*Economic Geology*
Vol. 60, 1965, pp. 1411-1421

# HYDROTHERMAL ALTERATION IN GS-3 AND GS-4 DRILL HOLES, MAIN TERRACE, STEAMBOAT SPRINGS, NEVADA[1]

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## ABSTRACT

Hot spring waters at Steamboat Springs, Nevada, deposit small amounts of mercury, antimony, gold, and silver and hydrothermally alter the rocks through which they flow. Two patterns of alteration can be recognized in the granodiorite bedrock underlying the Main Terrace: an ill-defined pattern of alteration related to depth, and a more distinct pattern consisting of zones of various mineral assemblages enveloping fractures. The alteration mineral assemblages related to fractures resemble the alteration mineral assemblages in granodiorite of the Butte, Montana, copper mining district.

Alteration related to depth includes the replacement of some plagioclase by hydrothermal K-feldspar in the upper 300 feet of the spring system, and the formation of albite and calcite from calcic plagioclase at depths greater than about 200 feet.

Near fractures, hornblende is the most reactive mineral and is replaced by random mixed-layer illite-montmorillonite and iron-rich chlorite. Biotite alters pseudomorphically to chlorite. Calcic plagioclase alters to mixed-layer illite-montmorillonite. Plutonic K-feldspar and quartz are generally unaffected.

The most intense alteration is immediately adjacent to fractures where all feldspars and previously formed chlorite, mixed-layer illite-montmorillonite, and calcite are replaced by illite (with less than 10 percent interlayered montmorillonite), quartz, and pyrite.

The $K^+/H^+$ ratio in the deep high-temperature waters suggests that the waters are in equilibrium with K-mica as determined by Hemley's reaction studies. Therefore, the present-day spring waters may still be producing the observed hydrothermal alteration. This hypothesis, coupled with the proven ability of these waters to deposit metals, indicate that the spring waters are similar to some ore-forming fluids.

STEAMBOAT SPRINGS, NEVADA, is an area of hot spring activity in southern Washoe County near the California-Nevada boundary (Fig. 1). Because mercury, antimony, gold, and silver are being deposited by the hot waters, the springs have long been of interest to economic geologists (7, 2, 15, p. 110–113). The possibility that the thermal waters will be useful in characterizing ancient ore-forming solutions is enhanced by the nearness of the spring system to the celebrated gold-silver deposits of the Comstock Lode and to epithermal mercury deposits (13).

A summary of past geologic studies in the area was given by Brannock and others (2), and White and others (16). The alteration mineralogy in

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[1] Publication authorized by the Director, U. S. Geological Survey.

