

## HYDROTHERMAL ALTERATION OF BASALTIC ANDESITE AND OTHER ROCKS IN DRILL HOLE GS-6, STEAMBOAT SPRINGS, NEVADA

By ROBERT SCHOEN and DONALD E. WHITE, Menlo Park, Calif.

*Abstract.*—Geothermal waters produced two recognizable patterns of hydrothermal alteration in the rocks in drill hole GS-6. During an early period, the rocks were subjected to potassium metasomatism that formed K-feldspar and celadonite from unstable feldspars and ferromagnesian minerals, respectively. A later period of hydrogen metasomatism produced mixed-layer illite-montmorillonite, montmorillonite, and kaolinite, probably as a series directly related to the intensity of alteration. The clays formed during hydrogen metasomatism are irregularly distributed with depth and probably are related to reactions involving CO<sub>2</sub> and H<sub>2</sub>S. This later period of argillization still may be in progress.

This paper presents the results of a mineralogic study of GS-6, one of eight holes drilled at Steamboat Springs, Nev., by the U.S. Geological Survey for geologic information. Steamboat Springs, located in the west-central part of Nevada, 10 miles south of Reno, is an area of active hot springs (fig. 1). Economic geologists have been interested in these springs for about 100 years because minerals of antimony and mercury, together with small amounts of gold and silver, precipitate from the hot waters.

The Steamboat Springs thermal area straddles the boundary between the Mount Rose and Virginia City quadrangles. The regional geology of these quadrangles has been described recently by Thompson and White (1964). White and others (1964) have presented the detailed geology of the thermal area, including an account of earlier studies and the logs of all drill holes, including GS-6.

The mineralogy of hydrothermally altered core from 4 of the U.S. Geological Survey drill holes has been described by Sigvaldason and White (1961, 1962), and Schoen and White (1965) similarly have described an additional 2 drill holes. In addition to presenting the detailed mineralogy of core from drill hole GS-6, the present paper compares the mineralogy of this drill hole with the others, and considers briefly the rela-

tionships between the compositions of waters and the observed alteration patterns.

The generalized geology of the thermal area is shown in figure 1. The basement rocks consist of a granodiorite pluton of late Mesozoic age intruded into metamorphosed sedimentary and volcanic rocks of probable early Mesozoic age. Tertiary and Quaternary volcanic and sedimentary rocks were deposited intermittently on the eroded surface of this basement, and andesite dikes intruded the granodiorite. Outcrops of the Tertiary volcanic and sedimentary rocks are too small to distinguish in figure 1, but core samples of these rocks, from drill hole GS-6, are shown in figure 2.

The oldest Cenozoic rocks found in the thermal area are soda trachyte flows, tuff breccias, and associated sediments of the Alta Formation of Oligocene(?) age. These were followed by andesite flows, tuff breccias, and andesite dikes of the Kate Peak Formation of Miocene or Pliocene age. The pre-Lousetown alluvium consists of silt, sand, and gravel. Local patches of orthoquartzite, pediment gravels, and chalcedonic hot-spring sinter are found associated with this alluvium. The Steamboat basaltic andesite of the Lousetown Formation was erupted in early Pleistocene time followed immediately by domes of pumiceous rhyolite of the Steamboat Hills Rhyolite. Pre-Lake Lahontan alluvium is approximately middle Pleistocene in age and consists of fragments of older rocks, many of which are cemented by hot-spring sinter. Post-Lousetown chalcedonic sinter consists of sinter older than deposits of Lake Lahontan and now mostly converted to chalcedony or cristobalite. Younger hot-spring sinter deposits, consisting largely of uncrystallized opal, range up to the present in age. Both Post-Lousetown chalcedonic sinter and the opaline hot-spring deposits are combined under "Sinter" in figure 1. Late Pleistocene alluvium that is contempo-



FIGURE 1.—Generalized geologic map of Steamboat Springs thermal area, Washoe County, Nev. (Modified from detailed map, White and others, 1964.)

