100.8	100.1
Specific gravity (powder)	2.60	2.64	2.65	2.64	2.62	2.61	2.68	2.59	2.64	2.66
Specific gravity (lump)	2.45	2.44	2.48	2.38	2.39	2.47	2.41	2.47	2.47	2.51
Prominent hydrothermal minerals.	Chalcedony (stibnite).	K-feldspar, quartz, pyrite, (clays, calcite).	K-feldspar, quartz, (clays, pyrite, calcite).	K-feldspar, quartz (pyrite).	K-feldspar, quartz, corrensite, (pyrite, calcite).	K-feldspar, chlorite, quartz, illite, montmorillonite, (calcite, pyrite, apatite(?)).	Illite-montmorillonite, chlorite, quartz, K-feldspar, (pyrite).	Illite-montmorillonite, chlorite, quartz, (pyrite).	Illite-montmorillonite, chlorite, quartz, (calcite, pyrite).	Illite-montmorillonite, chlorite, (calcite, quartz, pyrite).

[1] Or total Fe as Fe_2O_3.
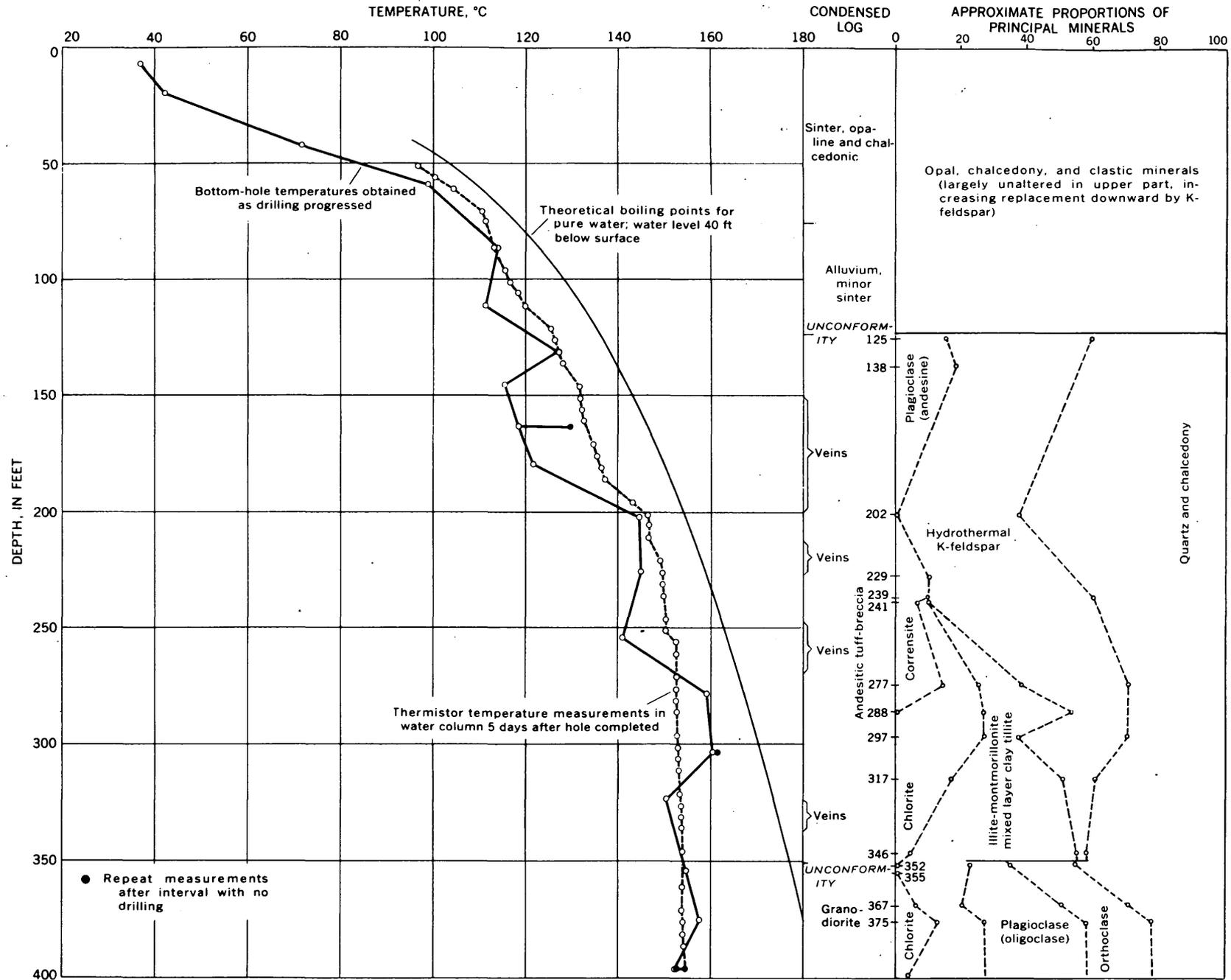
FIGURE 331.2.—Data from drill-hole GS-2, High Terrace, Steamboat Springs, Nev. Straight lines arbitrarily drawn between points of observation.