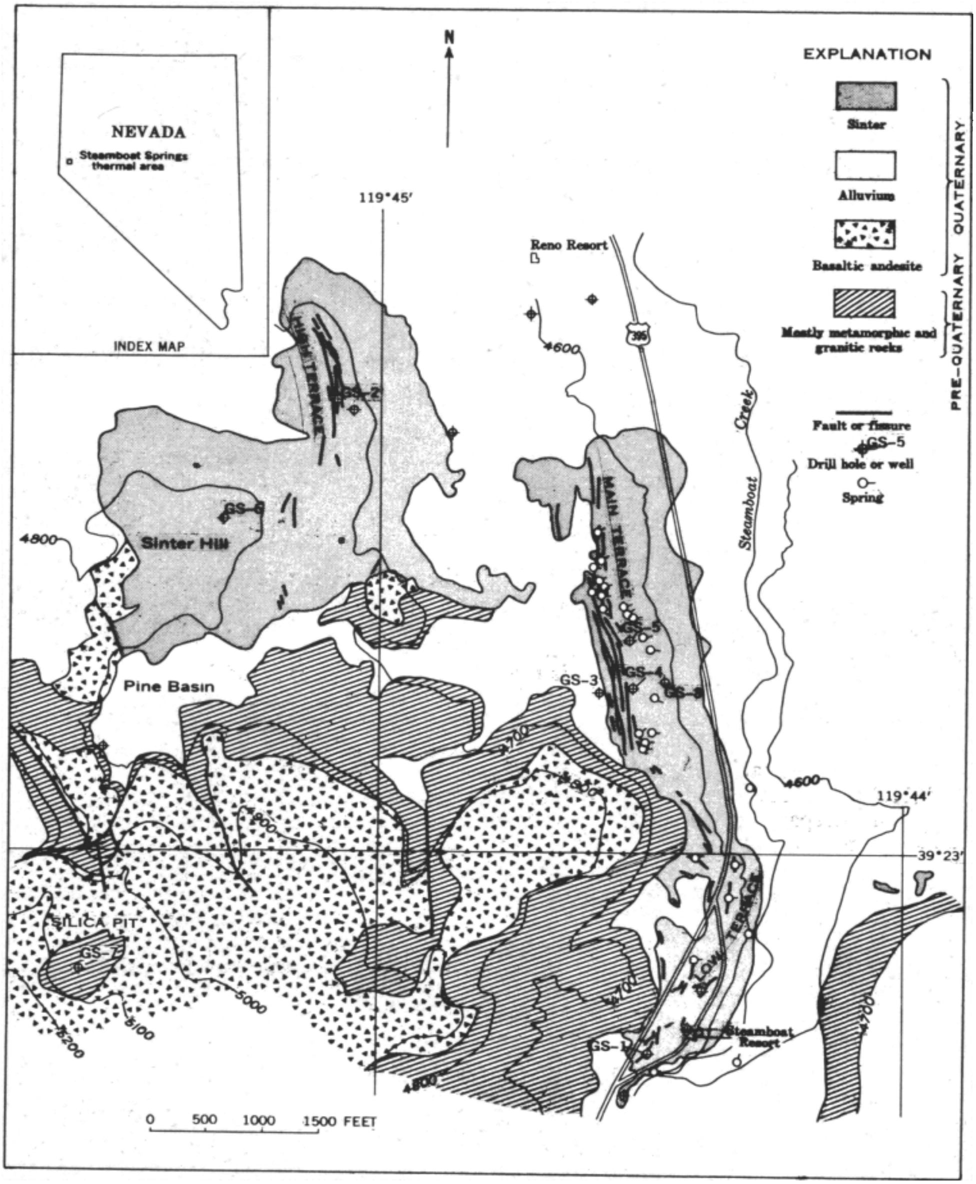


FIG. 1. Generalized geologic map of Steamboat Springs thermal area, Washoe County, Nevada. (From detailed map, D. E. White and others, 1964.)

core from four drill holes at Steamboat Springs was described by Sigvaldason and White (11, 12). The present report describes the alteration mineralogy in the core from two more drill holes in the Main Terrace, the most active part of the area, and considers briefly the relationships between the alteration and the present spring waters.

The pattern of rock alteration observed at Steamboat Springs is similar to that reported from Butte, Montana, and other famous mining districts, and we consider it probable that the present-day waters are still producing this alteration. Therefore, in spite of the fact that the metal deposits at Steamboat Springs are not rich enough to be classed as ore (2), the present-day thermal waters may be similar to some ore-forming solutions.

The basement rocks of the thermal area consist of a granodiorite pluton of late Mesozoic age intruded into metasediments and metavolcanics of probable early Mesozoic age. Tertiary and Quaternary volcanic rocks were extruded on the eroded surface of this basement, and andesite dikes were intruded into the granodiorite. Alluvium and silicious sinter were deposited intermittently during and after the last volcanic eruptions. The generalized geology and the locations of drill holes, springs, and fissure systems are presented in Figure 1. The drill holes described in this report, GS-3 and GS-4, intersect only granodiorite bedrock below the surficial alluvium and sinter.

## METHODS

The mineralogy of the rocks was determined by X-ray diffraction, microscopic study of thin sections, and chemical and spectrographic analyses. X-ray mineralogic analysis was performed on 5 gram samples ground dry for 15 minutes and packed in standard 2 cm aluminum mounts. Clay minerals were concentrated by centrifuging an aqueous suspension and making two successive withdrawals with a pipette of a small amount of suspension containing the less than 2 $\mu$ size material (3). The $<2\ \mu >0.5\ \mu$ fraction was then sedimented on a glass slide for X-ray diffraction analysis

Significant mineralogic variations in the drill core were determined primarily by X-ray methods. X-ray diffractograms of three samples of fresh granodiorite from outside the hot spring area were the basis for a semi-quantitative evaluation of changes in mineralogy effected by alteration.