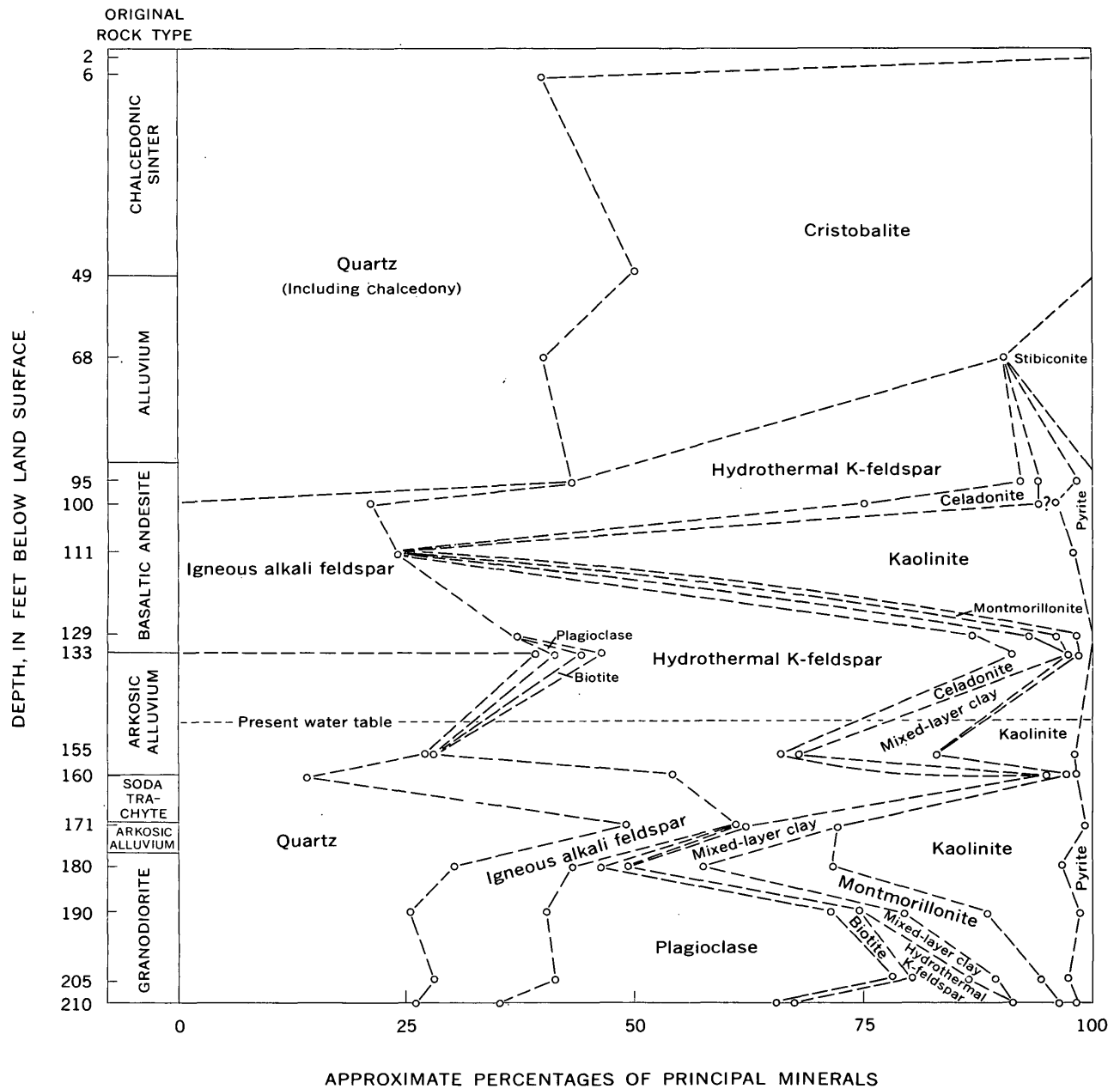


FIGURE 2.—Semi-quantitative plot of mineralogy from drill hole GS-6. Dashed lines arbitrarily drawn straight between sample points.

aneous with Lake Lahontan, and very small patches of Recent alluvium in the stream valleys, complete the depositional history of the area. All three alluvial units, Pre-Lake Lahontan alluvium, alluvium contemporaneous with Lake Lahontan, and Recent alluvium, are combined under "Alluvium" in figure 1.

During this time of extensive deposition in the Cenozoic, the Steamboat Springs thermal area was also undergoing episodes of deformation and periods of erosion. An account of the Cenozoic geologic history of the area and a more detailed description of

the stratigraphy can be found in the paper by White and others (1964).

Drill hole GS-6 is collared at an altitude of 4,838 feet in an extensive mass of relatively old silicious sinter known as Sinter Hill (fig. 1). The depth of the hole is 212 feet, and the depth to the water table is approximately 148 feet. Several months after drilling was completed, the water at the bottom of the drill hole had a temperature of 102.5°C, a pH of 6.7, a chloride content of only 12 parts per million, and a specific conductance of 372 micromhos. This ex-

tremely dilute water is very different from the fluids found in drill holes on the three thermally active terraces; typically, the temperature there is about 170°C, pH is about 6.2, chloride content is about 820 ppm, and specific conductance is about 3,000 micromhos. The dilute water of GS-6 is probably precipitation that fell on the area, percolated underground, and was heated moderately in the thermal environment.

Active construction of hot-spring sinter terraces is taking place today in the Steamboat Springs area at lower altitudes where hot chloride water containing 300 ppm or more of SiO<sub>2</sub> discharges at the surface (White and others, 1956). The sinter deposits of Sinter Hill prove that high-temperature, silica-bearing waters discharged in the past at altitudes at least 148 feet above the present water table. The different types and ages of the hot-spring sinters have been described in detail by White and others (1964).

Hydrothermal alteration of the rocks in the vicinity of GS-6 was a complex process, but two major stages of alteration can be recognized. An early period of potash metasomatism produced hydrothermal K-feldspar and celadonite as alteration products. This stage probably coincided with the construction of the silicious sinter deposit in which GS-6 is collared. During later hydrogen metasomatism, clay minerals and, locally, opal were produced. This last stage, dominated by argillization, still may be in progress today.

#### METHODS

X-ray diffraction was the principal tool used to study the mineralogy of whole-rock and clay fractions of all samples of drill core. Thin-section microscopy and chemical and spectrographic analyses of rocks and mineral concentrates provided essential additional information.