The illite-montmorillonite mixed-layer clay becomes increasingly abundant and K-feldspar correspondingly less abundant downward; the illite-montmorillonite mixed-layer clay reaches its maximum concentration near the contact with granodiorite. The proportions of the mixed-layer components are consistent throughout rocks penetrated; the expandable montmorillonite layers make up about 25 percent of the total clay as indicated by the (001)/(001) peak of the glycolated sample (Weaver, 1956, p. 206).

Small amounts of probable illite were observed microscopically in several samples below 250 feet in hole GS-2 but the occurrences could not be confirmed by X-ray analysis, presumably because of dominance of other clay minerals.

CONCLUSIONS

The hydrothermal mineral assemblages are virtually independent of the original rock type. The extent of alteration, however, is greatly dependent upon the proportion of minerals susceptible to attack.

The Low Terrace is still undergoing active alteration by slightly acid, carbonated waters, as indicated by pH and by high concentrations of bicarbonate and calcium in the water (table 331.3). Kaolinite is the most stable mineral; other silicates are probably metastable or are intermediate products.

The High Terrace has probably been inactive at the surface since Pleistocene. The most stable minerals are K-feldspar near the surface, and probably illite at depth. These minerals are in other stability fields than kaolinite in the system $K_2O-Al_2O_3-SiO_2-H_2O$ (Hemley, 1959, p. 246). Waters from both drill holes are very similar in potassium content, temperatures, and pH. The pH of both is 6.0± if nonerupted, and 8.0 or more if erupted because of loss of CO_2 (White, Sandberg, and Brannock, 1953, p. 496-498).

The mineralogy of the High Terrace is best explained by higher water temperatures in the past. Higher temperatures could have increased the extent of boiling in the upper part of the conduit system of the springs, thereby increasing pH by perhaps a unit or more because of the volatilization of free CO_2, and also increasing potassium slightly because of loss of water as steam. These changes favor deposition of K-feldspar over mica (illite), and presumably more than offset the effect of decrease in temperature upwards, which should favor deposition of mica (Hemley, 1959). A higher concentration of potassium than at present in the deep water also may be required to span the differences between the stability fields of kaolinite and K-feldspar.

TABLE 331.3.—*Analyses of thermal waters of Steamboat Springs, Nevada*

[Analysts W. W. Brannock and H. Kramer]

	Spring 27, Main Terrace	Drill-hole GS-1, Low Terrace	Drill-hole GS-2, High Terrace
Physical state	Discharging	Leaked from valve.	Erupted
Temperature at collection point, degrees C	89.2	47	>95
Bottom-hole temperature, degrees C		≈160	≈160
pH	7.9	6.1	8.8
Analysis, in parts per million:			
SiO$_2$	293		
Ca	5.0	18	4.4
Mg	.8	nil	nil
Na	653	627	655
K	71	60	73
Li	7.6	5.8	5.7
HCO$_3$	305	404	77
CO$_3$	nil	nil	94
SO$_4$	100	112	132
Cl	865	817	871
F	1.8	2.0	1.0
B	49	[2] 37	[2] 36
H$_2$S	4.7	11	1.1
Total as reported	2,356	[3] 2,094	[3] 1,950
Ratios:			
Ca/Na	0.008	0.029	0.007
K/Na	.11	.096	.11
Li/Na	.012	.0093	.0088
HCO$_3$/Cl [1]	.35	.50	.31
SO$_4$/Cl	.12	.14	.15
F/Cl	.002	.002	.001
B/Cl	.057	.045 (?)	.041 (?)