A strong X-ray peak, most nearly free from interference, was studied for each mineral. The maximum peak height for a mineral, on diffractograms of the three fresh granodiorites, was equated with the average volume percentage of the mineral reported by modal analyses. The maximum peak height was used so that any reduction could be related directly with degree of alteration. A further check on the peak height of quartz was obtained by calibrating against known artificial and natural rock standards. The amount of quartz determined against known standards was 2 to 4 percent less than that reported by modal analyses.

Comparison of the maximum X-ray peak height in the fresh granodiorite with the peak height in altered granodiorite gave a proportion that was assumed to be linearly related to the percentage of the mineral present in the altered rock. We are aware that this assumption is not strictly valid and for this reason calculated abundances are considered to be no more than semi-quantitative. The volume percentage increase of all the alteration phases was considered to equal the volume percentage decrease of all the primary phases and the distribution of alteration phases was again considered to be linearly related to peak heights.

Although modal and X-ray analyses of the three samples of fresh granodiorite indicated that quartz was a relatively constant 25 percent, X-ray results for quartz from pieces of almost fresh drill core ranged from 20 to 30 percent based on the known standards. Two samples GS-3-513 and GS-3-685 gave values of 16 and 18 percent quartz, respectively. As thin sections show that quartz is not replaced during hydrothermal alteration, this slight variation in quartz values is probably related to the difficulty of selecting representative rock chips from small pieces of diamond drill core. For this reason, X-ray peaks of quartz from altered rocks were interpreted as signifying 25 percent of the rock if they fell within the limits of 16 to 30 percent noted for the fairly fresh granodiorite. Only when the quartz peaks exceeded these limits was a greater percentage of the rock considered to be quartz.

This same reasoning cannot be applied to the other primary minerals in the rocks because these minerals are all replaced to some degree by the alteration. The accuracy of this method is undoubtedly low; however, its ability to pick up major and even minor changes in mineralogy has been verified in this study.

## MINERALOGY

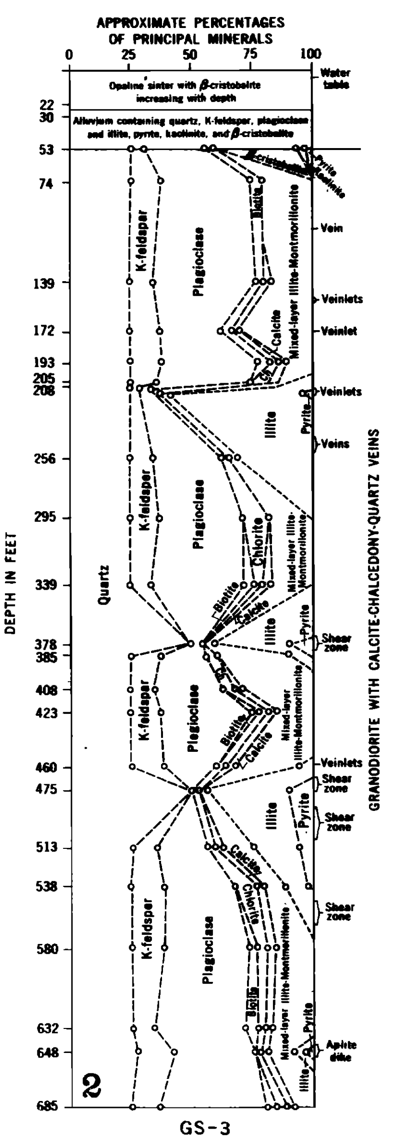
Fresh granodiorite from just outside the spring area contains plagioclase feldspar (oscillatory zoning near andesine with rims of oligoclase), quartz, orthoclase, biotite, hornblende, and chlorite in decreasing order of abundance. The minor chlorite indicates that even this granodiorite is not entirely fresh.

Granodiorite within the spring area is altered in relation to its distance from flow channels and presumably to the size and length of time each flow channel has existed. In addition, there is an ill-defined pattern of alteration related to depth. However, even the freshest granodiorite from the diamond drill holes is devoid of hornblende except sporadically near the surface in GS-1 drill hole (11, p. D117). Hornblende is clearly the most unstable mineral in the hydrothermal environment.