The mineralogy of the rocks cut by drill hole GS-6 is depicted in figure 2 as a semiquantitative plot of sample mineralogy versus sample depth. Details of the factors considered in the construction of such a diagram are given in an earlier paper (Schoen and White, 1965). In brief, modal analyses and X-ray diffractograms of unaltered rocks were used to evaluate the changes in mineralogy in hydrothermally affected rocks. The decrease in the height of an X-ray peak for a mineral from an altered rock is assumed to be linearly related to the decrease in abundance of the mineral in volume percent. Minerals produced by hydrothermal alteration are assumed to be equal in volume percent to the mineral or minerals they replaced. Application of these assumptions to the X-ray diffractograms, together with supporting evi-

dence from thin sections and chemical analyses, provide mineral percentages for each sample of drill core.

Chemical analyses of altered rocks and fresh rock equivalents of the igneous rocks in GS-6 are presented in table 1. Additional chemical, normative, and modal analyses for other rocks from the Steamboat Springs area are presented by White and others (1964, tables 1 and 2).

Good quantitative mineralogic control exists for the granodiorite that underlies most of the Steamboat Springs thermal area, because of its relative homogeneity and the availability of chemically and petrographically analyzed fresh samples. Therefore, the granodiorite samples in drill hole GS-6 were evaluated for semiquantitative mineralogy in the same manner used for drill holes GS-3 and GS-4 (Schoen and White, 1965). The mineralogic compositions of the fresh soda trachyte and basaltic andesite are known with less certainty because of their fine-grained groundmasses. However, quantitative control is still reasonably good. The highly variable original composition of the arkosic sediments makes it difficult to determine semiquantitative mineralogy in the altered equivalents.

Because of these practical limitations, as well as the recognized theoretical limitations imposed by assuming a linear relationship between X-ray peak height and volume percent, the diagram of the mineralogy of drill hole GS-6 (fig. 2) is only a semiquantitative estimate. The reported percentage for each mineral present may be in error by as little as 5 percent for quartz, but the error is likely to be greater for most of the others, especially the clays. Nevertheless, the determination of the relative amount of each mineral in a sample has been found to be reproducible. This is the major requirement for a study of alteration where relative changes are important.

#### MINERALOGY

The mineralogy of the drill core is plotted semiquantitatively against depth in figure 2, and chemical analyses of selected samples are shown in table 1. The field designated "igneous alkali feldspar" in figure 2 represents anorthoclase and sanidine in the volcanic rocks, orthoclase in the granodiorite, and mixtures of all three in the alluvium.

##### Post-Lousetown chalcidonic sinter

The silicious sinter, that extends to a depth of 50 feet in GS-6 (fig. 2), was originally deposited as amorphous opal (White and others, 1964) but is now composed principally of about equal amounts of chalcidonic quartz and opal ( $\beta$  or high cristobalite by X-ray).

TABLE 1.—Chemical analyses, by rapid methods, of rock from drill hole GS-6, Sinter Hill, Steamboat Springs, Nev., and of nearby unaltered equivalent rocks

[Analysts (U.S. Geol. Survey): Leonard Shapiro (1-12); S. M. Berthold and E. A. Nygaard (3-5, 7, 9, 11, 12); H. F. Phillips (1, 2, 6, 8, 10); K. E. White (1, 2, 6, 8, 10); W. W. Brannock (13)]

Analysis number.....	Altered rocks of GS-6										Unaltered nearby rocks		
	1	2	3	4	5	6	7	8	9	10	11	12	13
Sample depth (feet).....	2	6	68	100	111	129	160	190	205	210			
Description.....	Chalcedonic sinter	Chalcedonic sinter	Alluvium	Steamboat basaltic andesite of Lousetown Formation			Soda trachyte of Alta Formation	Granodiorite			Granodiorite	Soda trachyte of Alta Formation	Basaltic andesite of Lousetown Formation
SiO <sub>2</sub> .....	97.9	96.4	91.3	58.3	60.9	61.3	67.7	68.9	72.2	74.0	65.6	65.0	54.38
Al <sub>2</sub> O <sub>3</sub> .....	.06	.30	.84	19.6	19.6	18.5	13.8	15.1	11.4	12.8	16.5	18.6	17.83
Fe <sub>2</sub> O <sub>3</sub> .....	.12	.08	.04	1.6	1.0	1.2	.5	.05	.3	.02	2.2	1.5	2.57
FeO.....	.0	.0	.17	.87	.23	.70	.30	.81	.60	.74	2.1	2.0	4.97
MgO.....	.00	.01	.10	.14	.26	.10	.15	.90	.40	.53	1.7	.74	4.12
CaO.....	.00	.14	.40	.50	1.1	1.8	1.2	1.0	1.2	1.1	3.2	3.1	6.58
Na <sub>2</sub> O.....	.22	.20	.11	.78	1.6	2.5	1.6	1.8	1.8	2.1	3.6	5.0	4.03
K <sub>2</sub> O.....	.10	.10	.10	10.9	2.8	8.8	8.7	4.4	4.7	4.8	2.9	3.2	2.50
H <sub>2</sub> O.....	1.1	2.8	5.7	3.5	7.8	1.9	.0	4.2	2.9	1.9	.55	.25	.28
TiO <sub>2</sub> .....	.00	.00	.58	1.4	1.5	1.5	.42	.34	.35	.28	.55	.46	1.89
P <sub>2</sub> O <sub>5</sub> .....	.00	.00	.01	.46	.45	.56	.10	.06	.11	.06	.15	.21	.57
MnO.....	.00	.00	.02	.05	.01	.01	.05	.02	.04	.02	.06	.14	.11
FeS <sub>2</sub> .....	.02	.02		1.9	1.3	.62	4.5	1.9	3.7	2.1			.00
CO <sub>2</sub> .....	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	<.05	.09		.01
SO <sub>3</sub> .....			.12	<.2	.35		.62				.00		
Total.....	100	100	100	100	99	100	100	100	100	100	99	100	100
Specific gravity (powder).....	2.59	2.26	2.16	2.60	2.40	2.62	2.63	2.64	2.68	2.67	2.69	2.58	2.80
Specific gravity (lump).....	2.36	1.80	1.95	2.41	2.04	2.50	2.58	2.20	2.41	2.54	2.62	2.52	2.59