[1] Total combined carbonate calculated as equivalent HCO$_3$.
[2] May be low.
[3] SiO$_2$ not reported.

Hemley (Art. 408) has shown that the stability field of mica is wide in the $K_2O-Al_2O_3-SiO_2-H_2O$ system, but is greatly narrowed in the $Na_2O-Al_2O_3-SiO_2-H_2O$ system. His work suggests that in natural waters containing both K and Na, the differences between replacement of plagioclase by K-feldspar or by kaolinite is determined by as little as ½ unit of pH, 50° C in temperature, or a variation in concentration of potassium of ½ an order of magnitude.

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332. CORRELATION OF THE DEPOSITS OF LAKES LAHONTAN AND BONNEVILLE AND THE GLACIAL SEQUENCES OF THE SIERRA NEVADA AND WASATCH MOUNTAINS, CALIFORNIA, NEVADA, AND UTAH

By R. B. Morrison, Denver, Colo.

Modern stratigraphic studies of the deposits of Lakes Lahontan and Bonneville and of the Quaternary glacial deposits of the Sierra Nevada and Wasatch Mountains permit improved correlation of these sequences. Direct correlation is possible at only one locality: below the mouths of Little Cottonwood and Bells Canyons, south of Salt Lake City, Utah. Here, drift of one of the late Quaternary glaciations of the Wasatch Mountains intertongues and intergrades with part of the Lake Bonneville sequence (Art. 333; Richmond, Art. 334). Correlations can be made indirectly, however, between the remainder of the Lake Bonneville and Wasatch Mountain glacial sequences, and between these and the Lake Lahontan and Sierra Nevada sequences, by the use of new concepts of soil stratigraphy (Richmond, 1950; Richmond, Morrison, and Bissell, 1952).

The late Quaternary successions in all four areas have similar soil sequences, in terms of relative age and relative development of the soils. The physical record in each area indicates that the soils formed during distinct, widely separated intervals, in response to relatively infrequent combinations of climatic factors that induced erosional stability and a more rapid rate of chemical weathering than normal. The most strongly developed soils formed during the main intervals of lake desiccation or of deglaciation; weaker soils formed during the shorter recession intervals; soil profile development at other times was inappreciable. The soil-forming intervals were periodically repeated parts of whole climatic cycles—mainly fluctuations in temperature and precipitation—that are manifest in the Quaternary sequences of each area. The climatic cycles, and the depositional and soil-forming cycles induced by them, probably were essentially synchronous over the entire Wasatch Mountain to Sierra Nevada region because the whole region probably acted as a climatic unit during the Quaternary as it does now. Thus, soils of similar relative age and development in the four areas are assumed to have formed contemporaneously—in other words, they are assumed to be nearly time-parallel throughout this region. Because they formed during generally shorter intervals than the inter-soil sediments, they are considered to be more precise time-stratigraphic markers. The stronger soils are readily recognizable in the successions of each area and are the most reliable and useful markers; they provide the basic framework for correlation. The sediments and weaker soils intermediate in age between the main soils are correlated by matching those units that record depositional cycles, or parts of cycles, of similar relative age and similar climatic genesis—that is, units recording early lake cycles with each other and with units recording early glacial cycles; likewise, lake-recessional units are correlated with glacial-recessional units.

Figure 332.1 diagrams the means of correlation. (The stratigraphic units and interpretations of lake and glacial history listed below and in figure 332.1 are those given in the following papers in this review, or other references: for the Lake Lahontan area, Art. 329; for the Sierra Nevada, Blackwelder, 1931; Matthes, 1942, 1945; Putnam, 1950; and for the Lake Bonneville and Wasatch Mountains areas, Morrison, Art. 333, and Richmond, Art. 334.) First, soils of similar relative development are correlated, starting with the three youngest most strongly developed soils in each sequence; then, between main soils, the deposits that record depositional cycles of similar age and magnitude are correlated, as are any weakly developed soils.

By this method, the pre-Lake Lahontan soil of the