*Drill Hole GS-3.*—The fissure system of the Main Terrace, along which alteration is most intense, dips to the east, away from GS-3 (Fig. 1; detailed log in White and others, 1964, table 3). Hence, the granodiorite is relatively fresh except near fractures. Abundances of minerals computed from the X-ray data are plotted semiquantitatively in Figure 2. Major variations in percentages of the minerals occur at shear zones and veins, which are indicated along the right side of Figure 2. Sampling was not sufficiently closely spaced to define all zones of intense alteration.

Alteration controlled by fractures can be divided arbitrarily into a less intense zone of argillization away from fractures and an intensely altered zone of sericitization adjacent to fractures. The intensity of alteration is considered here to be the degree to which hydrogen metasomatism has affected the rock (6).

Thin sections show that in the argillic zone biotite is first bleached and then is replaced by chlorite. The chlorite replaces the bleached biotite pseudomorphically without any visible change in volume and with the same crystallographic orientation. The more calcic cores of the zoned plagioclase



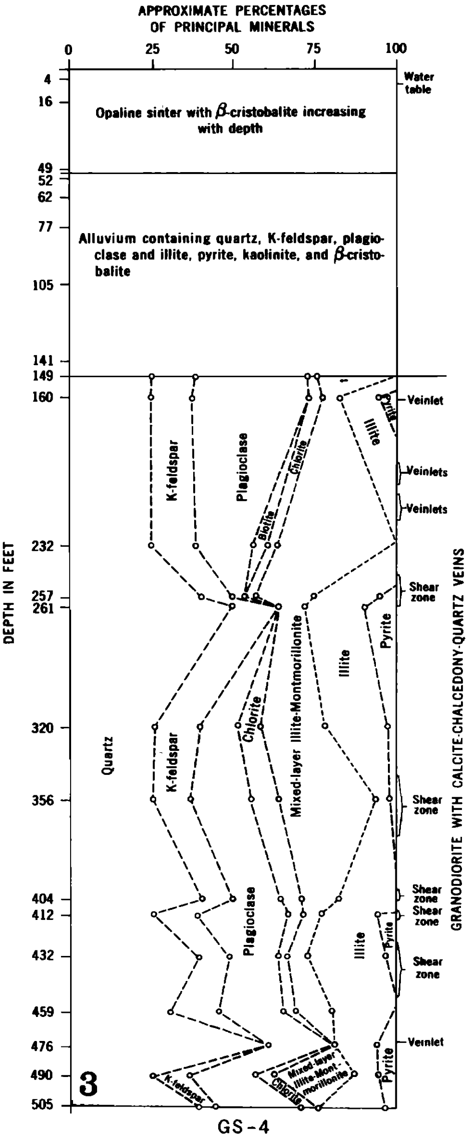


FIG. 2 (Left) Semiquantitative plot of mineralogy from drill hole GS-3, Main Terrace, Steamboat Springs. Straight lines arbitrarily drawn between points of observation. Ch = chlorite.

FIG. 3. (Right) Semiquantitative plot of mineralogy from drill hole GS-4, Main Terrace, Steamboat Springs. Straight lines arbitrarily drawn between points of observation.

crystals are replaced by fine-grained wormy mixed-layer illite-montmorillonite with low birefringence and a low index of refraction of about 1.53 or less. Quartz and orthoclase are unaltered in the argillic zone.

In the sericitic zone adjacent to fractures, only illite (sericite of Hemley and Jones, 1964, p. 542) quartz, and pyrite appear to be stable. Fine-grained illite with less than 10 percent interlayered montmorillonite and with fairly high birefringence is produced from the mixed-layer illite-montmorillonite of the argillic zone. Illite also replaces all remaining plagioclase and some orthoclase; where carried to completion all orthoclase is replaced. Chlorite, an alteration product itself, is replaced pseudomorphically by coarse-grained white mica that is probably chemically similar to the illite, and by pyrite. Chalcedonic silica forms in the sericitic zone, presumably from silica that is released by alteration of silicates in both the argillic and sericitic zones. The intense alteration of the sericitic zone overrides all lesser degrees of alteration including that related to depth.