The  $\beta$  cristobalite commonly is filled with inclusions, has an index of refraction ranging between 1.460 and 1.480, and is characterized by a strong 4.10A X-ray peak. Some  $\alpha$  (low) cristobalite may be present at a depth of 49 feet where the mineral grains contain few inclusions, have indices of refraction above 1.480, and produce a strong 4.06A X-ray peak. Cristobalite is absent from the upper few feet of the core and from other zones (irregularly distributed throughout the sinter) that have been completely converted to chalcedony.

#### Pre-Lake Lahontan alluvium

Alluvial sediments occur from a depth of 50 feet to 91 feet. At 68 feet, where the alluvium has been extensively opalized, its present chemical and mineralogical composition is very similar to that of the overlying sinter (table 1, fig. 2). Stibiconite, a hydrous antimony oxide, is present at a depth of 68 feet in sufficient amount to color powdered samples of alluvium a pinkish yellow and produce four characteristic X-ray diffraction lines. Rounded fragments of basaltic andesite are common in the lower part of the alluvium, and they are generally rimmed by the green iron-rich mica, celadonite.

#### Steamboat basaltic andesite of Lousetown Formation

The Steamboat basaltic andesite lava flow was penetrated from a depth of 91 feet to 133 feet (fig. 2). Where unaltered this rock consists of phenocrysts of plagioclase and olivine in a cryptocrystalline groundmass composed largely of monoclinic alkali feldspar. The plagioclase phenocrysts are rimmed by overgrowths of anorthoclase that, in turn, may grade into sanidine in the groundmass; a change that probably occurred during the rapid cooling associated with eruption. Quartz is very rare in the fresh rock, and the large amount in the sample at 95 feet is caused by the downward settling of alluvium into the scoriaeous top of the flow.

K-metasomatism of the basaltic andesite produced nearly pure hydrothermal K-feldspar from all the primary plagioclase phenocrysts and exchanged K for Na in most of the original anorthoclase and sanidine. Small amounts of celadonite and pyrite formed, during K-metasomatism, from primary olivine, aluminum released in the breakdown of plagioclase, and sulfide ions in the thermal water. Few minerals susceptible to further alteration remained in the altered basaltic andesite, thus partially explaining the paucity of clay

minerals produced during a later period of H-metasomatism.

The sample from a depth of 111 feet requires special discussion because it does not fit the patterns described in the preceding paragraph. The original plagioclase phenocrysts are completely replaced by disordered kaolinite; hydrothermal K-feldspar and celadonite are absent. Because elsewhere plagioclase is easily kaolinized in an acid environment but K-feldspar is commonly metastable and is the last silicate mineral to be altered, it is concluded that the basaltic andesite from 111 feet in depth near the center of the flow was insulated from the early episode of K-metasomatism. Subsequently, during an episode of H-metasomatism, while the K-feldspathized basaltic andesite was metastable, all plagioclase at 111 feet was kaolinized. The massive impermeable nature of the flow, and fracturing caused by structural deformation that occurred between the two periods of alteration, probably explain the difference in access of the altering fluids.

The identification of the small amount of kaolinite in the sample at 100 feet is questionable. The mineral has a 7A periodicity, a  $d_{001}$  spacing of 7.15Å, and is dioctahedral. Its index of refraction, however, is slightly above 1.57 and, therefore, the mineral may be dioctahedral septechlorite rather than kaolinite.

#### Pre-Lousetown alluvium

From a depth of 133 feet to 160 feet, arkosic alluvium contains abundant recognizable fragments of granodiorite and soda trachyte. Other fragments include andesite and metamorphic rocks.

The sample from a depth of 148 feet presents evidence that suggests a period of hydrothermal alteration predating the deposition of these sediments. A fragment of granodiorite contains chlorite that is pseudomorphic after primary biotite. The fragment is enclosed by a fine-grained matrix containing many bleached biotite flakes but none altering to chlorite. The pseudomorphic alteration of biotite to chlorite is common in drill holes GS-3 and GS-4 as an early product of H-metasomatism (Schoen and White, 1965). In GS-6, however, chlorite is very rare, apparently because K-metasomatism either bleached the biotite or converted it to celadonite. It is, therefore, possible that this granodiorite fragment was hydrothermally altered prior to its erosion and deposition. This supports White's conclusion that some hydrothermal activity predated the extrusion of the Steamboat basaltic andesite (White and others, 1964, p. B33).