Most of the fractures enclosed by sericitized granodiorite are filled with calcite, chalcedony, and quartz. Above the depth of 174 feet calcite is absent from these veins, evidently because of the increasing solubility of calcite with decreasing temperature.

Away from fractures, in the argillic zone that constitutes most of the rock in GS-3 drill hole, certain mineralogic changes related to depth can be defined. At depths greater than about 200 feet the calcic cores of plagioclase crystals are sometimes replaced by albite that is crystallographically parallel or nearly parallel to the original sodic rims. Patches of calcite also are found replacing the cores of calcic plagioclase crystals at depths greater than about 200 feet. These minerals occur in addition to, rather than instead of, mixed-layer illite-montmorillonite.

Above a depth of about 300 feet some plagioclase is replaced by hydrothermal K-feldspar in a manner similar to, but much less extensive than, that described by Sigvaldason and White (12) in the upper part of GS-5 drill hole. The hydrothermal K-feldspar is not distinguished from original orthoclase in Figure 2.

As previously stated, the intense alteration of the sericitic zone destroys the alteration minerals of the argillic zone as well as the alteration minerals related to depth. However, the degree of development of the sericitic zone is itself related to depth, being somewhat weaker near the surface. For this reason, complete replacement is not always effected in shallow sericitic zones.

X-ray diffractograms of the $<2\ \mu$ fraction show that the hydrothermal clay ranges from a well crystallized illite (with less than 10 percent interlayered montmorillonite) with a 10 angstrom periodicity that is relatively unaffected by heating to 550° C for 1 hour and glyclolation, to a random mixed-layer illite-montmorillonite with up to 45 percent montmorillonite layers. The mixed-layer illite-montmorillonite yields X-ray reflections similar to those reported by MacEwan (8, p. 167). This includes a reflection at about 30 angstroms without integral sub-order reflections. This phenomenon has been interpreted (14, p. 217; 8, p. 167) as due to some statistical regularity within a long sequence of layers.

Away from zones of intense alteration, mixed-layer illite-montmorillonite with a large percentage of montmorillonite layers is the abundant clay mineral. As zones of intense alteration are approached, the percentage of montmorillonite layers decreases. In the zones of intense alteration illite with less than 10 percent interlayered montmorillonite is the only clay mineral. These conclusions, derived from X-ray diffractograms of highly altered and less altered pieces of core, are corroborated in thin sections by a general increase of the lowest index of refraction of the mixed-layer illite-montmorillonite with more intense alteration.

Although the change from mixed-layer illite-montmorillonite to nearly pure illite seems to be continuous in the samples studied, two apparently distinct phases are indicated by X-ray diffraction in some samples. Therefore, illite and mixed-layer illite-montmorillonite are represented by separate fields in Figure 2, but the short-dashed boundary between them indicates our uncertainty of the nature of the difference.

The upper part of drill hole GS-3 passes through hot spring sinter and arkosic alluvium. Some of these rocks were altered in the past by strong sulfuric acid solutions percolating down from the then-existing surface to the water table in existence at that time. The sulfuric acid was formed by oxidation of hydrogen sulfide gas that separated at the water table from the rising spring waters. Similar acid conditions exist locally today on the Main Terrace, particularly adjacent to fissures, and an outstanding example has been described from GS-7 drill hole in the Silica Pit area 1 mile west of the Main Terrace (12).

The silicious sinter deposits consist entirely of amorphous opal at the surface but increasing amounts of $\beta$-cristobalite (high cristobalite) occur at depth, formed by crystallization of opal. The $\beta$-cristobalite is distinguished by a strong X-ray peak near 4.10 angstroms. Arkosic alluvium consisting of disintegrated granodiorite and fragments of volcanic and metamorphic rocks is composed dominantly of quartz, K-feldspar, and plagioclase. Where leached by acid the alluvium contains quartz, kaolinite, $\beta$-cristobalite and small amounts of pyrite, illite and rarely alunite.

For the purpose of examining the alteration effect of rising waters on the rocks, the near-surface acid leached zone must be ignored.