Volcanic plagioclase and some plutonic plagioclase were converted to hydrothermal K-feldspar during K-metasomatism of the alluvium. Celadonite and pyrite formed as products of the thermal water and the breakdown of all primary ferromagnesian minerals except biotite, which in general simply was bleached. Later H-metasomatism of the alluvium produced clay minerals from the most susceptible minerals, especially remnant plutonic plagioclase.

#### Alta Formation

An altered soda-trachyte lava of the Alta Formation occurs between a depth of 160 feet and 170 feet. Fresh trachyte from nearby areas consists of plagioclase phenocrysts and numerous tiny oriented sodic plagioclase crystals in a very fine grained groundmass of anorthoclase and quartz. Hornblende and biotite are common but minor in amount. Quartz makes up about 15 percent of the rock.

K-metasomatism of the trachyte converted all plagioclase and some of the anorthoclase to hydrothermal K-feldspar. Subsequent H-metasomatism (argillization) was relatively ineffective in altering the K-feldspar and residual anorthoclase to clay minerals.

A thin bed of arkosic sediment extends from a depth of 170 feet to 177 feet. This rock was originally composed entirely of granodioritic debris. K-metasomatism converted some plagioclase to hydrothermal K-feldspar, but most of the plagioclase persisted until later when it was changed to clay minerals by H-metasomatism. It is possible, however, that some of the clay minerals, especially kaolinite, might have formed by weathering of plagioclase prior to hydrothermal alteration.

#### Granodiorite

Granodiorite extends from 177 feet to the bottom of the hole at 212 feet. Fresh granodiorite contains plagioclase, quartz, orthoclase, biotite, hornblende, and chlorite in order of decreasing abundance. K-metasomatism changed some of the plagioclase to hydrothermal K-feldspar in the samples from depths of 205 feet and 210 feet. But at 180 and 190 feet no hydrothermal K-feldspar was produced and, instead, most of the plagioclase was altered to clay minerals, probably during later argillization. As mentioned in the preceding paragraph, the kaolinite may have formed by weathering prior to hydrothermal alteration.

#### Clay mineralogy

The clay minerals in these rocks deserve special mention because they are apparently related to differences in the alteration process.

Kaolinite, montmorillonite, and mixed-layer illite-montmorillonite are the common clay minerals in GS-6. The kaolinite is well crystallized except in core samples from above a depth of 155 feet, where it is disordered. The montmorillonite gives a 12.4A basal X-ray spacing which probably indicates natural saturation of the clay with sodium and potassium ions. When exposed to ethylene glycol vapor the montmorillonite expands to 17A in a normal manner. The mixed-layer illite-montmorillonite in GS-6 is present as two varieties. A regular mixed-layer illite-montmorillonite is present only in the granodiorite, whereas a randomly interlayered illite-montmorillonite is restricted to other rock types.

In the regular mixed-layer clay, the illite and montmorillonite layers are inferred to be present in equal proportions, and the  $d$ -spacing and intensity data are similar to those of the mineral allevardite (Brindley, 1956). In particular, the large increase in intensity of the 003 and 004 peaks after saturation with ethylene glycol is similar to that reported for allevardite (fig. 3A, B, C). Unlike allevardite, however, odd-order reflections cannot be detected after heating for 1 hour at 550°C, probably because of the small amount of clay contained in the samples (fig. 2). The  $d$ -spacings obtained from air-dried, glycolated, and heat-treated samples of this clay from depths of 180, 190, and 205 feet are consistent with an interpretation of equal amounts of 10A illite and 12.4A montmorillonite regularly interleaved. With the limited data available, it is best to refer to this mineral by the general name, regular mixed-layer illite-montmorillonite, rather than using the special name "allevardite".

In GS-6, random mixed-layer illite-montmorillonite is commonly found in hydrothermally altered rocks other than granodiorite (fig. 3D, E, F). This mineral is similar to that reported from granodiorite in drill holes GS-3 and GS-4 (Schoen and White, 1965). Excellent agreement in the proportions of component layers is generally obtained by assuming a 10A illite and a 12.4A montmorillonite that expands to 17.0A on glycolation. This clay mineral is somewhat similar to a random illite-montmorillonite interstratification reported by MacEwan (1956), especially in having a reflection at about 30A without integral suborder reflections (fig. 3E). According to Weaver (1956, p. 217) and MacEwan (1956, p. 167), this is due to some statistical regularity within a long sequence of layers. At present, we can offer no explanation for restriction of the more ordered mixed-layer clay to the granodiorite in GS-6.

#### Other drill holes

Comparison of the mineralogy of drill hole GS-6 with the six other drill holes already described in detail (Sigvaldason and White, 1961, 1962; Schoen and White, 1965), indicates generally similar alteration patterns for the same rock types.

As might be expected, GS-2, located only 1,500 feet northeast of GS-6 on the High Terrace (fig. 1), bears close resemblance mineralogically to GS-6, especially in regard to abundant hydrothermal K-feldspar in the upper part of the hole. GS-2 is 398 feet deep with maximum temperatures and chloride concentrations of 154°C and 464 ppm, respectively, indicating greater present-day hydrothermal activity than in GS-6. GS-2 contains some unreplaced volcanic plagioclase in the upper 200 feet, implying that the intensity of K-metasomatism was somewhat less than in GS-6, where all volcanic plagioclase was replaced. The deeper parts of drill hole GS-2 contain corrensite and chlorite (Sigvaldason and White, 1961, p. D120) that are either absent or very rare in GS-6. In GS-2, hydrothermal K-feldspar decreased with depth below 200 feet, and mixed-layer illite-montmorillonite increased. GS-6 is too shallow to evaluate these possibilities.

The strong hypogene H-metasomatism associated with fractures in GS-3 and GS-4 (Schoen and White, 1965) that produces a rock composed entirely of illite, quartz, and pyrite, is not evident in GS-6. Apparently the K-metasomatism that affected the rocks in GS-6 was characterized by  $K^{+1}/H^{+1}$  ratios that exceeded the stability limit of illite (Hemley, 1959, p. 246). In addition, silicification is unimportant in GS-6 because the minerals produced by K-metasomatism contain as much or more silica than the minerals they replace.

The common occurrence of an easily alterable mineral like celadonite above the water table indicates that the rocks in GS-6 have not been subjected to the intense sulfuric acid leaching noted in GS-7 (Sigvaldason and White, 1962) as well as near the surface in GS-3 and GS-4 (Schoen and White, 1965). This kind of alteration is caused by hydrogen sulfide gas escaping upward from a subsurface body of thermal water, oxidizing near the ground surface, and dissolving in water from precipitation or from condensing steam. The acid then percolates back down to the water table, reacts with unstable minerals on its way, and produces opaline residues. This type of intense leaching is rare in GS-6, occurring only in the upper part of the Pre-Lake Lahontan alluvium.

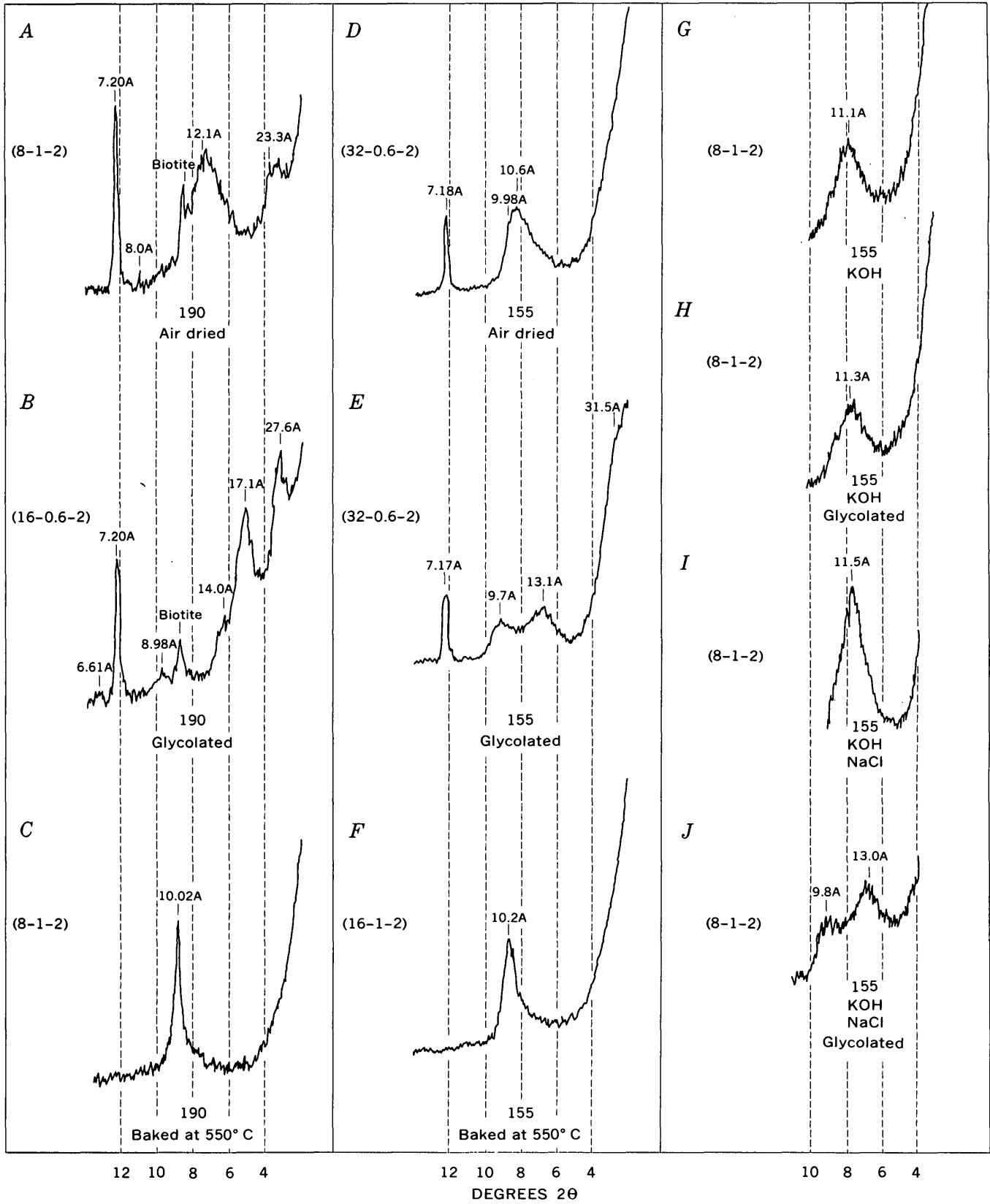


FIGURE 3.—X-ray diffractograms of representative clay-mineral fractions, drill hole GS-6. A-C, sample collected at 190 feet, D-J, sample collected at 155 feet. The nature of the treatment each sample was given prior to X-ray analysis is listed below each diffractogram. The numbers in parentheses show the scale factor, multiplier, and time constant, respectively, used during the recording of the X-ray diffractogram.