*Drill Hole GS-4.*—The mineralogy of drill core from GS-4 is plotted on Figure 3. The observed minerals and the pattern of alteration is similar to that of GS-3. However, because GS-4 intersects many closely spaced fractures related to the easterly dipping main zone of fissures that control up-flow of thermal waters (Fig. 1), the rock mass has been more pervasively altered. This is indicated in Figure 3 by the virtual absence of biotite and replacement calcite and the relative abundance of pyrite, hydrothermal quartz, and illite with little interlayered montmorillonite. Original plagioclase is relatively rare in GS-4, and much chlorite that replaced biotite has in turn been replaced pseudomorphically by white mica.

An anomalous situation is found near the bottom of GS-4. Intensely altered core from a depth of 476 feet containing illite, quartz, and pyrite is devoid of K-feldspar and yet contains abundant albitic plagioclase. A similar situation occurs at a depth of 505 feet although K-feldspar and chlorite are not completely replaced. The retention of plagioclase in the intensely altered zone of sericitization has not been noted elsewhere at Steamboat Springs.

## GEOCHEMISTRY OF ALTERATION

Twenty-five rock analyses made by standard rapid methods (10) were available for study of the rocks from GS-3 and GS-4. Analyses recalculated to constant rock volume show that $K_2O$, S, $H_2O$, and some $CO_2$ are added during alteration, and $SiO_2$, $Na_2O$, and some CaO are lost. The losses and gains of these chemical components can be related in detail to the changes in mineralogy previously described.

Hornblende, the mineral most susceptible to alteration, is replaced by mixed-layer illite-montmorillonite and iron-rich chlorite. Sodium and calcium probably first go into montmorillonite and then into solution during alteration and are removed from the rock. Some calcium forms calcite during this initial stage of alteration.

Chlorite, which typically occurs in pseudomorphic replacement of biotite, is green and pleochroic and generally exhibits an anomalous brown interference color. However, interference colors from some chlorite range from anomalous blue up to first order red. The chlorite flakes with red interference colors are length-slow and are interpreted to be iron-rich (1). Presumably potassium and silica and possibly some magnesium are lost and water added during the alteration of biotite to chlorite. The released potassium is probably fixed nearby in mixed-layer illite-montmorillonite that is replacing plagioclase feldspar. Analyses indicate that the illite is phengitic with the magnesium presumably derived from biotite and hornblende.

The alteration of plagioclase feldspar to mixed-layer illite-montmorillonite and calcite follows the often observed pattern of greatest instability for calcic plagioclase followed in the most intense alteration by the more sodic plagioclase. Silica, calcium, and some sodium are released as products of this alteration.

The most intense alteration observed in GS-3 and GS-4 produces illite from mixed-layer illite-montmorillonite by the fixation of potassium from the hydrothermal fluid. K-feldspar also alters to illite in this environment. The pseudomorphic replacement of chlorite by coarse-grained white mica (sericite) releases iron which combines with sulfur from solution to form pyrite. This causes an inverse relationship between chlorite and pyrite. Direct replacement of biotite by sericite, without an intervening stage as chlorite, has not been demonstrated.

Silica is released to solution during the alteration of all the primary silicate minerals and chlorite. Analyses indicate that intense alteration slightly reduces the amount of $SiO_2$ in a rock, but figures 2 and 3 show that quartz increases considerably in the intensely altered rocks. This paradox can be explained by the fact that about 75 percent of the fresh granodiorite is composed of minerals that yield some silica to solution during alteration. Much of this silica precipitates in the intensely altered rocks adjacent to veins, thus explaining their higher quartz content. But some silica escapes from the rock either to precipitate in the veins or to be carried off in the rising solutions. This loss of silica explains the lower $SiO_2$ content of rocks from the most intensely altered zone.

The pattern of alteration observed in GS-3 and GS-4 is very similar to that reported from Butte, Montana (9). At Butte, mild alteration yields a zone of montmorillonite and chlorite, and intense alteration destroys all original and early hydrothermal minerals and yields sericite, pyrite, and quartz. However, at Butte these two zones are separated by a zone in which montmorillonite and chlorite are converted to kaolinite. In GS-3 and in GS-4, no intermediate kaolinite zone is found.