### GEOCHEMISTRY

The general patterns of mineral distribution shown in figure 2 can be correlated with the kind and sequence of alteration reactions that occurred in the rocks.

#### K-metasomatism

The distribution of hydrothermal K-feldspar is primarily related to the original abundance of minerals most sensitive to K-metasomatism. Volcanic plagioclase is the feldspar most susceptible to replacement by K-feldspar during K-metasomatism, followed by plutonic calcic plagioclase, sodic plagioclase, volcanic alkali feldspars (anorthoclase and sanidine), and finally orthoclase, which is inert during K-metasomatism.

Olivine, hornblende, and pyroxene were destroyed during the early stages of the K-metasomatism, and the iron and magnesium liberated were used in forming celadonite. Therefore, the original distribution of celadonite and hydrothermal K-feldspar was somewhat similar. Later alteration has tended to argillize most of the celadonite, which may account for its apparent absence below a depth of 155 feet (fig. 2). Small amounts of celadonite, however, are recognizable in thin sections of most samples to the bottom of the hole. Celadonite is rare or absent in all other drill core from Steamboat Springs, and the abundance of celadonite in GS-6 is probably related to the high initial abundance of iron and magnesium in the rocks.

Biotite was converted to a bleached mineral pseudomorphic after the original biotite, during K-metasomatism, and exhibits a broadened and reduced 10A X-ray periodicity that does not expand with ethylene glycol. This bleached biotite is more resistant to H-metasomatism than some plutonic plagioclase, as evidenced by its presence in the highly argillized upper parts of the granodiorite.

#### H-metasomatism

The experimental work of Hemley (1959) indicates that the clay minerals K-mica (illite) and kaolinite precipitate from solution at moderate to low  $K^{+1}/H^{+1}$  ratios, respectively, and that K-feldspar precipitates at high  $K^{+1}/H^{+1}$  ratios. We conclude from this that the coexisting clay minerals and hydrothermal K-feldspar in GS-6 formed at different times and from different solutions. Because clay minerals form at the expense of feldspars in fluids with relatively low ratios of other cations to hydrogen ions (Hemley and Jones, 1964), the term H-metasomatism has been used in this report to describe this argillization.

Although K-feldspar can persist metastably in non-equilibrium environments, clay minerals are character-

ized by relatively rapid changes in response to changing environments. Environmental sensitivity of the random mixed-layer illite-montmorillonite of a sample from 155 feet in GS-6 is shown by X-ray diffractograms after soaking in 1*N* KOH at room temperature for 24 hours (fig. 3*G*); the same sample after glycolation (fig. 3*H*) showing the loss of expansibility compared to figure 3*E*; the same sample after soaking in 1*N* NaCl at room temperature for 43 hours (fig. 3*I*); and the same sample glycolated (fig. 3*J*) now apparently restored to the condition shown in figure 3*E*. If the clay minerals in GS-6 had formed prior to K-metasomatism, they should have been converted to K-mica or possibly even to K-feldspar. The fact that clays are now present in GS-6 indicates that they formed after K-metasomatism.

Kaolinite, however, may be an exception. Its constant iron- and magnesium-free composition and generally coarse grain size may make it less sensitive to alteration than other clay minerals. Thus, the abundant kaolinite that formed at the expense of plagioclase in the upper part of the granodiorite may be a result of ancient subaerial weathering. However, the presence of residual biotite in this zone seems inimical to this hypothesis. The origin of the unique mineral assemblage from a depth of 180 feet is still in doubt.

#### Genesis and distribution of clays

The three clay minerals in GS-6 (mixed-layer illite-montmorillonite, montmorillonite, and kaolinite) probably formed in response to decreasing  $K^{+1}/H^{+1}$  ratios and decreasing temperatures in the aqueous environment. Both variables favor the formation of montmorillonite from mixed-layer illite-montmorillonite and kaolinite from montmorillonite. This is in accord with Hemley's experimental work (Hemley and Jones, 1964) as well as the field observations of Altschuler and others (1963).

Several factors controlled the abundance and distribution of clay minerals in GS-6. Most important was the saturation of the rock with water of low cation/ $H^{+1}$  ratio. A low ratio of other cations to  $H^{+1}$  in the water is fundamental to the formation of clays (Hemley, 1959). Except for the sample from 111 feet, clay minerals are abundant only below a depth of about 150 feet, which is the level of the present-day water table (fig. 2). As an example, in the sample from 155 feet, which is below the water table, all plagioclase that was not previously altered to hydrothermal K-feldspar has been argillized. The sample from 133 feet and above the water table still contains unreplaced plagioclase and little clay.

A second factor is the relative abundance of easily alterable minerals at the time H-metasomatism began.