Comparison of the mineralogy of GS-3 and GS-4 with GS-1, 2, 5, and 7, described by Sigvaldason and White (11, 12), indicates generally good agreement. The agreement is especially good for GS-5, which is on the Main Terrace 425 feet north of GS-4. The kaolinite reported at depth in GS-1 on the Low Terrace may be equivalent to the intermediate kaolinite zone of Butte. We do not yet understand why kaolinite is developed so extensively in the Low Terrace, apparently unrelated to oxidation of $H_2S$ above the water table, but is absent in the deep alteration of the Main and High Terraces.

The mineral assemblage illite-quartz-pyrite, found in the sericitic zone immediately adjacent to fractures, is inferred to be in stable equilibrium with the deep hydrothermal fluid that moved upward along the fractures. The composition of this fluid can be inferred from experimental data on aqueous fluids in equilibrium with illite and can be compared with present-day hydrothermal fluids of the Steamboat Springs system.

At the temperature of the rocks in the lower part of the drill holes (about 170° C), illite would be stable in a solution whose molal ratio of $K^+$ to $H^+$ was between $10^{3.4}$ and $10^{5.2}$ in the presence of quartz and at a total pressure of 1,000 atmospheres. These values are extrapolated from the experimental data Hemley got from 200° C to 500° C (6 p. 548, and 5, p. 245). The effect of the much lower pressure in the drill holes (from 10 to 25 atmospheres) is presumably to move the stability field of illite to slightly lower $K^+/H^+$ ratios.

An average value for $K^+$ in waters from drill holes GS-3, 4, and 5 is 65 ppm or a molality of $1.67 \times 10^{-3}$. Water at depth, with all $CO_2$ in solution, has about 650 ppm total $CO_2$. Thermodynamic calculations based on theoretical values for the dissociation constants of $H_2CO_3$ at high temperature (4) indicate a molality of $H^+$ of $7.94 \times 10^{-7}$ for this water at 170° C. These calculations take into account the activity coefficients of the hydrogen and bicarbonate ions at 170° C. The effect of sodium not balanced by chloride, which must be balanced by bicarbonate, is also included in the calculations. Using these values the $K^+/H^+$ molal ratio of the present-day thermal waters at depth is $10^{3.3}$. This value lies in the kaolinite stability field close to the extrapolated boundary between kaolinite and illite. However, the effect of lower pressure would place this $K^+/H^+$ value slightly within the illite stability field.

Similarly, the calculated $Na^+/H^+$ molal ratio in the present-day thermal waters is $10^{4.5}$, a value also lying in the extrapolated kaolinite stability field but close to the boundary between kaolinite and montmorillonite (6, p. 549). The effect of lower pressure would be to favor the formation of montmorillonite over kaolinite. However, montmorillonite is not found close to fractures, which must mean that the $Na^+/K^+$ ratio in the hydrothermal fluid is not high enough to make stable a sodium-rich phase.

The fact that montmorillonite becomes a larger proportion of the mixed-layer clay with increasing distance from the fractures, indicates that the $Na^+/K^+$ ratio of pore fluids is increasing away from fractures. This increase in $Na^+/K^+$ is caused by: a decrease in $K^+$ due to the formation of illite in the sericitic zone, and an increase in $Na^+$ due to the breakdown of plagioclase feldspar. Orthoclase, the dominant potassium-rich mineral in the fresh rock, does not break down until it is encroached on by the sericitic zone where it provides $K^+$ to the pore fluids, and results, perhaps, in a slightly higher $K^+/H^+$ ratio than in the adjacent fracture.

Therefore, because illite appears to be a stable phase in the most altered rocks of drill holes GS-3 and GS-4, and because the water presently in the spring system has a calculated composition in which illite should be stable, we conclude that the present-day spring waters are producing the observed hydrothermal alteration. This hypothesis, coupled with the proven ability of these waters to deposit metals, indicate that the spring waters are similar to fluids that have formed some ore deposits.

## ACKNOWLEDGMENTS

The authors benefited from discussions of the calculation of hydrogen ion concentration at elevated temperatures with: G. G. Ehrlich, I. Barnes, W. L. Polzer, and J. J. Hemley. Critical review was graciously provided by J. J. Hemley and L. J. P. Muffler.

U. S. Geological Survey,
Menlo Park, California,
*Jan. 20, 1965*

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