This is well illustrated by comparing the sample from 160 feet (trachyte) with the sample from 171 feet (arkose). The volcanic plagioclase in the sample from 160 feet was previously replaced completely by hydrothermal K-feldspar, which remained metastable during subsequent argillization, whereas much of the plutonic plagioclase in the sample from 171 feet resisted K-feldspathization and was then still available for later argillization.

The anomaly of abundant kaolinite in the sample from 111 feet is, in part, related to the proximity of a fault zone (White and others, 1964, p. B17) that served as a channel for H-metasomatizing fluids.

### SYNTHESIS

The alteration of the rocks cut by drill hole GS-6 was a complex process that left fragmentary evidence. The conclusions based on this evidence are necessarily tentative, but we believe these conclusions have the fewest inconsistencies.

Hydrothermal alteration probably began in the vicinity of GS-6 after deposition of the Pre-Lake Lahontan alluvium. Hot silica-laden water rose and discharged onto the land surface, forming opaline sinter deposits. At the same time that sinter was forming at the surface, K-metasomatism was probably taking place at depth.

The high ratios of  $K^{+1}/H^{+1}$  necessary to produce K-metasomatism by the water were probably achieved by two mechanisms that were active at this time. As the hot water rose from depth, the decrease in confining pressure allowed boiling to occur, and volatiles such as  $CO_2$  and  $H_2S$  were rapidly lost to a vapor phase. The loss of  $CO_2$  caused a decrease in the  $H^{+1}$  activity and a consequent increase in the  $K^{+1}/H^{+1}$  ratio. Such a mechanism is probably responsible for restricting K-metasomatism to the upper part of the spring system. A contributory factor in causing high  $K^{+1}/H^{+1}$  ratios during the very early stages of activity may have been the freshness of the rock adjacent to deep channels in the spring system. The reaction of thermal water with fresh rock should have consumed more of the available  $H^{+1}$  while also assuring enough  $K^{+1}$  to yield fluids with higher  $K^{+1}/H^{+1}$  ratios than are now found in the thermal waters.

Many factors contributed toward ending K-metasomatism in the vicinity of GS-6. Among the more important are: (1) insulation of the deep channels by

altered rock, resulting in thermal waters near the surface having compositions high in  $H^{+1}$ ; (2) lowering of the water table below the land surface, which greatly reduced the throughflow of mineralized thermal water and allowed evolved  $H_2S$  to form sulfuric acid above the water table that subsequently drained downward to be incorporated in part by the water circulating at depth; and (3) sealing of the deep channels by deposition of minerals resulting in further decreases in the supply of thermal water. Both decreasing  $K^{+1}/H^{+1}$  ratios and decreasing temperatures favored the formation of clay minerals from the readily alterable minerals remaining in the rocks. This argillization still may be going on in the vicinity of drill hole GS-6.

### REFERENCES

- Altschuler, Z. S., Dwornik, E. J., and Kramer, Henry, 1963, Transformation of montmorillonite to kaolinite during weathering: *Science*, v. 141, p. 148-152.
- Brindley, G. W., 1956, Allevardite, a swelling double-layer mica mineral: *Am. Mineralogist*, v. 41, p. 91-103.
- Hemley, J. J., 1959, Some mineralogical equilibria in the system  $K_2O-Al_2O_3-SiO_2-H_2O$ : *Am. Jour. Sci.*, v. 257, p. 241-270.
- Hemley, J. J., and Jones, W. R., 1964, Chemical aspects of hydrothermal alteration with emphasis on hydrogen metasomatism: *Econ. Geology*, v. 59, p. 538-569.
- MacEwan, D. M. C., 1956, A study of an interstratified illite-montmorillonite clay from Worcestershire, England: *Clays and Clay Minerals*, Proc. 4th Natl. Conf., NAS-NRC pub. 456, p. 166-172.
- Schoen, Robert, and White, D. E., 1965, Hydrothermal alteration in GS-3 and GS-4 drill holes, Main Terrace, Steamboat Springs, Nevada: *Econ. Geology*, v. 60, p. 1411-1421.
- Sigvaldason, G. E., and White, D. E., 1961, Hydrothermal alteration of rocks in two drill holes at Steamboat Springs, Washoe County, Nevada: Art. 331 in *U.S. Geol. Survey Prof. Paper 424-D*, p. D116-D122.
- , 1962, Hydrothermal alteration in drill holes GS-5 and GS-7, Steamboat Springs, Nevada: Art. 153 in *U.S. Geol. Survey Prof. Paper 450-D*, p. D113-D117.
- Thompson, G. A. and White, D. E., 1964, Regional geology of the Steamboat Springs Area, Washoe County, Nevada: *U.S. Geol. Survey Prof. Paper 458-A*, p. A1-A52.
- Weaver, C. E., 1956, The distribution and identification of mixed-layer clay in sedimentary rocks: *Am. Mineralogist*, v. 41, p. 202-221.
- White, D. E., Brannock, W. W., and Murata, K. J., 1956, Silica in hot-spring waters: *Geochim. et Cosmochim. Acta*, v. 10, p. 27-59.
- White, D. E., Thompson, G. A., and Sandberg, C. H., 1964, Rocks, structure, and geologic history of the Steamboat Springs thermal area, Washoe County, Nevada: *U.S. Geol. Survey Prof. Paper 458-B*, p. B1-B63.